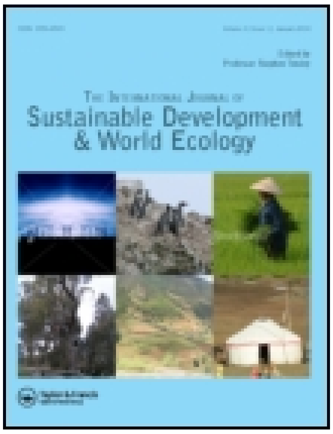

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Estimates of exposure of a coastal city to spatial use changes - a case study in Xiamen

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The coastal zone is an area where the interaction between land and sea is intense. It constitutes a highly dynamic and complex system that plays an important role in human survival and development. The vulnerability of coastal cities has increased due to global changes such as hazards, sea level rise, spatial use changes, etc. This study took Xiamen, a coastal city in Fujian Province, as an example to estimate exposure in relation to spatial use changes. The exposure value was defined as the land use intensity (LUI), comprised of five land-use/land-cover (LULC) types, and the shoreline use intensity (SUI), comprising 10 shoreline use types. The dynamic changes of these variables are discussed in detail from 1987 to 2007. The result show that the exposure value rose swiftly from 2.530 in 1987 to 2.707 in 1992, increased slightly to 2.747 in 1997 and 2.761 in 2002, and finally decreased slowly to 2.743 in 2007. The main reasons for such changes and future research directions are discussed.

Keywords: coastal zone; land use intensity; LULC; human influence; shoreline use intensity; vulnerability

Introduction

The coastal zone is an area where the interaction between land and sea is intense. It is a highly dynamic and complex system that plays an important role in human survival and development (Clark 1995). About 60% of the population, as well as two-thirds of cities with populations exceeding 2.5 million are located in coastal zones (Vitousek et al. 1997). In China, major coastal cities on the eastern seaboard account for 5.1% of the country by land mass but house 31.6% of the national population and are responsible for 67.3% of Gross Domestic Product (GDP) (Yan et al. 2007). Due to diverse natural and human pressures, many coastal cities are experiencing acute environmental problems, such as climate change, sea level rise, coastal erosion, pollution, degradation of dunes and saline intrusion to coastal aquifers and rivers (Clark 1995; Turner et al. 1998). The coastal city's vulnerability to both human and natural influences is particularly challenging. Over the last decade, backed by multidisciplinary collaborations in sustainability sciences, many scholars have become increasingly aware of coastal vulnerability to global changes at all relevant scales (EI-Raey 1997; Klein and Nicholls 1999; IPCC 2001, 2007; Dolan and Walker 2004; Demirkesen et al. 2008).

The presence of a perturbation or stress, sensitivity of the affected entity and the system's capacity to cope or respond (resilience) are major elements in vulnerability analysis of a coupled human–environment system (Turner et al. 2003; Fussel 2007). Exposure in this sense is defined as the nature and degree to which the systems are exposed to environmental changes under different scenarios, such as changing atmospheric carbon dioxide concentration, climate change, socio-economic variables and land-use change (Metzger et al. 2006). Different ecosystems are exposed to varying magnitudes and frequencies of disturbing forces, often resulting in different vulnerabilities (Luers et al. 2003). For example, an exposure index was constructed in relation to direction of prevailing winds and waves for a physical environmental model affecting coastal vulnerability to sea level rise (Bryan et al. 2001). Community vulnerability can be assessed through GIS-based maps, which combine physical and social factors (Clark et al. 1998). Coastal vulnerability to erosion can be assessed using a combination of potential coastal retreat and human occupation of land-use types in order to distinguish five possible forms of vulnerability (Dominguez et al. 2005). However, most research using exposure as a variable to build a coastal vulnerability index (CVI) have neglected the interaction of essential elements such as exposure, sustainability and adaptation capacities in vulnerability analysis (Szlafsztein and Sterr 2007). Some research has simplified exposure assessment in order to focus on the more explicit social variables that together determine coping ability (Clark et al. 1998). Local-scale coastal vulnerability research has given little attention to rapidly growing coastal cities, especially in developing countries.

Urbanisation is accompanied by land-use/land-cover change (LULC) (Grimm et al. 2008). The conversion rates of natural coastal areas into artificial areas have been even stronger than the population increase in many places (Alves et al. 2007); while currently there are not many on-going LULC studies in coastal areas (Huang et al. 2009). Researchers have tended to focus on the interpretation of coastline changes, but few have estimated the degree of land–sea spatial use changes in coastal cities (EI-Asmar 2002; Shaghude et al. 2003; Wang et al. 2005).

The present study took Xiamen as an example to provide a more comprehensive analysis of spatial use changes in coastal cities and to estimate exposure. The objectives of

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this study were to (1) clarify Xiamen temporal–spatial evolution from 1987 to 2007 using remote sensing (RS) and geographic information system (GIS) tools; (2) calculate land use intensity (LUI) according to the intensity level of different LULC types and their proportions; (3) calculate shoreline use intensity (SUI) according to the intensity of different shoreline use types and their proportions; (4) calculate an exposure value based on LUI and SUI; and (5) explain how exposure has developed and the relationship between spatial use changes and human activities throughout the examined period.

Data and methods

Study area

The study area, Xiamen City, is described in the Introduction. The eastern coastline of Xiamen starts from the Dadeng Sea and the Eastern Sea and continues west along the Western Sea. The coastline covers the sea area of Tong'an Bay in the north and Jiulongjiang Estuary in the south (Figure 1). As a Special Economic Zone of China since 1981, Xiamen has many of the characteristics of a free port and is becoming an attractive site for foreign investment. Since the 1980s, the city has developed rapidly, with an annual growth rate of more than 20% in both total population and GDP. The city is under increasing pressure as a result of rapid urbanisation, socio-economic growth and the expanding use of coastal resources.

Data sources

Xiamen spatial use information was acquired from Landsat TM multispectral images (30 m resolution) from 1987, 1992, 1997, 2002 and 2007. When selecting RS images, we not only need to consider weather on the day the image was taken, but also lunar cycles so as to choose data when the tide is ebbing. In addition, topographic maps, vegetation distribution maps and administration zoning maps were also used as supplementary data for image interpretations. Coastal LULC types were classified into seven groups: construction land, agricultural land, forest, freshwater, seawater, beach and unused land. The classification was performed using ERDAS software for geometric correction, atmospheric correction and matching, image enhancement, visual and digital interpretation, etc. of RS impacts in the research area.

The coastline was classified into two major categories according to the use type and physical characteristics: natural and manmade shoreline. Natural and manmade shorelines can be further classified as muddy, rocky, sandy and estuary shorelines. In addition, manmade shorelines have several types: fish farming, salt field, coastal tourism, transportation, urban and rural construction and protection shorelines. With the help of fieldwork, we georeferenced natural or man-made elements, identified morphological features and processed and confirmed the results obtained from RS image analysis.

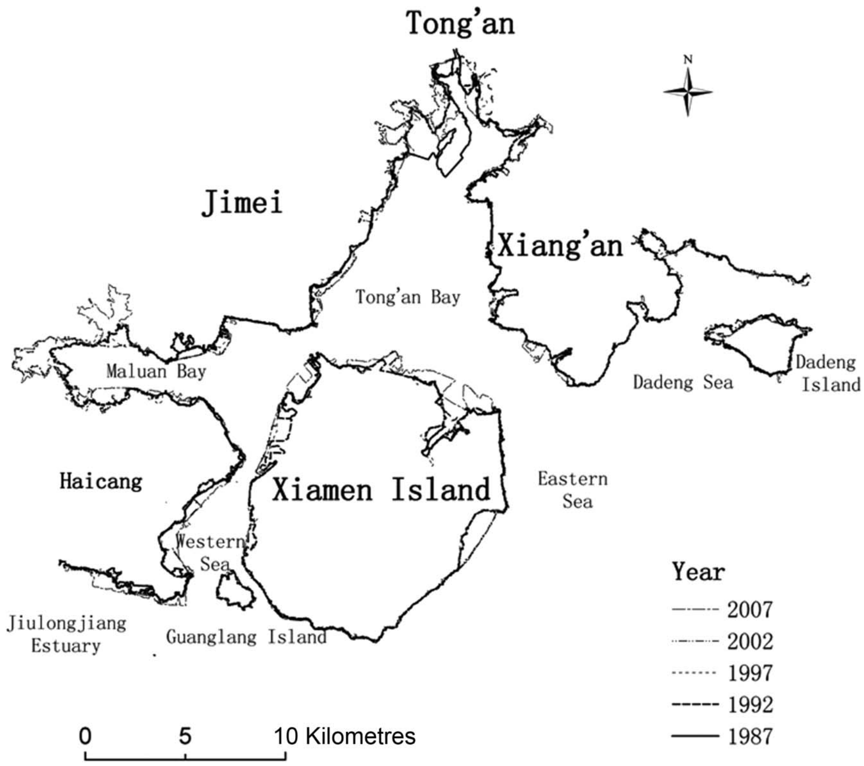

Figure 1. Map of Xiamen City.

Estimates of land use intensity

Land use intensity can be calculated from Equation (1) and provides the degree of the land use stress or perturbation:

$$\mathrm{LUI} = \sum_{i=1}^{n} (G_i \times C_i) \times 100\%, \qquad (1)$$

where LUI is the land use intensity of the investigated area; n is the main types of land use such as unused land, forest, freshwater, agricultural land and construction land in the investigated terrestrial system; C_i is the proportion of the ith type land use; G_i is the intensity level of the ith type of land use, which can be classified at several levels according to the degree and response to perturbations (modified from Zhuang and Liu 1997). We define the use classification of unused land as 1, forest or freshwater as 2, agricultural land as 3, and construction land as 4. Higher classification levels indicate more intense land use.

Estimates of seashore use intensity

Sea spatial use characteristics in coastal zones are mostly concentrated on the shoreline (Halsey and Abel 1990; Croce et al. 1995). The shoreline economic value and importance for coastal development and protection is approximately the same as the entire zone, so the shoreline is an excellent reflection of seashore use conditions. Shoreline use intensity can be calculated using Equation (2) and provides the degree of seashore use stress or perturbation:

$$\mathrm{SUI} = \sum_{i=1}^{n} (H_i \times K_i) \times 100\%, \qquad (2)$$

where SUI is the shoreline use intensity in the investigated area; K_i is the proportion of the ith type shoreline use; n is the types of shoreline use depicted as above; H_i is the intensity level of the ith type of sea use according to configuration and recoverability, and intensity level is assigned with the classification of land use as a reference: muddy, rocky or estuary shoreline is 1, beach, protection or coastal tourism shoreline is 2, fish farming or salt field shoreline is 3, and transportation or urban and rural construction shoreline is 4. Higher classification levels indicate higher intensity of shoreline use.

Exposure estimation

Using expert consultation methods, exposure to spatial use changes can be calculated based on LUI and SUI, as given in Equation (3). The results reveal characteristics such as magnitude and threshold of the coastal city exposure spatial use.

$$E = 0.5\mathrm{LUI} + 0.5\mathrm{SUI}, \qquad (3)$$

where E represents the exposure value of the investigated area; LUI is land use intensity; SUI is seashore use intensity. The larger the exposure value, the higher the pressure, disturbance and spatial use change in the investigated area.

Results

Land system dynamic changes

A map of LULC dynamic changes in Xiamen from 1987 to 2007 is provided in Figure 2. There were distinct changes in the land system in Xiamen from 1987 to 2007 (Table 1). One significant feature was the sustained expansion of construction land and decrease of agricultural land. Construction land increased significantly, with an area of 67.48 km^2 (5% of the city area) in 1987, increasing to 308.21 km^2 (21%) in 2007. Agricultural land increased slightly from 728.96 km^2 (49%) in 1987 to 737.62 km^2 (50%) in 1992, then decreased sharply year-on-year to 442.69 km^2 (29%) in 2007. Most agricultural land was transferred to construction land. Forest area decreased from 658.10 km^2 in 1987 (44%) to 541.54 km^2 (37%) in 1997, and after 1997 increased to 664.42 km^2 (44%) in 2007. This last trend was caused by the policy of reforestation of agricultural land after 1999. As a result of development of water conservancy construction projects, a slight increase in freshwater area was noted, with little temporal variation. Increasing from 10.73 km^2 (1%) to 62.30 km^2 (4%), the development of unused land was also a characteristic of urbanisation.

Sea system dynamic changes

Because not all RS images could be chosen at ebb tide, the interpretation of the beach area was not very precise. In a specific city research area, the area change trend of the seawater was mainly the opposite of land and beach area changes. The reclamation surrounding Xiamen Island focused on urban construction and occupation of near-shore waters (Figures 1 and 2); while the reclamation away from Xiamen Island aimed at aquiculture. For example, in some places in Tong'an Bay and Maluan Bay, agricultural land area near the coastline was changed to fish farms or salt fields, which have the same interpretation characteristic as seawater.

Xiamen Island and the nearby inland coastline can be treated as the mainland coastline; the island line study was only for surrounding big islands such as Gulang Island and Dadeng Island. The existing natural shoreline in Xiamen is rather small because the city has been in development from as early as 1684 and has subsequently suffered from intense human influence and interference. In 2007, the length of rocky shoreline was only 3.517 km, which is mainly on the southeast coastline of Xiamen Island, representing only 1.17% of the city's coastline. Sandy coastline, which accounted for 6.81% of the city coastline in 2007, was also short, with a total length of about 20.420 km, the bulk of which was located on the eastern and southern coast of Xiamen Island, the south coast of Gulang Island and the coast of Haicang District. The estuary shoreline was in the west–east estuary of Tong'an Bay and was only 0.512 km or 0.17% of the city's shoreline (Table 2). Although a considerable proportion of the coastline in Xiamen has historically been muddy, it has been built into a manmade shoreline

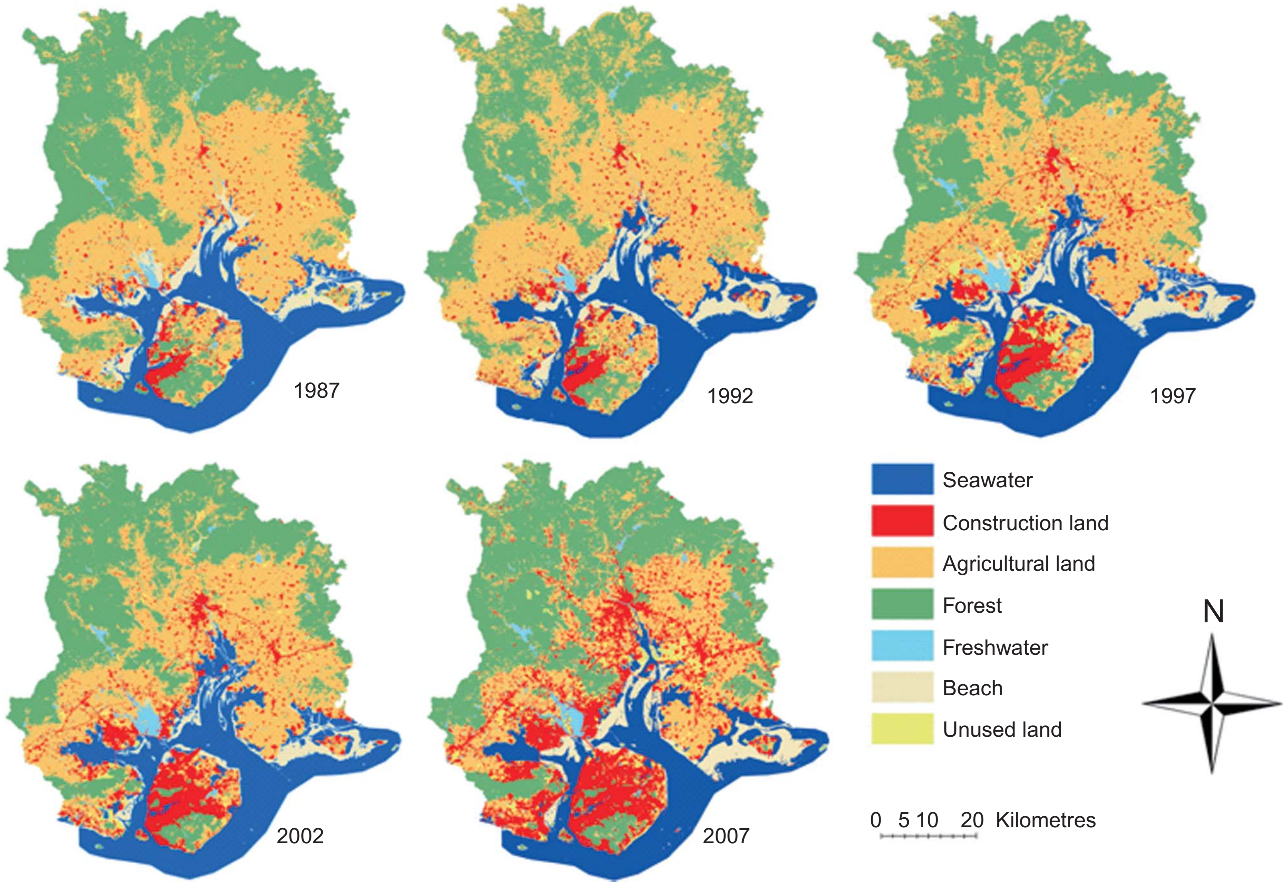

Figure 2. Map of LULC dynamic changes in Xiamen City from 1987 to 2007 (colour online).

Table 1. Land system dynamic changes in Xiamen City from 1987 to 2007.

	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
Land use	1987		1992		1997		2002		2007	
Construction land	67.48	5	94.82	6	132.99	9	169.55	11	308.21	21
Agricultural land	728.96	49	737.62	50	728.75	49	659.15	44	442.69	29
Forest	658.10	44	606.99	41	541.54	37	600.49	40	664.42	44
Freshwater	21.57	1	29.60	2	29.56	2	31.95	2	32.18	2
Unused land	10.73	1	16.50	1	49.69	3	23.92	3	62.30	4
Total area	1486.84	100	1485.53	100	1482.53	100	1485.06	100	1509.80	100

through bank protection and continuous reclamation for cultivation and construction. For the purposes of this paper, all muddy coastlines are categorised as manmade coastlines. In 2007, manmade coastlines were 266.378 km or 91.85% of the city shoreline.

From 1987 to 2007, the Xiamen shoreline length experienced an increase–decrease–increase process (Figure 1). Manmade coastline increased sharply from 1987 to 1992 because of an increase in cultivation ponds and salt field construction, which caused the coastline to zigzag and fragment. From 1992 to 2002, this manmade coastline became shorter because of conversion of cultivation ponds and salt fields to ports and docks. From 2002 to 2007, the construction projects increased because of rapid urbanisation, causing the transportation and construction shorelines to continue to grow, and the intensity and diversity of coastal development was boosted. Meanwhile, fish farming and salt field shoreline decreased sharply and protected shoreline increased gradually (Figure 3).

Estimates of exposure to spatial use changes

The LUI, SUI and exposure values of Xiamen city from 1987 to 2007 were calculated from Equations (1)–(3) and are shown in Table 3. The exposure value of Xiamen rose swiftly from 2.530 in 1987 to 2.707 in 1992, increased

Table 2. Shoreline use dynamic changes in Xiamen City from 1987 to 2007.

Shoreline type	1987 Length (km)	1987 Proportion (%)	1992 Length (km)	1992 Proportion (%)	1997 Length (km)	1997 Proportion (%)	2002 Length (km)	2002 Proportion (%)	2007 Length (km)	2007 Proportion (%)
Natural shoreline	21.306	7.34	25.074	7.37	21.655	8.35	24.357	8.90	24.449	8.15
Among										
Sandy shoreline	17.088	5.89	20.889	6.14	17.514	6.75	20.209	7.38	20.420	6.81
Estuary shoreline	0.609	0.21	0. 571	0.17	0.513	0.20	0.589	0.22	0.512	0.17
Rocky shoreline	3.609	1.24	3.614	1.06	3.628	1.40	3.559	1.30	3.517	1.17
Manmade shoreline	268.886	92.66	315.160	92.63	237.735	91.65	249.565	91.10	275.485	91.85
Among										
Protection shoreline	137.988	47.55	72.015	21.17	46.992	18.12	46.249	16.88	81.380	27.12
Coastal tourism shoreline	7.454	2.57	7.170	2.10	5.994	2.31	6.951	2.54	8.088	2.70
Fish farming & salt field shoreline	101.647	35.03	195.277	57.39	143.035	55.14	151.253	55.21	120.384	40.14
Transportation shoreline	9.158	3.16	17.011	5.01	17.156	6.61	17.035	6.22	26.263	8.76
Urban and rural construction shoreline	12.639	4.35	23.687	6.96	24.558	9.47	28.077	10.25	39.370	13.13
Total shoreline	290.192	100	343.234	100	259.390	100	273.922	100	299.934	100

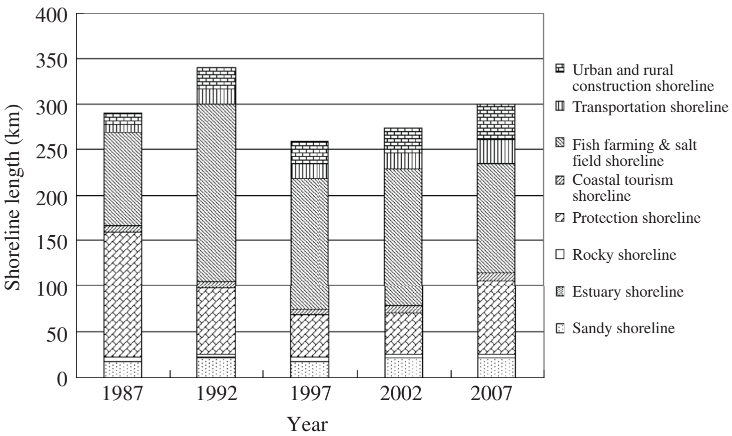

Figure 3. Shoreline use dynamic changes in Xiamen City from 1987 to 2007.

Table 3. Land use intensity, shoreline use intensity and exposure in Xiamen City from 1987 to 2007.

Year	1987	1992	1997	2002	2007
Land use intensity	2.574	2.613	2.637	2.656	2.660
Shoreline use intensity	2.486	2.801	2.857	2.866	2.825
Exposure to change	2.530	2.707	2.747	2.761	2.743

slightly to 2.747 in 1997 and 2.761 in 2002, and finally decreased slowly to 2.743 in 2007 (Figure 4).

Discussion

The results used to quantify the degree of disturbance to Xiamen spatial use changes from 1987 to 2007 show an increase–steady state–decrease trend. From 1987 to 1992, exposure increased dramatically and the slope of SUI was higher than the LUI, which means the effect of the sea system was more important, because of the increase of fish farming and salt field shoreline and dramatic decrease of protection shoreline. From 1992 to 2002, exposure increased: in the land system, the fluctuation of LUI was mainly affected by conversion of agricultural land to construction land; in the sea system, the increase in SUI was mainly caused by conversion of protection, fish farming and salt field shoreline to transportation, urban and rural construction shoreline. From 2002 to 2007, the LUI continued to grow because of urban sprawl, but SUI started to drop because of a distinct decrease in fish farming and salt field shoreline and an increase of protection shoreline. As a result, the exposure value decreased during this period.

The exposure values of Xiamen City to spatial use changes from 1987 to 2007 are clear from the discussion above: although the LUI increased at all times, exposure values increased from 1987 to 2002 and then decreased from 2002 to 2007 because of collaborative action for the

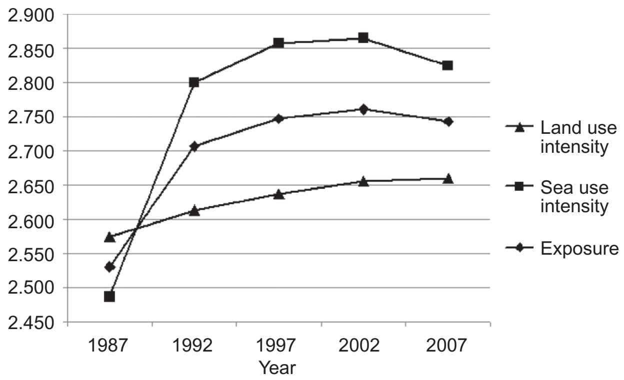

Figure 4. Exposure of Xiamen City to spatial use change from 1987 to 2007.

land and sea systems. Hence, for exposure estimate research in coastal cities, it is important to consider SUI. Exposure of coastal cities to spatial use changes is driven by intense population increase, expansion of industrial space, impacts of human activities with regard to reclamation and coastal protection, increased beach tourism, climate changes, and a multitude of other natural factors. The increase of coastal city areas exposed to spatial use changes may have an impact on geomorphology and reduced water surface area, cause water quality deterioration, resulting in a decline in quality of marine sediment, and thus a reduction in ecosystem services, threatening the delicate balance between ecosystems. The increase in use of coastal spaces can also cause conflicts between various economic sectors in coastal cities such as aquaculture, shipping, tourism, etc. Integrated coastal management (ICM), through an interspatial and intersectoral approach to promote sustainable development, should be used as a governance mechanism for maximising the benefits provided by the coastal zone and minimising conflicts between and harmful effects of human activities on social, cultural and environmental resources (Xue et al. 2004).

To evaluate the sea–land exposure, the dynamic changes of coastal cities is not enough. We should develop good forecasting capacities to analyse and simulate coastal urban spatial evolution. Ecosystem models and scenarios of spatial use changes and other environmental changes are encouraged to estimate ecosystem sensitivity and underscore the need to integrate consideration of environmental change into both coastal management and urban planning in order to help public sector managers develop mitigation, preparedness, response and recovery strategies that are tailored to local needs. This research could serve as a foundation for sensitivity, adaptation and vulnerability assessments.

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