Modeling the Total Allowable Area for Coastal Reclamation: A Case Study of Xiamen, China

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Abstract

This paper presents an analytical framework to estimate the Total Allowable Area for Coastal Reclamation (TAACR) to provide scientific support for the implementation of a coastal reclamation restriction mechanism. The logic of the framework is to maximize the net benefits of coastal reclamation subject to a set of constraints. Various benefits and costs, including the ecological and environmental costs of coastal reclamation, are systematically quantified in the framework. Model simulations are developed using data from Tongan Bay of Xiamen. The results suggest that the TAACR in Tongan Bay is 5.67 km^2, and the area of the Bay should be maintained at least at 87.52 km^2.

Keywords: Total allowable reclamation, Optimal reclamation area, Benefit and cost analysis, Xiamen

1. Introduction

Coastal areas have been the centers of human activity for millennia because of their remarkable biological productivity and high accessibility (WRI, 2001). About 40 percent of the world's population, half of the production and consumption activities are concentrated in the coastal zones which account for only 10% of all land area (Pernetta and Elder, 1993). The costal zones with high population density confront a common problem, the deficit of space. Coastal reclamation is the solution for almost all coastal societies to ease the pressure of land shortage. Large scale sea reclamation activities can be observed in island countries such as Japan, Korea, and Singapore, as well as non-island countries such as Holland, German, and United States (UNAOO, 2006). Although coastal reclamation can create useful space for agriculture, industry, and urban land area, it usually comes at a price of the environment (Li et al., 2008; Zhang et al., 2010). The conversion of sea to land permanently changes the natural characteristics of the ocean and coastal environment and damages considerably the marine ecosystems which human-kind depends on (Xia et al., 2007; Hoeksema, 2007; Airoldi and Beck, 2007; Halpern et al., 2008).

In China, about 13.4 million ha of tidal lands have been reclaimed for agriculture, salt-making, mariculture, and other industrial and urban development uses since the middle of the 20th century (Fu et al., 2010). This has led to the losses of almost half of the country's coastal wetlands and 73 percent of the country's mangroves, which has, in turn, led to a decrease in shellfish production and a loss of general productivity in the reclaimed areas (SOA, 2003; PEMSEA, 2003)

The existing laws and regulations in China have not been effective in controlling coastal reclamation. Usage charge regime in Sea Area Use Management Law of PRC (SAUML) promulgated in 2001 provides the economic incentive to control coastal reclamation (Article 33). But the present usage charge standard for coastal reclamation is too low to curtail the activity level (Peng et.al. 2011). The central government's review and permitting regime for large scale sea area use project requires that projects with reclaimed sea area above 50 hectare must get the approval from the State Council (Article 18). To avoid the stringent review of a large scale project, developers often divide the whole project into several smaller projects. The reduction and exemption provisions of sea area use charge (article 35 and 36 of SAUML) further restrict the application of economic incentives to control large scale coastal reclamation projects implemented by the government.

Marine Environmental Protection Law of PRC (MEPL) implemented in 1982 (amended in 1999) requires that an environmental impact assessment (EIA) must be conducted for any new, reconstruction or expansion ocean/coastal construction project, including coastal reclamation projects (article 43 and 48). Unfortunately, the EIA typically focus on a single project and does not consider the cumulative environmental impacts of other related projects in the same area. As a result, the EIA requirement cannot effectively control excessive reclamation.

Moreover, the majority of coastal reclamation projects are resulted from local government backed development programs. Even though the central government calls for strict restrictions on coastal reclamation, a large number of reclamation plans are still being put forward in coastal provinces. As a new national coastal development strategy unfurls,[1] there will be a demand for an additional 5,780 km^2 of sea area to be reclaimed by the year 2020 in China (Task Force of CCICED, 2010), which undoubtedly will exert severe impacts on the coastal environment. Thus, there is an urgent need to develop a new approach to control effectively coastal reclamation and to harmonize the demand for reclamation and the protection of marine and coastal ecosystems. One of the solution is to set up a coastal reclamation restriction mechanism, known as the "red-line system," similar to that in the nation's arable land protection policy (Task Force of CCICED, 2010).

The coastal reclamation red-line system involves the establishment of a critical minimum sea area in each specific bay, and the minimum area will be written into law. The estimation of the critical minimum sea area should consider fully the multiple benefits and costs associated with reclamation. The red-line system is expected to be more effective in controlling reclamation, since anyone, including the government, who tries to pass the line must change the law first, which is a difficult and lengthy process. To implement the system at a specific bay, it is essential to figure out the total allowable areas for coastal reclamation (TAACR) at that location. The main advantage of the TAACR approach described here over other command and control management alternatives lies in the fact that the development of TAACR is science-based and captures the tradeoffs between economic growth and environmental protection.

The remainder of the paper is organized as follows. Section 2 presents the analytical framework and models to estimate TAACR. Data sources, specific estimation procedures, and results are presented in Section 3. Limitations of the study are discussed in Section 4. Conclusions are included in Section 5.

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[1] http://news.xinhuanet.com/local/2009-06/24/content_11573216.htm

2. Methods

2.1. Basic model

The basic idea of estimating the TAACR is straightforward in theory. Reclaimed land can be used for food production, urban development, and attracting new investment, which contribute to various social benefits. Meanwhile, coastal reclamation involves a series of costs, including social and environmental costs. From the standpoint of the society, the objective of a social planner in charge of coastal reclamation is to maximize the net societal benefit by choosing an optimal set of location and scale for reclamation. The estimated optimal reclamation area with its localization is the TAACR.

The net benefit maximization problem is a static problem described by:

$$\text{Max.}\quad NB = \sum_{i=1}^{n}[p_i \times f(x_i) - c(x_i)] - \sum_{i=1}^{n}\sum_{k=1}^{m} C^k(x_i) \tag{1}$$

s.t.

$$h_i(x_i) \le h_i \max \tag{2}$$

where NB is the net benefit of coastal reclamation; i (= 1, $2, 3,\ldots, n$) is the reclamation location index; p_i is for the price of products from the reclaimed land at the location i; $f(x_i)$ stands for the production function which is a function of the area of reclaimed land at location i, x_i; $c(x_i)$ denotes the production cost function for reclaimed land at location i; k (= $1, 2, 3,\ldots, m$) is the index for reclamation cost components; $C^k(x_i)$ stands for the cost function for the k^{th} component at location i; and function h_i denotes the constraint for reclamation at location i, such as scale constraint and no net loss of key coastal ecosystems, which is a linear function in x.

For a solution to the problem, x_i* (a specific reclamation area at each location i), the necessary conditions for optimality are the Kuhn-Tucker conditions. It is assumed that the total reclamation costs are quasi-convex, all separate cost functions are convex, and the objective function is quasi-concave. The Hessian matrix to the Lagrangian is negative semi-definite, and a unique maximum exists.

The necessary Kuhn-Tucker conditions are given in (3) – (6).

$$p_i \times \frac{\partial f(x^*_i)}{\partial x_i} - \frac{\partial c(x^*_i)}{\partial x_i} - \sum_{k=1}^{m} \frac{\partial C^k(x^*_i)}{\partial x_i} - \lambda_i \frac{\partial h(x^*_i)}{\partial x_i} = 0 \tag{3}$$

$$h_i(x^*_i) \le h_i \max \tag{4}$$

$$\lambda_i h_i(x^*_i) = 0 \tag{5}$$

$$\lambda_i \ge 0 (= 0 \quad if \quad h_i(x^*_i) < h_i \max) \tag{6}$$

The condition in (3) ensures optimality, (4) is feasibility conditions, (5) is the complementary slackness condition, and (6) is a non-negativity condition. λ_i is the Lagrangian multipliers, which represents shadow prices. The optimality condition (3) indicates that the socially optimal level of coastal reclamation (x_i*) should be set at the point where marginal social costs equal marginal social benefits.

2.2. Revenue of coastal reclamation

The revenue from coastal reclamation at a specific location *i* is reflected in the term $[p_i \times f(x_i) - c(x_i)]$ in equation (1), which is the difference between the value of goods produced from the reclaimed land and the costs turning the reclaimed land into the goods. In natural resource economics (Hartwick, 1997), this difference is the rent or the price of reclaimed land. Considering that the reclaimed land accounts for a small portion of existing land supply and thus the addition of the reclaimed land will not affect the market price of existing coastal land, the marginal revenue of reclaimed land can be estimated using the market price of adjacent land.

As mentioned above, the reclaimed land can be used for different uses. The price of land for different use is different. Moreover, the price of land located in different place varies significantly. The price of reclaimed land at location *i* can be calculated as the weighted average value according to the planned use pattern:

$$P_i = \sum_{j=1}^{j=J} P_{ij} \times s_{ij} \quad (7)$$

where j (= 1, 2, 3,…, J) is the index for the land use; P_{ij} stands for the price of land in location i for use j; s is the weight.

2.3. Cost of coastal reclamation

The cost of costal reclamation can be grouped into four parts: (1) engineering cost, (2) ecosystem damages, (3) cost of siltation, and (4) reduction in environmental carrying capacity. Engineering cost is the cost of filling the sea area which can be estimated through field investigation or engineering analysis.

The coastal ecosystems provides various services to society, such as providing food and materials, storing and cycling nutrients, filtering pollutants from inland freshwater systems, protecting shorelines from erosion and storms, regulating global hydrology and climate, and accepting and assimilating waste. Coastal reclamation will destroy all these services in the reclaimed area and reduce the ability of adjacent ocean and coastal ecosystems to provide above services. The value of coastal ecosystem services must be assessed so that damages to the ecosystems resulting from reclamation can be estimated.

Coastal reclamation will change the hydrological condition and lower the tidal volume of the bay, which will lead to an increase in siltation in navigation channels. Dredging cost can be used to assess the cost of siltation. The reduction in the tidal volume also leads to a reduction in the capacity of coastal waterbody to absorb wastes. As a result, coastal communities must take measures to increase their waste treatment capacity. The increased treatment costs can be used to estimate the cost associated with the reduction in environmental carrying capacity.

2.4. Annual value

In China, prices of land reflect the present value of land use right in the period prescribed by law. The statutory maximum life of commercial and industrial use is 70 and 50 years, respectively. Other estimates, such as the costs of ecosystem damages, are often expressed in terms of annuity. In the study, we compare the benefits and costs associated with reclamation using the annual values.

Benefits (e.g., price of land) and costs in lump-sum payments are converted into average annual values using the formula below.

$$A = S\frac{(1+r)^n r}{(1+r)^n - 1} \tag{8}$$

where A is the annuity of benefits or costs; S is the associated lump-sum values; r is the discounted rate; and n is the number of years.

Engineering costs of coastal reclamation (C^{ENG}) incurred upfront typically lead to a stream of benefits into indefinite future. Thus, the annual value of engineering cost C^{ENGA} is calculated as:

$$C^{ENGA} = C^{ENG} \times r \tag{9}$$

3. The case study

Located at the southeastern coast of China's Fujian Province, to the west of Taiwan Strait, Xiamen covers a land area of 1,565 km^2 and a sea area of 340 km^2 with a coastline of 234 km. Xiamen's economic development and well-being depend heavily on its surrounding seas for natural resources, goods and services. As shown in Figure 1, the study area has a long history of coastal reclamation. A total of 128.72 km^2 sea area has been reclaimed since the 1950s (Table 1). An estimate in 2006 indicated that the areas of West Sea and Tongan Bay had decreased 58% and 27%, respectively, due to the coastal reclamation (Zhang et al., 2008).

Large scale reclamation has led to the disappearance of 90% of the natural mangroves and the destruction and alteration of natural habitats of various living resources. Together with other human activities, coastal reclamation has resulted in the degradation of marine environmental quality, an increase in eutrophication and associated red tides,[2] reductions in fisheries resources and other marine species,[3] and

[2] The number of red tide occurrences increased from 0 in the 1980s to 5 times in 2010 (Xiamen Ocean and

siltation of navigation channels.

With the deterioration of environmental and resource conditions, the development in Xiamen is not sustainable. However, to cope with rapid economic development, population growth, and urbanization, a reclamation plan of 20 km^2 has been proposed (Figure 2), in which the eight planned areas to be reclaimed in Tongan Bay (TA1 to TA8) represent a total of 15.22 km^2 (16.33% of the current bay area) (see Table 2). There is an urgent need for Xiamen to assess the optimal scale and location for coastal reclamation and to identify an effective approach to preserve the minimum sea area that can maintain the resilience and health of its marine ecosystems.

In this section, we describe an empirical estimation of TAACR in the Tongan Bay of Xiamen, whose area has decreased to 93.2 km^2 from 127 km^2 over the years due to coastal reclamation. We explain the procedures for compiling data and model computation, together with background information related to the benefit and cost functions of coastal reclamation. The 20-year government bond rate 4.5% is taken as the social discount rate for our baseline calculation.

3.1. Parameter estimation

According to the plan, reclaimed land will be mainly used for commercial and industrial purposes.[4] To establish the benefit function for the reclaimed land, we assemble the land price for commercial and industrial uses in areas adjacent to each of the planned reclamation locations (column 5 and 6 in Table 2). Using the shares for commercial and industrial uses (column 3 and 4 in Table 2) and equations (7) and (8), the weighted average prices for different planning reclamation areas are calculated (last column in Table 2). We use a linear benefit function for each reclaimed area i in

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Fisheries Bureau, Personal communication, 2012).

[3] Annual fishery catch decreased from 25 thousand ton in 1990 to 7.4 thousand ton in 2010 (Xiamen Statistics Bureau, 1991 and 2011).

[4] As shown in Table 1, the reclaimed land was mostly used for mariculture and salt making in the earlier years, and later converted to industrial and commercial uses because land values are significantly higher for these uses.

the study: $B_i(x_i) = P_i x_i$.

The results of studies on reclamation projects in Xiamen indicate that the average fixed and operation costs of coastal reclamation are 600 yuan/m^2 and 60 yuan/m^2, respectively (TIO and 4th NFRDI, 2002; 4th NFRDI, 2002; PDRINBYR, 2003). Thus, the estimate of 660 yuan/m^2 is used as the engineering cost in the study. The lump-sum cost is converted to an annual value of 29.7yuan/ m^2 using equation (9). The engineering cost function, $C_i^{ENGA}(x_i)$ is: $C_i^{ENGA}(x_i) = 29.7x_i$.

The Coastal and Ocean Management Institute of Xiamen University (COMI, 2012) has developed estimates of the values associated with ecosystem services for each Xiamen's coastal areas (Table 3). Coastal reclamation will destroy all the services provided by these areas. Thus, the values of ecosystem services can be used as the costs of ecosystem damages due to reclamation. The costs functions of ecosystem damages, $C_i^{ED}(x_i)$ can be written as: $C_i^{ED}(x_i) = e_i x_i$, where e_i is the value of ecosystem services listed in column 2 in Table 3.

Fujian Marine Institute and the State Key Laboratory of Marine Environmental Science at Xiamen University (2006) have developed models of hydrodynamics, sand and mud sediments, and water quality for the West seas and Tongan Bay. These models have been used to assess the impacts of various proposed reclamation schemes. In the present study, different reclamation scenarios are examined to evaluate the cumulative effects of reclamation at an increasing scale (column 2 in Table 4). The volume of siltation per year and tidal volume per period[5] are list in columns 4 and 6 in Table 4.

According to the Xiamen Port Bureau, the average unit dredging cost is 29.7 yuan/m^3. Thus, the dredging costs associated with different reclamation scenarios can be calculated as the product of the unit cost and the volume of siltation (column 5 in Table 4). The value of environmental carrying capacity for different reclamation scenarios is estimated as (column 7 in Table 4):

[5] There are two tidal periods in Xiamen Sea area per day.

$$V = 365 \times 2 \times \Delta c \times v \times c \quad (10)$$

where $\triangle c$ is the difference in COD concentrations between inner and outer Tongan Bay ($\triangle c$ = 0.02mg/L, Xiamen EPB, 2006); v is the tidal volume; and c is the unit cost of treatment of COD (c = 4300 yuan per ton, TIO, 1995).

Using the cost estimates in Table 4, we construct the marginal cost functions with respect to reclamation area (x) using Ordinary Least Squares regressions, and the results are as follows:[6]

$$\frac{dC^{dc}}{dx} = 0.0008x + 1.244 \qquad (R^2=0.95) \quad (11)$$

$$\frac{dC^{ecc}}{dx} = 0.306x + 5.298 \qquad (R^2=0.99) \quad (12)$$

Equations (11) and (12) are the marginal drudging cost function and the marginal treatment cost function, respectively.

3.2. The optimal reclamation scheme

The net benefit maximization problem was solved using the information from the previous sections and the GAMS software. The scale constraint for each location, h_i max, in equation (4) is its planned area (column 2 in Table 2).[7] The results show that the optimal reclamation area in Tongan Bay is 567.85 ha^2 (5.68 km^2) at a discount rate of 4.5% (see Table 5). This optimal area is 37.31% of the total planned reclamation area, suggesting that the proposed reclamation plan is economically inefficient from the stand point of the entire society. With the TAACR estimated at 5.68 km^2, we argue that the area of Tongan Bay must be maintained at a minimum of 87.52 km^2 so that the social well-being can be preserved.

The optimal location and scale of reclamation are shown in Table 5. The results indicate that there should be no reclamation at location TA8, and the optimal

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[6] All parameters are statistically significant at 1% level.

[7] The planned reclamation location and sizes were selected to avoid environmentally sensitive areas in the region.

reclamation scales at location TA3 and TA5 are less than half of what are planned.[8]

We develop a sensitivity analysis with respect to discount rate using two alternative discount rates, 2% and 8%, respectively. As shown in columns 4 and 5 in Table 5, under low discount rate, 2%, the TAACR is zero. Even with high discount rate, 8%, the optimal reclamation area is 789.42 ha^2, about half of the total planned area. The area of Tongan Bay must be maintained at a minimum of 85.31 km^2. Thus, the results clearly indicate that our estimation is robust with respect to discount rate.

4. Discussion

Although the analytical framework developed in the study presents an effective way to assess the tradeoffs between development and conservation, the framework has several limitations. First, several ecosystem damage costs are modeled as linear functions in the study. However, many of these costs are nonlinear due to nonlinear interactions in the natural systems (Barbier et al. 2008). In addition, we do not have a good understanding of the ecological thresholds in the study area. When a system crosses a threshold, a very small change in economic activity can have enormous impacts and result in irreversible loss of critical natural capital (Farley, 2012).

Finally, the natural and socioeconomic systems are highly complex and dynamic. Our static model cannot capture the full effects of the dynamic interactions in the coastal systems. Sustainable development is an evolutionary process, and sustainability is not a static objective. Thus, an adaptive management system must be in place to cope with various uncertainties (Rammel et al. 2007). In fact, our estimation of the TAACR for Xiamen should not be viewed as static, and it should be reevaluated periodically so that new knowledge can be incorporated into the analysis to guide future reclamation or restoration plans.

5. Conclusions

While creating useful land for agriculture, industries, and urban development,

[8] Downsizing the reclamation scale at these sites will involve reassessment and re-planning at each site, which is beyond the scope of this study.

coastal reclamation permanently changes the natural characteristics of the ocean and coastal environment and causes considerable damages to the marine ecosystems. Policymakers must be careful about the tradeoffs between the short-term interest to provide additional land and the long-term interest to ensure the sustainable use of the marine and coastal ecosystems. By assessing the optimal scale and location for reclamation, we may be able to meet the current demand for land to facilitate economic development while maintaining the health and resilience of the coastal ecosystems. The analytical framework and models developed in the study covers multiple benefits as well as cost components associated with coastal reclamation. The inclusion of multiple uses and environmental and ecological effects in the analysis is vital, since it is essential to consider the welfare from the stand point of the whole society. Our empirical estimation captures both internal and external effects.

Our results indicate that the optimal reclamation scale is 5.68 km^2 in Tongan Bay, Xiamen with a discount rate of 4.5%. Even with high discount rate, 8%, the optimal size of reclamation is about half of what is planned. If we focus more on the long-term ecological benefits by using a lower discount rate of 2%, the optimal reclamation area should be zero. In order to maintain the ability of the coastal ecosystems to provide various services to society, Xiamen should reexamine and reformulate its plan for coastal reclamation so that the area of Tongan Bay is kept at a minimum of 87.52 km^2.

It must be stressed that the estimated optimal reclamation area should be viewed as the maximum, because some costs, such as the damages to adjacent coastal ecosystems and the increased treatment costs for other pollutants such as nutrients resulted from the reduction in environmental carrying capacity, are not included in the current assessment for lack of data.

Although this study examines a case in Xiamen, the general framework presented here is transferable to other locations and can be used to examine reclamation proposals at different scales. Finally, as noted, the estimated Total Allowable Area for Coastal Reclamation (TAACR) must be written into law as part of the red-line system to ensure an effective control of coastal reclamation.

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Table 1. Historical coastal reclamation and land uses

Year	Reclamation area (hm^2)	Share (%)	Uses
1950s-1960s	5504	42.76	Originally, the reclaimed areas were mainly used for mariculture and salt making. But these areas have switched to urban and industrial uses.
1970s	2907	22.59	
1980s	297	2.31	Industrial zones, urban development, and infrastructure (road, airport and dock, etc.)
1990s	983	7.64	
2000s	3180	24.71	
Total	12872	100.00	

Data source: Xiamen Ocean and Fisheries Bureau (Personal communication, 2012).

Table 2. Revenue from planned reclamation areas

Location	Area[1] (hm²)	Share of different uses[2]		Price of land[3] (yuan/m²)		Weighted average price (P_i)(yuan/m²)
		Commercial	Industrial	Commercial	Industrial	
TA1	16	0.8	0.2	3700	700	146.69
TA2	115	0.25	0.75	3700	700	70.19
TA3	213	0.25	0.75	3700	700	70.19
TA4	59	0.55	0.45	2900	250	80.92
TA5	429	0.55	0.45	2700	200	74.59
TA6	84	0.8	0.2	2500	150	95.85
TA7	161	0.75	0.25	2500	150	90.33
TA8	445	0.25	0.75	2500	150	35.17

Data sources: [1, 2] Xiamen Development and Reform Commission and Xiamen Ocean and Fisheries Bureau.

[3] Xiamen Land and Real Estate Bureau and field survey.

Table 3. Value of ecosystem services of planned reclamation area and engineering cost

Location	Value of ecosystem services (e_i) (yuan/m^2)	Engineering cost (yuan/m^2)	
		Present value (C^{ENG})	Annual value (C^{ENGA})
TA1	9.13	660	29.7
TA2	9.53		
TA3	9.53		
TA4	9.16		
TA5	9.16		
TA6	9.16		
TA7	9.16		
TA8	9.16		

Data source: COMI, 2012.

Table 4. Dredging cost and value of carrying capacity of different reclamation scenarios

Scenarios	Description	Area (hm^2)	Siltation (m^3)	Dredging cost (10^4 yuan)	Tidal volume ($10^6 m^3$)	Value of environmental carrying capacity (10^4 yuan)
1	No reclamation	0	724399	2151.47	713.20	4477.47
2	TA1	16	724819	2152.71	711.62	4467.56
3	TA1+TA2	131	725266	2154.04	705.48	4429.00
4	TA1+TA2+TA3	344	725729	2155.42	693.91	4356.35
5	TA1+TA2+TA3 +TA8	789	726262	2157.00	671.19	4213.71
6	TA1+TA2+TA3 +TA8+TA7	950	726743	2158.43	662.78	4160.95
7	TA1+TA2+TA3 +TA8+TA7 +TA4	1009	727171	2159.70	658.99	4137.11
8	TA1+TA2+TA3 +TA8+TA7 +TA4+TA5	1438	727696	2161.26	637.41	4001.68
9	TA1+TA2+TA3 +TA8+TA7+A4 +TA5+TA6	1522	728131	2162.55	632.18	3968.84

Data source: Fujian marine institute and the State Key Laboratory of Marine Environmental Science (Xiamen University), 2006.

Table 5. Estimation results and sensitive analysis

Location	Planned area (hm^2)	Optimal reclamation area (hm^2) Discount rate (%)		
		4.50%	8%	2%
TA1	16	16.00	16.00	0.00
TA2	115	81.22	115.00	0.00
TA3	213	81.22	160.90	0.00
TA4	59	59.00	59.00	0.00
TA5	429	97.01	193.52	0.00
TA6	84	84.00	84.00	0.00
TA7	161	149.40	161.00	0.00
TA8	445	0.00	0.00	0.00
Total	1522	567.85	789.42	0.00

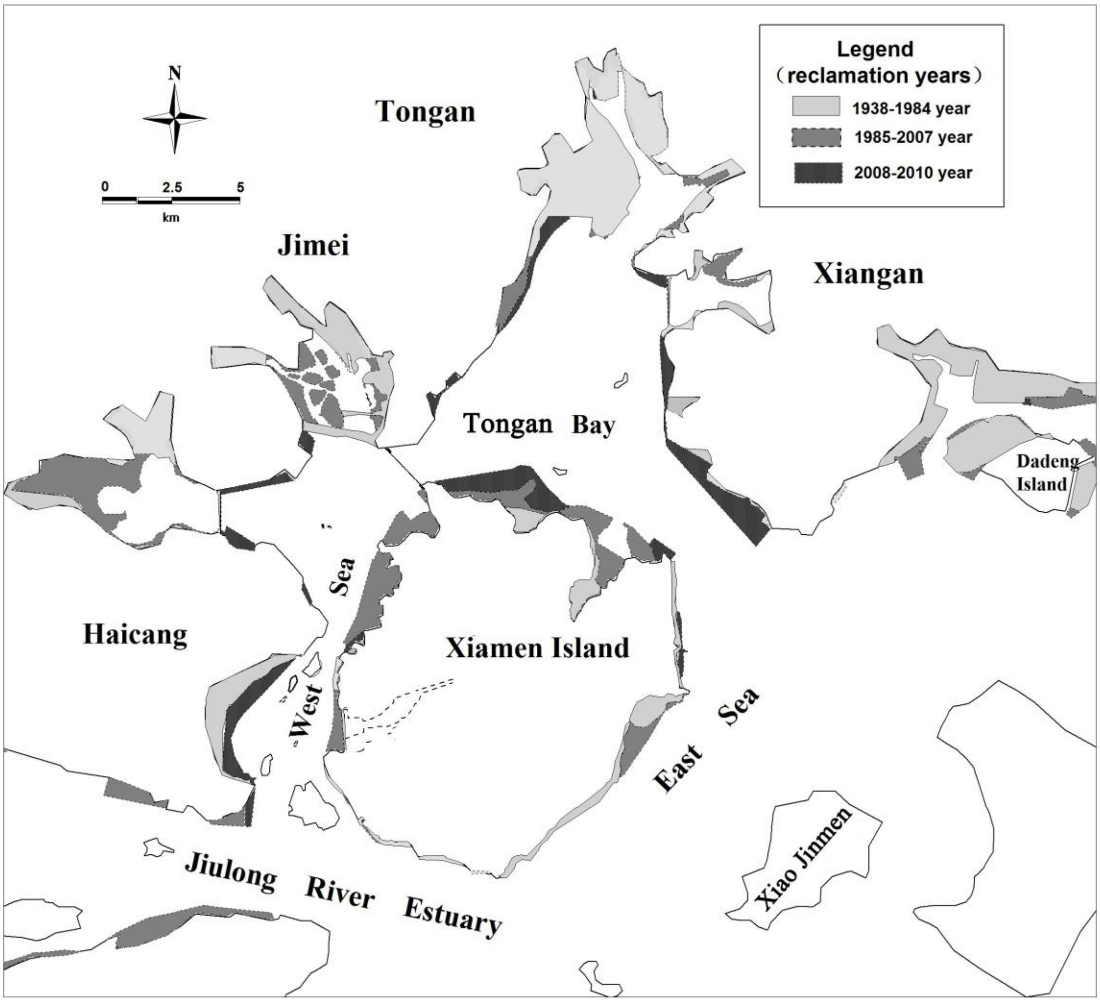

Figure 1. Historical development of coastal reclamation in Xiamen

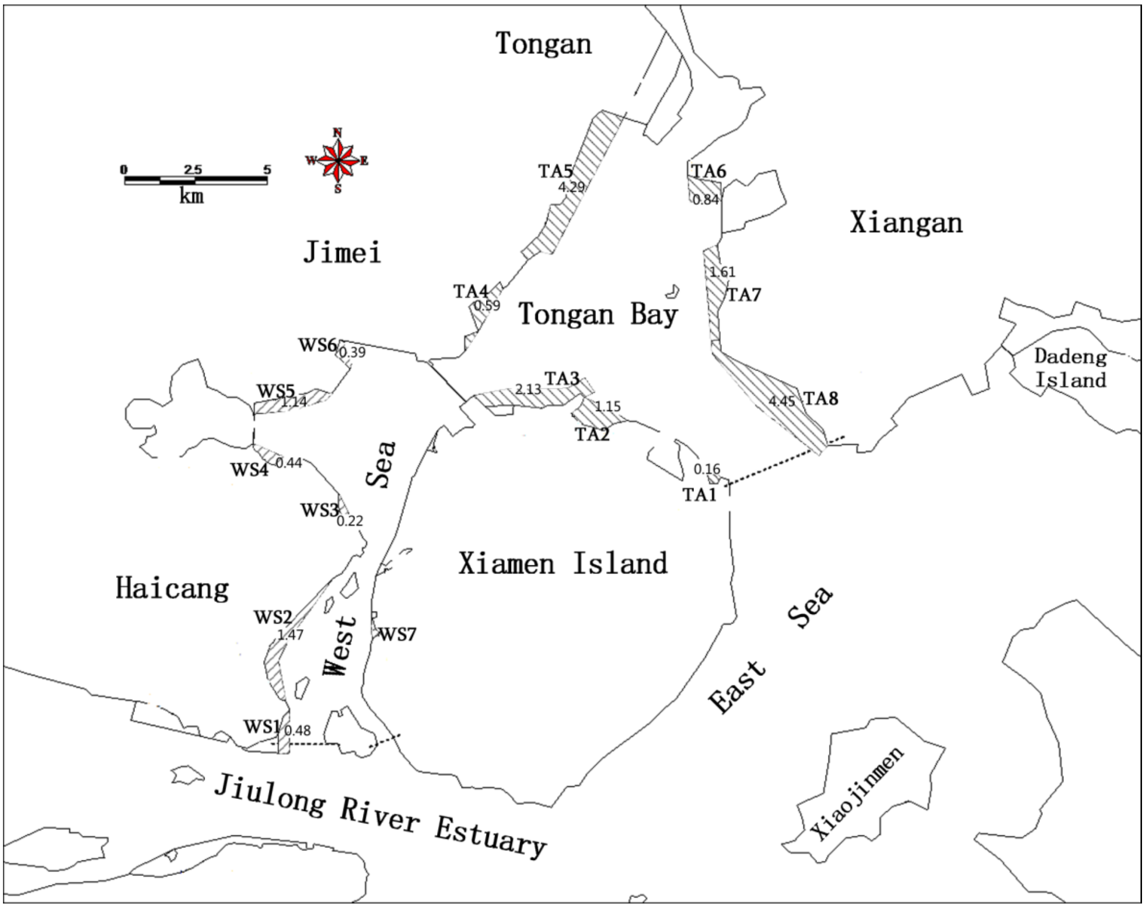

Figure 2. Location and area of planned reclamation（shadow areas are the planned reclamation sites）