

The impact of sea level rise on Singapore

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ABSTRACT. Global climate change is expected to cause sea level rise, which will have major effects on Singapore because it is a small, low-lying island state. With the high degree of urbanization and industrialization on the island, land is scarce and very valuable. Examining three sea level rise scenarios for the next century, we explore whether Singapore should defend their coast or allow it to be inundated. Across ten coastal sites representing all market land in Singapore, we found that protection was the lowest cost strategy. The annual cost of protecting the coasts of Singapore will rise over time as the sea level rises and will range from 0.3 to 5.7 million US\$ by 2050 to 0.9 to 16.8 million US\$ by 2100. The present value of these costs ranges from 0.17 to 3.08 million US\$ depending on the sea level rise scenario.

1. Introduction

Sea level rise is seen as one of the more prominent consequences of climate change (Rijsberman, 1991). According to the Intergovernmental Panel on Climate Change (IPCC) 2001 (Church *et al.*, 2001), it is very likely that warming will contribute significantly to future sea level rise, through thermal expansion of sea water and widespread loss of land ice. Human habitat could be affected significantly, as nearly 20 per cent of the world's population lives within 30 km of the sea, and approximately 40 per cent live within 100 km of the coast (Cohen *et al.*, 1997; Gommès *et al.*, 1998). A 1998 study by Nicholls and Mimura (1998) has estimated that by 2100, 600 million people will inhabit the coastal floodplain below the 1000-year flood level.

As indicated by Nurse *et al.* (2001), low-lying coastal regions and islands in particular are the most vulnerable to rising seas. The problem may be even more severe in the future as coastal populations worldwide expand. The major effects of a rise in sea level are the loss of land due to inundation and erosion, increased flooding during storm surges and rainstorms, and the intrusion of saltwater into aquifers, estuaries, and wetlands (Titus, 1993). This paper examines the potential loss of coastal land to rising seas in Singapore using a method first developed by Yohe *et al.* (1995). We calculate the value of potentially lost market land each decade over the next century and the cost of protection. We assume that Singapore will choose the least cost adaptation option, which in this case turns out to be protection of all market lands along the coast. The study demonstrates that this cost–benefit

approach can be used to study the impacts of sea level rise to locations outside the United States.

The magnitude of these impacts depends on many critical variables. First, impacts will depend on the magnitude of sea level rise, which remains uncertain. We examine three scenarios that reflect the likely range of sea level rise scenarios predicted by the IPCC (Church *et al.*, 2001). Another critical factor is the amount of low-lying land along the coast. We take an intensive sample of the coast using ten representative sites from around Singapore. Using the best available contour maps, we measure the amount of land at risk of inundation in each site in each decade. The value of this land depends on its scarcity, and the type of land use. We measure Singapore land values in each location and then project how those land values are likely to change over time. We then examine whether Singapore could adapt. Singapore has a long history of reclaiming land from the sea. The country is highly organized, technologically sophisticated, and wealthy. Using US estimates that were confirmed by Singapore engineers, we calculate the cost of building sea wall protection around the island. We assume that sea walls will be constructed each decade to confront the rising seas expected that decade. Thus we envision a dynamic adaptation. We assume that the sea walls will be constructed if they are cheaper than letting the land be inundated (Fankhauser, 1995). The building of sea walls, of course, would require all coastal landowners to be coordinated in this work. We assume that the government will do this efficiently.

Given the high value of land across the island, we find that the least cost strategy for Singapore is to protect all market land along the coast. We consequently design an adaptation policy that heightens sea walls gradually each decade to keep pace with the rising sea. Other countries, with lower land values, may well come to a different conclusion, that allows for a mixture of inundation and protection over time. The results cannot be generalized to all island nations but the method can be applied universally. The paper does not examine non-market land, such as beaches, marshes, and mangroves. Because these lands do not have market values, they require a completely different approach, which is developed in another paper (Ng and Mendelsohn, 2003).

The next section of this paper describes the methods employed for data collection and analysis. Section 3 shows the detailed application of the methods on the Commercial and Business District of Singapore, and presents the results in great detail. Section 4 presents the results for all Singapore and assesses the total costs resulting from different sea level rise scenarios. This section also contains a sensitivity analysis that explores how the results change under different assumptions. The analysis of the results and the ultimate decision whether to adapt or abandon is made in the final section.

2. Methods

This study evaluates three dynamic sea level rise scenarios (see figure 1) that reflect the range of sea level rise predictions for the next century from global warming (Church *et al.*, 2001). In all three scenarios, sea level rise is expected to increase gradually each decade. By 2100, the cumulative

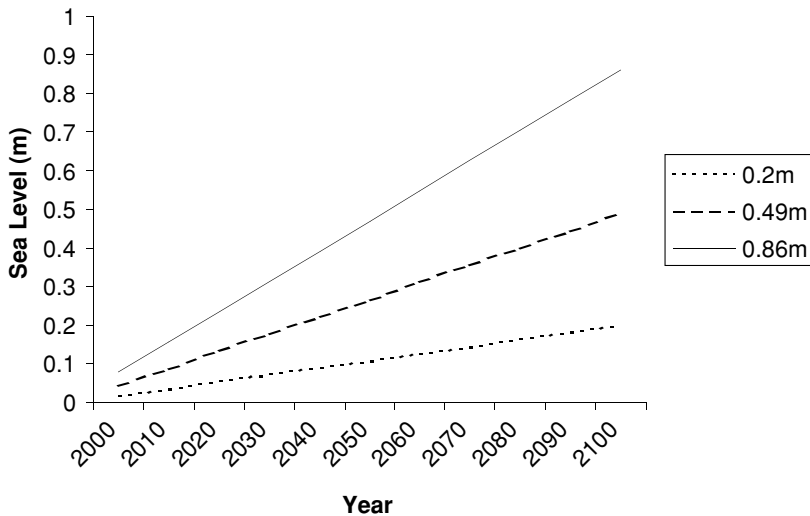


Figure 1. *Sea level rise scenarios*

Source: Adapted from IPCC 2001 (Church *et al.*, 2001).

Notes: The slope of each line is determined by the degree of increase in sea level. The highest range of the predicted sea level rise (0.86 m) has the steepest line. This implies that the higher the sea level scenario, the greater the rate of sea level rise.

sea level rise is predicted to be 0.2 m, 0.49 m, or 0.86 m. For each scenario, both the protection costs and the value of potentially inundated land will increase over time. For all the scenarios, this is a dynamic problem that requires a dynamic policy. Accordingly, the analysis examines the least cost strategy for coping with sea level rise each decade.

A method for assessing the impact of sea level rise has been developed and applied to the United States coastline (Neumann and Livesay, 2001; Smith and Tirpak, 1988; Yohe *et al.*, 1995, 1996, 1999). This study takes this methodology and applies it to Singapore. This is the first application of the model outside the United States. Given the much smaller coastline of Singapore, we are able to conduct a more careful and precise analysis of the coastline. Whereas the US study sampled 30 out of 980 potential sites (a 3 per cent sample), we examined ten of 30 potential sites (a 33 per cent sample). Although countries may be tempted to do a complete census of their coastline, this is not necessary to obtain an accurate estimate of impacts. As long as the sample is representative of the entire coastline, a sampling approach is sufficient. The ten sites chosen in this study reflect land used for industrial, residential, and commercial purposes. A harbor and an offshore oil refinery island were also incorporated into this study. As mentioned in the introduction, the study does not include non-market land because it has no market value and must be evaluated using alternative methods (Ng and Mendelsohn, 2003).

The potential loss of land due to sea level rise was estimated by using spot elevation measurements to interpolate between contours on Singapore

Ministry of Defense topographical maps at a scale of 1:50,000. The benefit of protecting the coastline is the value of the land that would have been inundated. The cost of protection is the cost of constructing and maintaining the physical barriers to hold back the sea.

It is assumed that the value of market land will increase over time as the economy of Singapore grows. Because land in Singapore is already scarce, we assume that land value will increase proportionally with GDP. Given projections of GDP growth of 2 per cent a year (Ministry of Trade and Industry, 2002), we assume that the real value of land in Singapore will increase by 2 per cent every year

$$p(t) = e^{\rho t} - p(0)$$

where $p(t)$ is the rental value of land in a future time t , $\rho = 2\%$, and $p(0)$ is the current rental value.

This study compares the cost and benefit of protecting each coastal site from inundation and chooses the least cost alternative, whether to protect or abandon. Estimates for the ten sites are then extrapolated to the whole country. All estimates in this study have been expressed in terms of Singapore dollars (2000 SG\$: 1 SG\$ is approximately 0.55 US\$) unless otherwise stated.

We follow a conservative approach measuring the value of developed land. We estimate the value of only the land as though it had no structure on it. If the land were inundated, society would lose the rents on this land for the period it was flooded. As suggested by Neumann and Livesay (2001), the value of the inundated land is represented by the value of land located inland from the ocean. If coastline is inundated, new land becomes beachfront. The country consequently does not lose beachfront property through inundation but rather interior land.

Neumann and Livesay (2001) also include the value of structures (not only land) in their analysis. They assume that owners would have considerable foresight and begin to depreciate structures that would be inundated decades in advance. The depreciation would reduce the economic losses to the structure caused by inundation. Because we do not include structural values in this study, depreciation is not taken into account in this study. Only land values were used to determine the benefits of protection and not structural values. The only foresight we are assuming in this study is that society can anticipate the sea level rise expected in the next decade. Although omitting structures underestimates the value of the coastland, we find that the values of the land are so high in Singapore that protection is always employed. The damage estimates consequently are not affected by the land only assumption in this study. However, other countries may well want to include the value of existing structures in their analysis. If structures are included, countries must consider whether owners will depreciate existing structures over time in anticipation of inundation.

The present value (PV) in t_0 of the decadal benefit of protecting coastland from t_0 to $t_0 + 10$ is

$$PV[B(t_0, t_0 + 10)] = \int_0^{10} p(t)e^{-rt} dt \quad (1)$$

where B represents the benefit of land protection for the next ten years starting in t_0 and ending in $t_0 + 10$, p is the rental value of potential inundated land area, and r is the real discount rate at 4 per cent.

The cost of coastal protection in this study is based on the cost of constructing and maintaining coastal hard structures, such as dikes, seawalls, or bulkheads. The capital cost of constructing a one-meter tall hard structure of one-meter length is estimated to be \$5,310 (Neumann and Livesay, 2001). It has been recognized that construction costs increase geometrically with height (Neumann and Livesay, 2001). This is mainly due to the trapezoidal shape of the structure, whose base needs to be increased proportionally with its height. The additional construction costs, $CC(t)$, required to update hard structures each decade consequently increase with the square of the height of the structure, H (Neumann and Livesay, 2001; Yohe *et al.*, 1999).

$$CC(t) = 5310 * [H(t_0 + 10)^2 - H(t_0)^2] * L \tag{2}$$

where L is the length of the wall.

We assume that structures are built in the first year of each decade to handle the sea level rise, $H(t_0 + 10) - H(t_0)$, expected that decade. Additional height will be built on top of the existing wall as sea level rises. Annual maintenance costs, required to ensure the function of the walls over time, are assumed to be equal to 4 per cent of the construction cost (Yohe *et al.*, 1999). These maintenance costs must be discounted for the entire decade. A 4 per cent discount rate is applied throughout this analysis to discount all real costs back to the present value. The present value of the costs of protection in the beginning of each decade is

$$PV\{C[t_0, T]\} = CC(t) + \int_0^{10} .04 CC(t) e^{-rt} dt \tag{3}$$

The first term is the construction cost that decade and the second term is the maintenance costs over the decade. The cost of coastal protection in this study is based on the physical construction of sea walls.

If storm surges intensify or become more frequent due to climate change, there would be additional protection costs. The increased risk of inundation from storms would require even higher sea walls for protection. This additional cost is not included in this study, as Singapore is not within storm belts (Wong, 1992). Whether there is an increased storm risk from climate change is not yet known. The magnitude of the impacts from storms requires extensive analysis of storm surges that goes beyond the scope of this paper.

Protection will occur as long as the net present value of protection is positive. In other words, we assume that protection will occur whenever the present value of benefits is greater than the present value of protection costs

$$PV\{B[t_0, T]\} > PV\{C[t_0, T]\} \tag{4}$$

Table 1. *Areas (sq km) of possible inundated land under three sea level rise scenarios from 2000 through 2100 in CBD*

Year	Area of inundated land		
	0.2 m	0.49 m	0.86 m
2000	0.05	0.11	0.20
2010	0.09	0.23	0.40
2020	0.14	0.34	0.60
2030	0.19	0.45	0.80
2040	0.23	0.57	0.99
2050	0.28	0.68	1.19
2060	0.32	0.80	1.39
2070	0.37	0.90	1.59
2080	0.42	1.02	1.79
2090	0.46	1.14	1.99
2100	0.51	1.25	2.19

Notes: The areas provided in table 1 are potential dryland lost if the CBD is allowed to be inundated. These amounts increase in proportion with the increase in sea level.

We assume that Singapore will react to sea level rise efficiently. This will require a well-designed and funded public program.

3. Commercial and business district example

In order to demonstrate how this model works, we examine the commercial and business district (CBD) of downtown Singapore in detail. The downtown is a well-developed, and concentrated financial and commercial hub, thus making it one of the highest-valued regions in Singapore.

The potential area of inundated land was calculated using spot elevation measurements to interpolate between different contours on Singapore Ministry of Defense topographical maps using a complete census of the coastline around the CBD. All the estimated points obtained from the interpolation of the contours along the coastline of the CBD provide the width of the land along the coast that would be inundated, for each sea level rise scenario. Table 1 presents the time series of inundated land for the CBD, in decadal increments, for the three sea level rise scenarios.

The values of the inundated land are predicted to appreciate over time. The value of the potential lost land from inundation is the benefit of protection (Yohe *et al.*, 1995). Table 2 displays the current land values in the CBD for each sea level scenario. The land value per sq km is the highest in the country for the CBD. These economic losses could be prevented by the appropriate implementation of protection actions. The cost of protection will include the construction cost (fixed cost) and the maintenance cost (variable cost), both of which depend on the height of the hard structure built. We assume that the sea wall will mirror the sea level rise. The total protection costs will hence increase with the sea level rise (table 3). Figure 2 shows how these costs escalate with time.

The cost and benefit of protection were assessed to calculate the net benefits of protection for each sea level rise scenario. The results are

Table 2. Value of inundated land (in millions of 2000 SGD) for three sea level rise scenarios in CBD

Year	Value of inundated land		
	0.2 m	0.49 m	0.86 m
2000	36.62	80.56	146.47
2010	65.91	168.44	292.93
2020	102.53	248.99	439.40
2030	139.14	329.55	585.86
2040	168.43	417.43	732.33
2050	205.05	497.98	878.79
2060	234.34	585.86	1,025.26
2070	270.96	659.10	1,171.72
2080	307.58	746.97	1,318.19
2090	336.87	834.85	1,464.66
2100	373.49	915.41	1,603.80

Note: These estimates include projected increases in land values.

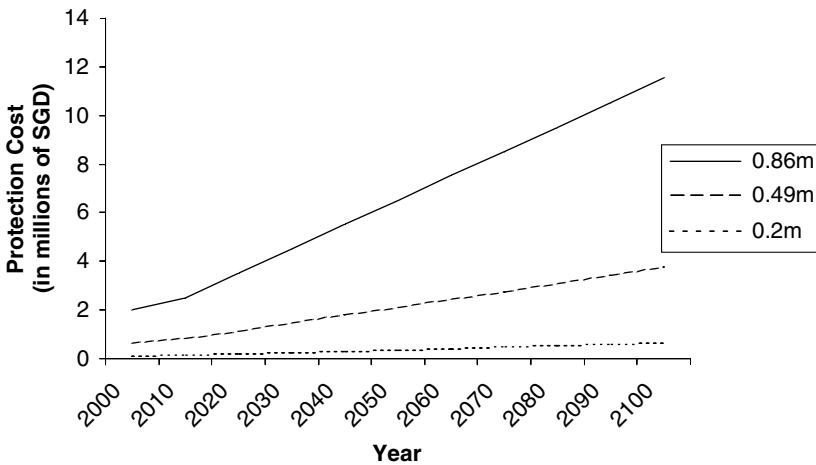


Figure 2. Cost of protecting Singapore’s CBD due to increase in the sea level

presented in figure 3. The net benefits of protection are expected to increase linearly with time for all three sea level scenarios. The net benefits are also shown to be positive, which implies that the benefits of protection are higher than the costs of protection. The value of possible inundated land is greater than the protection cost. The CBD will be protected in every decade.

4. National results

The methods and assumptions described in the previous sections are applied to all ten coastal sites and extrapolated to the entire country. Tables 4 and 5 depict the potential areas and values of potential inundated dryland

Table 3. Decadal cost of protection (in millions of SGD) for CBD Singapore

Year	Sea level rise scenario								
	0.2 m			0.49 m			0.86 m		
	CC	MC	TC	CC	MC	TC	CC	MC	TC
2000	0.02	0.008	0.03	0.15	0.05	0.20	0.46	0.15	0.61
2010	0.03	0.010	0.04	0.19	0.06	0.25	0.57	0.19	0.76
2020	0.04	0.014	0.06	0.26	0.09	0.35	0.80	0.26	1.07
2030	0.06	0.018	0.07	0.33	0.11	0.45	1.03	0.34	1.37
2040	0.07	0.022	0.09	0.41	0.13	0.54	1.26	0.42	1.68
2050	0.08	0.027	0.11	0.48	0.16	0.64	1.49	0.49	1.98
2060	0.09	0.031	0.12	0.56	0.18	0.74	1.72	0.57	2.28
2070	0.11	0.035	0.14	0.63	0.21	0.84	1.95	0.64	2.59
2080	0.12	0.039	0.16	0.71	0.23	0.94	2.18	0.72	2.89
2090	0.13	0.043	0.17	0.78	0.26	1.04	2.41	0.79	3.20
2100	0.14	0.047	0.19	0.86	0.28	1.14	2.63	0.87	3.50

Notes: The decadal total costs (TC) of protection include the construction costs (CC) of the hard structures and the maintenance costs (MC) involved. These values have been discounted to the present values within each decade, at a discount rate of 4 per cent.

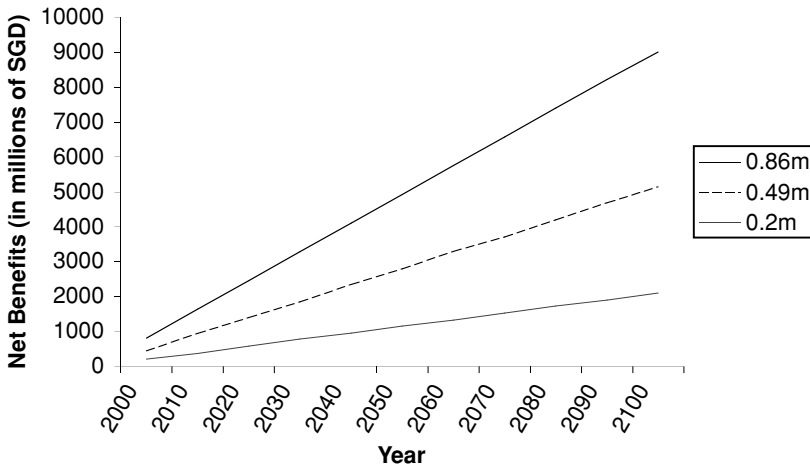


Figure 3. Net benefits of CBD protection in Singapore, for three sea level rise scenarios

for each site respectively, in the 0.86m sea level rise scenario. The ten coastal sites include the CBD, Loyang, Marine Parade, Sentosa, Pulau Bukom, Keppel Harbor, Jurong, Tuas, Kranji, and Woodlands. Out of these ten sites, four are industrial areas (Loyang, Jurong, Tuas, and Kranji) and two are residential areas (Marine Parade and Woodlands). Sentosa is a well-developed recreational offshore island, Pulau Bukom is another offshore island, which is an oil refinery, and Keppel Harbor is one of the six terminals belonging to the Port of Singapore.

Table 4. Time series of inundated land areas (sq km) for each coastal site under the 0.86 m sea level scenario

Year	Marine				Pulau Keppel					
	Loyang	Parade	CBD	Sentosa	Bukom	Harbor	Jurong	Tuas	Kranji	Wood lands
2000	0.05	0.09	0.20	0.01	0.20	0.02	0.11	0.10	0.07	0.05
2010	0.10	0.18	0.40	0.02	0.39	0.05	0.22	0.20	0.14	0.11
2020	0.14	0.27	0.60	0.03	0.59	0.07	0.33	0.30	0.21	0.16
2030	0.19	0.36	0.80	0.04	0.78	0.09	0.44	0.40	0.28	0.21
2040	0.24	0.45	1.00	0.05	0.98	0.12	0.55	0.50	0.35	0.26
2050	0.29	0.54	1.20	0.06	1.17	0.14	0.66	0.60	0.42	0.32
2060	0.34	0.63	1.40	0.07	1.37	0.16	0.77	0.70	0.49	0.37
2070	0.39	0.72	1.60	0.08	1.56	0.18	0.88	0.80	0.56	0.42
2080	0.43	0.81	1.80	0.09	1.76	0.21	0.99	0.89	0.63	0.47
2090	0.48	0.90	2.00	0.10	1.95	0.23	1.10	0.99	0.70	0.53
2100	0.53	0.99	2.19	0.11	2.15	0.25	1.24	1.09	0.78	0.58

Notes: These values represent the area of dryland lost if no protection measures are carried out, from 2000 to 2100, for the ten coastal sites selected in this study. The area of land inundated increases with time, as the sea level increases.

Table 5. Values of inundated land (in millions of 2000 SGD) for each coastal site under the 0.86 m sea level rise scenario

Year	Marine			Keppel					
	Loyang	Parade	CBD	Sentosa	Harbor	Jurong	Tuas	Kranji	Wood lands
2000	3.21	46.84	146.47	1.85	4.67	5.313	4.70	3.83	20.15
2010	6.42	93.68	292.93	4.02	9.34	10.50	9.39	7.66	40.30
2020	8.98	140.51	439.40	6.01	14.01	15.68	14.09	11.49	60.44
2030	12.19	187.35	585.86	8.03	18.68	20.87	18.78	15.33	80.59
2040	15.40	234.19	732.33	10.04	23.35	26.05	23.48	19.16	100.74
2050	18.61	281.03	878.79	12.05	28.02	31.23	28.17	22.99	120.89
2060	21.82	327.87	1025.26	14.04	32.69	36.42	32.87	26.82	141.03
2070	25.03	374.71	1171.72	16.05	37.36	41.60	37.56	30.65	161.18
2080	27.59	421.54	1318.19	18.06	42.03	46.79	42.26	34.48	181.33
2090	30.80	468.38	1464.66	20.08	46.69	51.97	46.95	38.31	201.48
2100	34.01	515.22	1603.80	22.08	50.76	58.44	51.65	42.15	221.63

Notes: These values of potential inundated land only illustrate the land value, which excludes all property and structure values. A 2 per cent appreciation rate was applied to show the increment due to increase in GDP. The land value for Pulau Bukom was not available and hence omitted from this table.

These ten sites represent the major developed land uses in Singapore. Pulau Bukom was selected because of the crucial role the oil refinery industry plays in the Singapore economy. Singapore is the third largest oil-refining center in the world (The Maritime and Port Authority of Singapore, 2002). Keppel Harbor was selected also because of its significant contribution to the economy. Singapore has been the world's busiest port in terms of shipping tonnage since 1986 (The Maritime and Port Authority

Table 6. *Present value of total costs of protection (in millions of 2000 SGD) for each coastal site in the 0.86 m sea level scenario*

Year	Marine				Pulau Keppel		Jurong	Tuas	Kranji	Wood lands
	Loyang	Parade	CBD	Sentosa	Bukom	Harbor				
2000	0.22	0.26	0.61	0.11	0.51	0.30	0.24	0.25	0.16	0.23
2010	0.27	0.32	0.76	0.13	0.64	0.38	0.30	0.31	0.20	0.29
2020	0.38	0.45	1.07	0.19	0.89	0.53	0.42	0.44	0.28	0.40
2030	0.49	0.58	1.37	0.24	1.15	0.69	0.54	0.56	0.36	0.52
2040	0.60	0.71	1.68	0.29	1.41	0.84	0.66	0.69	0.44	0.63
2050	0.71	0.84	1.98	0.35	1.66	0.99	0.78	0.81	0.52	0.75
2060	0.82	0.97	2.28	0.40	1.92	1.14	0.90	0.94	0.60	0.86
2070	0.92	1.10	2.59	0.45	2.17	1.29	1.02	1.06	0.68	0.98
2080	1.03	1.23	2.89	0.51	2.43	1.45	1.14	1.19	0.75	1.10
2090	1.14	1.36	3.20	0.56	2.68	1.60	1.26	1.31	0.83	1.21
2100	1.25	1.49	3.50	0.61	2.94	1.75	1.38	1.44	0.91	1.33

Notes: The total costs of protection presented in this table include the construction costs (fixed cost) and the maintenance costs (variable cost) for each coastal site. A 4 per cent discount rate was applied to calculate the present value of the costs of protection. Each value represents the cost of infinite protection till T , which is 2100 in this study, for that particular sea level increase.

of Singapore, 2002) and thus it is heavily dependent on the efficiency and quality of the port.

The land value of Pulau Bukom was not available, as it is solely utilized by one oil company. However, because of the extremely high value of this developed site, including the extensive investment in refining capacity, it is safe to assume this site will be protected.

Table 6 presents the total costs of protection for all ten sites. Protection should occur in each decade. The cost of sea level rise is consequently the cost of building and maintaining hard protective coastal structures. We assume that the real construction and maintenance costs per linear meter are the same throughout the island.

It is clearly recorded in table 7 that the values of potential inundated land are significantly larger than the protection costs for all three sea level rise scenarios. Protection has positive net present values. Singapore should adapt to sea level rise by imposing protection measures to prevent dryland inundation. Protection of the coastline proved to be a considerably less costly solution to sea level rise than inundation.

The subject of sea level rise is surrounded by uncertainties. Sensitivity analysis (table 8) is therefore used to include various alternative assumptions that will accommodate unpredictable changes related to future sea level rise and its consequences. Sea wall construction and maintenance costs could be underestimated in this model. Hence, doubling these two values will take additional costs, such as potential disruption and planning costs, into account. The sensitivity analysis shows that if the cost of construction is doubled, there will be a 100 per cent increase in total protection cost, while doubling the maintenance cost will lead to a 25 per cent increase.

Table 7. Total economic impacts on Singapore, from 2000 to 2100, for three sea level rise scenarios

2050	0.2 m	0.49 m	0.86 m
Potential land inundated	2.23	5.45	9.56
Decadal value of land	1,872 (1,040)	4,539 (2,521)	7,980 (4,433)
Decadal protection cost	5.58 (3.10)	33.49 (18.61)	103.17 (57.32)
2100	0.2 m	0.49 m	0.86 m
Potential land inundated	3.96	9.70	17.02
Decadal value of land	6,769 (3,760)	16,599 (9,221)	29,090 (16,161)
Decadal protection cost	16.40 (9.11)	98.42 (54.68)	303.19 (168.45)
Present value of protection costs	0.30 (0.17)	1.80 (1.00)	5.55 (3.08)

Notes: The areas of potential land inundation are presented in sq km. The values of land and related discounted values are in millions of 2000 SG\$ with millions of 2000 US\$ in parentheses.

It is possible that rebuilding the sea walls every ten years may not be possible if the construction is highly disruptive and difficult. We consequently explore what difference it would make if the construction intervals must be longer. The analysis explores both a 20-year and a 30-year interval. Allowing the sea walls to be rebuilt every 20 years increases the costs of the program by 194 per cent. Allowing the walls to be rebuilt every 30 years will increase the overall cost by 367 per cent. The costs are so much higher because the walls have to be built in anticipation of so much more sea level rise. One is consequently faced with very high immediate costs for sea walls that must be designed for conditions that are far into the future.

The predicted sea level rise scenarios are directly related to the height of the sea walls built. In order to understand the relation between the height and protection cost of the walls, a sensitivity analysis has been conducted to address different height increases in the model. If the height of the walls is increased by 5 per cent to 50 per cent, the total cost of protection will increase by 10 per cent to 125 per cent.

The benefit of protection could vary according to the different predictions of economic growth. GDP is projected to grow at an annual rate of 2 per cent, at which land value is assumed also to increase proportionally. Alternative assumptions regarding future economic growth have been included in the sensitivity analysis. A lower growth rate of 1 per cent will decrease the benefit of protection by 0.98 per cent, conversely a growth rate of 3 per cent will result in an increase of 0.98 per cent in land value. The decision

Table 8. *Sensitivity analysis results*

	<i>Percentage change in protection cost</i>
Double cost of construction	100
Double cost of maintenance	25
Rebuilding sea wall every 20 years	194
Rebuilding sea wall every 30 years	367
<i>Percentage change in height of sea wall</i>	<i>Percentage change in protection cost</i>
5	10
10	21
15	32
20	44
25	56
30	69
35	82
40	96
45	110
50	125
	<i>Percentage change in protection benefit</i>
Economic growth of 1%	-0.98
Economic growth of 3%	0.98

Note: The construction cost of the wall is linearly related to the total cost function.

to protect remains the same in these two cases. Hence, the results are not sensitive to the growth rate assumption.

5. Discussion

This study calculates the potential economic costs of sea level rise for Singapore. The cost of protection and the cost of inundation are compared. The study finds that the extremely high land values in Singapore justify protection of market land across the island. In Singapore, the damages from sea level rise are just the costs of adaptation, and the cost of building and maintaining hard structures along the coast. Protection is the most desirable and efficient solution to sea level rise for the market land of Singapore. Even if construction and maintenance costs are higher than expected, the total protection cost is still significantly lower than the benefit.

Sea walls must be built along an entire coast to be effective. The coastal plan must clearly be coordinated by the government. However, the government must consider carefully who will pay for this program of protection. One choice is that all citizens of Singapore will have to pay through income taxes or property taxes. Another alternative is that the cost of protection be borne entirely by landowners along the coast. The cost of protection could be integrated into the price of coastal land. These two

policies will have a dramatic affect on the relative price of coastal versus interior land on the island and consequently will probably affect coastal development as well.

The potential lost dryland due to sea level rise inundation could range from 4 sq km to 17 sq km (table 7) depending on the sea level rise scenario. This is equivalent to a loss of 0.6 to 2.7 per cent of the total area in the country. This is a relatively small change in the amount of land in the island. Further, in Singapore, all the land will be protected so that no land is actually lost. However, in other islands or coastal regions, sea level rise might threaten a substantial fraction of the developable land of a country to inundation. In this study, we took the value of land as given. We did not examine how a sea level rise scenario might change land prices. If a scenario resulted in a substantial fraction of land in an island being inundated, land prices would rise. In the mainland, the fraction of land inundated would be small (except possibly for a small coastal country) and so would have no effect on land prices in general. For an island, land in other places is not a perfect substitute for land on the island. For islands that lose a substantial fraction of total land, analysts must conduct a general equilibrium analysis that would incorporate the effects on land prices caused by a non-marginal reduction of land supply.

Even with a complete protection response, sea level rise still imposes costs on Singapore. The country will have to build ever-higher hard structures along its coasts to keep the sea out. Since it is not certain how much the sea will rise each decade, the walls should be built anticipating future increases. However, as shown in this analysis, if the walls simply anticipate the expected change over the next decade, the overall cost of the program is not that great. The cost is higher, if changes are made every 20 or 30 years. In this case, walls will have to be built to anticipate a much greater amount of sea level rise and so, at each point, they will have to be higher. The sensitivity analysis reveals that the costs increase 194 per cent if decisions must be made in 20-year intervals and by 367 per cent if they are made every 30 years.

The costs also greatly depend upon the sea level rise scenario. Annual construction and maintenance costs will run about 0.3 million US\$ by 2050 and 0.9 million US\$ by 2100 with a 0.2 m scenario. A 0.87 m scenario, however, will cost 5.7 million US\$ by 2050 and 16.8 million US\$ by 2100. For these two scenarios, the present value of this stream of expenditures for the next century is 0.17 and 3.08 million US\$ for Singapore, respectively.

This study demonstrates that careful adaptation to sea level rise can reduce the cost of coastal impacts dramatically. The decadal construction approach assumed in this study provides a series of precise and necessary steps against a dynamic change. This approach reduces the present value of protection costs considerably and protects a valuable resource from inundation. The results found for Singapore, that 100 per cent protection is optimal, may not apply universally around the world. Sites with much lower land values may have to be inundated as the cost of protection may exceed the land value. However, the study demonstrates that the methods used in this study can be applied universally and are not specific just to the United States.

This study presents a sophisticated dynamic analysis of sea level rise for Singapore. However, further research is still required. Clearly, there remains considerable uncertainty about the speed of sea level rise. Another factor that needs to be addressed is the relevance of storms in the economic assessment of sea level rise. The study does not address storm damage, which could affect the desired height of sea walls and the resulting flood damages. If the frequency or severity of storms increase, there will be increased damages and ever-more protection needed (West and Dowlatabadi, 1999).

This study examined only market land. Another important question concerns what happens to non-market land, such as beaches, marshes, and mangroves. The analysis of non-market land requires a completely different set of methods because of the absence of market values for these land uses. A separate study of non-market values suggests that damages to these resources will require a mix of protection and loss, and will raise the overall cost of sea level rise to Singapore (Ng and Mendelsohn, 2003).

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