

Article

Beach Nourishment as an Adaptation to Future Sandy Beach Loss Owing to Sea-Level Rise in Thailand

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Abstract: A recent study suggested that significant beach loss may take place on the coasts of Thailand by the end of the 21st century as per projections of sea-level rise by the Intergovernmental Panel on Climate Change (IPCC). The present study adapts a framework and provides broad estimations for sand volumes and costs required to apply beach nourishment to each coastal zone in Thailand using a technique based on the Bruun rule assumption. Results indicate that a minimum of USD 2981 million (the best scenario) to a maximum of USD 11,409 million (the worst scenario) would be required to maintain all sandy beaches at their present width. Further, the effect of filling particle size on beach nourishment was analyzed in this study. The cost of beach nourishment ranges between USD 1983 and 14,208 million when considering filling particle size diameters of 0.5 and 0.2 mm. A zonal sand volume map for all 51 sandy beach zones in Thailand was created for use as an overview to help decision makers develop a more feasible adaptation plan to deal with the future sea-level rise for Thailand.

Keywords: sea-level rise; sandy beach; beach erosion; beach nourishment; climate change adaptation; Thailand

1. Introduction

Global sea-level rise (SLR) and climate change can lead to coastal erosion and cause serious problems for populations in low-lying coastal areas [1]. A SLR can cause physical and socio-economic damages to coastal regions because sandy beaches are one of the most important coastal resources for tourism and they also perform the function of environmental preservation [2]. A loss of beach areas could lead to the potential loss of coastal structures as beaches normally dissipate wave energy, and, eventually, it could cause monetary damages to coastal populations [3]. Previous studies have indicated several coastal communities worldwide, including Thailand, are vulnerable to SLR and storm surges that could bring massive socio-economic loss due to the continuously growing population [4–6]. Therefore, these coastal areas require some additional actions to protect from SLR.

The Intergovernmental Panel on Climate Change (IPCC) 5th assessment reports indicated a projected global mean sea-level increase by 8–16 mm/yr in the late 21st century (2081–2100) [7]. Further, some studies that investigated the increasing trends of sea level from tide gauges indicated a rise in sea levels in Thailand [8,9] and provided warnings for the safety of Thailand's coastal areas. Further, the IPCC 5th assessment reports projected the regional SLR along Thailand's coastlines to range between 0.39–0.61 m. Recently, Ritphring et al. [10] projected sandy beach loss caused by future SLR

for all coastlines of Thailand based on four Representative Concentration Pathway (RCP) scenarios, i.e., RCP2.6, RCP4.5, RCP6.0 and RCP8.5, and reported that, between 2081 and 2100, Thailand will possibly lose 46–72% of the present beach areas. Thus, it is important to preserve sandy beach areas.

Sandy beach is one of the important coastal resources of Thailand. Some of the beaches serve as attractive tourism spots that bring significant income to the country, and they also provide a recreational area for local people [11,12]. Sandy beaches also serve as a habitat for wildlife species and nurseries. The beaches in southern Thailand are known for sea turtle nesting places [13]. Moreover, sandy beaches can provide several other services such as coastal protection, carbon sequestration, or water catchment and purification [14]. The erosion of sandy beaches may imply the loss of these services. Therefore, the beaches need some essential actions to preserve and maintain their benefits.

On the global scale, several studies have investigated adaptation techniques to deal with SLR. For example, Hinkel et al. [15] determined the costs of installing dikes to protect the coastal population from SLR on a global scale and suggested that it would require billions of dollars. Using hard structures such as sea walls, dikes, or detached breakwater to prevent shorelines from erosion may not be appropriate in some beaches especially in tourism spots. They not only cause the beaches to have poor scenery; the ill-designed coastal structures could also neglect potential negative effects [3]. For example, the detached breakwater altered the wavefield resulting in the sandy beach erosion at its adjacent coastline [16,17].

Beach nourishment is considered a more preferred adaptation technique as it can avoid the negative effects of installing hard structures on the coastal environment [18]; further, beach nourishment has been successfully adopted in many parts of the world [19]. Yoshida et al. [2] proposed a framework for beach nourishment as an adaptation to beach erosion induced by SLR for all Japanese coastlines. Their framework was based on future beach width resulting from SLR based on Udo and Takeda's study [20], and it aimed to specify vulnerable beach areas and estimate the sand volume and costs required to maintain beach width to satisfy different beach functions. However, currently, adaptation plans to deal with future SLR in Thailand are lacking. Thus, this study aims to (1) develop a framework for beach nourishment, (2) to estimate the sand volume and costs using Yoshida's method with the results of beach loss projection and beach data set from Ritphring et al.'s [10] study, (3) to map zonal volume and costs of sand for all sandy beach zones in Thailand in order to be used as a guideline for coastal management planning to deal with SLR.

2. Methods

2.1. Study Area

Thailand's coastlines are located nearby the South China Sea (Figure 1) and they cover ~3148 km including 2055 km in the Gulf of Thailand (GoT) and 1053 km in the Andaman Sea. The Department of Coastal and Marine Resources (DMCR) of Thailand has categorized the beaches into 64 zones based on physical characteristics, where 51 zones comprise sandy beaches. In Thailand, sandy beaches generally have a small beach width with an average of 34.8 m. Sand particle size on these beaches' averages at 0.3 mm, of which sand particles 0.2–0.5 mm in size cover more than 80% of the beach; further, the beach's foreshore slope ranges between 1–14°.

Figure 2 is adapted from Ritphring et al.'s [10] study and shows the present beach width and the projections of the future beach width caused by SLR evaluated from Coupled Model Intercomparison Project 5 (CMIP5) as per the 4 RCP scenarios [7]. The histogram distribution of beach width for both existing and projected beaches is shown in Figure 3. Figure 4 displays the database of the physical characteristics of sandy beaches including grain size and slope collected in Ritphring et al.'s [10] study. The beach slope and grain size diameters were obtained from field measurements over 230 locations for all 51 sandy beach zones, as shown in Figure 1. The beach width data was collected through satellite images during 2009–2015 and it was measured from the shoreline to the inland boundary (the dry

beach zone of the beach profile). Meanwhile, the sand particle size was measured by the standard sieve analysis and the beach slope was measured by angle meter at the foreshore in the swash zone.

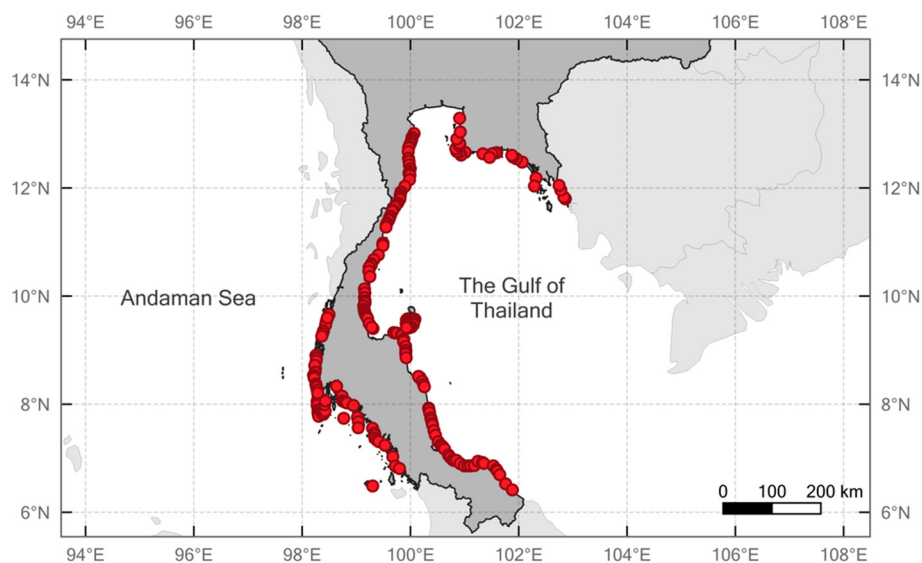


Figure 1. The study area of Thailand. The red signs represent the field measurement location of sediment size and foreshore slope measurements.

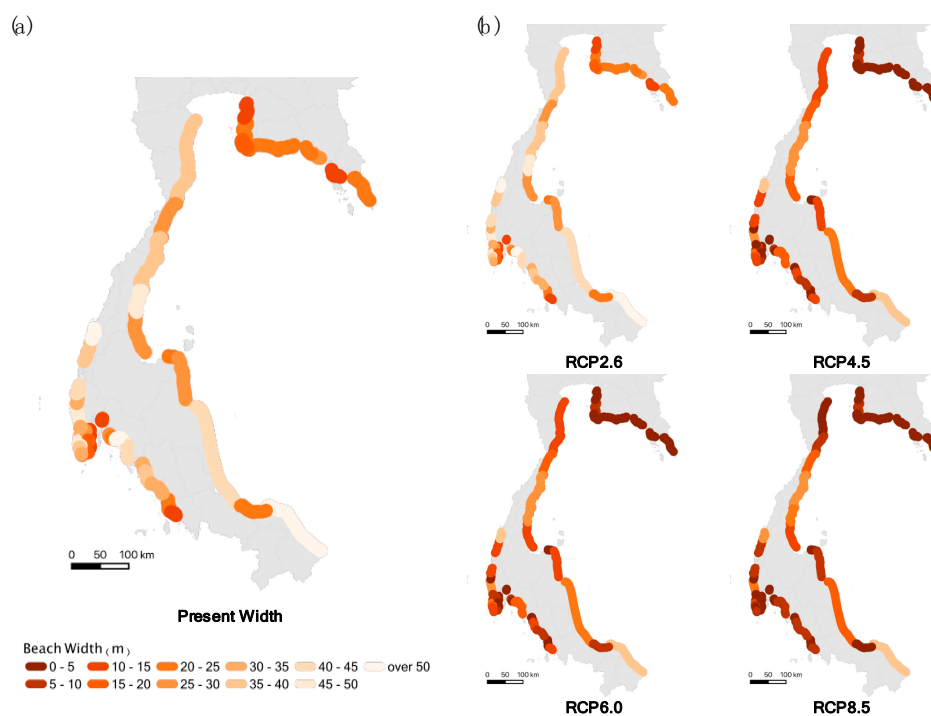


Figure 2. Beach width at (a) the present condition (b) the Future (2080–2100) projections based on 4 RCP scenarios adapted from the results of beach loss projection due to SLR by Ritphring et al. study [10] in which the calculation was based on the Bruun rule assumption.

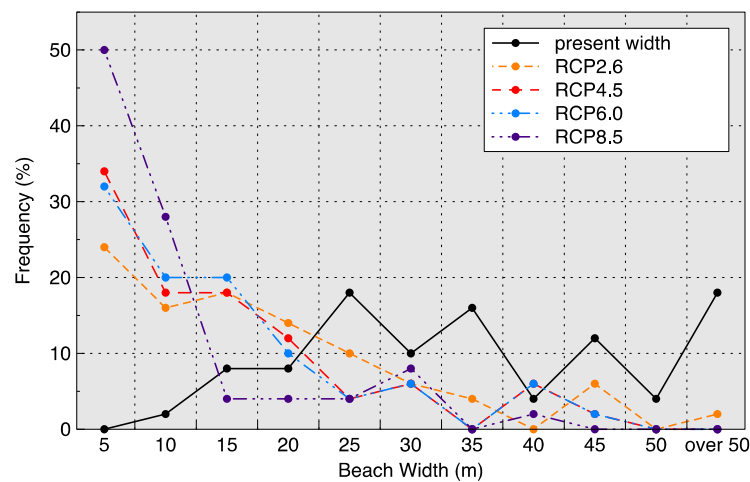


Figure 3. Frequency distributions of the present beach width and the Future (2080–2100) beach width for four Representative Concentration Pathway (RCP) scenarios.

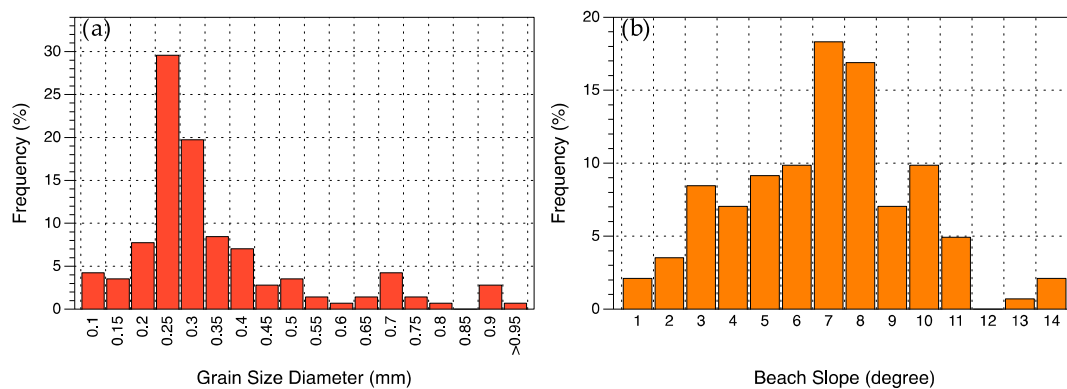


Figure 4. Beach characteristics by field measurement over 230 locations for all beach zones. (a) The average sediment size was collected at the foreshore of the beach and the size was measured through standard sieve analysis. (b) The average beach slope measured by an angle meter at the foreshore of each sandy beach. The figure was reproduced from Ritphring et al. [10].

Figures 2 and 3 show the projected severe beach width scenario in 2081–2100. Currently, the average beach width is ~35.4 m; however, it is projected that 24–50% of sandy beaches zones will be reduced to less than 5 m as per the RCP2.6 and RCP8.5 scenarios. Further, in the worst-case scenario, none of the beaches will retain a beach width greater than 50 m. Beaches in the upper GoT seem to be the most affected when the study considers a maximum remaining width of 15 m. Thus, it is evident that Thailand’s sandy beaches require considerable attention to mitigate future SLR effects.

2.2. Framework for Beach Nourishment

This study adopted similar steps as that in Yoshida et al.’s study [2], wherein beach nourishment was only adopted for vulnerable areas as shown in Figure 5. The framework is as follows:

Step 1: Determine the future shoreline retreat. In this step, data are obtained from Ritphring et al.’s [10] study where future (2081–2100) shorelines retreat were determined based on four RCP scenarios. Figure 2 displays the projected future beach width according to their study.

Step 2: Identifying the vulnerable beach areas. A vulnerable area can be determined by comparing the beach width obtained in Step 1 with the beach width to be protected among different beach width options (10, 20, and 30 m) and by maintaining the present shoreline. The beach width to be protected is selected based on beach benefits that have not been widely evaluated for Thailand, unlike those in Yoshida’s study.

Step 3: Estimating beach nourishment volume and cost of required sand for each option in step 2.

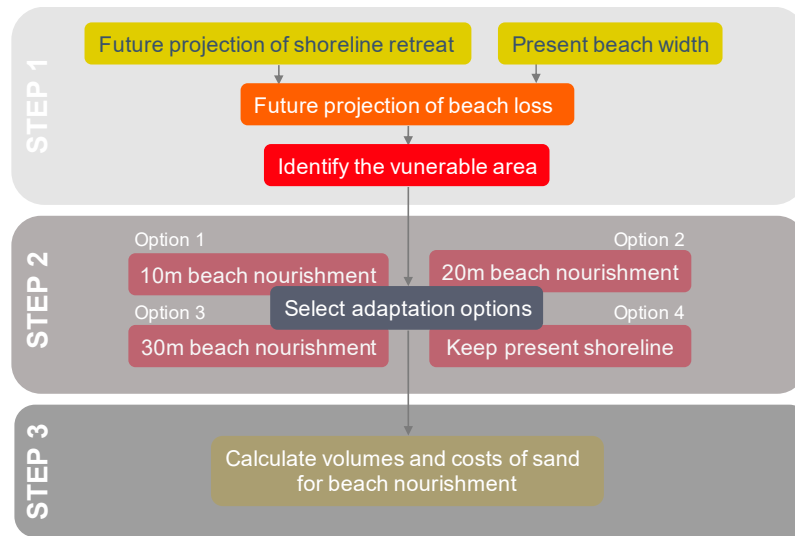


Figure 5. Framework for beach nourishment in Thailand adapted from Yoshida et al. [2].

2.3. Beach Nourishment Model

A model mechanism was developed in Yoshida et al.'s study [2] based on an equilibrium profile concept. The concept considers beach nourishment for maintaining the beach width for each option (Y_*); the beach profile increases by adding sand with the amount of S_n . After the nourishment, the shoreline is expected to retreat because of SLR, and the nourishment is expected to maintain the future beach width to values larger or equal to Y_* .

The beach model was based on the assumption of an equilibrium profile concept [21]. The equilibrium profile largely depends on the grain size and is delimited by its seawards distance at the depth of closure (DoC), where sediments transported by waves are neglected. The equilibrium profile is given by

$$h = Ay^{2/3} \quad (1)$$

where h is the water depth, A is the scaling parameter based on sediment size (d_{50}), and y is the distance in the seaward direction. When SLRs occur, the beach profile needs to be raised vertically to compensate for the amount of SLR to maintain the equilibrium profile. Based on this assumption, the sand volume can be calculated by

$$V_p = S_n Y_0 + \int_0^{W_*} (Ay^{2/3} + B) dy - \int_0^{W_*} (Ay^{2/3}) dy \quad (2)$$

where V_p is the profile change volume (m^3/m), Y_0 is the dry beach width, S_n is the height of the added sand, i.e., the amount of vertical increase in the equilibrium profile required to maintain the beach width to be protected Y_* , and W_* is the cross-shore distance to closure at depth h_* . The amount of vertical increase in the equilibrium profile S_n can be equated as

$$S_n = S - \left(\frac{h_* + B_h}{W_*} \right) (Y_0 - Y_*) \quad (3)$$

where S is the SLR, h_* is the DoC, and B_h is the berm height. Equation (3) is modified from the Bruun rule [22]. The amount of SLR after beach nourishment causes an allowable retreat ($Y_0 - Y_*$) after the profile increases by S_n .

Total sand volume can be generated by multiplying the vertical increase in Equation (3) with the beach length. The DoC can be calculated as [23]

$$h_* = 2.28H_{e,t} - 68.5 \left(\frac{H_{e,t}^2}{gT_{e,t}^2} \right) \quad (4)$$

where $H_{e,t}$ is the significant wave height that exceeds 12 h per t years, $T_{e,t}$ is the significant wave period with a 12-hour-per- t -year exceedance, and g is the gravitational acceleration. After determining the value of h_* , we can determine the value of DoC (h_*), and it is substituted into Equation (1) to find y_* or the cross-shore distance. The berm height (B_h), which requires an entire period-averaged significant wave height and period, can be determined using [24]

$$B_h = 0.125H_b^{5/8} (gT_s^2)^{3/8} \quad (5)$$

where H_b is the breaking wave height and T_s is the mean significant wave period. The breaking wave height can be obtained using [25]

$$\frac{H_b}{H_s} = (\tan \alpha)^{0.2} \left(\frac{H_s}{L_s} \right)^{-0.25} \quad (6)$$

where H_s is the mean significant wave height, α represents the beach slope in degrees, and L_s is the significant wavelength. When all variables are determined and combined with SLR data (S), they can be substituted into Equation (3) to compute the amount of sand increase in the vertical direction (S_n).

The datasets used in this study include the projected SLR data in the future period, significant wave height and wave periods, grain size diameters, and beach slope; all datasets were collected and can be found in Ritphring et al.'s study [10]. For projected SLR data, the ensemble-mean regional SLR data (1-degree latitude–longitude resolution) of 21 CMIP5 models for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios from 2081–2100 relative to the reference period from 1986–2005 were used [7]. The projected SLR along Thailand coasts varies by regions but no significant differences among the GoT and the Andaman Sea, although SLR in the upper GoT may be slightly larger than the other regions. Overall, the ensemble-mean SLR along the coasts of Thailand ranged between 0.34 and 0.41, 0.21 and 0.49, 0.42 and 0.51, and 0.55 and 0.65 m for RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. The average of the ensemble mean SLR along the entire coastline of Thailand is 0.39, 0.46, 0.48, and 0.61 m for RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. These SLRs resulted in projected beach losses of 46–72% of the current sandy beaches area.

For the wave data, we adopted the three-hour significantly reanalyzed wave data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) for 1980–2010 (30-year period), which is the largest wave dataset available for Thailand coasts. The entire period-averaged significant wave height and period were used to calculate the DoC and the berm height of the beach at the present condition.

To find the volume of sand for beach nourishment at each beach zone, the particle size of sand is a very important parameter; the fill volume depends on grain size diameters [21]. If the filled particle is finer than the native sand, a larger amount of sand will be required to fill the same designed volume as the coarser sand. Therefore, this study considered the same size for the filling particle and the native sand and grain sizes of 0.2 and 0.5 mm for all sandy beach zones in Thailand to determine the effect of sand size on the volume and costs for beach nourishment.

To determine the cost of sand, this study adopted the value from the DMCR wherein the range of unit costs of sand were collected from the reports of coastal construction projects. The unit costs of sand in this study ranges between THB 487–1183 per cubic meter (USD 15.5–37.5/m³) [26].

3. Results and Discussion

3.1. Sand Volume and Cost of Beach Nourishment

Figure 6a shows the sand volume required for the nourishment of each RCP scenario; a minimum of 204 million m^3 (RCP2.6) and a maximum of 306 million m^3 (RCP8.5) of sand would be required to preserve the existing shorelines (approximately 35 m) when implementing the beach nourishment project using native sand particle sizes. Further, Figure 6a indicates that, to compensate for the sand loss by SLR, 128–379 million m^3 of sand would be required. When considering the sensitivity of grain size diameters, a minimum sand volume of 128 million m^3 for RCP2.6 with 0.5 mm (the lower bound of the yellow area in Figure 6a) and a maximum of 379 million m^3 for RCP8.5 with 0.2 mm (the upper bound in Figure 6a) would be necessary. For the maximum designed beach width of 50 m, the difference between the maximum and minimum volume of sand is approximately 234 million m^3 .

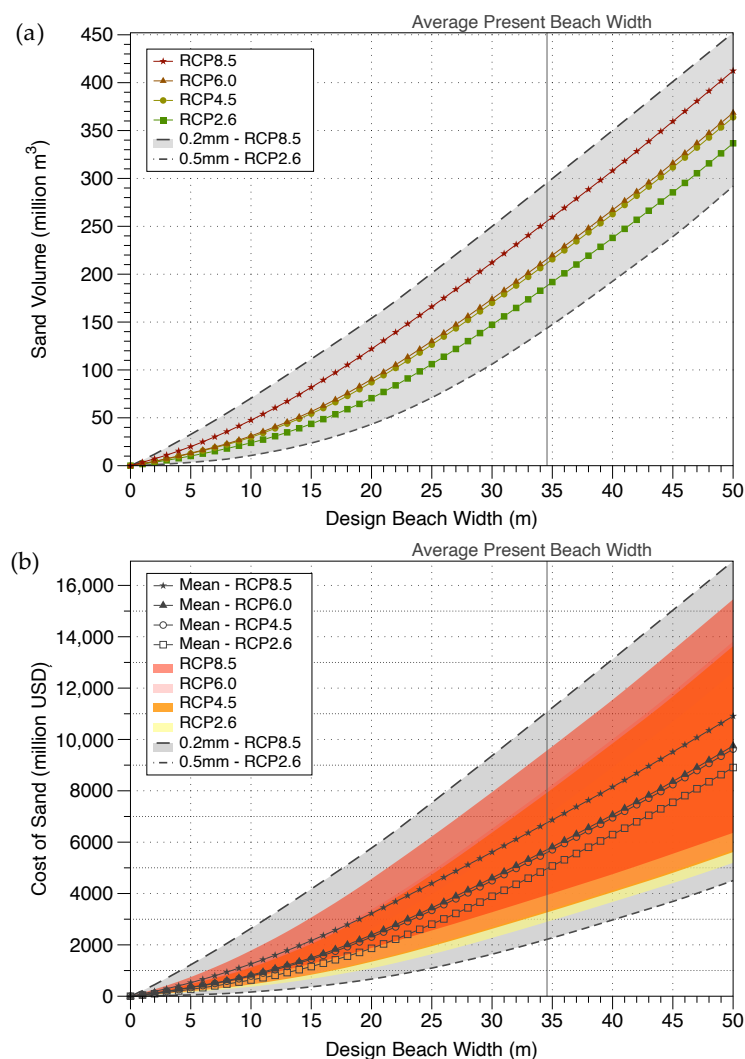


Figure 6. Volume and costs of sand for beach nourishment to combat SLR in each RCP scenarios. (a) The total volume of sand for each designed beach width for entire sandy beach in Thailand; (b) the summation of costs for beach nourishment. (a) The calculations of the colored lines for each RCP scenario were based on the same size for filling particle and native particle. The upper and lower bounds of grey-shaded area were calculated based on particle sizes of 0.2 and 0.5 mm. (b) The sand volumes were multiplied by the maximum unit cost of USD 37.5/ m^3 and the minimum unit cost of USD 15.5/ m^3 of sand, respectively. The warm color-shaded areas represent cost ranges (minimum to maximum) with lines representing the mean costs for each RCP scenario.

According to the coastal engineering project reports of the Thai government, a cubic meter of sand costs approximately USD 15.5–37.5. Hence, the costs of beach nourishment could range between a minimum of USD 2981 million to a maximum of USD 11,408 million to maintain shorelines at the present position for all sandy beach zones as shown in Figure 6b. Further, about USD 572–3510, 1291–6297, and 2474–9678 million would be required to maintain shorelines at 10, 20, and 30 m, respectively, when considering the native particle size. The grey areas in Figure 6b indicate the sensitivity of the grain size to the costs of sand. The maximum costs of sand required to compensate the beach loss on all sandy beach zones is equal to USD 14,208 million when considering a sand particle size of 0.2 mm for the RCP8.5 scenario, and USD 1983 million when considering the sand size of 0.5 mm for the RCP2.6 scenario. For the 50-m designed beach width, the total cost difference could be USD 15,241 million.

3.2. A Zonal Sand Volume Map for 51 Sandy Beach Zones

Applying beach nourishment to the entire country may not be practical as it requires massive sand volume and seems over budget. Some of the beaches would have higher demands than the others, such as a tourism beach. Therefore, this study shows a zonal beach nourishment profile volume and its corresponding costs in Figure 7. The 51 sandy beach zones in Thailand comprise 21 zones in the GoT and 30 zones in the Andaman seaside. The sandy beach zones in the GoT have an average beach width of 29.9 m, and those in the Andaman Seaside, that of 37.8 m. In the GoT side, there are 13, 20, and 21 zones that need beach nourishment to maintain beach widths of at least 10, 20, and 30 m, respectively, for RCP2.6, while all 21 sandy beach zones in the GoT require the beach nourishment project to preserve the beach width to at least 20 m for RCP8.5. In the Andaman seaside, there are 15, 21, and 27 zones that need beach nourishment to widen the beach to at least 10, 20, and 30 m, respectively, for RCP2.6, while for RCP8.5, 25, 27, and 30 zones require beach nourishment to maintain beach widths of 10, 20, and 30 m, respectively. In the case of maintaining the beach at present width, the sandy beach zones in the Andaman Sea, where most of beach tourism attractions locate, need larger amounts of sand than those in the other part. The zone-average profile volume is 228–353 m³/m for RCP2.6 and RCP8.5, respectively; this is because the beaches there will probably experience the severer SLR and the beach width in those areas are larger compared to ones in the GoT. Meanwhile, the beaches in the middle and lower GoT apparently have smaller demand for beach nourishment with the zone-average profile volume of 83–133 m³/m for RCP2.6 and RCP8.5, respectively. It is also questioned that the sandy beaches in those areas should be maintained at the present width as they have a lower tourism capacity than the other region despite being regularly used by the local villagers [12]. However, the other benefits of the beach should be further discussed.

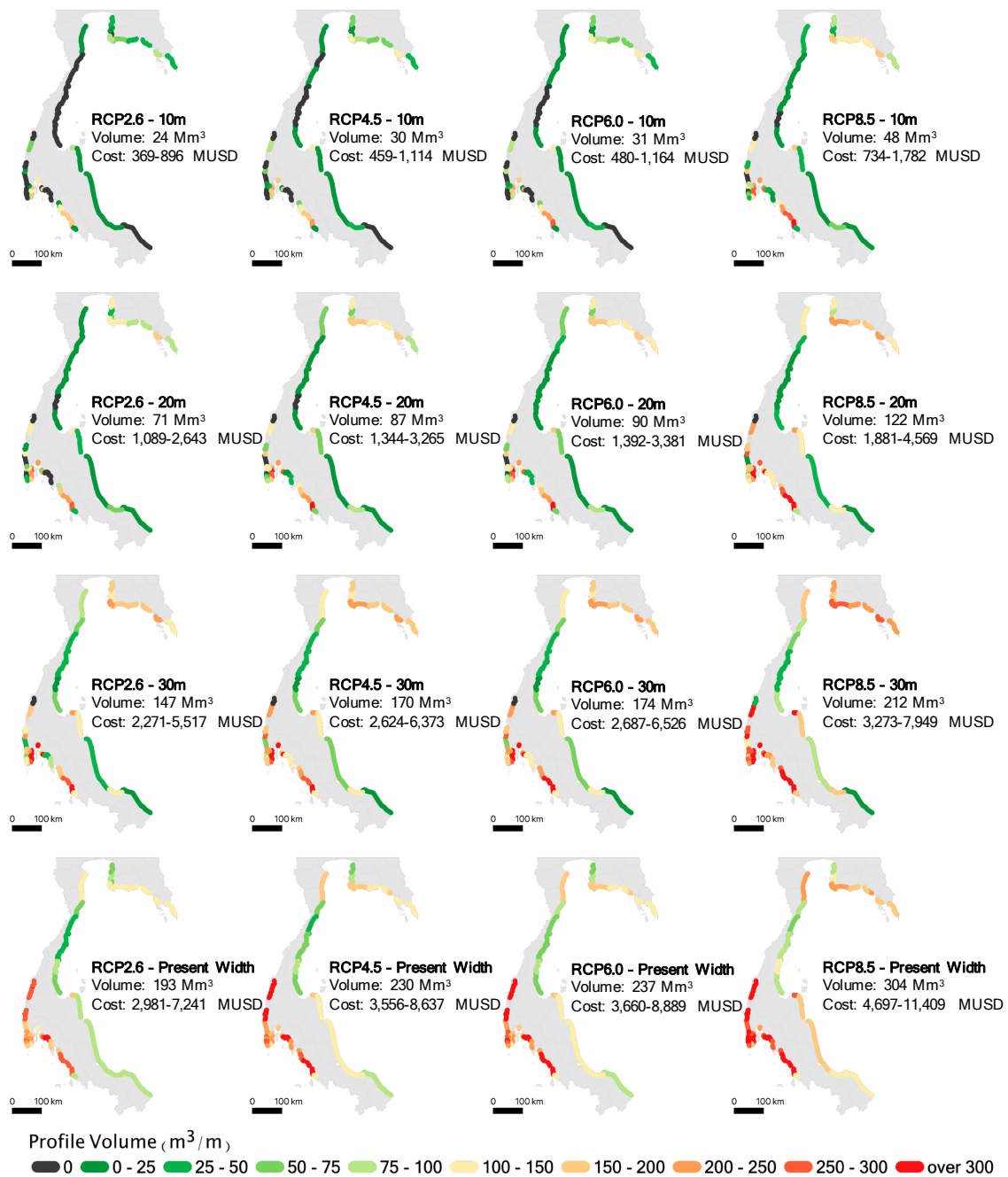


Figure 7. The profile volume in m^3/m of sand for beach nourishment for each sandy beach zone and designed beach width, 10, 20, 30 m and present beach width (the top row to bottom row, respectively), for RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (left column to right column, respectively). The total volume for the entire sandy beaches is presented with the maximum and minimum cost of sand in million USD (MUSD). The sand volume was calculated by applying the same size of the filling particle and the native particle.

3.3. The Feasibility of the Beach Nourishment Project in Thailand

Beach nourishment was usually considered a soft solution to preserve the shoreline from long-term erosion [18]. The Department of Coastal and Marine Resources of Thailand is promoting this solution instead of building hard structures to avoid the negative effect of a hard solution. Recently, Thailand successfully adapted the first beach nourishment project at the famous Pattaya Beach, Chon Buri Province. With the total cost of THB 429 million (USD 13.1 million) and a sand volume of 360,000 m³, it has widened the beach to the designed width of 50 m from the previous width of 20.95 m [12,27]. The beach nourishment project is believed to attract more tourists and larger tourism revenue in the future. In conclusion, beach nourishment could be considered a new and suitable solution for coastal management in Thailand.

Regarding the availability of filling sand, there are some examples from the literature that successfully adapted the dredged sand from the navigation canal [28] or the nearby the local marina for the beach nourishment [29]. Thailand has the same potential to do so as well. There is a study reported about an increase of sand bar areas in the river embayment at the Lower Mae Ping, central Thailand, causing the shallower riverbed, and eventually the rapid overflow during flooding [30]. The additional dredging projects are required in the site. Meanwhile, the Pattaya Beach Nourishment project also used the filling sand from the seabed near the beach. As beach nourishment in Thailand is not widely applicable at present, detailed studies regarding the availability of the suitable sand sources may be needed.

According to the World Bank, Thailand has a Gross Domestic Product (GDP) of approximately USD 505 Billion. The budget needed for the beach nourishment project (to keep present beach width option) is equal to 0.59% (RCP2.6, minimum cost) and 2.26% (RCP8.5, maximum cost) of Thailand's 2018 GDP. However, regarding the responsible organization for coastal management, there are three main departments that are accountable for coastal erosion in Thailand, including the Marine Department, the Department of Coastal and Marine Resources, and the Department of Public Works and Town & Country Planning. These organizations received a budget for coastline protection and management of over USD ~48.50 million for 2020 [31–33]. With this rate, they will have to save the budget for 61 and 235 years (RCP2.6 and RCP8.5, respectively) to keep the entire sandy beaches at present shoreline position. These numbers imply that the cost of beach nourishment to compensate for the sandy beach loss due to the future SLR is seriously gigantic, comparing to the current budget from three governmental organizations. Therefore, this research's output framework and zonal sand volume map for 51 sandy beach zones would be helpful in the decision-making stage. It can support the coastal policy planner to select the appropriate beaches for adaptation.

3.4. The Limitations and Recommendations for Future Research

The projection of the beach erosion due to SLR using the Bruun Rule has been largely controversial and considered as an unsuitable method for a highly complex sedimentary environment. The Bruun Rule was said to be based on the unrealistic assumption that maybe inexistent in nature [34]. For example, it assumes that the SLR always causes beach erosion. It considers no net longshore sediment transport and neglects any changes in the beach profile other than SLR. The major problem regarding the application of the Bruun Rule is the determination of active profile slope which largely depends on the DoC [1]. There are several input parameters for DoC determination associated with large uncertainties and they may question the reliability of the projection. A recent study [35] has suggested that the accuracy of DoC computation using reanalyzed wave data is limited by the spatial resolution of the data and the DoC equation coefficients proposed in the past literature are site-specific. However, to confirm this study's calculated DoC accuracy, the measured DoC data for Thailand's coastlines is further required. Furthermore, several alternatives could be more appropriate for determining beach loss due to SLR. For instance, a process-based model proposed by [1] provides a probabilistic estimation of SLR-induced beach erosion which is considered to be a more appropriate technic for coastal risk assessment than a deterministic method like the Bruun Rule. The authors of [36] have modified

the Bruun Rule model by adding all phenomena affecting shoreline change including onshore sand transport, sand sources and sinks, and longshore sediment transport gradient which could provide more accurate results of beach loss projection. However, the models require a load of observed coastal data such as wave height, sediment budgets, historical shoreline changes that are not available for most of the coasts of Thailand. This research conducted on a national scale, and based on the availability of the data set, the Bruun Rule is still a viable method to be used for the projection of future beach loss due to SLR [20]. It should be noted that, due to the mentioned limitations of the Bruun Rule, this study can only provide a broad estimation for sand volume and costs of beach nourishment.

By following the framework illustrated in Figure 5, along with the zonal beach nourishment volumes suggested in Figure 7, this study shows the preliminary costs of beach nourishment required to help project planners tackle future SLR. However, the costs presented exclude additional expenditures such as transportation, maintenance, or related labor costs, which may considerably increase the projected costs in this study. Further, this study only considers costs for sand required to compensate for beach loss caused by SLR and excludes the storm- and wave-related erosion that may significantly increase costs larger than this study's estimation. In addition, the study did not consider the land subsidence due to the groundwater extraction which dominantly contributes to the relative SLR in the upper GoT especially the sandy beaches nearby delta area [37]. This potentially exacerbates the erosion and may increase the costs of adaptation. Although the sand volumes and its costs projected by this study may be lower than the future potential costs, this study's output can be taken as the minimum cost estimation and can be more beneficial than no-action to conserve the sandy beaches.

In Yoshida's study [2], designed beach widths of 10, 20, and 30 m serve specific purposes such as preventing disasters, preserving the coastal ecosystem, and tourism, respectively. Designed beach widths are normally related to beach benefits; some studies used the cost-benefit analysis to design an optimum beach width [38]. However, the determination of the beach benefits remains a challenge for coastal management planners [14], especially in Thailand because there are very few studies that investigate beach benefits, especially on the national scale. In addition, severe erosion can cause a considerable economic loss in areas that attract a considerable amount of tourism [39]. Thus, the integration of engineering sciences and environmental economics has become a necessity for decision makers.

In future research, when the beach benefits are estimated, the results of this study will prove to be more beneficial for beach nourishment project planners when designing optimum beach widths to serve specific purposes.

4. Conclusions

This study adapted the framework for beach nourishment practice and provided preliminary estimation for sand volumes and costs required to tackle the beach loss problem caused by the projected future SLR for each coastal zone in Thailand. The results rely on the assumption that filling sediment size is the same as the native sand size, and they indicated that a minimum of USD 2981 million (RCP2.6) and a maximum of USD 11,409 million (RCP8.5) would be required to maintain all beaches at the present width using the beach nourishment practice. Additionally, the presented framework is an initial effort aiming to raise the awareness of the role of adaptation and the impacts of future SLR.

However, the proposed framework is only a one-time nourishment (for a future period, 2081–2100), and this study only considered beaches that would be affected by SLR. In future work, beach replenishment time intervals should also be assessed. The benefit of the beach needs to be evaluated to determine optimum beach widths and a further cost-benefit analysis is necessary for realistic nourishment in design practice. Since Thailand's governmental annual budget is relatively small when comparing to the presented cost of beach nourishment, we should carefully implement this solution together with the consideration of beach's economic value and the budget for the beach preservation.

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

Abbreviations

CMIP5	Coupled Model Intercomparison Project Phase 5
DMCR	Department of Coastal and Marine Resources of Thailand
DoC	Depth of Closure
ECMWF	European Centre for Medium-Range Weather Forecasts
GoT	Gulf of Thailand
IPCC	Intergovernmental Panel on Climate Change
MUSD	Million United State Dollar
RCP	Representative Concentration Pathway
SLR	Sea-Level Rise
USD	United States Dollars

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