Cost-Benefit Analysis of Mixing Gray and Green Infrastructures to Adapt to Sea Level Rise in the Vietnamese Mekong River Delta

Pham Thi Oanh 1,*, Makoto Tamura 1,2, Naoko Kumano 3 and Quang Van Nguyen 1

1 Climate Change and Development, VNU-Vietnam Japan University, Hanoi 10000, Vietnam; makoto.tamura.rks@vc.ibaraki.ac.jp (M.T.); quangmda@gmail.com (Q.V.N.)
2 Global and Local Environment Co-Creation Institute, Ibaraki University, Ibaraki 310-8512, Japan
3 Graduate School of Agriculture, Ehime University, Ehime 790-8577, Japan; kumano.naoko.xi@ehime-u.ac.jp
* Correspondence: oanhpham.241191@gmail.com

Received: 9 October 2020; Accepted: 4 December 2020; Published: 11 December 2020

Abstract: This study evaluated inundation impacts and the economic damage resulting from sea level rise (SLR) in the Vietnamese Mekong River Delta (VMRD), and identified the effectiveness of mixing gray and green infrastructures using cost-benefit analysis. The results showed that the VMRD could potentially be heavily affected by SLR. Without the implementation of proper adaptations, more than 90% of this area could be below sea level and nearly 20 million people could be affected by inundation by the end of the 21st century. The total economic damage could reach more than 22,000 billion US$ (2010 real value) by 2100 with no discount rate. These threats may increase the pressure on the region to ensure well-being, equity, and progress towards achieving sustainable development goals. However, achieving these goals will require the implementation of adaptations for upgrading and restoring in the region. This study assessed the effectiveness of adaptations and demonstrated that mixing gray and green infrastructures could benefit coastal inhabitants at a cost of 12 to 19 billion US$.

Keywords: inundation; adaptation; protection; dike; mangrove; cost-benefit analysis

1. Introduction

The Vietnamese Mekong River Delta (VMRD), located at the end of the Mekong basin, is one of the largest deltas in the world. In 2018, the 40,816 km² region was inhabited by approximately 18 million people [1]. The VMRD has long played an important role in the socioeconomic development and food security of the country. For example, in terms of agricultural productivity, the region accounts for 53% of all rice produced, 65% of all aquaculture, 75% of all fruit, and more than 90% of the total value of Vietnam’s agricultural exports. The VMRD is a flat, low-lying delta with an average elevation of 0.7 m to 1.2 m above sea level, except for some areas in An Giang Province [2]. The elevation of the coastal areas in the VMRD ranges from 0.3 m to 0.7 m above sea level and the length of the coastline is more than 1300 km. Given these natural conditions, the VMRD is considered to be highly vulnerable to sea level rise (SLR), as most of the regions are very close in elevation to the mean sea level [3,4]. Indeed, the region is already highly susceptible to the effects of SLR, including erosion, salt intrusion, and flooding during high tides [5,6]. Consequently, inundation due to SLR may be the main future challenge affecting this area, as increases in sea level would lead to extensive economic damage and social problems. Several studies have proposed that SLR could markedly impact more than 20 million people living along the coast and elsewhere as mass migration occurs to other areas [7–9].

Selecting appropriate strategies to adapt to SLR is therefore a major concern in the VMRD. Three main approaches have been proposed to date to deal with the impact of SLR in coastal areas:
retreat, accommodation, and protection [7,10,11]. Protection strategies can take the form of gray infrastructure (e.g., sea dikes, sea walls, and breakwaters); green infrastructure (e.g., mangrove forests and coral reefs), and a combination of the two. In the face of SLR impacts, the Vietnamese government started to focus on protection of the coastal area with Decision No. 667/QD-TTg issued by the Prime Minister of Vietnam in 2009 [12]. The decision is effectively divided into three periods: 2009–2012, 2013–2016, and 2017–2020, with the main objective being the construction of sea dike systems from the central to the south of the country operated using a sluice system. The main function of the system would be to prevent salinization of the soil, to protect residential areas, and maintain agricultural productivity and aquaculture inside the dikes. At present, earthen dikes (rubble mound breakwaters) have mainly been constructed along with auxiliary developments, such as embankments and breakwaters. On the other hand, the current system has encountered problems due to inadequate technical standards and covering the entire coastline has not been possible [13,14]. At local scale, previous studies assessed the effectiveness of gray infrastructure measures to adapt to SLR (Kien Giang and Tra Vinh) [15,16]. However, gray infrastructure will negatively impact the VMRD ecosystem and environment [17], and the high costs involved mean that such measures can be less widely applied, and consequently, that they will have reduced effectiveness [18,19].

In the area of green infrastructure, various conservation and coastal restoration projects have been undertaken in mangrove forests to mitigate against the impacts of SLR in the VMRD [20]. In recent years, rapid SLR has destroyed the mangrove forest ecosystem ([21,22]) and it is also slowing down the growth of mangrove forests [23]. The VMRD supports nearly 66,000 ha of mangrove forests [24]. However, these mangrove forests are unevenly distributed and are affected by natural factors, such as SLR, and economic activities. Mangrove forests have been well managed in some areas, such as in the three districts of Ba Tri, Thanh Phu, and Thoi Thuan in Ben Tre and Bac Lieu provinces. Conversely, mangrove forests have been seriously reduced in other coastal provinces, such as Kien Giang, Ca Mau, Soc Trang, and Tra Vinh provinces [2]. Moreover, mangrove forests are threatened by SLR, because sea levels may rise above the average elevation of the mangroves themselves [25,26]. Low-lying areas of the coastal delta have also been exposed to the effects of SLR, increasing erosion [26]. One of the limitations of green infrastructure is that it cannot be widely applied, and areas of application need to be carefully considered. Hence, each type of response has specific advantages and disadvantages, and this synergy may play an important role in developing an integrated and comprehensive response to adapting to SLR [27]. Mixing gray and green infrastructures could potentially be a promising solution for protecting the coastal areas of Vietnam and a way to help these areas to adapt to SLR in the 21st century. Indeed, it is this strategy of preserving, restoring, and enhancing elements of the natural system that will enable natural ecosystems to function in conjunction with gray infrastructure to maximize benefits and reduce the cost of adaptations [20,28].

The aims of this study are threefold. First, the research evaluates physical impacts of SLR in the VMRD using three general circulation models (GCMs) described in Couples Model Intercomparison Project 5 (CMIP5). The paper uses the Model for Interdisciplinary Research on Climate-Earth System Model (MIROC-ESM), Geophysical Fluid Dynamics Laboratory (GFDL), and the Norwegian Earth System Model (NorESM) to estimate inundation impacts using Representative Concentration Pathways (RCP8.5). Second, it aims to estimate the affected population and economic damage that can be attributed to SLR in the VMRD using Shared Socio-economic Pathways (SSP) to better understand the changes in socio-economic areas in the future. These pathways can be applied to designing future socio-economic scenarios, developing appropriate climate policy measures, and implementing appropriate adaptation solutions [29]. Although the VMRD is vulnerable to SLR, relatively few studies that provide an overview of SLR relating to economic damage and adaptation effectiveness in the long term have been undertaken in the VMRD to date [8,30,31]. These previous studies were typically limited in terms of spatial scale [15,16] and few quantitative assessments of the entire region (including inland areas) have been undertaken. Finally, the effectiveness of adaptation strategies, such as mixing gray and green infrastructures in the VMRD, is examined. Our research fills current gaps by estimating
the economic damage due to inundation in the VMRD and analyzing the cost-benefits of mixing gray and green infrastructures under uncertain SLR and socio-economic development scenarios. Using new datasets, our results can provide the latest information for selecting optimal adaptation strategies in the VMRD.

The remainder of this manuscript is structured as follows. Section 2 provides an overview of impact assessments and cost-benefit analysis (CBA) of adaptations. In addition, the datasets of current and future socio-economic scenarios are described. Section 3 presents the socio-economic damage due to SLR and the effectiveness of mixing gray and green infrastructures in the VMRD. Section 4 summarizes the key findings and provides some discussion.

2. Materials and Methods

2.1. Overview

This research assesses the impacts of SLR and evaluates the effectiveness of adaptations using a CBA. Figure 1 shows three main steps used to structure this study based on different primary and secondary data sources. First, information on SLR scenarios and the socio-economic scenarios was collected at the global scale and then downscaled to the VMRD. SLR damage without adaptations was calculated using three outcomes: (1) the potential size of the inundated area (km$^2$), (2) the number of people affected (million people/year), and (3) the economic damage to land use in billion US dollar (US$). This study estimated the population that will be affected and economic damage resulting from dry land loss due to SLR in the 21st century. It does not consider other impacts, such as that of SLR on coastal and marine ecosystem services, infrastructure, and other activities. Second, SLR impacts with and without adaptations were then evaluated to identify the standard for the adaptation system. Finally, the effectiveness of mixing gray and green infrastructures was assessed and compared with other adaptation strategies from different socio-economic scenarios.

![Figure 1. Overview of this research.](image)

2.2. Data

Table 1 presents the input dataset used in this research. As reported previously [32], inundated areas and temporal changes in inundation were estimated using topographic data (ETOPO1), astronomical
high-tide data (i.e., mean higher high water level: MHHWL), and sea surface height data (globally averaged steric sea level) from three GCMs, adjusted vertically at the geoid.ETOPO1 provides land elevation data (mean sea level: MSL) and water depth data at a 1-arc-minute resolution; data from this global relief model of the Earth’s surface, which integrates land topography and ocean bathymetry, was averaged on a grid with at a resolution of 2.5-arc-minutes. The elevation map was smoothed to a resolution of approximately 10 cm to ensure consistency with the land elevation and water depth ETOPO1 data. Global tidal data were obtained from TPXO7.2 [33]. High tides (MHHWL), which occur roughly twice a month, were combined with the four major component tides (M2, K1, S2, and O1). Our analysis focuses on ordinal inundation due to SLR and astronomical high tide (MHHWL), but does not consider other temporary effects on sea level, such as storm surges associated with typhoons [28]. To evaluate the impacts of SLR, the SLR scenario and the inundation map data were overlaid with geospatial data of the VMRD using a geographic information system (GIS).

We estimated the potential size of the affected population and the economic damage based on Shared Socio-economic Pathways (SSPs), which are used to represent possible trends in population and economic growth. The SSPs are an important input for global climate impact models and are adopted [34]. Five socio-economic scenarios have been applied at a global scale and rescaled to a national scale [35,36]. SSP1 (Sustainability) focuses on the development of environmental protection measures, social welfare, and sustainable consumption in ways that minimize the consumption of natural resources. This scenario is considered to be associated with high levels of economic development and a population decrease in the 21st century. SSP5 (Fossil-fueled Development) is similar to SSP1 in terms of economic development and population growth; however, in this scenario, economic growth is based on the promotion of fossil fuel energy and the consumption of natural resources. SSP2 (Middle of the Road) assumes that the world has a moderate growth in both population and economy in the future, while SSP3 (Regional Rivalry) and SSP4 (Inequality) describe global development less optimistically, with less investment in social welfare and continued population growth through the 21st century with an increase in social inequality. In summary, SSP1 and SSP5 are scenarios in which there is rapid economic development with a decline of the population. SSP3 and SSP4 represent scenarios of slow economic growth accompanied by population growth, and SSP2 is a scenario in which medium economic and population growth occurs worldwide [35]. Probabilistic combinations of RCP/SSP were not considered here. Although combinations of RCP8.5 and SSP1 may be rare, the study identified the range between the minimum and maximum impacts.

Our study area covers all of the VMRD. Specifically, it includes Can Tho city, seven coastal provinces ranging from Long An to Kien Giang, and five other provinces. The secondary socio-economic data for the VMRD was collected from sources published by the Vietnamese government. Population information was obtained from statistical yearbooks published by the national government of Vietnam and Mekong Province with a base year of 2010. Land use data were aggregated by the Ministry of Agriculture and Rural Development (MARD) for each province in the VMRD. The value of land use was determined by Vietnam government regulations. This value does not directly represent the market value of land, but it is used for compensating or supporting owners in the case of damage. This value is averaged by the land price range of the Vietnam government and the location of the parcel. Since there are large disparities between different price points, the averaged value was chosen. The costs of sea dikes and mangrove forest rehabilitation were calculated based on previous studies [15,37].
Table 1. Short description of the input data used in each process.

| Data Source                                      | Description                                      |
|--------------------------------------------------|--------------------------------------------------|
| MIROC-ESM, GFDL, NorESM (RCP8.5) [32]           | Topographic data (ETOPO1) Mean higher high water level (TPXO7.2) |
|                                                  | Land use classes [24]                            |
| VMRD land use planning                           | Shapefile, mapping inundated areas               |
| VMRD administrative map                          | Shapefile, province-level administrative boundaries and mapping inundated areas |
| VMRD socio-economic condition                    | Land price bracket, Population density          |
|                                                  | Estimating the socio-economic damage             |
| Socio-economic scenarios                         | SSP scenarios; Gross domestic product           |
|                                                  | GDP, Population, Estimating socio-economic damage |
| Cost of mixing gray and green infrastructures    | Estimating the effectiveness of mixing gray and green infrastructures |

2.3. Methods

2.3.1. Mapping the Inundation Area

SLR is one of the main impacts of climate change. At global scale, average sea level has increased by 3 mm/year since the 1990s [39]. Many studies agree that the mean sea level will continue to rise during the 21st century [24–26], possibly by as much as 0.3–1.2 m by the end of the 21st century under different RCP scenarios [27]. This study employed RCP8.5 for the global SLR scenario. RCP8.5 is a high-greenhouse gas emission scenario which projects that the radiative forcing will continue to increase up until 2250. In this study, SLR scenarios were prepared for each decade until 2100. For adaptation strategies in the VMRD, we developed the adaptation scenarios in which the coastline has a full dike system. Specifically, we evaluated different cases for the height of dike system, i.e., from 1 m to 4 m, to identify the optimum height (standard) for protection. If the dike system is not high enough, it will not be effective for protecting inland areas. This standard is thus constant, while other conditions change.

The land use maps for inundation and administrative areas were overlaid using ArcGIS (ver. 10.7, ESRI, Redlands, CA, USA). The SLR scenarios were converted to vector polygons and overlaid with a land use planning map and administrative boundary map of the VMRD to identify inundated areas. We assumed that the land use and the administrative boundaries in the VMRD will remain unchanged in the 21st century. To simplify the calculations for the value of land use loss due to SLR, more than one million segments in nearly 70 types of land use in the VMRD were grouped into seven main groups which accounted for most of area in the VMRD. Specifically, these groups included land for cultivation of annual crops, including paddy fields and land for cultivation of other annual crops; land for forests; land for aquaculture; land for cultivation of perennial trees; rural residential land; urban residential land; and land for salt production. Land for community activities and land currently covered by permanent waters such as dams and rivers were not evaluated. The area of potentially inundated areas (m²) was obtained and recalculated. This study had to estimate “potentially inundated areas” and “affected population” for the reference scenario without adaptations because there are no accurate and consistent elevation data or maps for installed dikes in coastal areas.

2.3.2. Estimating Economic Damage Due to SLR without Adaptations

The economic damage attributed to dry land loss without adaptations can be estimated by multiplying the inundated area and the value of the land estimated according to Vietnamese government regulations [40]. The land values vary according to the economic growth rate of SSP and are summed when calculating the total damage. The cost of land loss is calculated based on the assumption that the type of land use and the policy of Vietnam government may not change until the end of 21st century. The cost of land use was estimated using the equation:
\[ DC = \sum UC_i \times PI_t \times Area_i \]  

(1)

where \( DC \) is the cost of land use estimated by total damage to dry land of type \( i \) (US$) under SSP1-5, \( UC_i \) is the average unit cost of land use \( i \) (US$/m^2), \( Area_i \) is the potentially inundated area of land use \( i \) (m^2), and \( PI_t \) is the price index in year \( t \) under SSP1-5. All monetary values were converted to 2010 US$ using the exchange rate in 2010.

The total affected population due to SLR in the VMRD without adaptations is normally calculated using the population of the province multiplied by the percentage of inundated area. This value is then summed under the different socio-economic scenarios (SSP1-5) with the assumption that the population growth rate in the VMRD is equivalent to the growth rate of the Vietnamese population [41]. The 2010 population (at the province level) was used as the base year for the estimation. The affected population was estimated by:

\[ P_{\text{affected}, \text{i}, t} = \sum P_{\text{i}, t} \times r_{\text{i}, t} \]  

(2)

where \( P_{\text{affected}, \text{i}, t} \) is the potential population affected by SLR in province \( i \) in year \( t \), \( P_{\text{i}, t} \) is the total population of province \( i \) in year \( t \) and is given as \( P_{\text{i}, 2010} \times a_t \), \( a_t \) is the population growth rate in year \( t \) from 2010, and \( r_{\text{i}, t} = \frac{\text{Potential inundated area of province } i \text{ (km}^2\text{)}}{\text{Total area of province } i \text{ (km}^2\text{)}} \) is the percentage of the inundated area in province \( i \) in year \( t \).

Our previous study [42] evaluated the uncertainty of inundation impacts using eight GCM, two RCP (2.6 and 8.5), and three SSP (1–3) scenarios at a global scale. The findings showed that inundation due to SLR impacts appear to be more dependent on SSPs. Further, the findings also showed that the difference between RCP2.6 and RCP8.5 may be rather small in the short term (approximately two decades), but they may vary markedly by the end of this century. If we only rely on the current climate commitments set out in the Paris Agreement, then temperatures can be expected to increase by 3.2 °C this century [43], which is a trajectory that lies approximately between RCP6.0 and RCP8.5. Therefore, this study employed the RCP8.5 scenario for all estimates.

2.3.3. Estimating the Cost and Benefit of Adaptations

The total cost of the adaptations is multiplied by the length of the protection area, the unit cost of each adaptation option, and a price index adjusted according to the economic growth rate assumed by the different scenarios. The cost of adaptations can therefore be calculated as:

\[ AC_A = UC_A \times PI_t \times L_A \]  

(3)

where \( AC_A \) is the total cost of adaptation option \( A \) (US$) under SSP1-5, \( UC_A \) is the unit cost of option \( A \) (US$/km), \( L_A \) is total length of option \( A \) (km), and \( PI_t \) is the price index in year \( t \) under SSP1-5.

The benefit of the adaptations was calculated by:

\[ B = \sum DC^0 - \sum DC^A \]  

(4)

where \( B \) is the benefit of the adaptations, which is defined as the economic damage that was avoided due to the adaptations, \( \sum DC^0 \) is the economic damage without adaptations, and \( \sum DC^A \) is the economic damage with the adaptation options.

3. Results

3.1. Potentially Inundated Area in the VMRD

Figure 2 shows the land use of the potentially inundated area. Table 2 shows the percentage of inundated area for each land use type in the VMRD in 2100. In all SLR scenarios without adaptations, the VMRD was found to be affected strongly by SLR. The inundated area increases dramatically by 2050 and slightly in the second half of this century. Under the GFDL and NorESM, the area of inundation
in the VMRD will increase by 35,427 km$^2$ from 2010 to 2100. Under the MIROC-ESM, the inundated area will increase by 25,368 km$^2$ from 2010. By 2100, estimates of the inundated area obtained by the NorESM, GFDL, and MIROC-ESM are approximately 37,014 km$^2$, 36,531 km$^2$, and 36,910 km$^2$, which accounts for more than 90% of the total area of VMRD. In particular, as shown in Table 2, all of the GCMs indicate that most agriculture, aquaculture, and residential areas of VMRD will be inundated by 2100. Specifically, most of the land used for cultivation of annual crops including paddy fields will be inundated; land for cultivation of perennial trees and land for production forests also will largely be below sea level. In addition, around 93% of rural residential areas and 85% of land for urban residential areas will also be inundated. Thus, SLR not only affects agricultural activities, which are the main livelihood of the people in this region, but it also affects their living standards and the ability to ensure food security because most of Vietnam’s agricultural production occurs in the VMRD.

Regarding administrative areas, almost all provinces in the VMRD are at high risk of inundation and more than 90% of these provinces may be inundated by the end of this century. Moreover, if adaptation solutions are not implemented, some of the coastal provinces in low-lying areas, such as Vinh Long, Soc Trang, Bac Lieu, and Tra Vinh, may be inundated by up to 99% by 2050. Two provinces, Dong Thap and An Giang, may have the lowest inundated area in 2100, and less than 80% of these provinces may be under the sea.

Table 2. Percentage of inundated area by land use in the Vietnamese Mekong River Delta (VMRD) by 2100.

| Land Use                              | GFDL (%) | MIROC-ESM (%) | NorESM (%) |
|---------------------------------------|----------|---------------|------------|
| Land for cultivation of annual crops  | 92.52    | 93.40         | 93.73      |
| Land for production forests           | 87.67    | 85.19         | 89.16      |
| Land for aquaculture                  | 56.70    | 57.26         | 57.26      |
| Land for cultivation of perennial trees| 85.15    | 89.04         | 85.24      |
| Rural residential land                | 92.36    | 93.18         | 93.51      |
| Urban residential land                | 83.80    | 85.16         | 87.39      |
| Land for salt production              | 68.84    | 68.84         | 68.84      |
Sustainability 2020, 12, x 8 of 20

3.2. Estimating Socio-Economic Damage without Adaptations

Figure 3 presents an overview of economic damage due to SLR in the VMRD under five socio-economic scenarios (SSP1-5) without adaptations. Overall, the differences among SSPs affect economic damage more than GCM. The economic damage is the highest under SSP5 and there is only a slight difference between SSP3 and SSP4, which are associated with the lowest economic damage, in the range of 0.2–0.5% of GDP due to having smaller economic growth assumptions. Under the MIROC-ESM, the total economic damage may increase to 4622–17,073 billion US$ in 2100 from 972 billion US$ in the earlier half of this century, accounting for more than 0.5% of the total national GDP in 2100. The damage is slightly lower under the GFDL and higher under the NorESM, with damage amounting to 4508–16,891 billion US$ and 4598–17,230 billion US$, respectively.

In the earlier half of this century, the average annual economic damage estimated using the MIROC-ESM is lower than the GFDL and NorESM. The damage is slightly different between the GFDL and NorESM. In the latter half of this century, the economic damage is highest for the NorESM/SSP5, amounting to 388 billion US$ without a discount rate. The annual economic damage may reach 341 billion US$ under the MIROC-ESM/SSP5, 339 billion US$ under the GFDL/SSP5, and NorESM/SSP5 damage may reach 361 billion US$ in 2100. The annual economic damage is the highest when estimated using the NorESM and lowest when estimated using the MIROC-ESM.
Figure 4 presents the total population in the VMRD at risk from SLR in the 21st century without adaptations under the different scenarios. The total population at risk of SLR in the VMRD roughly increases early in this century but decreases through the rest of the 21st century. In 2100, the number of people affected by SLR may reach up to 10.06–19.44 million under the NorESM. In the MIROC-ESM, the population affected is estimated to be between 10.19 and 19.37 million. The GFDL shows a slightly lower population than the other GCMs, ranging from 10.06 to 19.12 million. The population at risk is the highest under SSP3 and lowest under SSP4. The remaining scenarios show a decline in the trend of total population at risk until the end of the 21st century. Under SSP1, SSP4, and SSP5, the population at risk increases until the middle of this century before decreasing after 2060 due to a decline in the national population and migration due to SLR. SSP2 presents a slower decline in the number of people affected compared to the other scenarios. The provinces with high population densities, such as Tien Giang, Can Tho, and Vinh Long, are particularly vulnerable, followed by Kien Giang, Soc Trang, and Long An, in which around 1 million people will be affected by SLR by the end of the 21st century.

![Figure 4. Total population at risk in the VMRD in the 21st century.](image)

In comparing Figures 3 and 4, the medium GCM, the MIROC-ESM, is used to demonstrate the effectiveness of the sea dike system. Four dike height scenarios ranging from 1 m to 4 m are used to estimate their effectiveness. Figure 5 compares the inundation impacts under cases with and without adaptations. The inundated area and economic damage due to SLR can be significantly reduced by constructing sea dikes along the coastline. In a dike system with a height of 1 m to 3 m, the VMRD may begin to be at risk of inundation in 2050 to 2100, respectively. For a dike of 4 m, the VMRD will no longer be at risk of inundation in the 21st century. These findings show that a sea dike system could effectively protect the inland areas if the height of the sea dikes is adequately constructed.

Along with a reduction in the inundating impact corresponding to the height of dike, the economic damage was also recalculated for the adaptation scenarios mentioned above. Figure 6 illustrates the economic damage with adaptations and no discount rate. The figure shows that adaptations can dramatically reduce the economic damage in all socioeconomic scenarios. For example, a sea dike measuring 1 m in height can reduce the total economic damage from about 2453 billion US$ to 3391 billion US$ under different scenarios. The findings show that economic damage can be reduced in proportion to dike height. When the dike height is 4 m, the economic damage will be zero. These decreases in the extent of the economic damage show the effect of the protection system. Consequently, the technical standard adopted for the dike system in the VMRD should be at least 4 m high.
Along with a reduction in the inundating impact corresponding to the height of dike, the economic damage was also recalculated for the adaptation scenarios mentioned above. Figure 6 illustrates the economic damage with adaptations and no discount rate. The figure shows that adaptations can dramatically reduce the economic damage in all socioeconomic scenarios. For example, a sea dike measuring 1 m in height can reduce the total economic damage from about 2453 billion US$ to 3391 billion US$ under different scenarios. The findings show that economic damage can be reduced in proportion to dike height. When the dike height is 4 m, the economic damage will be zero. These decreases in the extent of the economic damage show the effect of the protection system. Consequently, the technical standard adopted for the dike system in the VMRD should be at least 4 m high.

3.3. Cost of Mixing Gray and Green Infrastructures

This part of the study assumes that the VMRD does not have any concrete dikes. We also compared the costs of earthen dikes, upgrading to a concrete dike system that is stronger and has a longer life span, and combining mangrove forests with concrete dikes (Figure 7).

In order to carry out its protection function, according to technical design standards, the sea dike system must have an average life expectancy of at least 50 years and be able withstand the effects of extreme weather events. Currently, the coastal regions in the VMRD that were selected for building dikes were based on projected simulations of wave level; earthen dikes should be constructed where waves are lower than 0.5 m, while in areas with higher waves, earthen dikes with a hard revetment should be selected [24]. Due to the lack of experimental data on the cost of dike construction, the costs estimated in this study were based on the government’s budget for current dike construction efforts [24,35]. Estimates for concrete dike construction were based on the calculations of Danh (2012) [14] Vo (2012) [15]. Both of these studies estimated the construction costs of the dikes, including labor costs, material costs, and land use costs. These estimates were crude costs that did not consider disaster reduction costs or factors such as inflation and other additional costs.
The Vietnamese government’s strategy for mitigating against SLR in the Mekong Delta region stipulates that the mangrove belt width should be at least 500 m to protect the earthen dikes located behind them. Therefore, this study assumes that a mangrove belt with a minimum width of 500 m functions the same as a sea dike with a height of 4 m. The lifetime of a mangrove forest is 50 years and the growth period required before a mangrove forest can perform its protection function is 10 years. In reality, mangrove costs are calculated as the initial cost as well as the costs required to protect the mangrove. The initial cost of reforestation depends on the type of tree, the location, and the preparation required before planting. The cost of planting mangrove trees can vary from 605 US$/ha to 3721 US$/ha, depending on the planting location [44]. Planted mangroves are assumed to be replanted more than once due to damage incurred by storms. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) estimated the cost of planting mangroves based on 13 successful projects in the VMRD; they determined the costs to be 8000 US$/ha [24]. The maintenance costs were determined at a relatively high level, 7442 US$/ha per year, including mangrove protection costs, such as the construction of wooden and bamboo fences. Most of this cost was attributed to labor costs and was only estimated for the first 10 years after afforestation [16]. Table 3 shows the unit cost of the protection
system in 2010. Their unit costs are adjusted using the GDP deflator and the price index according to the rate of economic growth assumed by the SSPs.

Table 3. Unit cost of adaptation options using dikes and mangrove trees in 2010.

| Cost Category       | Upgrade Earthen Dike to 4 m High | 4 m-High Concrete Dike | 350 m-Wide Mangrove Belt | 500 m-Wide Mangrove Belt |
|---------------------|---------------------------------|------------------------|--------------------------|--------------------------|
| Construction cost   | 0.189                           | 3.75                   | 0.28                     | 0.4                       |
| Maintenance cost    | 0.0095                          | 0.04                   | 0.27                     | 0.37                      |
| Rebuilding cost     | 0.189                           | -                      | -                        | -                         |

Unit: million US$/km.

The coastline of the VMRD is 1302 km long and includes 945 km of mangrove forest [2]. It is assumed that the area’s existing earthen dikes will be upgraded to a height of 4 m and that no mangrove forest/concrete dikes have been built in the area. This section presents the results of a CBA of mixing gray and green infrastructures in the VMRD to adapt to SLR.

Mixing gray and green infrastructures is evaluated as follows: (1) A concrete dike system with a height of 4 m is constructed in the areas without mangrove forests; (2) Mangrove forests can grow in the suitable areas; (3) The lifespan of concrete dikes is 100 years; (4) The lifetime of mangrove forests is 50 years, and mangrove forests require 10 years before they can perform any protective function.

The total cost of mixing gray and green infrastructures in the VMRD ranges from 12.31 billion US$ to 19.08 billion US$. Most of these costs come from the maintenance costs for mangrove forests; the afforestation cost of mangrove forest only ranges from 4% to 5% of the total cost. More than 70% of the total cost consists of the maintenance cost for the mangrove forest. The maintenance cost for the mangrove forest is approximately 15 times higher than the cost of afforestation and nearly seven times higher than the cost of sea dike maintenance.

3.4. Cost-Benefit Analysis of Mixing Gray and Green Infrastructures and Comparison with Other Options

Figure 8 illustrates a CBA of mixing gray and green infrastructures in the 21st century. One of the benefits associated with mixing gray and green infrastructures is cost effectiveness. The findings showed that the net present value (NPV) is positive and that the benefit cost ratio (BCR) is higher than 1, indicating that combining gray and green infrastructures could be an effective adaptation option. The NPV varies from 2098 billion US$ to more than 4000 billion US$. The benefit of this adaptation was attributed to a reduction in economic damage that would be associated with its implementation.
Table 4 compares the effectiveness of mixing gray and green infrastructures with other adaptation options. The second option is the combination of earthen dikes and mangrove trees (current adaptation strategy), and the third one is concrete dikes. The results show that concrete dikes have the lowest cost, and that the combination of earthen dikes and mangrove forest has the highest cost in all scenarios. However, the benefit obtained from earthen dikes combined with mangrove forest, or mixing gray and green infrastructures, is higher than the benefit from concrete dikes alone. The positive net present value (NPV) ranges from 2103 billion US$ (concrete dike, SSP4) to 4410 billion US$ (mixing gray and green, SSP5). Overall, mixing gray and green infrastructures has the highest NPV in all SSP scenarios, although the BCR is lower than the concrete dike option. The results also indicate that the benefit of SLR adaptations can exceed the costs required for setting up a protection system. SSP5 shows the highest BCR, whose cost is 19.08 billion US$ and the total benefit is 4404 billion US$.

| Table 4. | Comparison of mixing gray and green infrastructures with other adaptations (discount rate = 3%). |
|----------|------------------------------------------------------------------------------------------------|
|          | SSP1 | SSP2 | SSP3 | SSP4 | SSP5 |
| Mixing gray and green | Benefit | 3303.0 | 2809.0 | 2132.9 | 2111.7 | 4404.7 |
|          | Cost | 16.4 | 14.2 | 12.4 | 12.3 | 19.1 |
| Earthen dikes and mangroves | Benefit | 3307.9 | 2813.1 | 2136.2 | 2115.0 | 4410.9 |
|          | Cost | 21.9 | 18.7 | 16.0 | 15.8 | 25.8 |
| Concrete dikes | Benefit | 3290.2 | 2798.0 | 2124.1 | 2103.1 | 4388.5 |
|          | Cost | 15.5 | 14.1 | 12.5 | 12.4 | 18.0 |

3.5. Sensitivity Analysis

3.5.1. Change in Discount Rate

The CBA depends decisively on discount rate. In order to deal with uncertainty that may occur in the future, a discount rate is often applied to estimate the impacts of changes in key individual factors. This section uses 8% and 10% values to examine sensitivities of benefit and cost to such changes.

The data presented in Tables 5 and 6 suggest that the discount rate can affect the results of CBA. When the discount rate increases, the values of NPV and BCR of adaptations decrease inversely and proportionally. If the higher discount rate significantly reduces the benefits and cost of mixing gray and green infrastructures, then the final outputs also decrease. However, it still has greater benefits than the cost.

| Table 5. | Cost-benefit analysis with the discount rate = 8%. |
|----------|--------------------------------------------------|
|          | SSP1 | SSP2 | SSP3 | SSP4 | SSP5 |
| Benefit | 1302.4 | 1198.8 | 1104.0 | 1090.3 | 1427.5 |
| Cost | 6.5 | 6.3 | 6.2 | 6.1 | 6.7 |
| NPV | 1295.9 | 1192.5 | 1097.9 | 1084.1 | 1420.8 |
| BCR | 200.1 | 190.1 | 179.6 | 177.5 | 212.3 |

| Table 6. | Cost-benefit analysis with the discount rate = 10%. |
|----------|--------------------------------------------------|
|          | SSP1 | SSP2 | SSP3 | SSP4 | SSP5 |
| Benefit | 1040.9 | 976.3 | 921.5 | 911.6 | 1109.2 |
| Cost | 5.7 | 5.6 | 5.5 | 5.5 | 5.8 |
| NPV | 1035.2 | 970.7 | 916.0 | 906.0 | 1103.4 |
| BCR | 183.2 | 174.7 | 167.0 | 165.2 | 192.1 |

Unit: billion US$.
3.5.2. Change in the Width of Mangrove Belt

The previous section assumes that a 500 m-wide mangrove forest can have a similar effect as a 4 m-high sea dike. However, a 350 m-wide mangrove belt can also markedly reduce the impact of waves in the VMRD [5,16,45]. To evaluate the impact of technical standards on the effectiveness of mixing gray and green infrastructures, this section compares the impact of input data with the final results. Table 7 shows the CBA results obtained when the width of the mangrove belt changes to 350 m. Other inputs, such as the construction cost of dikes and the lifespan of the structures, are kept unchanged. The results demonstrate that changes in the technical standards of inputs can affect the results. In the cases where the width of the mangrove forests is decreased from 500 m to 350 m, the BCR of options increased about 1.7 times for SSP1-5.

Table 7. Cost-benefit analysis with changes in the width of the mangrove belt (discount rate = 3%).

|       | SSP1   | SSP2   | SSP3   | SSP4   | SSP5   |
|-------|--------|--------|--------|--------|--------|
| Benefit | 3299.1 | 2805.6 | 2130.2 | 2108.9 | 4388.4 |
| Cost   | 13.1   | 11.4   | 10.0   | 9.9    | 15.3   |
| NPV    | 3286.0 | 2794.2 | 2120.3 | 2099.0 | 4373.1 |
| BCR    | 251.3  | 245.7  | 214.0  | 213.5  | 287.1  |

Unit: billion US$.

4. Discussion

4.1. Discussion and Recommendations

This research examined the inundation impacts of SLR in the VMRD and the effectiveness of adaptations. Within the scope of this study, the application of mixing gray and green infrastructures was found to be the most effective measure for adapting to SLR in the VMRD. The findings showed that most of the VMRD could be inundated by SLR in the 21st century if no adaptations are employed, and most of the provinces in this region could be inundated by 2100. Even in provinces with the lowest levels of inundation, such as Dong Thap and An Giang provinces, approximately 80% of their area would be below sea level. Coastal provinces such as Vinh Long, Soc Trang, Bac Lieu, and Tra Vinh may be inundated by up to 99% in the first half of this century. Clearly, such levels of inundation would severely affect the majority of the population living in the VMRD. In the worst-case scenario, up to 19 million people may be affected by 2100; conversely, in the best-case scenario, the affected population may be slightly over 10 million. This result is higher than that estimated in previous studies [4,8]. The reason for this disparity in the results may be due to differences in selecting the input data used to identify the inundated area and assuming the no adaptations scenario. Compared with previous studies, this study is considered to have improved SLR scenarios for identifying inundated areas; these scenarios were based on differences in sea level elevation and the topography of the coastline, including the linkage between land topography and ocean bathymetry [28].

The economic damage attributed to the loss of dry land was also estimated to be between 4508 billion US$ (GFDL/SSP3) and 17,230 billion US$ (NorESM/SSP5) in 2100. This value was also greater than previous estimates in studies on Vietnam [13]. This disparity was considered to be because the value of real estate is much higher than the annual GDP, which increases the present value of the land. Establishing a sea dike system around the VMRD would help to reduce the extent of damage due to inundation by SLR.

However, building a sea dike system in the VMRD would be expensive. At a discount rate of 3%, a concrete dike system would be the most cost-effective option. The lowest cost for protecting the system would be 12.4 billion US$ (concrete dike/SSP4), but costs could increase up to 25.8 billion US$ if the mangrove option combined with earthen dikes is used. When mixing gray and green infrastructures, the cost of this system can range from 15.8 billion US$ (SSP4) to 25.8 billion US$ (SSP5). The main reason for this high cost is that mangrove forests occupy the majority of the system and
the maintenance costs are similar to afforestation costs. Another reason for this difference in cost is attributed to the construction costs of the mangrove forest and the sea dike systems. Specifically, the construction costs of the mangrove forests include repairing damage due to natural disasters, while the construction cost of a concrete sea dike does not include this factor.

The CBA showed that the benefits of adaptations can be much higher than the costs for all adaptations under all socio-economic scenarios. The combination of sea dikes and mangrove forests has the highest NPV among all the adaptation options. In other words, this system is well suited for adapting to SLR in the VMRD. This finding corroborated those of previous studies [15,40], which showed that the benefits to the VMRD are higher than the costs of robust protection system against SLR in the 21st century. Indeed, the BCR of those studies in the VMRD ranged from 75 to more than 100. The sensitivity analysis showed that the benefits of adaptations can markedly outweigh the costs, even when changing the discount rate and width of the mangrove forests. These findings also illustrate that the discount rate and the protection standards impact the effectiveness of adaptations.

Without adaptations, the VMRD faces extensive damage due to SLR. All of the adaptation options examined have some level of effectiveness against increases in SLR; however, mixing gray and green infrastructures is the most effective of all options. The VMRD has large areas of mangrove forest, which means that the costs associated with afforestation and maintenance that are required to set up a combination of gray and green infrastructures will be relatively low.

Finally, by applying multiple scenarios, our findings showed that the impact of the SLRs on the VMRD depends on uncertainties in the 21st century. Most previous studies focused on temporary impacts, e.g., [46–48]. However, this study employed the latest SLR scenarios based on RCPs from CMIP5 and SSP. Furthermore, the study also updated the cost and benefit of the protection options to assess their potential effectiveness in the VMRD. Consequently, this study may stimulate further research and discussion on adaptations to SLR and climate change in the future.

The current adaptation solutions employed in the VMRD need to be improved by increasing technical standards. If such improvements are possible, then a combination of gray and green infrastructures could be used to protect the region for a long time. The following recommendations should be considered when adopting the gray and green infrastructure scenario in the VMRD. Concrete dikes should be constructed to protect the inland areas where the coastal zone is experiencing damage due to SLR. Afforestation and protection of the mangrove forest should be considered in areas where mangrove forests are decreasing. The quantity and quality of the existing mangrove system should be considered in areas with well-established mangrove forests. The most important key factor for the successful application of adaptation strategies is increasing the awareness of climate change, SLR impacts, and the benefits of mixing gray and green infrastructures among local communities [49–51].

4.2. Limitations of the Research and Future Work

Although our findings clarified impacts of SLR and effectiveness of adaptations, several aspects remain to be addressed. First, it is generally difficult for a CBA to assign values to all of the benefits and costs associated with this project. This study has only focused on one of the direct impacts of SLR on terrestrial environments, and other factors such as the impact of SLR on coastal and marine ecosystems, infrastructure, and human activities are not considered. Changes in land use and agri-aquaculture activities in the VMRD have exerted a pressure on the mangrove system, for instance, the growth of the shrimp farming have led to a reduction in mangrove goods and services [51]. In addition, the construction of sea dikes may affect the ecosystems in the VMRD region, which is a sensitive and vulnerable area [52]. The interaction of sea dikes and mangroves should also be considered and evaluated in subsequent studies.

Second, this study does not deal with all of the uncertainties associated with SLR and their adaptations in the future. We used RCP8.5 for the SLR scenarios as the worst-case scenario for the 21st century. RCP8.5 is a high-emissions scenario and does not consider the mitigating effect of
climate policy on greenhouse gas emissions [53]. As described in Section 2.3, if we only rely on the current climate commitments set out in the Paris Agreement, temperatures can be expected to rise by 3.2 °C in this century [54]; such an increase would fit a trajectory somewhere between RCP6.0 and RCP8.5. The extent of future damage could therefore be potentially less severe than that presented in our estimates. In addition, adaptation pathways can reduce the expenditure of adaptation through careful deployment of interventions over time, i.e., by taking low regrets decisions that are viable across multiple possible futures [55]. This method of adaptive pathways was first tested for delta environments by [56].

Third, our study does not consider the effect of other natural factors on the effectiveness of adaptations, such as land subsidence due to groundwater depletion. By 2050, with the current rate of subsidence, it is likely that most of the VMRD will be below sea level [57]. Moreover, both sea dikes and mangrove can be affected by erosion. Mangrove forests in the VMRD are declining both in terms of area and forest quality, which may increase planting costs and forest conservation. Sea dikes in this area also do not guarantee adaptability due to the natural and human impacts [13].

Fourth, the multiple benefits of mangroves, such as ecosystem services, are not considered. Mangroves have been proposed as being a promising solution for protecting coastal ecosystems, providing economic benefits such as medicine and timber, and enhancing habitat and facilitate aquaculture [58,59]. The mangrove system is able to absorb and store large amounts of carbon, limiting climate change in the future [60].

The factors outlined above can have direct impacts on the results, which means that the proposed benefits may actually be significantly higher than those estimated in this study. Therefore, further research is required in order to address these benefits in the future. Nevertheless, the study demonstrated that combining gray and green infrastructures may be a promising solution for adapting to SLR in the VMRD.

5. Conclusions

Our study addressed the impacts of SLR and effectiveness of adaptations in the VMRD in the future. We estimated the direct impacts of SLR in the VMRD in the 21st century, from both an economic and social perspective. Our results showed that without adaptations, the VMRD may be inundated by SLR in the future. We employed multiple GCMs to deal with the uncertainty of SLR and the socio-economic developments in the future. We consider that it is essential for policymakers and other participants to minimize the risk of SLR in the VMRD. The main results illustrate the need for adaptations in the VMRD and that combining gray and green infrastructure may be the most effective adaptation option for this area where economic losses and social impacts may be significant.

Author Contributions: Conceptualization, M.T.; methodology, M.T. and N.K.; software, P.T.O.; validation, M.T. and Q.V.N.; formal analysis, P.T.O.; investigation, P.T.O.; resources, M.T. and N.K.; data curation, P.T.O.; writing—original draft preparation, P.T.O.; writing—review and editing, M.T. and Q.V.N.; visualization, P.T.O.; supervision, M.T.; project administration, M.T.; funding acquisition, M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the Environment Research and Technology Development Fund (JPMEERF20172012, JPMEERF20S11811) of the Environmental Restoration and Conservation Agency of Japan and JSPS KAKENHI Grant Number 20K12300.

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

References
1. General Statistical office of Vietnam. Statistical Year Book Vietnam 2018; Statistical publishing house: Hanoi, Vietnam, 2019.
2. Southern Institute of Water Resources Planning (SIWRP). Review Seadyke Planning from Quang Ngai to Kien Giang; Ministry of Agriculture and Rural D: Hanoi, Vietnam, 2017.
3. Syvitski, J.P.M.; Kettner, A.J.; Overeem, I.; Hutton, E.W.H.; Hannon, M.T.; Brakenridge, G.R.; Day, J.; Vorosmarty, C.; Saito, Y.; Giosan, L.; et al. Sinking deltas due to human activities. *Nat. Geosci.* 2009, 2, 681–686. [CrossRef]

4. MONRE. *Climate Change and Sea Level Rise Scenarios for Viet Nam; Ministry of Natural Resources and Environment: Hanoi, Vietnam, 2016*.

5. Besset, M.; Gratiot, N.; Anthony, E.J.; Bouchette, F.; Goichot, M.; Marchesiello, P. Mangroves and shoreline erosion in the Mekong River delta, Viet Nam. *Estuar. Coast. Shelf Sci.* 2019, 226, 106263. [CrossRef]

6. Anthony, E.J.; Brunier, G.; Besset, M.; Goichot, M.; Dussouillez, P.; Nguyen, V.L. Linking Rapid Erosion of the Mekong River Delta to Human Activities. *Sci. Rep.* 2015, 5, 14745. [CrossRef]

7. Klein, R.J.T.; Nicholls, R.J. Assessment of Coastal Vulnerability to Climate Change. *AMBIO* 1999, 28, 6.

8. Carew-Reid, J. *Rapid Assessment of the Extent and Impact of Sea Level Rise in Viet Nam; International Centre for Environment Management (ICEM): Brisbane, Australia, 2008*. Available online: [http://www.icem.com.au/documents/climatechange/icem_slr/ICEM_SLR_final_report.pdf](http://www.icem.com.au/documents/climatechange/icem_slr/ICEM_SLR_final_report.pdf) (accessed on 12 November 2020).

9. Neumann, B.; Vafeidis, A.T.; Zimmermann, J.; Nicholls, R.J. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding—A Global Assessment. *PLoS ONE* 2015, 10, e0118571. [CrossRef] [PubMed]

10. IPCC. *FAR Climate Change: The IPCC Response Strategies; WMO (World Meteorological Organization): Geneva, Switzerland; UNEP (United Nations Environment Programme): Nairobi, Kenya; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2000*. Available online: [https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_far_wg_III_full_report.pdf](https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_far_wg_III_full_report.pdf) (accessed on 12 November 2020).

11. Linham, M.M.; Nicholls, R.J. *Technologies for Climate Change Adaptation: Coastal Erosion and Flooding; UNEP Riso Centre on Energy, Climate and Sustainable Development: Roskilde, Denmark, 2010; ISBN 978-87-550-3855-4*.

12. Vietnam Central Government. *Decision 667/QĐ-TTg: Approval on the Program to Strengthen and Upgrade the Sea Dyke System from Quang Ngai to Kien Giang*; Prime Minister: Hanoi, Vietnam, 2009.

13. Van, M.; Tri, M.; Quy, N.; Vrijling, J.K. Risk based approach for safety standard of coastal flood defences in Vietnam. *J. Water Resour. Environ. Eng.* 2008, 23, 204–216.

14. Tamura, M.; Yasuhara, K.; Ajima, K.; Trinh, V.C.; Pham, S.V. Vulnerability to climate change and residents’ adaptations in coastal areas of Soc Trang Province, Vietnam. *Int. J. Glob. Warm.* 2018, 16, 102. [CrossRef]

15. Vo, T.D. *Adaption to Sea Level Rise in the Vietnamese Mekong River Delta: Should a Sea Dike Be Built? Research report/Economy and Environmental Program for Southeast Asia; EEPSEA: Singapore, 2012; ISBN 978-981-07-1998-2*.

16. Tas, S. *Coastal protection in the Mekong Delta: Wave Load and Overtopping of Sea Dikes as Function of Their Location in the Cross-Section for Different Foreshore Geometries; Delft University of Technology: Delft, The Netherlands; University of Danang: Da Nang, Vietnam, 2016*. Available online: [http://coastal-protection-mekongdelta.com/download/library/118.CoastalProtectionMasterThesis2016_EN.pdf](http://coastal-protection-mekongdelta.com/download/library/118.CoastalProtectionMasterThesis2016_EN.pdf) (accessed on 20 September 2020).

17. Tuan, A.; Thien, N.H.; Ní, D.V.; Quoi, L.P.; Tu, N.D. *A Story of Water and Human in Vietnam Mekong River Delta (Chuyện nước và con người ở Đồng bằng sông Cửu Long); International Union for Conservation of Nature and Natural Resources (IUCN): Gland, Switzerland, 2014*.

18. McGranahan, G.; Bălăk, D.; Anderson, B. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urban.* 2007, 19, 17–37. [CrossRef]

19. Reguero, B.G.; Beck, M.W.; Breusch, D.N.; Calil, J.; Meliane, I. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS ONE* 2018, 13, e0192132. [CrossRef]

20. Browder, G.; Ozment, S.; Becsos, I.R.; Gartner, T.; Lange, G.-M. *Integrating Green and Gray; World Resources Institute: Washington, DC, USA, 2019*; p. 140.

21. Ellison, J.C.; Zouh, I. Vulnerability to Climate Change of Mangroves: Assessment from Cameroon, Central Africa. *Biologia* 2012, 1, 617–638. [CrossRef]

22. Albert, S.; Saunders, M.I.; Roelfsema, C.M.; Leon, J.X.; Johnstone, E.; Mackenzie, J.R.; Hoegh-Guldberg, O.; Grinham, A.R.; Phinn, S.R.; Duke, N.C.; et al. Winners and losers as mangrove, coral and seagrass ecosystems respond to sea-level rise in Solomon Islands. *Environ. Res. Lett.* 2017, 12, 094009. [CrossRef]

23. Krauss, K.W.; McKee, K.L.; Lovelock, C.E.; Cahoon, D.R.; Saintilan, N.; Reef, R.; Chen, L. How mangrove forests adjust to rising sea level. *New Phytol.* 2014, 202, 19–34. [CrossRef] [PubMed]
24. Stefan, A.G. Coastal Protection for the Mekong Delta: A Decision Support Tools; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Bonn and Eschborn, Germany, 2018.

25. Gilman, E.L.; Ellison, J.; Duke, N.C.; Field, C. Threats to mangroves from climate change and adaptation options: A review. Aquat. Bot. 2008, 89, 237–250. [CrossRef]

26. Godoy, M.D.P.; de Lacerda, L.D. Mangroves Response to Climate Change: A Review of Recent Findings on Mangrove Extension and Distribution. An. Acad. Bras. Ciênc. 2015, 87, 651–667. [CrossRef] [PubMed]

27. IPCC. IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate; Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., et al., Eds.; 2019; In press. Available online: https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_FullReport.pdf (accessed on 15 September 2020).

28. Tamura, M.; Kumano, N.; Inoue, T.; Yokoki, H. Impact and cost assessment of coastal protection mixing green infrastructure against sea level rise in Vietnam. In Proceedings of the Hanoi Forum, Hanoi, Vietnam, 8–11 November 2018; p. 5.

29. Asuncion, R.C.; Lee, M. Impacts of Sea Level Rise on Economic Growth in Developing Asia. Asian Dev. Bank 2017, 507, 10.

30. Arndt, C.; Tarp, F.; Thurlow, J. The Economic Costs of Climate Change: A Multi-Sector Impact Assessment for Vietnam. Sustainability 2015, 7, 4131–4145. [CrossRef]

31. Chinowsky, P.S. WIDER Working Paper 2014/148 Cost and Impact Analysis of Sea Level Rise on Coastal Vietnam; UNU-WIDER: Helsinki, Finland, 2014.

32. Tamura, M.; Kumano, N.; Yotsukuri, M.; Yokoki, H. Global assessment of the effectiveness of adaptation in coastal areas based on RCP/SSP scenarios. Clim. Chang. 2019, 152, 363–377. [CrossRef]

33. Egbert, G.D.; Erofeeva, S.Y. Efficient Inverse Modeling of Barotropic Ocean Tides. J. Atmos. Ocean. Technol. 2002, 19, 183–204. [CrossRef]

34. IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.

35. O’Neill, B.C.; Kriegler, E.; Ebi, K.L.; Kemp-Benedict, E.; Riahi, K.; Rothman, D.S.; van Ruijven, B.J.; van Vuuren, D.P.; Birkmann, J.; Kok, K.; et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 2017, 42, 169–180. [CrossRef]

36. Murakami, D.; Yamagata, Y. Estimation of Gridded Population and GDP Scenarios with Spatially Explicit Statistical Downsampling. Sustainability 2019, 11, 2106. [CrossRef]

37. Wölcke, J.; Albers, T.; Roth, M.; Vorlauffer, M.; Korte, A. Integrated Coastal Protection and Mangrove Belt Rehabilitation in the Mekong Delta—Prefeasibility Study for Investments in Coastal Protection along 480 Kilometers in the Mekong Delta; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Bonn/Eschborn, Germany, 2016.

38. General Statistical Office of Vietnam. Statistical Year Book Vietnam 2010; Statistical Publishing House: Hanoi, Vietnam, 2011.

39. IPCC. Climate Change 2014: Impacts, Adaptation, and Vulnerability: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Field, C.B., Barros, V.R., Intergovernmental Panel on Climate Change, Eds.; Cambridge University Press: New York, NY, USA, 2014; ISBN 978-1-07-64165-5.

40. Hinkel, J.; Klein, R.J.T. Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. Glob. Environ. Chang. 2009, 19, 384–395. [CrossRef]

41. Wolff, C.; Vafeidis, A.T.; Lincke, D.; Marasmi, C.; Hinkel, J. Effects of Scale and Input Data on Assessing the Future Impacts of Coastal Flooding: An Application of DIVA for the Emilia-Romagna Coast. Front. Mar. Sci. 2016, 3. [CrossRef]

42. Tsuchida, K.; Tamura, M.; Kumano, N.; Masugana, E.; Yokoki, H. Global impact and uncertainty assessment of sea level rise based on multiple climate models. J. Jpn. Soc. Civ. Eng. G Environ. 2018, 74, 167–174. [CrossRef]

43. National Oceanic and Atmospheric Administration (NOAA). Natural and Structural Measures for Shoreline Stabilization. Available online: http://sagecoast.org/docs/SAGE_LivingShorelineBrochure_Print.pdf (accessed on 15 September 2020).
44. Verhagen, H.J. The Beneficial Effects of Mangrove Forest to Sea Defence Structures. In Threats to Mangrove Forests; Makowski, C., Finkl, C.W., Eds.; Coastal Research Library; Springer International Publishing: Cham, Switzerland, 2018; Volume 25, pp. 475–495. ISBN 978-3-319-73015-8.

45. Tran, Q.B. Effect of mangrove forest structures on wave attenuation in coastal Vietnam. Oceanologia 2011, 53, 807–818. [CrossRef]

46. Vo, T.D.; Khai, H.V.K. Using a Risk Cost-Benefit Analysis for a Sea Dike to Adapt to the Sea Level in the Vietnamese Mekong River Delta. Climate 2014, 2, 78–102. [CrossRef]

47. Vu, D.T.; Yamada, T.; Ishidaira, H. Assessing the impact of sea level rise due to climate change on seawater intrusion in Mekong Delta, Vietnam. Water Sci. Technol. 2018, 77, 1632–1639. [CrossRef]

48. Smajgl, A.; Toan, T.Q.; Nhan, D.K.; Ward, J.; Trung, N.H.; Tri, L.Q.; Tri, V.P.D.; Vu, P.T. Responding to rising sea levels in the Mekong Delta. Nat. Clim. Chang. 2015, 5, 167–174. [CrossRef]

49. Vietnam Central Government. Decision 2139/QĐ-TTg The National Strategy on Climate Change; Prime Minister: Hanoi, Vietnam, 2011.

50. Ha, T.T.T.; van Dijk, H.; Bush, S.R. Mangrove conservation or shrimp farmer’s livelihood? The devolution of forest management and benefit sharing in the Mekong Delta, Vietnam. Ocean Coast. Manag. 2012, 69, 185–193. [CrossRef]

51. Kam, S.P.; Badjeck, M.-C.; Teh, L.; Teh, L.; Tran, N. Autonomous Adaptation to Climate Change by Shrimp and Catfish Farmers in Vietnam’s Mekong River Delta; WorldFish Center: Penang, Malaysia, 2012; Volume 24.

52. Torell, M.; Salamanca, A.M. Wetlands Management in Vietnam’s Mekong Delta: An Overview of the Pressures and Responses; WorldFish Center: Penang, Malaysia, 2003.

53. van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.-F.; et al. The representative concentration pathways: An overview. Clim. Chang. 2011, 109, 5–31. [CrossRef]

54. United Nations Environment Programme. The Emissions Gap Report 2019; UNEP: Nairobi, Kenya, 2019; ISBN 978-92-807-3766-0.

55. Kapetas, L.; Fenner, R. Integrating blue-green and grey infrastructure through an adaptation pathways approach to surface water flooding. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 2020, 378, 20190204. [CrossRef]

56. Haasnoot, M.; Middelkoop, H.; Offermans, A.; van Beek, E.; van Deursen, W.P.A. Exploring pathways for sustainable water management in river deltas in a changing environment. Clim. Chang. 2012, 115, 795–819. [CrossRef]

57. Minderhoud, P.S.J.; Coumou, L.; Erkens, G.; Middelkoop, H.; Stouthamer, E. Mekong delta much lower than previously assumed in sea-level rise impact assessments. Nat. Commun. 2019, 10, 3847. [CrossRef] [PubMed]

58. Menéndez, P.; Losada, I.J.; Torres-Ortega, S.; Narayan, S.; Beck, M.W. The Global Flood Protection Benefits of Mangroves. Sci. Rep. 2020, 10, 1–11. [CrossRef] [PubMed]

59. Alverson, K. Vulnerability, Impacts, and Adaptation to Sea Level Rise: Taking an Ecosystem-Based Approach. Oceanography 2012, 25, 231–235. [CrossRef]

60. Sanderman, J.; Hengl, T.; Fiske, G.; Solvik, K.; Adame, M.F.; Benson, L.; Bukoski, J.J.; Carnell, P.; Cifuentes-Jara, M.; Donato, D.; et al. A global map of mangrove forest soil carbon at 30 m spatial resolution. Environ. Res. Lett. 2018, 13, 055002. [CrossRef]

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.