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Coastal adaptation to climate change in Japan: a review

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ABSTRACT
In parallel with many other countries, the government of Japan has started to tackle coastal adaptations to climate change. In 2020, the national Basic Policy for Coastal Protection was revised to add the statement that coastal management should account for future changes in coastal hydrodynamic conditions due to climate change. Following this policy, the management body of each coast is requested to revise the Basic Plan for Coastal Protection by 2025. This paper first reviews the current legal frameworks and measures of coastal protection and conservation, such as disaster prevention and mitigation against stormy waves, storm surges and tsunamis, beach conservation, and maintenance of coastal protection facilities. Second, the paper outlines the recent actions taken for coastal adaptation to climate change. With example cases in Osaka and Tokyo bays, it is described how design conditions such as design waves and water levels should account for the influence of climate change. It is also described how adaptive beach management should be implemented accounting for projections of future beach changes. Finally, the paper discusses future challenges in coastal adaptation strategies to climate change in Japan, such as introduction of integrated coastal zone management and other potential options that have not been implemented in Japan.

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1. Introduction

Global warming has various impacts on coastlines: it may cause sea level rise and intensify storm waves and surges, resulting in an increase in the frequency of coastal flooding events, and it may also intensify coastal erosion and thus reduce the space available for human activities and nearshore habitats. According to the sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), for example, it is virtually certain that the global mean sea level will continue to rise over the 21st century, and the projected sea level rise magnitudes by 2100 are 38 cm under SSP1–1.9, the most optimistic scenario, and 77 cm under SSP1–8.5 (Intergovernmental Panel on Climate Change 2022b). The sea level around Japan is also projected to rise, while the alongshore variation in the projected sea level rise is relatively small. The projected sea level rise totals around Japan are 39 cm under the RCP2.6 scenario and 71 cm under RCP8.5 (Ministry of Education, Culture, Sports, Science and Technology, and Japan Meteorological Agency 2020, hereafter, MEXT and JMA, 2020). It has also been reported that storm surges in three major bays in Japan, i.e. Tokyo, Osaka and Ise Bay, will be amplified by intensified typhoons in the future (MEXT and JMA, 2020). Mori et al. (2020) noted that the ensemble average of the projected maximum storm surges by the end of the 21st century reported by different studies exceeded the present design sea level anomaly in each bay. It is also projected that sea level rise will most likely cause shoreline retreat around Japan (Ministry of the Environment (MOE, hereafter), 2020). According to Udo and Takeda (2017), the losses of beach areas along the entire coast of Japan from 2081 to 2100 will be 62% under the RCP2.6 scenario and 83% under the RCP8.5 scenario. Mori et al. (2018) also projected a decrease in the sandy beach area in Japan due to sea level rise and claimed that approximately one-third of beaches may disappear under the RCP 8.5 scenario.

In parallel with many other countries (e.g. Delta Programme Coast 2013; Environment Agency 2020), the government of Japan has also started to tackle coastal adaptations to climate change. In 2020, the national Basic Policy for Coastal Protection was revised, and the revised policy added the statement that coastal management should account for future changes in coastal hydrodynamic conditions due to climate change. Following this policy, the management body of each coast is requested to revise the Basic Plan for Coastal Protection by 2025. This review paper outlines the current legal frameworks and measures of coastal protection and conservation in Japan and discusses the current situations and challenges of coastal adaptation strategies to climate change.

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Table 1. Framework of the Basic Policy for coastal protection (Ministry of Agriculture, Forestry and Fisheries and Ministry of Land, Infrastructure, Transport and Tourism 2020).

I. Basic Guiding Principle for Coastal Protection	
1. Basic Principle for Coastal Protection	1–1
2. Basic Matters for Coastal Protection	1–2
(1) Basic matters for coastal defense	
(2) Basic matters for maintenance and conservation of coastal environment	
(3) Basic matters for appropriate public use of coastal areas	
3. Basic Matters for Maintenance of Coastal Protection Facilities	1–3
(1) Basic matters for new construction or improvement of coastal protection facilities	
(2) Basic matters for maintenance or repairing of coastal protection facilities	
4. Other Important Matters for Coastal Protection	1–4
(1) Promotion of actions based on wide and integrated viewpoints	
(2) Promotion of regional cooperation and education for coastal protection	
(3) Promotion of survey and study	
II. Coastal Zones for Establishment of Basic Plan for Coastal Protection	
71 coastal zones are specified, in which the Basic Plan for Coastal Protection should be established.	2
III. Basic Matters for Establishment of Basic Plan for Coastal Protection	
1. Basic Matters to be Determined	3–1
(1) Basic matters for coastal protection	
(2) Basic matters for maintenance of coastal protection facilities	
2. Other Important Matters to be Considered	
(1) Consistency with other related plans	
(2) Cooperation and coordination with other related public organizations	
(3) Involvement of local residents and disclosure of information	
(4) Revision of the plan	

2. Coastal protection in Japan

2.1. *Seacoast law and national policy for coastal protection*

In Japan, coastal management is governed by the Seacoast Law, and the Seacoast Law states that the national government first determines the Basic Policy for Coastal Protection. Based on this Basic Policy, each coastal management body, such as a prefecture, should determine the Basic Plan for Coastal Protection at each coast. The following sub-sections outline the Seacoast Law and the Basic Policy for Coastal Protection. Hereafter, the literal translation of these Japanese documents is typed in italic form.

2.1.1. *The seacoast law*

The Seacoast Law was established in 1956. While the original 1956 Seacoast Law aimed only for coastal protection, it was amended in 1999 to account not only for coastal protection but also for coastal environment and coastal use. While coastal protection focuses on countermeasures of coastal erosion and disaster prevention and mitigation from various coastal hazards, such as tsunamis, storm surges, and stormy waves, the revised Seacoast Law in 1999 states that it is important to contribute to national land conservation through the maintenance and conservation of the coastal environment and the management and appropriate public use of coastal zones.

In the Seacoast Law, coastal management is designated to the prefectural governor. The tasks of the coastal management body are to determine and designate the area for coastal protection and to conserve the designated coastal protection area through the installation and maintenance of coastal protection facilities. In principle, the target area for coastal protection should be determined within 50 m seaward from the low water line and 50 m landward from the high tide line. The coastal protection facilities specified in the Seacoast Law include coastal dikes, groins, revetments, parapets, detached breakwaters, and beaches. Here, a beach can be considered a coastal protection facility only if it has been designated so by the coastal management body. The Seacoast Law also states that the national government should determine the Technical Standards for Coastal Protection Facilities, specifying the required minimum technical standards for the design of coastal protection facilities. Coastal management bodies should determine the properties of coastal protection facilities, such as their scales, layouts, and structures, based on the Technical Standards for Coastal Protection Facilities.

2.1.2. *The basic policy for coastal protection*

The Seacoast Law states that the national government first determines the Basic Policy for Coastal Protection, and based on this Basic Policy, each coastal management body, such as a prefecture, should determine the Basic Plan for Coastal Protection at each coast. Table 1 outlines the framework of the Basic Policy for Coastal Protection. In the section 1-1 indicated in Table 1, the Basic Policy for Coastal Protection states as follows: *the principle idea of coastal protection and conservation is to ensure a beautiful, safe, and lively coastal area for the next generations, and based on this principle, integrated coastal conservation measures should be planned to realize the desirable harmony of coastal protection against various coastal hazards; the conservation and maintenance of the coastal environment; and the facilitation of the appropriate public use of coastal areas*.

In the section 1-2 indicated in Table 1, basic matters for coastal protection are described for the following three items: (i) coastal defense; (ii) maintenance and conservation of coastal environment; and (iii) appropriate public use of coastal areas. Translations of some sentences for each of these three items are listed below.

> *(1) Coastal defense*
> *At each coast, the level of coastal defense should be determined based on investigations of natural conditions such as the meteorologic, hydrographic and topographic conditions, history of coastal disasters, projections of future coastal hazard changes, and sociological conditions of the hinterland, such as the population, assets, and land use. The defense level against tsunamis is determined for tsunamis with return periods of few or several decades to ahundred and several tens of years based on the history of tsunami inundation events around the target coast. The defense level against storm surges is determined for the sum of sea level anomalies and the effect of waves. The sea level anomaly is determined based on the recorded highest sea level or the predicted sea water level based on past data and numerical simulations. Ahigher coastal defense level accounting for future changes in coastal hazards may be taken if the target coast is more vulnerable to inundation, such as the coast around Tokyo, Ise and Osaka Bays, along which the hinterland has alarge zero-meter zone with the ground level being lower than the mean sea level and the region containing adense population and assets.*
>
> *Adaptive management approaches should be taken for shore protection against coastal erosion. In this approach, coastal protection measures should account for the coastal erosion mechanism and for projections of future topography changes due to climate change and the impacts of human activities based on the long-term monitoring of nearshore bathymetry and the entire sediment transport system. The effectiveness of conducted measures should also be monitored, and then the optimal measures should be decided based on projections of future topography changes. If the coast has already eroded, the goal of coastal protection in general should be to maintain and conserve the existing coast, while if necessary, goals can also be set for recovery of eroded beaches. In addition to the local protection of the target eroding coast, coastal protection measures should also account for the continuity of littoral sediment transport and maintain the appropriate sediment transport balance over the entire sedimentary system. Shore protections of capes and remote islands are a high priority for the protection of national territorial land and sea.*
>
> *(2) Conservation and maintenance of coastal environment*
> *Since the carrying capacity of coastal environments is limited, we should avoid or minimize activities that may disturb the coastal environment, and lost or disturbed coastal environments should be recovered as much as possible. Appropriate conservation and maintenance measures should be implemented to achieve desirable harmony between the natural environment and human activities. Special measures and attention should be taken for coasts that have precious environments, such as scenic spots, natural parks, academically or scientifically important natural areas, natural monuments, and precious natural habitats. Some human activities, such as driving entry, should be controlled or regulated for conservation of the environment, and appropriate and prompt actions should be prepared in advance for incidents such as oil spills to minimize and mitigate their impacts on the environment.*
>
> *(3) Appropriate public use of coastal areas*
> *Coastal management bodies should conduct the installation and maintenance of coastal facilities to utilize various coastal functions and facilitate the public use of coastal zones. Appropriate and prompt actions should also be taken to address damages to those facilities and neglected ships that may ruin the coastal landscapes and public usage. Coastal management bodies should also maintain appropriate public access to the seashore to account for the conservation of the natural environment.*

Here, examples of "*activities that may disturb the coastal environment*" are described in the introduction of Basic Policy for Coastal Protection such as fouling of the coast and driving on the beach. While details of *"desirable harmony between the natural environment and human activities"* are not specifically described in the Policy, it should indicate the state in which both conservation of natural environment and social demands for coastal protection and public use are satisfied.

In the section 2 indicated in Table 1, the Basic Policy for Coastal Protection states that a Basic Plan for Coastal Protection should be established for each of 71 coastal zones which are specified in the separate table in the document. Here, the coastal zone is a segment of the alongshore coast of Japan, and the littoral range of each segment is determined based on the similarity of bathymetric and hydrographic conditions and the continuity of littoral sediment transport.

In the section 3-1 in Table 1, the Basic Policy for Coastal Protection states that matters required for establishment of the Basic Plan for Coastal Protection. Translations of main matters described in this section are listed below.

> *(1) Basic matters for coastal protection*
> *(i) The present condition of the coast and future direction of coastal conservation*
> *Long-term state of the coast should be determined based on natural and social characteristics.*
> *(ii) Coastal defense*
> *Goals of coastal defense such as target areas and defense level, and detailed measures to achieve these goals should be determined.*
> *(iii) Coastal environment*
> *Detailed measures to be implemented for maintenance and conservation of coastal environment should be determined.*
> *(iv) Appropriate public use of coastal areas*
> *Detailed measures to be implemented to promote appropriate public use of coastal areas should be determined.*

(2) Basic matters for construction and maintenance of coastal protection facilities

(i) New construction and improvement of coastal protection facilities

Areas where coastal protection facilities are newly constructed or improved; type, scale and layout of coastal protection facilities; and areas where receive benefits by coastal protection facilities and the land use of these areas.

(ii) Maintenance and repair of coastal protection facilities

Areas with coastal protection facilities; type, scale and layout of coastal protection facilities; and methods of maintenance or repair of coastal protection facilities

2.2. Coastal protection and disaster prevention measures against storm surges and high waves

Coasts in Japan require appropriate protection and disaster prevention measures against storm surges and high waves induced by typhoons and winter storms. Disaster prevention measures are most important around Tokyo, Ise and Osaka Bays, where the large lowland areas behind the coasts have high populations and dense assets and the coastlines are threatened by severe storm surge disasters. In 1959, for example, the storm surge induced by Typhoon Vera, also known as Ise-Wan Typhoon in Japan, caused a severe coastal flooding disaster with more than 5,000 deaths. Six decades after Typhoon Vera, Japan again experienced severe, record-breaking-level typhoons, such as Typhoon Jebi and Trami around Osaka Bay in 2018 (Mori et al. 2019) and Typhoon Faxai (Suzuki et al. 2020) and Hagibis (Shimozono et al. 2020) around Tokyo Bay in 2019.

After the frequent experiences of severe storm surge disasters in the 1950s, Japan constructed concrete seawalls and water gates as disaster prevention measures against storm surges. Figure 1 shows the history of the total stretch of coastal protection facilities such as seawalls. Figure 2 shows an example of a revetment and seawall. As seen in Figure 1, the total length of the sea wall reached 3,000 km by 1980 and stayed nearly constant afterward.

The height of the seawall is determined by the sum of the design water level and the required height accounting for the influence of high waves. In general, the design water level is determined based on either (i) the recorded highest sea level, (ii) the sum of the mean high-water springs and the recorded highest sea level anomaly due to a storm surge, or (iii) the sum of the mean high-water springs and the estimated highest storm surge induced by the specified typhoon. In Tokyo Bay, for example, the estimated storm surge height is based on a virtual typhoon with an intensity equivalent to that of Ise-Wan Typhoon and the worst potential track that would cause the highest storm surge at each target coast. Unlike the determination of design wave conditions, probabilistic approaches such as the occurrence probability of the past recorded sea level anomaly have not been applied in Tokyo, Osaka or Ise Bays, three major bays in Japan. The required height for the influence of high waves is determined as the height by which the estimated wave overtopping rate is limited below the allowable rate. Here, in general, the wave overtopping rate is estimated for waves with return periods of 30 to 50 years.

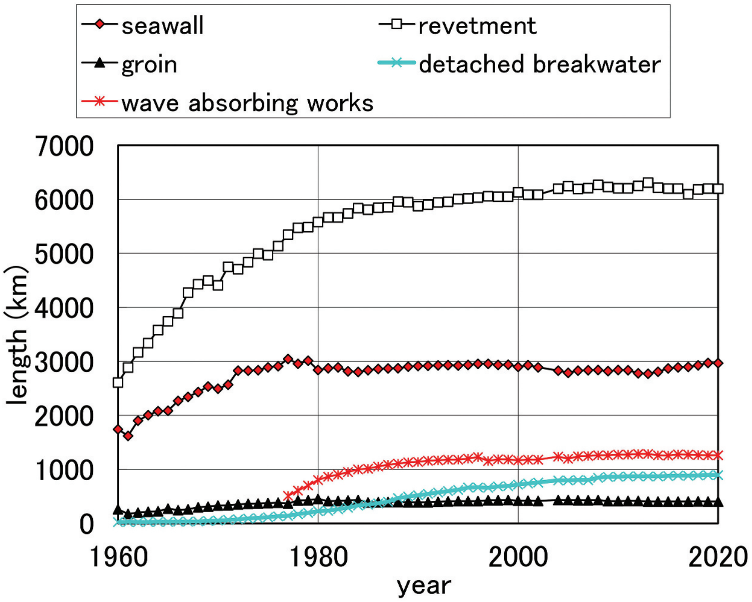

Figure 1. History of the total stretch of installed coastal protection structures in Japan.

Figure 2. Example of a revetment and seawall on the Urayasu coast in Chiba Prefecture, located at a in Figure 5.

In addition to seawalls and dikes, shore protection measures are often combined with offshore structures such as detached breakwaters and artificial reefs, which dissipate wave energy and thus reduce the required height of seawalls and dikes against wave overtopping. Such a combination of coastal protection facilities, including not only facilities along coastlines such as dikes, seawalls and parapets but also offshore structures, is called integrated coastal protection measures. In recent years, the application of such integrated coastal protection measures has been encouraged since an integrated approach can lower the required height of the seawall and benefit the conservation of desired coastal landscapes. As seen in Figure 1, the total length of constructed detached breakwaters has shown a drastic increase since 1980. Moreover, beach nourishment has also been selected as a coastal protection facility that allows wave energy to dissipate near the shore. The Seacoast Law also states that coastal management bodies can designate sandy beaches as coastal protection facilities and conduct maintenance of designated beaches to ensure the required coastal protection functions. Beaches designated as coastal protection facilities are required to maintain their coastal protection function over a long period of time against design wave conditions. Due to these requirements, the number of designated beaches was still only two as of December 2022. Figure 3 shows an aerial photograph of Ishikawa coast that has the first beach designated as coastal protection facilities. Location of the coast is indicated in Figure 5, presented later.

2.3. *Disaster prevention and mitigation measures against tsunamis*

While the southern and eastern coasts of Japan face the Pacific Ocean and have suffered tsunamis, coastal protection and disaster prevention measures against tsunamis are of importance along most coasts. In the 2011 Great East Japan Earthquake, the observed tsunami height exceeded 10 m and caused severe disasters along a 530-km stretch of the east coast of Japan (Mori, Takahashi, and the 2011Tohoku Earthquake Tsunami Joint Survey Group 2012). In the near future, moreover, the coasts of Japan may suffer severe tsunamis due to Nankai megathrust earthquakes and earthquakes along the Japan Trench.

After the experience of coastal flooding induced by the 1960 Valdivia earthquake and tsunami, dikes, parapets, and water gates were constructed as coastal protection facilities against tsunamis. While these structures were designed to protect the hinterlands

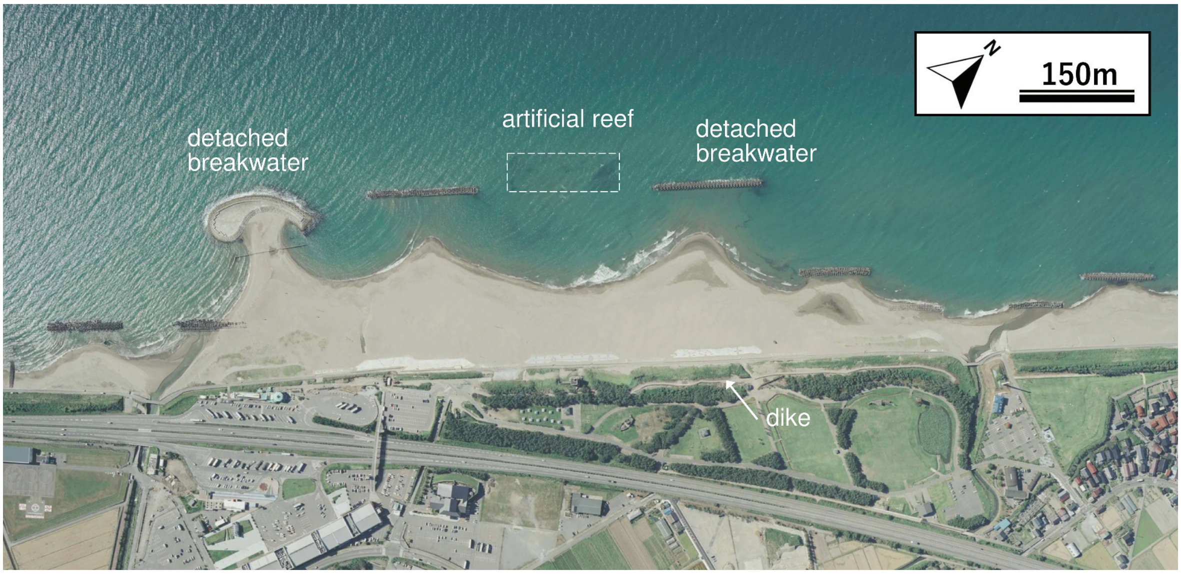

Figure 3. The first beach designated as coastal protection facilities on the Ishikawa coast located at B in Figure 5.

from tsunamis, the 2011 Great East Japan Earthquake Tsunami overflew the dikes and caused them to collapse over a total alongshore stretch of approximately 190 km. One of most important lessons learned from this severe tsunami disaster was that we should not rely too much on coastal dikes for disaster prevention from tsunamis. After the 2011 disaster, the concept of two different tsunami levels was introduced, and based on this concept, in general, the functions of coastal dikes should be determined for Level-1 tsunamis with return periods of several decades to a hundred years and a few decades. In the case of a Level-2 tsunami, the maximum possible tsunami at each coast, the tsunami would likely overflow the coastal dikes, and thus, comprehensive disaster mitigation strategies should be implemented by combining shore protection structures and nonstructure-based early evacuation plans (Sato 2015; Suppasri et al. 2016). The required heights of the dikes to protect against tsunamis should be determined for Level-1 tsunamis. If the target coast is partially protected by the breakwater constructed around the bay mouth, the required height of the dike accounts for the tsunami-reduction effect of these breakwaters. Finally, the actual heights of coastal protection structures such as dikes, seawalls and parapets should be determined through considerations of the various functions of coastal structures, accounting not only for tsunamis but also for the design sea level and design wave conditions.

The 2011 tsunami collapsed breakwaters and dikes along the coast, and the ground areas around these structures were severely scoured and eroded (Udo, Takeda, and Tanaka 2016; Yamashita et al. 2016). Such severe bed deformation around the structures appeared to enhance the collapse of the structures and required significant restoration work after the disaster. Based on these lessons, a new concept for the design of dikes and seawalls was introduced: dike and seawall structures should be designed so that severe and sudden collapse of the structures is avoided even under an overflowing tsunami. Through investigations of the damage mechanisms of dikes and seawalls, such as scour, it was found that an effective way to reinforce coastal dikes is to cover the top, front and backside slopes of the dike with concrete blocks and to reinforce the landside toe of the dike against scour (Kato et al. 2012, 2013, 2014). Such reinforced structures have been introduced not only to the dikes restored after the 2011 tsunami but also to those along the coasts where severe tsunami attacks are anticipated due to Nankai megathrust earthquakes (Inukai et al. 2017). It should also be noted that seismic reinforcement of these coastal structures is also being conducted since the seismic waves associated with earthquakes also significantly impact the deformation and subsidence of these structures (Hara 2017).

2.4. Measures against coastal erosion

The total alongshore stretch of beaches in Japan is approximately 5,000 km (Ministry of Land, Infrastructure, Transport and Tourism, Water Management and Land Conservation Bureau, Coast Office 2021), approximately one-seventh of the entire coastline stretch. These beaches have been eroded everywhere as a result of the imbalanced littoral sediment transport due to the construction of coastal structures and chronic decrease in sediment supply from rivers (Uda 2010). Tanaka et al. (1993) investigated the changes in shoreline location extracted from topographic maps and noted that the average beach area loss rates across Japan were 0.7 km^2/year over the 70 years before 1978 and 1.6 km^2/year from 1978 to 1992. Watanabe et al. (2022) conducted a similar analysis and found that the change in the beach area due to shoreline retreat from 1992 to 2006 was small (Figure 4). Figure 5 shows locations of coasts where annual shoreline retreat was more than 3 m. It should, however, be noted that the beach area itself decreased in this period due to forestation and land use of the land side areas of the beaches. Defeo et al. (2021) noted that coastal squeeze is caused by encroachment on both sides of the beach: the shoreline retreats due to erosion and sea level rise, and the land side retreats due to land use for recreation, urbanization and industrial activities. Japan also faces long-term coastal squeeze problems from both the sea and land sides of the beaches.

The principle concept of shore protection against coastal erosion is to maintain the present shoreline locations. In the past, counter measures against coastal erosion were simply the construction of revetment and wave dissipation works before the 1980s. After the 1980s, similar to shore protection against storm surges, the concept of integrated coastal protection was

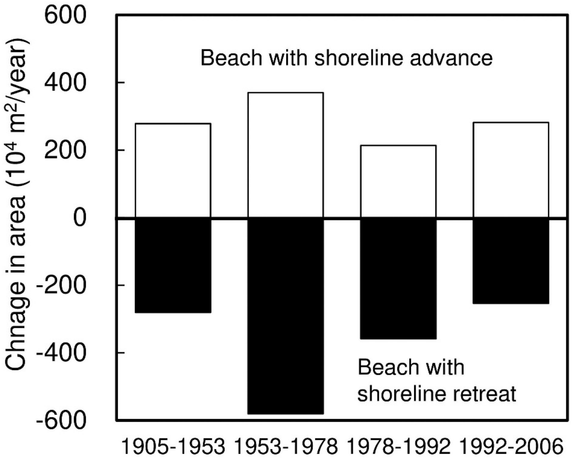

Figure 4. History of area change of beaches where the shoreline was advanced or retreated (modified from the source: Watanabe et al. 2022).

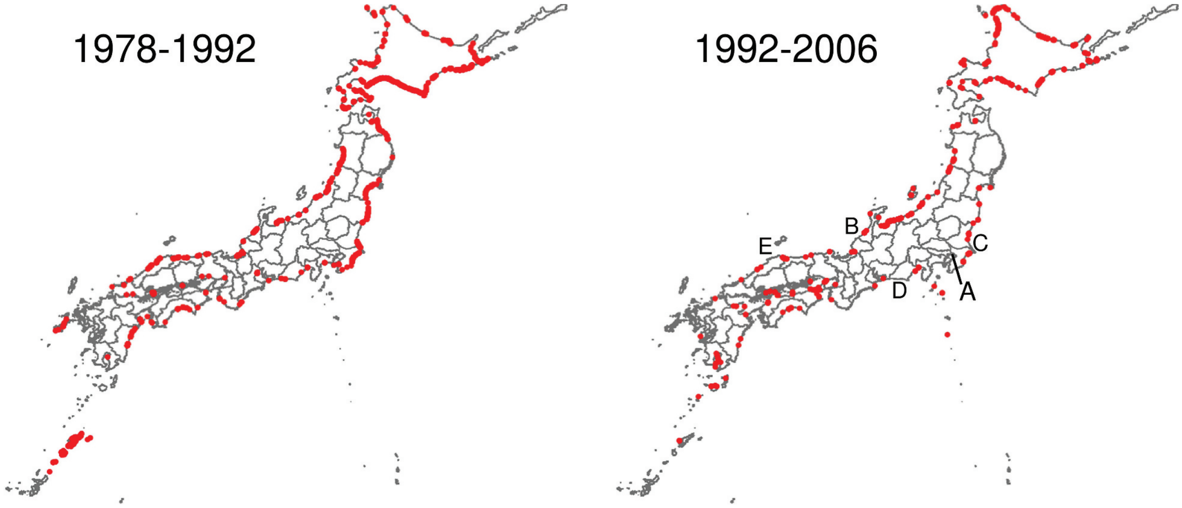

Figure 5. Locations of coasts (red dots) with annual shoreline retreat of more than 3 m in two different period from 1978 to 1992 and from 1992 to 2006. Capital letters indicate the locations of: (A) Urayasu coast, (B) Ishikawa coast, (C) Kashima-nada coast, (D) Fukude fishery port, and (E) yumigahama coast (modified from the source: Watanabe et al. 2022).

introduced. For example, the total lengths of groins, detached breakwaters, and artificial reefs increased to 404 km, 711 km and 185 km, respectively, as of 2021. A headland, a groin with a breakwater attached on the head of the groin, combines the effects of groins and detached breakwaters. A headland has merit in its longer alongshore interval than groins, allowing headlands to achieve dynamic equilibrium conditions between littoral drift and the beach. Examples of coastal protection measures involving headlands can be seen at various coasts, such as the Kashima-nada coast in Ibaraki Prefecture (e.g. Uda, Sumiya, and Sakuramoto 1988) (Figure 6). On the Kaike coast in Tottori Prefecture, multiple detached breakwaters and artificial reefs are combined to achieve a stable beach.

In addition to these structure-based solutions, non-structural measures such as beach nourishment, sand bypassing and sand recycling are also combined as a part of the comprehensive sediment management of the entire sedimentary system. Under this concept of comprehensive sediment management, various sediment control measures are comprehensively integrated to maintain the desired conditions of the entire sedimentary system from the headwater to the coast. Examples of these measures include dredging deposited sediments from dam reservoirs and riverbeds; placement of these dredged sediments on the downstream sides of dams; beach nourishment using sediments dredged from riverbeds; and sand bypassing and recycling along the coasts (e.g. Hadano, Sato, and Sakurazawa 2017; Matsuba, Sato, and Hadano 2017; Shibutani, Matsubara, and Kuroiwa 2013; Yajima et al. 1983). Figures 7 and 8 show examples of sand-bypassing system at Fukude fishery port and sand recycling at the Yumigahama coast. In the last two decades from 2000 to 2020 in Japan, the annual beach nourishment volume was approximately 600,000 m^3.

Figure 6. Headlands along the Kashima-nada coast, located at C in Figure 5.

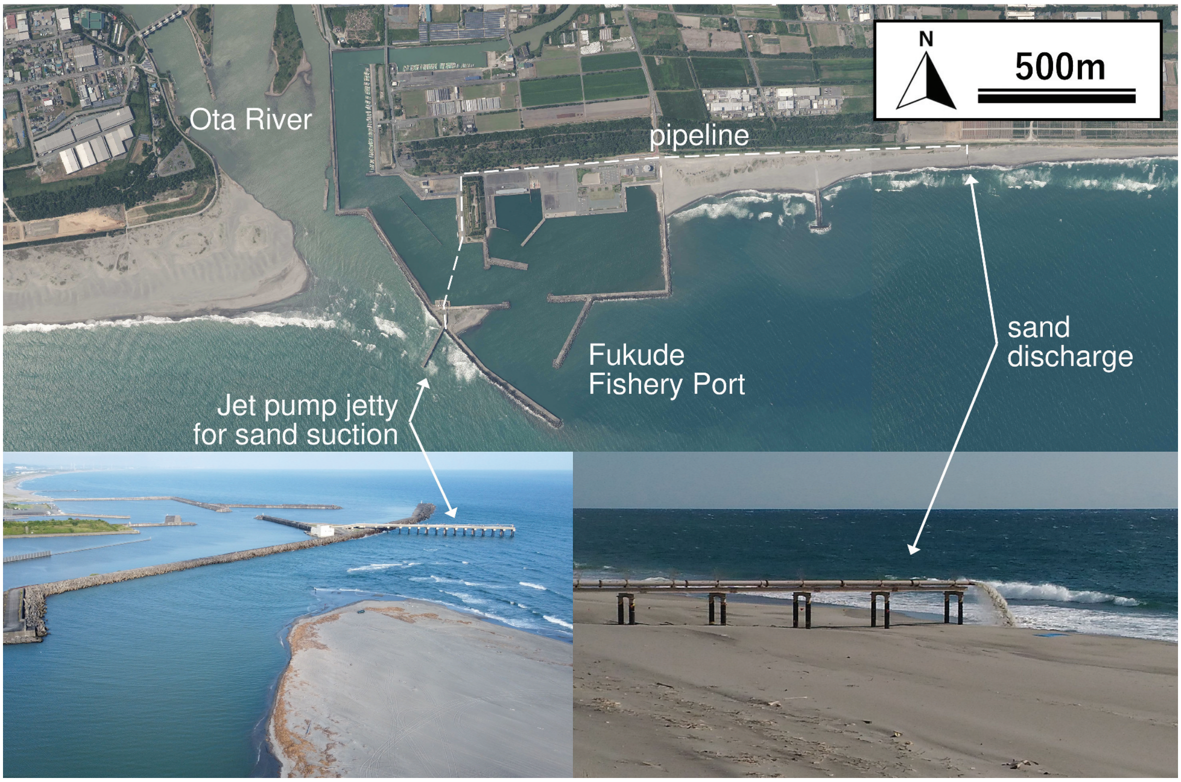

Figure 7. Sand bypassing system across Fukude fishery port, located at D in Figure 5.

2.5. Maintenance of shore protection facilities

As described in Section 2.2, most concrete coastal protection facilities, such as revetments and dikes, were constructed by 1980 in Japan. One of the important issues faced in coastal protection and conservation in Japan is, therefore, maintaining these aged facilities. As of 2015, the total alongshore stretch of coastal protection facilities with ages unknown or older than 50 years was approximately 40% of that of all coastal protection facilities, and this ratio is estimated to reach approximately 70% by 2035 (Ministry of Agriculture, Forestry and Fisheries and Ministry of Land, Infrastructure, Transport and Tourism 2020). The Basic Policy for Coastal Protection requires a coastal management body to formulate the plan for the lifespan expansion of coastal facilities and, following this plan, to conduct inspections, necessary repairs and reinforcement of these facilities.

3. Coastal adaptation to climate change

3.1. National policy on coastal protection considering climate change

In Japan, discussions and investigations on the impacts of climate change on the coast started in approximately 1990. The Coastal Engineering Committee under the Japan Society of Civil Engineers, for example, launched a working group in 1991 to investigate the impacts of climate change on coastal natural systems and infrastructures; the outcomes of this working group were published in 1994 (Coastal Engineering Committee, Japan Society of Civil Engineers Subcommittee on Global Environmental Problems 1994). The national government has also conducted a series of technical committee meetings to investigate the impact of climate change on the coasts and to discuss appropriate adaptation strategies. These successive technical meetings resulted in the suggestion of the following policy: (i) the impact of climate change on the coasts should be continuously monitored; and (ii) adaptive coastal protection and conservation measures should be taken in response to gradually intensifying external forces (Ministry of Land, Infrastructure, Transport and Tourism, Coastal Global Warming Adaptation Strategy Review Committee 2011).

In 2019, to further clarify the actual coastal adaptation measures designed to combat climate change, the government of Japan launched a technical committee to investigate how coastal protection and conservation should be conducted under the influence of climate change. This committee conducted the following investigations: (i) the future changes in coastal hydrodynamics such as sea level rise and the intensification of storm surges and high waves; (ii) the impacts of hydrodynamic changes on the coasts; (iii) how the hydrodynamic forces acting on the coasts should be determined; and (iv) how coastal maintenance and conservation measures should be planned and implemented.

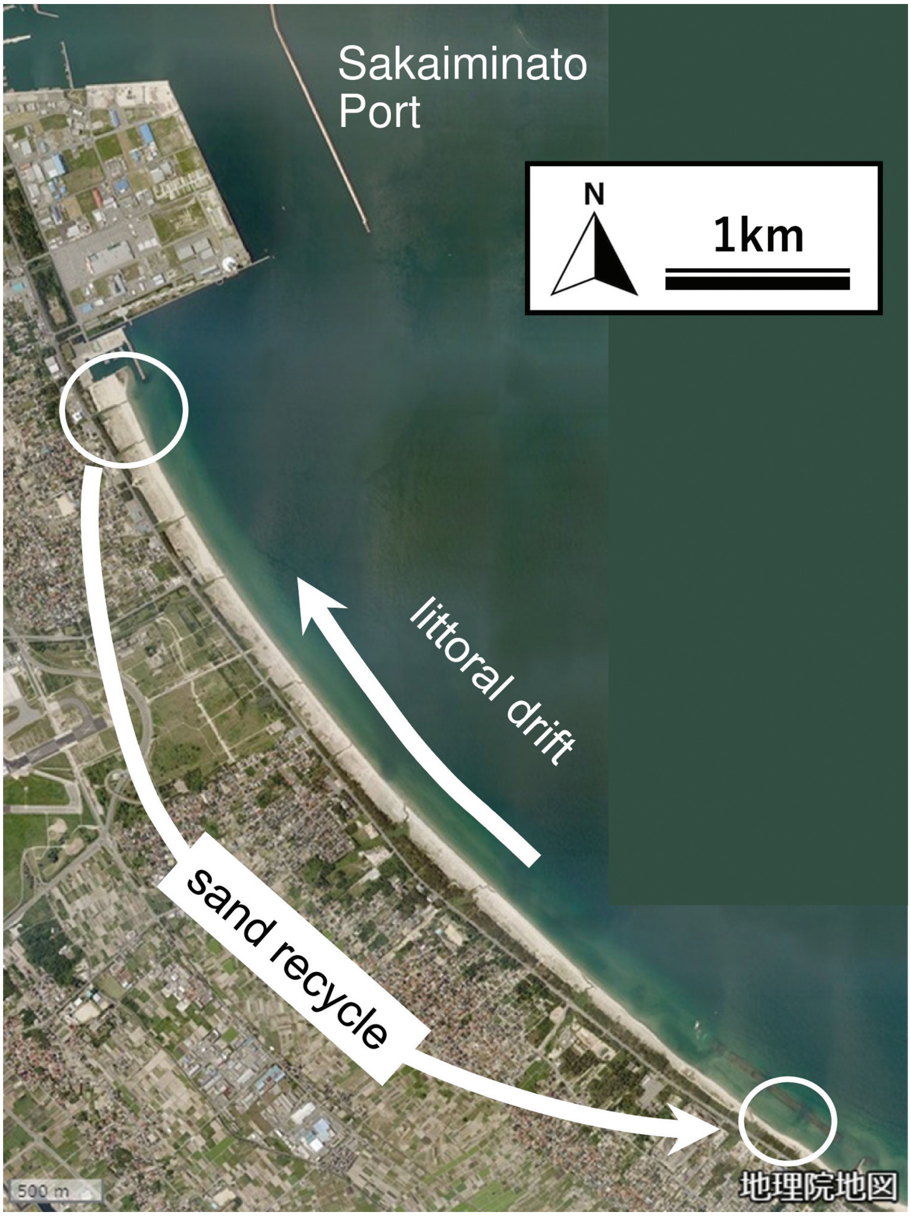

Figure 8. Sand recycling at the Yumigahama coast, located at E in Figure 5.

In 2020, the committee published a report suggesting the following items for coastal adaptation strategies (Ministry of Land, Infrastructure, Transport and Tourism 2020): (i) coastal conservation and protection plans should explicitly account for the future changes in coastal phenomena due to climate change; (ii) as of now, in general, the planning of coastal protection and conservation measures can be made for the projected future changes in coastal phenomena based on the RCP2.6 scenario; (iii) for sea level rise, the RCP 8.5 scenario, under which a sea level rise of 1 m is projected by 2100, should also be accounted for in the case that requires longer perspectives; (iv) coastal protection and conservation measures should account for the appropriately projected storm surges and high waves; (v) projections of future coastal phenomena can be made based on the Database for Policy Decision-Making for Future Climate Change (d4PDF) (Mizuta et al. 2017; Umeda, Nakajo, and Mori 2019); (vi) efforts should be made to implement comprehensive measures against storm surges and tsunamis that combine coastal protection facilities and non-structural measures such as integrated land use planning accounting for disaster prevention/mitigation; and (vii) cooperation with management bodies of rivers and reservoirs should be strengthened to promote comprehensive sediment management plans accounting for the impact of the climate change on sediment budget over the entire sedimentary system.

Following this report, in 2020, the government of Japan revised the Basic Policy for Coastal Protection as was outlined in section 2.1.2. This was the first time in Japan that the revised policy clearly stated that coastal conservation and protection should explicitly account for the influence of climate change and that the coastal protection levels against various hazards should be appropriately determined to sufficiently accommodate the long-term changes in the hydrodynamic forces that occur due to the influence of climate change. Here, the coastal protection level is specified in terms of the design water level and design waves. In the policy, it is specified that the design water level should account for the future sea level rise and amplification of sea level anomalies due to intensified climate conditions such as typhoons. It is also specified that the design wave height should also account for the influence of intensified climate conditions such as typhoons and winter storms. Furthermore, the Policy states that integrated and systematic disaster prevention/mitigation measures should be conducted in cooperation with related organizations to defend the consecutive coastal hinterland. Through such cooperation, for example, consistency of defense levels should be assured among not only coastal facilities but also other facilities in the hinterland. For essential counter measures against coastal erosion, the Policy also states that adaptive beach management based on projections of future changes should be implemented, and that various related organizations should cooperate to promote a comprehensive sediment management of the entire sedimentary system, accounting for the nationwide projection of the impact of climate change on long-term sediment budget.

3.2. Projection of the design high tide level and wave

The Government of Japan issued a notice titled “Methodology for determination of the design force acting on coastal protection facilities accounting for the influence of climate change,” following the revision of the “Technical standards for coastal protection facilities” in 2011. In this notice, the design forces acting on coastal protection facilities should be generally based on the average values of future projections under the RCP 2.6 scenario, i.e. the 2° warming scenario introduced in Working Group I (WGI), the Fifth Assessment Report of IPCC (IPCC-AR5) (IPCC 2013). This notice also states that the coastal management body should account for the uncertainties in climate projections and in the efficiency of the improvement and maintenance of coastal protection facilities in their decisions regarding to what extent the influence of climate change should be accounted for in determining design conditions such as the design water level and design wave.

The reference material attached to the abovementioned note shows examples of methods for future projections of sea level anomalies and waves, as listed in Table 2. These methods are classified into two groups, A and B. Group A estimates sea level anomalies and waves based on specified typhoons with modifications accounting for the influence of climate change. Here, a specific typhoon is selected from historical typhoons, such as Ise-Bay Typhoon in 1954 and Muroto Typhoon in 1934, that caused severe storm surge disasters and are used to obtain the present design conditions of coastal protection facilities. The influence of global warming is then accounted for by increasing the central pressure depth of the specified typhoon. In Group A, A-1 and A-2 differ from each other in terms of their computation methods of the typhoon wind and pressure fields. For example, A-1 uses an empirical typhoon model (e.g. Myers 1954), while A-2 uses physics-based numerical prediction models such as the Weather Research & Forecasting model (WRF; Skamarock et al. 2008). On the other hand, methods in Group B use a large number of arbitrary typhoons. The three methods in Group B differ from each other in how these typhoons are specified, as outlined in Table 2. For example, the following subsections outline the cases used to estimate future sea level anomalies and waves in Osaka Bay and Tokyo Bay.

3.3. Example cases of coastal protection adaptations to climate change

3.3.1. Reconstruction of water gates in Osaka Bay

This section outlines an example case in Osaka Prefecture in which the design high tide and wave were revised while accounting for the influence of climate change (Osaka Prefectural Council for River Structures 2021). After significant storm surge disasters occurred in 1950 and 1961 around Osaka Bay, Osaka Prefecture constructed three water gates at the mouths of three major rivers flowing through the Osaka lowland area in 1970. Figure 9 shows locations of these three water gates. These water gates were designed for the assumed extreme conditions in which a typhoon equivalent to Ise Bay typhoon passed the worst potential track for each coast around Osaka Bay during high tide. These water gates were also designed to prevent tsunami disasters, and thus, Osaka Prefecture expects that these disaster prevention facilities should be well maintained so that these structures will retain sufficient disaster prevention functions until the end of the 21st century. Therefore, it was decided that these structures should be designed so that their functions should be assured over the entire lifetimes of the structures and their components even under future intensified forces due to climate change. The following subsections outline how these forces are determined and how the design concept accounting for

Table 2. Estimation methods of future sea level anomalies and waves (Ministry of Agriculture, Forestry and Fisheries and Ministry of Land, Infrastructure, Transport and Tourism 2021).

Atmospheric force	Notes	Influence of global warming	Applicability
A. Specified typhoon	A typhoon equivalent to historical severe event such as Ise-Bay-Typhoon and Muroto Typhoon		
A-1. Parametric typhoon model	Empirical typhoon model (e.g. Myers model)	Increase in the central pressure depth based on the projected data base such as d2PDF and d4PDF.	Consistent with the coasts where the specific typhoon used for the present design and plan occurred. Probabilistic estimations can be obtained by combining models with ensemble datasets in B-1.
A-2. Physics-based numerical prediction model	Mesoscale numerical weather prediction model (e.g. WRF)	Dynamical downscaling of the specific typhoon under pseudoglobal warming conditions derived based on databases such as d2PDF and d4PDF (e.g. Ninomiya et al. 2016).	Applicable to the coast where the same approach without global warming was applied. It should be noted, however, that the computed typhoon is not perfectly consistent with one that may occur in the present climate (e.g. tracks).
B. Many unspecified typhoons	Large number of samples enables probabilistic estimation		
B-1. Global climate model Mesoscale climate model	Typhoons extracted from global climate models or the downscaling of global models, such as d2PDF and d4PDF.	While d2PDF and d4PDF include the influence of global warming, the computed results require bias corrections to ensure consistency with the current design conditions (e.g. Yamamoto, Mori, and Kjerland 2018)	A large number of samples enables probabilistic determination of the design conditions. Suitable for coast where the design conditions are determined by the values corresponding to a specified return period.
B-2 Climatological approach	Storm surge is empirically estimated from climatological conditions based on GCM accounting for the concept of the maximum potential intensity (MPI).	Estimations are based directly on d2PDF and d4PDF and include the influence of global warming (e.g. Ariyoshi and Mori 2018)	Applicable to coasts where a specific typhoon was used for the present design and plan.
B-3. Stochastic typhoon model (STM)	Monte Carlo simulation of waves and surges corresponding to a number of synthetic typhoons generated by the STM based on the statistical characteristics of past typhoons.	STM can be modified accounting for the future projection data such as d4PDF (e.g. Umeda, Nakajo, and Mori 2019)	A large number of samples enables the probabilistic determination of the design conditions. Suitable for coasts where the design conditions are determined by the values corresponding to a specified return period.

the impact of climate change was made for reconstruction of water gates.

(1) Mean high-water springs

Updating the temporal variations in the mean high-water springs (MHWS) observed at the Osaka tide gauge station, it was confirmed that the recent MHWS tends to be higher than the one used for the present design high water: O.P. +2.2 m. Here, O.P. (Osaka Peil) indicates the low water level in Osaka Bay, and O.P. +0.0 m=T.P. +1.3 m with T.P. (Tokyo Peil, mean water level in Tokyo Bay). The MHWS in 2100 was therefore determined by summing the MHWS in the typhoon seasons within the period from 1986 to 2005, O.P. +2.3 m, and the projected sea level rise. Here, the period from 1986 to 2005 was determined so that it corresponded to the baseline period of the present climate used by the IPCC. The amount of sea level rise in 2100 was determined based on the projected sea level rise reported in the *Special Report on the Ocean and Cryosphere in a Changing Climate* (Oppenheimer et al., 2019). According to the report, the highest and the lowest projected global average sea level rise, that of the area around Japan, and that of the area around Osaka Bay ranged from 0.25 to 0.67 m under the 2° warming scenario and from 0.58 to 1.28 under the 4° warming scenario. In Osaka, the sea level rise corresponding to the design water level was set to 0.7 m from the base year to the future, from 2051 to 2111. This value was determined based on the values of the 95th percentile projected sea level rise under the 2° warming scenario of the global average (0.59 m), around Japan (0.67 m), and around Osaka Bay (0.62 m). Here, relatively severe conditions were selected based on the following discussions: the in-service period of these water gates will most likely be extended even after 2100; the sea level will likely keep rising even after 2100; and the impacts of sea level rise will spread widely and continuously even under daily conditions. In contrast to the 2° warming scenario, the sea level rise under the 4° warming scenario, the most pessimistic CO2 emission scenario, was set to 0.9 m based on the median values of projections of the global average (0.84 m), the average around Japan (0.90 m) and the average around Osaka (0.86 m).

(2) Sea level anomalies and waves

The properties of typhoons, such as the atmospheric pressure, wind speed and wind directions, under the future climate can be determined through two different methods: (i) methods based on the projected data given by the Global Climate Model (GCM) and (ii) those based on the specific typhoon used for the present design but with the influence of global

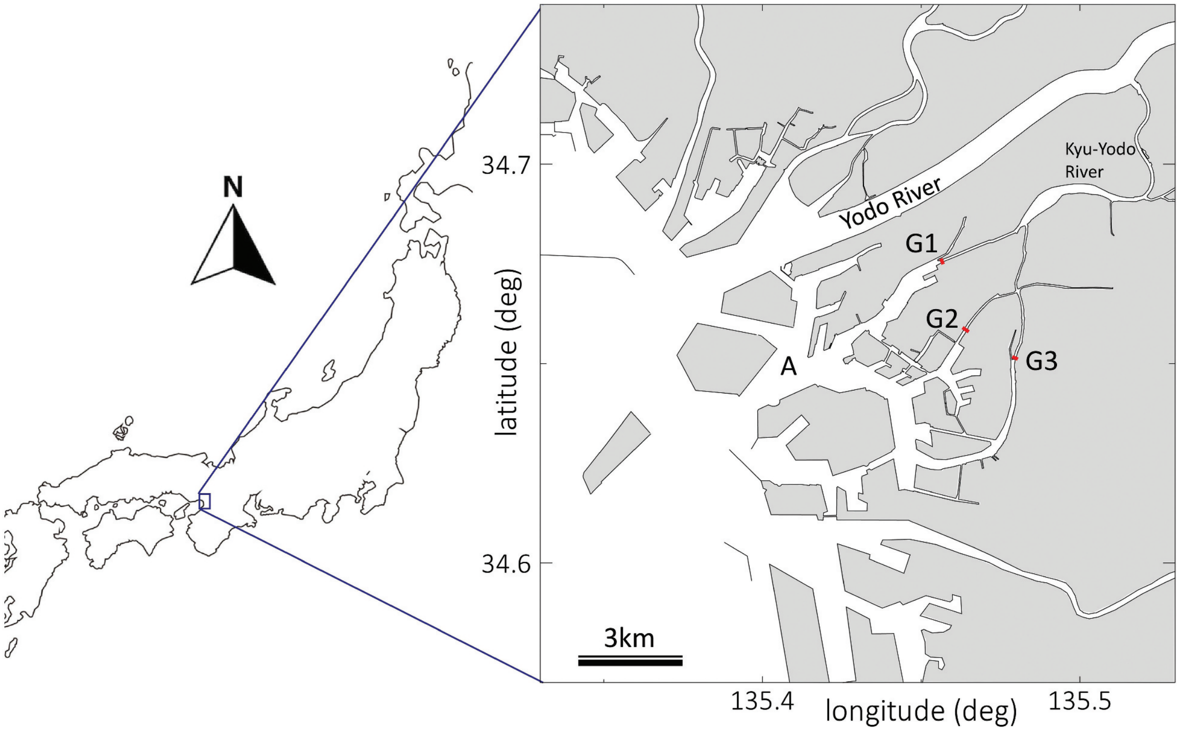

Figure 9. Osaka Bay and locations of three water gates, Aji river water gate(G1), Shirinashi river water gate (G2) and Kizu river water gate (G3).

warming. The first method corresponds to B-1 in Table 1, while the second method corresponds to A-1 in Table 1. In this investigation, Osaka Prefecture used the d2PDF climate change projection data for the 2° warming scenario and those of d4PDF for the 4° warming scenario. The spatial resolutions of these data are 20 km for both d2PDF and d4PDF. Through comparisons of these two methods, the second method (A-1 in Table 1) was adopted here, as this method was more consistent with the present design policy.

The central pressure of the typhoon in the future climate was determined through comparisons of climate projection data of the present climate and the future climates (in both the 2° warming and 4° warming scenarios). The typhoon intensity was determined so that the return period of the typhoon events was equivalent between the present climate and the future climate. Based on this concept, the central pressure of the typhoon under future climate conditions was determined through the following procedures.

1. Based on the observed typhoon data, the return period of the typhoon event was estimated to be equivalent to the Ise-Bay typhoon with a central pressure of 940 hPa, which was used for the present coastal protection plan.
2. The central pressure of typhoons with the same return periods was estimated based on the climate projection data of the present and future climates.
3. The amplification factor was computed as a ratio of the obtained central pressure depths under the future and present climate conditions.
4. This amplification factor was multiplied by the present central pressure depth, i.e. 1013 hPa-940 hPa = 73 hPa, to obtain the maximum central pressure depth of the future typhoon, which was then used for the revision of the coastal protection plan.

Through these procedures, the amplification factor and the minimum central pressure were found to be 1.09 and 933 hPa under the 2° warming scenario and 1.21 and 925 hPa under the 4° warming scenario, respectively. The radius to the maximum wind of the future typhoon was determined based on the relationship of the central pressure and the radius of the Ise Bay typhoon. The migration speed of the future typhoon was set to be equivalent to that of the Ise Bay Typhoon since no clear difference in typhoon migration speed was observed between the present and future climates in the abovementioned dataset.

The sea level anomaly was computed by a two-dimensional horizontal storm surge model based on nonlinear shallow-water equations with external forces induced by the abovementioned typhoons. In this computation, it was assumed that the water gates were closed. At the upstream boundaries of the rivers flowing into Osaka Bay, the volume fluxes were specified by the discharge corresponding to the design water level under the present climate conditions. The computed sea level anomaly at the Kyu-Yodo River mouth, the location indicated by the capital letter, A, in Figure 9, was higher than the present anomalies of the design water level by 0.5 m under the 2° warming scenario and 1.2 m under the 4° warming scenario. Similarly, the increase in the sea level anomaly due to the influence of climate change in front of these water gates was 0.72 ~ 1.06 m under the 2° warming scenario and 1.65 ~ 1.94 m under the 4° warming scenario. Since the computation was performed using the model based on the latest knowledge and the updated higher resolution bathymetry data that differs from the one used for setting of the current design conditions in 1961, we should note that the above mentioned increase in sea level anomalies is not solely due to the impact of climate change. In contrast to relatively large increase in sea level anomalies, projected design wave heights showed no significant increase, which may be partly due to the shielding effects of surrounding structures. These results indicate that coastal management body should note that the projections of future design conditions may be affected by various factors such as evolution of computational model and topography change.

(3) Crown height of the water gate accounting for the influence of climate change

Integrating the influences of sea level rise, sea level anomalies and waves, the required crown heights of the water gates were set to OP +8.64 m under the 2° warming scenario and to OP +9.85 m under the 4° warming scenario. Difference from the present height, the OP +7.40 m values were therefore 1.24 m and 2.45 m, respectively. These three water gates are not affected by intensified precipitation due to climate change since river water is discharged from other water gates.

(4) Design concept for reconstruction of the water gate

Based on the future projections described in the preceding sub-sections, the design concept for reconstruction of water gates was decided. A part of translations of the design concept decided by Osaka Prefectural Council for River Structures (2021) are listed below.

In all scenarios for climate change projections, a temperature rise of 2° above pre-industrial levels will occur between 2040 and 2050. Therefore, the design should be done so that there will be no rework or regret in the next generation. On the other hand, future external forces, determined from the results of climate change projection, should include uncertainties due to climate projections, scenarios, and the time when the external forces will rise. Accounting for such uncertainty, we should avoid overinvestment in the present design.

Basically, the external forces for the design should be based on the 2° warming scenario, which is consistent with the policy of national government. However, we should note that the external forces can be as high as the ones corresponding to the 4° warming scenarios or higher. The design should accommodate such higher external forces beyond the design external forces through post-construction measures such as reinforcement.

Since each structural component of the water gate has different conditions such as service life, renewal time, and applicability of reinforcement, counter measures against climate change should be determined for respective components. These counter measures can be classified into two: "proactive measures" in which measures are taken in advance; and "adaptive measures" in which measures are taken after confirming the impact of climate change.

Proactive measures should be taken for gateposts, piers, floor slabs and foundations because it is virtually difficult to repair these components while they are in service. The gate strength should also be determined as proactive measures since it is virtually difficult to change while the water gate is in service.

Adaptive measures should be taken for mechanical and electrical equipment because it has a short service life and adaptive measures can be made at the time of renewal. Adaptive measures can also be taken for the height of the gate since it is possible to raise the gate after the construction. It is important to design the water gate so that reliable gate operation is assured even if the size of components of the water gate are increased through adaptive measures in the future. This concept should also be reinvestigated and, if necessary, revised, responding to the progress of the projections of climate change.

3.3.2. Revision of the basic plan for coastal protection along Tokyo Bay

This section outlines another example case, the revision of the Basic Plan for Coastal Protection along Tokyo Bay. While the Tokyo Bay area has a significantly large lowland area with a dense population and assets and concentrated industry, the area is prone to storm surge disasters and has suffered several storm surge inundation events, such as that induced by Typhoon Kitty in 1949. After the severe storm surge disaster occurred around Ise Bay in 1959, coastal protection works such as seawalls and water gates were reconstructed, and the construction of all outer seawalls along Tokyo Bay had been completed by 2003.

Following the revision of the Basic Policy for Coastal Protection in 2020, the Tokyo Metropolitan government started to work on revising the Basic Plan for Coastal Protection of Tokyo. In March 2023, the Tokyo Metropolitan Government published the revised shore protection basic plan (Tokyo Metropolitan Government, 2023).

In the revised basic plan, the sea level rise from 2000 to 2100 was set to 0.6 m, which corresponds to the highest projections of various GCMs under the RCP 2.6 scenario, i.e. the 2° warming scenario. The potential amplification of sea level anomalies and waves due to intensified typhoons was investigated through comparisons of the following three methods: (i) computations of waves and storm surges with the force induced by a specified synthetic typhoon set to be equivalent to that of the Ise-Bay typhoon with an amplified intensity accounting for the influence of climate change; (ii) sea level anomalies and waves with return periods of 50 years based on observed data; and (iii) wave hindcasts of the top five historical extreme wave events. Here, method (i) corresponds to A-1 in Table 1, and the minimum central pressure of the typhoon was set to 930 hPa, that of a typhoon with a return period of 100 years under the future climate conditions. This central pressure is lower than that of the Ise Bay typhoon. The tracks of these model typhoons were determined by shifting the tracks of the Ise-Bay typhoon and the other two past typhoons that caused the highest storm surges in Tokyo Bay in the east–west directions. The computations of waves and storm surges were performed for these specified typhoons with different tracks, and the highest results were used at each location along Tokyo Bay. For the storm surge computation, the boundary conditions at the upstream boundaries of the rivers were determined by the volume flux equivalent to the present design high-water discharge of each river. Among the results computed with these three methods, the first method yielded the highest elevation and was thus adopted for the subsequent determination of the required seawall height. As a result, the required seawall heights increased at some locations, with ranges changing from A.P. +4.6 ~ 8.0 m to A.P. +5.6 ~ 8.0 m. Here, A.P. (Arakawa Peil) indicates the low water level in Tokyo Bay, and A.P. +0.0 m=T.P. +1.1344 m.

The revised basic plan also states that the required seawall raising should be conducted in a stepwise manner. In the first step, the seawall raise magnitude should be determined by the sum of the required height under the climate conditions 50 years in the future and the allowance for uncertainty (30 cm). In the second step, the required seawall height should target the climate conditions in 2100, while the specific required height should be revised later, accounting for the latest knowledge of the long-term sea condition trends.

3.4. Adaptive beach management based on projections of future beach changes

In Japan, countermeasures against coastal erosion are conducted only after severe coastal erosion problems have clearly appeared. These reactive, delayed countermeasures result in little mitigation of coastal erosion or required relatively long-term coastal protection measures. To avoid such delays in effective countermeasures, the revised Basic Policy of Coastal Protection in 2020 stated the importance of accommodative coastal management accounting for projections of beach topography changes. Under this policy, coastal conservation and protection measures are accommodatively planned based on future projections of local topography changes, the entire sediment transport system, and the mechanisms of coastal erosion while accounting for the influence of global warming and human activities. To realize such accommodative coastal management, continuous monitoring is necessary to evaluate and confirm the effectiveness of the present conservation and protection measures and to apply the findings to the planning of future measures.

MLIT organized the Advisory Panel on Tsunami-Resistant Communities and Beach Conservation, focusing on "how regional development resilient to tsunami disasters and the conservation of sandy beaches should be achieved" in 2018. The midterm report of the workshop of this advisory panel states that accommodative and feasible management should be planned and conducted for the protection and conservation of sandy beaches through an integrated overview of the entire sediment transport system (Ministry of Land, Infrastructure, Transport and Tourism 2019). The report claims that to conduct efficient and effective management of long sandy beaches in Japan, the Basic Plan for Coastal Protection should be revised to include more strategic approaches to coastal management. For example, various coastal protection and conservation measures at each coast should be conducted in the order of their priority. Coastal management bodies should determine the priority ranking accounting for indices such as the relative importance of the beach and the hinterlands to be protected by the beach and the level of progress of beach erosion. The report also proposes the following procedures for ranking the priorities of beach conservation and protection measures.

(1) Rank classification of sandy beaches

The beach ranks are determined based on the extent of erosion progress and the relative importance of the hinterland area to be protected, as shown in Figure 10. In Figure 10, five different ranks are indicated by a, b, c, d and e, and the apostrophe on each letter indicates the beaches at which continuous beach conservation measures and management have already been conducted. The beach characteristics of each rank are described as follows.

a: Severe erosion and deterioration of disaster prevention/protection functions

b: Severely eroded but disaster prevention/protection functions are retained. Further beach erosion may deteriorate the disaster prevention/protection functions.

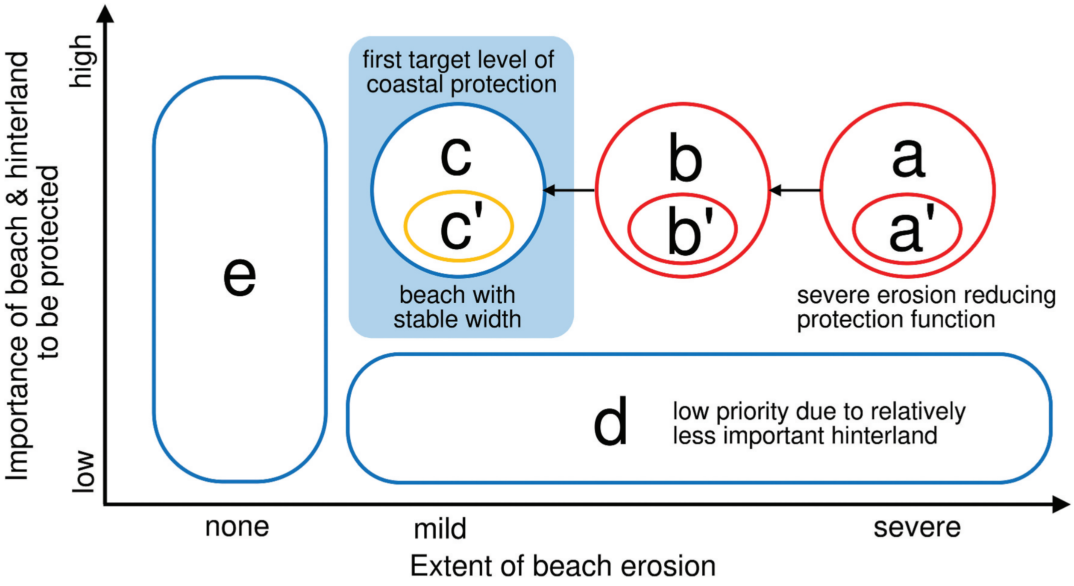

Figure 10. Classifications of beach ranks based on the importance of the hinterland area and the extent of erosion (based on Ministry of Land, Infrastructure, Transport and Tourism 2019).

c: Sufficient beach width is kept stable, and disaster prevention/protection functions are retained.

d: The hinterland area is less important, and the priority of beach protection is low.

e: A vast and stable beach width is maintained.

While the report does not describe the specific criteria for rank classification of each sandy beach, the management body of each sandy beaches is responsible for these classifications, monitoring, and future revisions of the classification based on the monitoring results. Each management body should determine the contents of monitoring, such as monitoring subject, spatiotemporal coverage and resolution, and required accuracy, based on the required level of dynamic management of the beach. Then, monitoring system, organizations, and methodologies should be determined. Obtained data should then be investigated with the past data and future projections.

(2) Rank classification of coastal zones

As shown in Figure 11, the rank of each coastal zone is determined based on combinations of the above-mentioned ranks of the sandy beaches belonging to each coastal zone. In the figure, A, B, C, D and E are the ranks of the coastal zones, whereas a, b, c, d and e are the ranks of each sandy beach segment. As shown in Figure 11, the rank of each coastal zone is automatically determined by the following rule.

A: The coastal zone having “a”-rank sandy beaches.

B: The coastal zone having “b”-rank beaches but not beaches ranked higher than “b”-rank.

C: The coastal zone having “c”-rank beaches but not beaches ranked higher than “c”-rank.

D: The coastal zone having “d”-rank beaches but not beaches ranked higher than “d”-rank.

E: The coastal zone having “e”-rank beaches but not beaches ranked higher than “e”-rank.

Based on the classified rank of each coastal zone, coastal management bodies should determine their required functions. For example, the required disaster prevention/protection function should be to keep the wave runup height lower than the designed crest height of the coast, and the required environment and coastal usage function should be specified by other properties, such as the sandy beach width. The report also states that the coastal management body should focus on required environmental and coastal usage functions if the sandy beach is ranked c (not c′), d, or e. After the determination of the required function of each sandy beach, each management body should determine the target criteria for management, such as the shoreline location, entire sediment transport budget, shore vegetation area, and area of the beach used for recreation. Based on these target criteria, the Basic Plan for Coastal Protection and

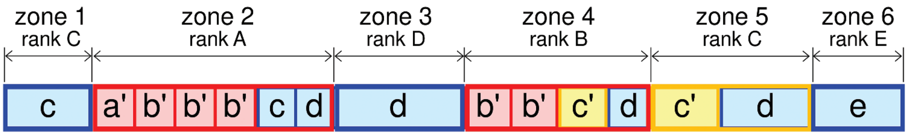

Figure 11. Example of the rank classification of coastal zones (based on Ministry of Land, Infrastructure, Transport and Tourism 2019).

designation of coastal preservation zones should be revised accordingly. If a sandy beach is ranked as c,' moreover, the management body should consider designating the beach as a coastal conservation/protection facility.

4. Challenges for coastal adaptation in Japan

4.1. *Introduction of the concept of integrated coastal zone management to coastal adaptation*

The present coastal adaptation policy in Japan aims to retain the same disaster prevention level along the same coastline even in a future affected by the influence of global warming because the area of plain lands is limited and most of the nearshore plain areas are filled with residential buildings or industrial facilities. Most of the coasts also has coastal protection facilities such as seawalls and coastal dikes to protect the nearshore plain areas from tsunamis and storm surges. These coastal areas with coastal protection facilities may suffer coastal erosion and lose sufficient disaster prevention functions in the future due to the impacts of global warming, such as sea level rise and the amplification of sea level anomalies and storm waves. If we keep the same coastal protection line, i.e. maintain the cross-shore locations of coastal dikes, some coasts with relatively narrow sandy beaches will most likely lose the beach areas in front of these structures in the future.

To retain such sandy beaches, recent coastal protection measures have tended to combine the construction of coastal protection facilities with beach nourishment. Moreover, against severe coastal hazards such as tsunamis and storm surges that exceed the targeted disaster protection level of these facilities, disaster mitigation measures are planned in the hinterlands to minimize fatalities against the estimated worst hazard conditions through combinations of "soft" measures such as evacuations and "hard" measures such as the construction of seawalls and evacuation towers.

On the other hand, the report of the Working Group II of IPCC AR6 (Intergovernmental Panel on Climate Change 2022a) suggested that coastal adaptation should aim not only to maintain the coastal protection function at the same protection line but also to include various other measures such as raising the ground level, adapting buildings such as reinforcing buildings to enhance flood resistance, landfilling, and the retreat of certain land use types such as the relocation of residential areas. In addition to the construction of coastal structures and nourishment, the report also suggests other options for coastal protection, such as the use of natural resources such as mangroves. The report also notes that structure-based coastal protection at the same locations carries the risk of severe damages once these structures collapse and fail to play their expected coastal protection functions. In addition, the construction of coastal protection structures may cause further development in the area exposed to the risk of coastal disasters.

To assure the sustainability of coastal adaptation measures, the concept of integrated coastal zone management (ICZM) should be further enhanced in Japan. Isobe (1998) introduced examples of ICZM in Japan and discussed issues for the further promotion of ICZM in Japan. Especially for coastal adaptation, the revised Basic Plan for Coastal Protection should consider various other potential options that have not yet been applied in Japan. The following subsections discuss how these other options can be combined in the context of ICZM to reach desirable coastal adaptation strategies in Japan.

(1) Nature-based solutions

IUCN (2016) defines nature-based solutions (NbS) as follows. *"Nature-based solutions are actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits."* Here, disaster prevention is also counted as a social challenge; thus, disaster prevention and mitigation measures utilizing the natural environment are also NbS. NbS may also have merits due to their relatively high resilience and low cost (e.g. Kuwae and Crooks 2021). In Japan, words such as "green infrastructure" and "ECO-DRR" may be more frequently used than NbS. For example, MLIT published the report "*Grand Design of National Land 2050*" that proposed principles and ideas for the development and preservation of national land in 2050. In this report, the development and maintenance of green infrastructure was listed as a basic strategy for obtaining the desired national land. Moreover, the MOE established the Workshop on National Biodiversity Strategies, and the report published by this workshop in 2021 stated that the application and promotion of green infrastructures and ECO-DRR, which have various functions, including disaster prevention and mitigation, are important actions to be taken to realize the desired features of a society in harmony with nature by 2050.

International guidelines (e.g. Bridges et al. 2021) illustrate examples of NbS that are applicable to coastal adaptation measures. Among these options, some natural resources may be applicable to the coasts in Japan. First, sandy beaches have effective wave dissipation function and foot protection functions for coastal structures. Sandy beaches can be designated as coastal protection facilities if their stability against waves is assured. Sand dunes, most of which are located along the coastlines on the Japan Sea side and are often managed separately from sandy beaches, also serve the function of protecting the hinterland area against tsunamis (e.g. Yamanaka and Shimozono 2022). Coral reefs and mangroves also have wave dissipation functions and are found along subtropical coasts such as the coasts of the Amami Islands in Kagoshima, Ryukyu Islands in Okinawa, and Ogasawara Islands in Tokyo. To ensure the sustainable wave dissipation effects of coral reefs, appropriate coral restoration and preservation measures may be required for protection against threats of coral deterioration, such as bleaching due to ocean temperature rise. Coastal forests also have disaster mitigation functions along the coasts of temperate and subarctic regions, such as the coasts of the main islands of Japan and Hokkaido (Chang and Mori 2021). While coastal forests such as black pines were originally planted as windbreaks and to block wind-blown sand transport, these coastal forests also have effects on the dissipation of tsunami inundation (Tanaka et al. 2014). Eelgrass beds, which are widely distributed all over the coast of Japan with a total area of approximately 330 km^2, have certain effects on wave dissipation and CO2 absorption. The maintenance and preservation of environments suitable for the growth of eelgrass are required to enhance the functions of eelgrass beds.

NbS can be conducted not solely by nature itself but also through combinations with hard structures such as coastal dikes. For example, the sand covering both the sea- and land-side slopes of concrete coastal dikes has the effects of both expansion of the sand dune vegetation area and reinforcement of the coastal dikes (Matsushima and Zhong 2022). In Hamamatsu City, Shizuoka, a coastal dike was constructed with Cemented Sand and Gravel (CSG) to protect the hinterland area tsunamis, and the slopes on both sides of the dike were covered by soil with planted black pines on the surface so that the entire structure would be harmonized with the surrounding environment and the landscapes of the sand dunes (Figure 12).

One of the challenges in NbS is that, in contrast to hard structures, most NbS do not have the concepts of the in-service period or external forces for design and thus have no clear standards of maintenance levels or methodologies. It is also not clear to what extent we can rely on the expected functions of NbS. A sandy beach, designated as a coastal protection facility, is an exceptional case of NbS. The management body of the designated sandy beach is required to monitor the shoreline locations and conduct appropriate maintenance so that the designated beaches retain their functions to limit the wave runup height lower than the designed level even if the beaches are deformed by waves.

Another challenge in NbS in Japan is that hard-type coastal protection structures and natural environments, such as coral reefs, are controlled by different management bodies. For the further promotion of integrated NbS measures and hard structures, various related organizations need to jointly collaborate with each other to improve the reliability of NbS through investigations of various aspects, such as the resilience and cost-effectiveness of NbS, and to clarify the methods and roles of the organizational bodies to ensure the sustainable maintenance and management of these integrated NbS.

Figure 12. A coastal dike in Hamamatsu city, Shizuoka, located at D in Figure 5. Top and both sides of CSG dike were covered by soil.

(2) Integration of disaster mitigation measures on hinterlands

In addition to protections along the coastlines, integrations of various disaster mitigation and prevention measures are essential tasks for improving the resilience of coastal areas. Raising the ground level of the hinterlands along coasts has disaster mitigation effects by reducing the inundation area and depth due to tsunamis and storm surges. Before the disaster of the 2011 Great East Japan Earthquake and Tsunami, raising the ground level was privately conducted only in a relatively small, limited area within the flood-prone region. After the 2011 disaster, ground raising was largely performed in the area damaged by tsunami inundation. The reinforcement of buildings to enhance flood resistance was effective in reducing the number of buildings collapsed and washed away by inundation. In Japan, the local government can designate the disaster risk area due to various hazards, such as tsunamis, storm surges and floods, and in the designated disaster risk area, the local government can regulate the types of buildings and structures. However, the number of designated cases within disaster risk areas is limited. Nagoya City in Aichi Prefecture, for example, designated the area damaged by Ise Bay Typhoon in 1959 as a disaster risk area, and the structures of houses and elevation of rooms in houses are now regulated in this area. While the Federal Emergency Management Agency (FEMA) provides financial aid widely for individual residents to elevate their homes (Federal Emergency Management Agency 2023) in the United States, such aid is limited in Japan, including in terms of building reformation projects aiming to enhance disaster resilience in disaster risk areas. In addition to these building measures, well-urbanized regions should also have disaster prevention and mitigation measures to protect themselves against the inundation of underground spaces such as subways and underground shopping complexes. Although such underground protection measures focus mostly on flood disasters, the same measures should also be prepared against storm surges and tsunamis.

(3) Advancement of coastal protection lines by land reclamation

In Japan, land fill and land reclamation have been conducted to expand the areas of farmlands and lands designated for industrial use. The total area of reclamation from 1945 to 1999 was 1,483 km^2, out of which 38% was reclaimed for farmlands, 33% for residential areas, and 29% for industrial use (Yasui and Yabunaka 2002). On the other hand, the area of tidal flats was largely reduced. Some reclaimed lands have residential areas on the seafront side. Some of these residential areas were damaged by the overtopping waves induced by Typhoon Jebi in 2018 (e.g. Hattori et al. 2020; Mori et al. 2019). While the advancement of the coastline by land-filling and reclamation may have disaster reduction effects on the hinterland area, such land reclamation may also promote seaward advancement of the populated area, which subsequently requires additional coastal protection measures. Furthermore, land reclamation may significantly negatively impact the ecosystems of the surrounding tidal flats. It is therefore quite difficult to maintain the desired sustainable coastal environment and protection functions provided by land reclamation in Japan.

(4) Managed retreat and resettlement

While another option for disaster mitigation measures against intensified storm surge and waves is to move the nearshore residential areas inland, Japan has no such administrative scheme to move houses from disaster-prone areas to safer areas based on future projections of hazards before the actual incidence of a disaster. After the 2011 Great East Japan Earthquake and Tsunami disaster, approximately 37,000 houses were relocated from the nearshore inundated area under a project designed for promoting group relocation and disaster mitigation, and these inundated areas were designated as disaster risk areas where residential land use was restricted. The total area of this designated disaster risk area was 227 km^2.

For flood disaster prevention and mitigation, the government of Japan launched a new policy, “River Basin Disaster Resilience and Sustainability by All (RBDRSA),” in which comprehensive and multilayered actions were taken for (i) flood prevention; (ii) exposure reduction; and (iii) the enhancement of disaster resilience (Koike 2021). For example, one of the actions taken for exposure reduction and the enhancement of disaster resilience was the designation of flood-prone zones. Conditions for the designation of flood-prone zones vary among each local government, and as of now, these conditions are based on past records of precipitation and tide levels. RBDRSA also states that these conditions should account for the future impacts of climate change.

The setback of coastal dikes has a positive impact on the coastal environment, as it enlarges the habitat spaces of marine organisms. Along the Ise-wan-Seinan coast in Mie Prefecture, located on the southwest side of Ise Bay, for example, the coastal dike was set back for the preservation of the coastal environment in 2009. As a result, the amount of new coastal vegetation increased and stabilized (Watanabe et al. 2014). In the restoration of coastal dikes damaged by the 2011 Great East Japan Earthquake and Tsunami, setbacks were selected at three coasts for the conservation of nearshore biodiversity (Kurosawa 2021).

If the setback of coastal dikes and properties in hinterlands can be synchronized with the shoreline retreat, sandy beaches can also be set back without losing their widths. On coasts where shoreline retreat is anticipated due to future sea level rise, such systematic setback of coastal facilities and properties through land use regulations based on projected shoreline retreat may be a promising and sustainable measure for maintaining sandy beaches with required coastal protection functions. In North Carolina, United States, for example, the setback factor, the distance in which no buildings are allowed, is determined based on the past record of long-term shoreline retreat (North Carolina Department of Environmental Quality 2022). In Japan, the authors could not find any case in which coasts prone to severe erosion were designated as disaster risk areas. To do so, it will be necessary to build a regional consensus for future setbacks and develop a reliable methodology for accurately projecting future shoreline retreat.

The total population of Japan was 127.09 million people in 2015 and is expected to decrease to 88.08 million people by 2065. It is also projected that the population will be less than 60 million by 2100 (National Institute of Population and Social Security Research 2022). Such population shrinkage is expected to be more notable in local districts, and thus, the setback option may be more feasible in local districts in the future. It should, however, be noted that, as was pointed out by Bragg et al. (2021), consensus building for future setbacks will require close communication with local residents.

4.2. *Uncertainties in climate change projections*

Projections of sea level rise and future amplifications of storm surges due to climate change contain uncertainties, and thus, when planning and designing coastal protection facilities, those in charge should appropriately account for such uncertainties to avoid suggesting overdesigned structures and unnecessary reconstruction works. In the IPCC AR6 report, the future climate projections are performed by various GCMs for five different CO2-emission scenarios. As discussed in Section 3.1, projections of the design waves and sea level anomalies along the coast of Japan are based on the d4PDF database containing large ensemble simulations of climate conditions in the future and in the latter half of the 20th century under different warming scenarios. These ensemble simulation results enable the probabilistic future changes to be estimated while accounting for uncertainties. As shown in Table 1, several options are used for projecting the future design waves and sea level anomalies based on these datasets. Mori et al. (2020) compared recent existing studies on the maximum sea level anomalies in three major bays in Japan, i.e. Tokyo, Osaka and Ise Bays, and showed that the future increases in the projected sea level anomalies in these studies fell in the range from 0.7 to 1.7 m.

In the case of the water gates in Osaka Bay introduced in Section 3.2, each component of the water gates has different conditions, such as different life periods, renewal timing, and reinforcement applicabilities. Osaka Prefecture therefore classified these components into two adaptation types: (i) the proactive type and (ii) reactive type (Osaka Prefectural Council for River Structures 2021). In the proactive type, certain measures are taken before the impacts of climate change appear, while in the reactive type, necessary measures are taken after confirming the impacts of climate change. Reactive-type measures should have merits in accommodating uncertainties if a facility structure has flexibility to allow stepwise gradual reformation and respond to the unexpected intensification of external forces in the future.

It is also important to enhance the resistance of coastal facilities to significant collapse under severe external forces beyond the design level, which may occur due to underestimations of the projected impacts of climate change. Significant and sudden collapse of coastal protection facilities would cause severe inundation damage in the hinterlands. As discussed in Section 2.3, coastal dikes were severely collapsed by the 2011 tsunami, and in the process of restoring these collapsed coastal dikes, a new concept in structural design was introduced so that the reinforced coastal dikes could avoid sudden and significant collapse under overflowing tsunamis to retain the disaster mitigation functions of the dikes. The Seacoast Law was also revised in 2014, and the revised law states that, if necessary, coastal dikes should have reinforced structures to avoid sudden and significant collapses under severe storm surges and waves beyond the design level. While further research and investigation are required to obtain effective designs of structures while aiming to enhance their resistance to significant collapse under storm surges and waves (Takeshita et al. 2018), this concept and related knowledge and techniques should be considered an effective climate change adaptation measure.

4.3. Impact of adaptation measures on coastal environments and public uses

Climate change causes significant impacts not only on coastal hazards but also on the coastal environment and human activities around the coast. For example, sea level rise and wave amplification may reduce the areas of sandy beaches, the habitat spaces of marine organisms, and the field area available for public use and human activities. The nearshore zone has unique environments that provide habitats that are indispensable for some marine organisms. For example, coastal plants grow in very unique and often severe nearshore environments. Some sandy beaches on the Pacific coast of Japan provide limited egg-laying sites for loggerhead turtles, an endangered species. Thus, the loss of such sandy beaches may also threaten the survival of endangered species.

The use of coastal areas reinvigorates human activities and local economies and is thus an important factor in maintaining sustainable and lively coastal regions. The important factors that attract people and stimulate their use of the coasts are the unique features of the coastlines themselves, such as the landscapes, environments, and various coastal activities. The use of the coasts in Japan includes various activities, such as walking, bathing, beach sports and various events.

Coastal adaptation measures, such as the reformation of coastal protection facilities, should also have significant impacts on the coastal environment and human activities. For example, raising the crest level of coastal dikes to protect hinterlands with dense populations and assets from the intensified hazards due to sea level rise and amplified waves may affect coastal landscapes and require additional land area for expanding the widths of coastal dikes.

The designs of coastal adaptation measures should therefore account for the resulting impacts of the measures on coastal environments and the human usage of the coastal area. For example, countermeasures against coastal erosion should be planned so that protected sandy beaches retain sufficient space for the habitats of marine organisms and human activities. A required goal of countermeasures against coastal erosion is generally determined from the viewpoint of coastal protection functions, such as retaining the present shoreline location or sufficient beach width to limit the runup heights of design waves to be lower than the crest levels of the coastal dikes. For the maintenance of unique and various coastal functions, it is also important to add other requirements accounting for different aspects, such as sufficient beach widths for coastal vegetation, egg-laying sites for loggerhead turtles, and human activities such as bathing.

One effective option for planning coastal adaptation measures is zoning coastal areas while accounting for the local variations in the relative importance levels of three aspects described in the Seacoast Law: (i) disaster prevention, (ii) the coastal environment, and (iii) coastal usage. On some coasts, the Basic Plan for Coastal Protection determines segmented regions with different relative importance levels of the abovementioned three aspects. It is desirable that each coastal management body conduct more detailed and subdivided zoning based on the local characteristics of each coast. The concepts of green infrastructure, Eco-DRR and NbS accommodate various objectives, including not only coastal protection but also the preservation of marine organism habitats and the effective use of coasts for human activities. These concepts can be applied to sandy beaches, dunes and coastal forests. To allow better application of these concepts, further investigations and studies should be conducted on the evaluation methods of the coastal protection functions of green infrastructures, better combinations of green and hard infrastructures, and methodologies for the effective and sustainable maintenance and management of green infrastructures.

Compared to the data and knowledge related to coastal protections, those related to coastal environments and usage are limited. Significant and continuous monitoring efforts should therefore be made to acquire data and knowledge regarding the abovementioned investigations and studies for the promotion of Eco-DRR and NbS. While the MOE conducted the *National Survey on the Natural Environment* and obtained data on coral reefs and marine forests such as mangrove, seagrass and kelp forests, there are limited monitoring data on beach ecosystems (Suda 2017). MLIT conducts the *National Census on Beach-inhabiting Plants and Animals* every five years to obtain data on nearshore organisms at a limited number of beaches. Such monitoring campaigns should be expanded to the entire coast of Japan, and based on the collected data, further analyses should be conducted to capture the long-term and wide-area ecosystem trends. The human usage of the coasts should be monitored in terms of the number of sea bathers. The continuous monitoring of other activities and uses of coasts should also be carried out.

5. Conclusions

This paper first outlined the current legal frameworks and measures of coastal protection and conservation in Japan and then described the current policy and plans involving coastal adaptation measures to combat climate change, followed by discussions of the challenges faced in future coastal adaptation strategies. Japan has a long stretch of coastlines vulnerable to the impacts of climate change through the intensification of coastal hazards. The revised Basic Policy for Coastal Protection states that the coastal protection level, in general, should target the projected coastal hazard under a 2° warming scenario, in which the impacts of climate change account not only for sea level rise but also for the future amplification of storm surge and waves. To achieve the sustainable adaptation of coastal protection and conservation, several challenges must be solved, such as (i) the optimum integration and selection of various coastal protection measures; (ii) evaluation of the reliability, feasibility and sustainability of various measures such as NbS and setback; (iii) determining how to accommodate the uncertainties of various projections; and (iv) integrated coastal zone management accounting for the desirable harmony of the coastal environments and human usage of coasts.

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Disclosure statement

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References

Ariyoshi, N., and N. Mori. 2018. “Future Projection of Storm Surge Height at Three Major Bays in Japan Using Maximum Potential Intensity of Typhoon in Western North Pacific.” *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 74 (2): I__619–I__624. in Japanese. https://doi.org/10.2208/kaigan.74.I_619

Bragg, W. K., A. T. Gonzalez, A. Rabearisoa, and A. D. Stoltz. 2021. “Communicating Managed Retreat in California.” *Water* 13 (6): 781. https://doi.org/10.3390/w13060781.

Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan, eds. 2021. *International Guidelines on Natural and Nature-Based Features for Flood Risk Management*. Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/41945/3/NNBF-Overview-2021.pdf.

Chang, C., and N. Mori. 2021. “Green Infrastructure for the Reduction of Coastal Disasters: A Review of the Protective Role of Coastal Forests Against Tsunami, Storm Surge, and

Wind Waves." *Coastal Engineering Journal* 63 (3): 370–385. https://doi.org/10.1080/21664250.2021.1929742.

Coastal Engineering Committee, Japan Society of Civil Engineers Subcommittee on Global Environmental Problems. 1994. "Coastal Effects of Global Warming." 221. (in Japanese) http://www.jsce.or.jp/committee/cec/active/gep/index.html .

Defeo, O., A. McLachlan, D. Armitage, M. Elliott, and J. Pittman. 2021. "Sandy Beach Social–Ecological Systems at Risk: Regime Shifts, Collapses, and Governance Challenges." *Frontiers in Ecology and the Environment* 19 (10): 1–10. https://doi.org/10.1002/fee.2406.

Delta Programme Coast. 2013. National Coastal Strategy - Compass for the Coast. http://rijksoverheid.minienm.nl/nvk/NationalCoastalStrategy.pdf.

Environment Agency. 2020. "National Flood and Coastal Erosion Risk Management Strategy for England." 117. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/920944/023_15482_Environment_agency_digitalAW_Strategy.pdf .

Federal Emergency Management Agency. 2023. Hazard Mitigation Assistance Program and Policy Guide. 597. https://www.fema.gov/sites/default/files/documents/fema_hma-program-policy-guide_032023.pdf.

Hadano, K., S. Sato, and T. Sakurazawa. 2017. "Beach Recovery Due to Sand Bypassing at Fukude-Asaba Coast." *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 73 (2): I__805–I__810. in Japanese. https://doi.org/10.2208/kaigan.73.I_805

Hara, T. 2017. "Resilience Efforts in the Kochi Prefecture in Preparation for the Nankai Trough Earthquake." *Journal of Disaster Research* 12 (4): 755–765. https://doi.org/10.20965/jdr.2017.p0755.

Hattori, N., Y. Tajima, Y. Yamanaka, and K. Kumagai. 2020. "Study on the Influence of Infragravity Waves on Inundation Characteristics at Minami-Ashiyahama in Osaka Bay Induced by the 2018 Typhoon Jebi." *Coastal Engineering Journal* 62 (2): 182–197. https://doi.org/10.1080/21664250.2020.1724247.

Intergovernmental Panel on Climate Change. 2022a. *"Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 3056. Cambridge University Press. https://doi.org/10.1017/9781009325844.

Intergovernmental Panel on Climate Change. 2022b. "Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities." In *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press 321–446. https://doi.org/10.1017/9781009157964.006.

Inukai, K., Y. Kuriyama, S. Sato, F. Kato, N. Mizutani, K. Harada, M. Jinbo, T. Iwasa, and T. Fukuda. 2017. "Experimental Study of Structures for Coastal Dike Resilient to Tsunami Overflow in Suruga Coast." *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 73 (2): I__1057–I__1062. in Japanese. https://doi.org/10.2208/kaigan.73.i_1057

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA:Cambridge University Press. 1535.

Isobe, M. 1998. *"Toward Integrated Coastal Management in Japan"*. ESENA. https://nautilus.org/esena/toward-integrated-coastal-management-in-japan/.

IUCN (International Union for Conservation of Nature). 2016. "Resolution 69 on Defining Nature-Based Solutions (WCC-2016-Res-069)." IUCN Resolutions, Recommendations and Other Decisions. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2016_RES_069_EN.pdf.

Kato, F., Y. Suwa, A. Hatogai, and K. Fujita. 2014. "A Study on Structures of Coastal Dike That Persist Disaster Mitigation Effects Against Tsunami Overflow." *Journal of Japan Society of Civil Engineers, Ser B2 (Coastal Engineering)* 70 (1): 31–49. in Japanese. https://doi.org/10.2208/kaigan.70.31.

Kato, F., Y. Suwa, K. Watanabe, and S. Hatogai. 2012. "Mechanisms of Coastal Dike Failure Induced by the Great East Japan Earthquake Tsunami." *Coastal Engineering Proceedings* 1 (33): 40. structures 40. https://doi.org/10.9753/icce.v33.structures.40.

Kato, F., Y. Suwa, K. Watanabe, and S. Hatogai. 2013. "Damages to Shore Protection Facilities Induced by the Great East Japan Earthquake Tsunami." *Journal of Disaster Research* 8 (4): 612–625. https://doi.org/10.20965/jdr.2013.p0612.

Koike, T. 2021. "Evolution of Japan's Flood Control Planning and Policy in Response to Climate Change Risks and Social Changes." *Water Policy* 23 (S1): 77–84. https://doi.org/10.2166/wp.2021.287.

Kurosawa, T. 2021. "Facility Against Tsunamis and Green Infrastructure—A Case Study of Post-Disaster Reconstruction After the Great East Japan Earthquake." *Coastal Engineering Journal* 63 (3): 200–215. https://doi.org/10.1080/21664250.2021.1877916.

Kuwae, T., and S. Crooks. 2021. "Linking Climate Change Mitigation and Adaptation Through Coastal Green–Gray Infrastructure: A Perspective." *Coastal Engineering Journal* 63 (3): 188–199. https://doi.org/10.1080/21664250.2021.1935581.

Matsuba, Y., S. Sato, and K. Hadano. 2017. "Rapid Change in Coastal Morphology Due to Sand-Bypassing Captured by UAV-Based Monitoring System." *Proceedings of the International Conference on Coastal Dynamics 2017*. 1529–539.

Matsushima, H., and X. Zhong. 2022. "Challenging a Hybrid Between Green and Gray Infrastructure: Coastal Sand-Covered Embankments." In *Green Infrastructure and Climate Change Adaptation. Ecological Research Monographs*, edited by F. Nakamura. Singapore: Springer. https://doi.org/10.1007/978-981-16-6791-6_20.

Ministry of Agriculture, Forestry and Fisheries and Ministry of Land, Infrastructure, Transport and Tourism. 2020. "The Basic Policy for Coastal Protection" 12. (in Japanese) https://www.mlit.go.jp/river/kaigan/main/coastplan/bp.pdf.

Ministry of Agriculture, Forestry and Fisheries and Ministry of Land, Infrastructure, Transport and Tourism. 2021. *Reference Materials for Setting Unplanned Forces for Coastal Protection Facilities Based on the Impact of Climate Change*. in Japanese.

Ministry of Education, Culture, Sports, Science and Technology, and Japan Meteorological Agency (MEXT and JMA). 2020. "Climate Change in Japan 2020 (Detailed Version)." 149–184. (in Japanese) https://www.data.jma.go.jp/cpdinfo/ccj/2020/pdf/cc2020_shousai.pdf.

Ministry of Environment (MOE). 2020. "Assessment Report on Climate Change Impacts in Japan", 39–83, https://www.env.go.jp/content/000047546.pdf.

Ministry of Land, Infrastructure, Transport and Tourism. 2019. "Interim Report on Beach Conservation." Advisory Panel on Tsunami-Resistant Communities and Beach Conservation, 9p. https://www.mlit.go.jp/river/shinngikai_blog/tsunamiKondankai/sunahamahonbun.pdf. (in Japanese)

Ministry of Land, Infrastructure, Transport and Tourism. 2020. Coastal Conservation in Response to Climate Change. Investigative Committee for Coastal Conservation in Response to Climate Change. 20. (in Japanese) https://www.mlit.go.jp/river/shinngikai_blog/hozen/index.html.

Ministry of Land, Infrastructure, Transport and Tourism, Coastal Global Warming Adaptation Strategy Review Committee. 2011. "Global Warming Adaptation Review Manual for Renewal of Coastal Protection Facilities (Draft)." (in Japanese) https://www.mlit.go.jp/common/000188326.pdf .

Ministry of Land, Infrastructure, Transport and Tourism, Water Management and Land Conservation Bureau, Coast Office. 2021. "." in Japanese. https://www.mlit.go.jp/river/toukei_chousa/kaigan/pdf/20220418.pdf .

Mizuta, R., A. Murata, M. Ishii, H. Shiogama, K. Hibino, N. Mori, O. Arakawa, et al. 2017. "Over 5,000 Years of Ensemble Future Climate Simulations by 60-Km Global and 20-Km Regional Atmospheric Models." *Bulletin of the American Meteorological Society* 98 (7): 1383–1398. https://doi.org/10.1175/BAMS-D-16-0099.1.

Mori, N., N. Fukui, and T. Shimura. 2020. "A Review Of Maximum Storm Surge Heights in Japanese Three Major Bays Considering Climate Change." *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 76 (1): 1–6. in Japanese. https://doi.org/10.2208/kaigan.76.1_1

Mori, N., S. Nakajo, S. Iwamura, and Y. Shibutani. 2018. "Projection of Decrease in Japanese Beaches Due to Climate Change Using a Geographic Database." *Coastal Engineering Journal* 60 (2): 239–246. https://doi.org/10.1080/21664250.2018.1488513.

Mori, N., T. Takahashi, and the 2011 Tohoku Earthquake Tsunami Joint Survey Group. 2012. "Nationwide Post Event Survey and Analysis of the 2011 Tohoku Earthquake Tsunami." *Coastal Engineering Journal* 54 (1): 1250001-1-1250001–27. https://doi.org/10.1142/S0578563412500015.

Mori, N., T. Yasuda, T. Arikawa, T. Kataoka, S. Nakajo, K. Suzuki, Y. Yamanaka, and A. Webb. 2019. "2018 Typhoon Jebi Post-Event Survey of Coastal Damage in the Kansai Region, Japan." *Coastal Engineering Journal* 61 (3): 278–294. https://doi.org/10.1080/21664250.2019.1619253.

Myers, V. A. 1954. Characteristics of United States Hurricanes Pertinent to Levee Design for Lake Okeechobee, Florida. Hydrometeorological Report No. 32, US Weather Bureau, USA

National Institute of Population and Social Security Research. "Population Projections for Japan (2017 Estimates)." (in Japanese) Accessed June 22, 2022. https://www.ipss.go.jp/pp-zenkoku/j/zenkoku2017/pp29_gaiyou.pdf.

Ninomiya, J., N. Mori, T. Takemi, and O. Arakawa. 2016. "Impact Assessment of Future Storm Surge Due to Typhoon Vera as Revealed by Pseudo-Global Warming experiments." *Journal of Japan Society of Civil Engineers, Ser B2 (Coastal Engineering)* 72 (2): I__1501–I__1506. in Japanese. https://doi.org/10.2208/kaigan.72.I_1501.

North Carolina Department of Environmental Quality. 2022. "Oceanfront Construction Setback & Erosion Rates." Accessed 17 November 2022. https://deq.nc.gov/about/divisions/coastal-management/coastal-management-oceanfront-shorelines/oceanfront-construction-setback-erosion-rate#:~:text=As%20specified%20in%20Rule%2015A,default%20setback%20factor%20is%202.

Oppenheimer, M., B. C. Glavovic, J. Hinkel, R. van de Wal, A. K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R. M. DeConto, T. Ghosh, et al. 2019. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O.]*, edited by D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, and A. Alegriía, 321–445. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157964.006

Osaka Prefectural Council for River Structures. 2021. Matters Concerning the Reconstruction of the Three Major Floodgates (Report). 7. (in Japanese) https://www.pref.osaka.lg.jp/kasenkankyo/kasenkouzoubutu/kikouhendou_shingi.html.

Sato, S. 2015. "Characteristics of the 2011 Tohoku Tsunami and Introduction of Two Level Tsunamis for Tsunami Disaster Mitigation." *Proceedings of the Japan Academy, Series B* 91 (6): 262–272. https://doi.org/10.2183/pjab.91.262.

Shibutani, Y., Y. Matsubara, and M. Kuroiwa. 2013. "Effect of the Coastal Conservation Due to Beach Nourishment of Tottori Sand Dune Coast" In Proc. of the Int. Conf. on Asian and Pacific Coasts, Bali, Indonesia, 78–84.

Shimozono, T., Y. Tajima, K. Kumagai, T. Arikawa, Y. Oda, Y. Shigihara, N. Mori, and T. Suzuki. 2020. "Coastal Impacts of Super Typhoon Hagibis on Greater Tokyo and Shizuoka Areas, Japan." *Coastal Engineering Journal* 62 (2): 129–145. https://doi.org/10.1080/21664250.2020.1744212.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X. Huang, W. Wang, and J. G. Powers. 2008. "A Description of the Advanced Research WRF Version 3." *NCAR Tech* 113. Note NCAR/TN-475+STR. https://doi.org/10.5065/D68S4MVH

Suda, Y. 2017. *Nature and Conservation of Sandy Shores, Introduction to Sandy Beach Ecology*, 1–22. Seibutsukenkyusha. (in Japanese).

Suppasri, A., P. Latcharote, J. D. Bricker, N. Leelawat, A. Hayashi, K. Yamashita, F. Makinoshima, V. Roeber, and F. Imamura. 2016. "Improvement of Tsunami Countermeasures Based on Lessons from the 2011 Great East Japan Earthquake and Tsunami — Situation After Five Years." *Coastal Engineering Journal* 58 (4): 1640011-1-1640011–30. https://doi.org/10.1142/S0578563416400118.

Suzuki, T., Y. Tajima, M. Watanabe, N. Tsuruta, H. Takagi, T. Takabatake, K. Suzuki, et al. 2020. "Post-Event Survey of Locally Concentrated Disaster Due to 2019 Typhoon Faxai Along the Western Shore of Tokyo Bay, Japan." *Coastal Engineering Journal* 62 (2): 146–158. https://doi.org/10.1080/21664250.2020.1738620.

Takeshita, T., F. Kato, N. Fukuhara, T. Igarashi, T. Koizumi, and T. Uda. 2018. "Experiment on Coastal Dike Resiliency Against Unexpected Wave Overtopping." In Proceedings of the 28th International Ocean and Polar Engineering Conference, ISOPE-I-18-454, Sapporo, Japan, 1490–1497.

Tanaka, S., M. Koarai, and M. Fukazawa. 1993. "Shoreline Change of Japan Based on Topographic Maps." *Proceedings of the Coastal Engineering Japan* 40:416–420. in Japanese. https://doi.org/10.2208/proce1989.40.416.

Tanaka, N., S. Yasuda, K. Iimura, and J. Yagisawa. 2014. "Combined Effects of Coastal Forest and Sea Embankment on Reducing the Washout Region of Houses in the Great East Japan Tsunami." *Journal of Hydro-Environment Research* 8 (3): 270–280. https://doi.org/10.1016/j.jher.2013.10.001.

Tokyo Metropolitan Government. 2023. "Basic Plan for Coastal Protection of Tokyo Bay (Tokyo Section)." (in Japanese) https://www.kouwan.metro.tokyo.lg.jp/jigyo/tokyowanengan_kaiganhozen_tokyo_honpen_R4d.pdf .

Uda, T. 2010. "Japan's Beach Erosion." *Advanced Series on Ocean Engineering* 31:418. https://doi.org/10.1142/7332.

Uda, T., M. Sumiya, and H. Sakuramoto. 1988. "Stabilization of Coast by Construction of Headlands on the Kashimanada Coast, Japan." *Proceedings International Conference on Coastal Engineering* 1 (21): 2791–2805. https://doi.org/10.9753/icce.v21.207.

Udo, K., and Y. Takeda. 2017. "Projections of Future Beach Loss in Japan Due to Sea Level Rise and Uncertainties in Projected Beach Loss." *Coastal Engineering Journal* 59 (2): 1740006-1-1740006–16. https://doi.org/10.1142/S057856341740006X.

Udo, K., Y. Takeda, and H. Tanaka. 2016. "Coastal Morphology Change Before and After 2011 off the Pacific Coast of Tohoku Earthquake Tsunami at Rikuzen-Takata Coast." *Coastal Engineering Journal* 58 (4): 1640016-1-1640016–16. https://doi.org/10.1142/S0578563416400167.

Umeda, J., S. Nakajo, and N. Mori. 2019. "Development of Global Stochastic Tropical Cyclone Model by Using Large Ensemble GCM Simulation data(d4PDF)." *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 75 (2): I__1195–I__1200. in Japanese. https://doi.org/10.2208/kaigan.75.I_1195

Watanabe, K., F. Kato, Y. Suwa, and K. Yamada. 2022. "Shoreline Change Monitoring Using a Topographic Map." *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 78 (2): I__571–I__576. in Japanese. https://doi.org/10.2208/kaigan.78.2_I_571

Watanabe, K., H. Kusaka, T. Inada, and Y. Suwa. 2014. "Field Study on Coastal Vegetation Establishment on New Beach Formed by Setback Dike." *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 70 (2): I__1026–I__1031. in Japanese. https://doi.org/10.2208/jscejoe.70.I_1026

Yajima, M., A. Uezono, T. Yauchi, and F. Yamada. 1983. "Application of Sand Bypassing to Amano-Hashidate Beach." *Coastal Engineering in Japan* 26 (1): 151–162. https://doi.org/10.1080/05785634.1983.11924365.

Yamamoto, Y., M. Mori, and M. Kjerland. 2018. "Development of Bias Correction Method for Tropical Cyclones in Global Climate Model and Future Change Projection of Storm Surge Using AMR Model." *Journal of Japan Society of Civil Engineers Ser B2 (Coastal Engineering)* 74 (2): I__607–I__612. in Japanese. https://doi.org/10.2208/kaigan.74.I_607

Yamanaka, Y., and T. Shimozono. 2022. "Tsunami Inundation Characteristics Along the Japan Sea Coastline: Effect of Dunes, Breakwaters, and Rivers." *Earth Planets and Space* 74 (19). https://doi.org/10.1186/s40623-022-01579-5.

Yamashita, K., D. Sugawara, T. Takahashi, F. Imamura, Y. Saito, Y. Imato, T. Kai, et al. 2016. "Numerical Simulations of Large-Scale Sediment Transport Caused by the 2011 Tohoku Earthquake Tsunami in Hirota Bay, Southern Sanriku Coast." *Coastal Engineering Journal* 58 (4): 1640015-1-1640015–28. https://doi.org/10.1142/S0578563416400155.

Yasui, M., and K. Yabunaka. 2002. "A Transition of Land reclamation policy in Japan." *Proceedings of Civil Engineering in the Oceans* 18:119–124. in Japanese. https://doi.org/10.2208/prooe.18.119.