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Research article

Adaptation strategies for future coastal flooding: Performance evaluation of green and grey infrastructure in South Korea

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ABSTRACT

Climate change is contributing to an increasing frequency and intensity of floods in Korea. This study predicts areas with a high probability of flooding in coastal areas of South Korea owing to future climate change, which is likely to cause extreme rainfall and sea-level rise, using a spatiotemporal downscaled future climate change scenario with random forest, artificial neural network, and k-nearest neighbor techniques. In addition, the change in coastal flooding risk probability according to the application of different adaptation strategies (green spaces and seawalls) was identified. The results showed a clear difference in the risk probability distribution in the absence and presence of either adaptation strategy. Their effectiveness in moderating future flooding risks is subject to change owing to strategy type, geographic region, and urbanization intensity and the results show that green spaces are slightly more effective than seawalls when forecasting for 2050. This demonstrates the importance of a nature-based strategy. Moreover, this study highlights the need to prepare adaptation measures according to regional characteristics to mitigate the impact of climate change. Korea is surrounded by seas on three sides that have independent geophysical and climate characteristics. The south coast has a higher risk of coastal flooding than the east and west coasts. In addition, a higher urbanization rate is associated with a higher risk probability. This implies that climate change response strategies for coastal cities are necessary as the population and socioeconomic activities of coastal urban areas are likely to increase in the future.

1. Introduction

Climate change is one of the most dangerous environmental problems that humans face at present and poses profound global and regional impacts. Climate change contributes to an increase in the frequency and intensity of extreme drought, heavy rain, and heat waves (IPCC et al., 2022). Floods caused by heavy rains and abnormal climates cause substantial damage to various regions around the world. (Merz et al., 2021). It is expected that more than a billion people will live in low-lying coastal areas by 2060 (Neumann et al., 2015). Coastal areas with a high concentration of economic activity are particularly at risk of extreme weather events owing to climate change, as they are exposed to cyclones, tsunamis, afnd other coastal hazards. (Ferreira et al., 2019; Kron, 2013; Reguero et al., 2015, 2020). The global sea level is currently rising by 3–4 mm per year because of ocean warming and land ice melting and is projected to rise by 0.3–2.0 m by 2100 (Watson et al., 2015; Yi et al., 2015). Therefore, the damage to coastal areas will likely be even more severe in the future because of the combined risk effects of climate change, including heavy rain and sea-level rise (Barnard et al., 2015; Caldwell et al., 2009; Church et al., 2013; Rendón et al., 2022; Vitousek et al., 2017). Korea is a peninsula surrounded by the sea on three sides, with many large cities being in coastal areas. Approximately 27.5% of the total population of Korea lives in coastal areas (Oh et al., 2020) and 1.3 million people are forecasted to experience coastal flooding by 2050, and further exposed to Pacific typhoons (Kulp and Strauss, 2019). The cost of damage to property caused by Typhoon Maemi (2003) and Rusa (2002) was $6.6 billion and $5.3 billion, respectively (Ministry of Public Safety and Security, 2015). Without an appropriate response to coastal flooding, increasing property loss and fatalities are inevitable.

The steps for responding to disaster events, such as coastal flooding, can be divided into three major parts (Reguero et al., 2018): 1) identifying areas vulnerable to hazards, 2) predicting how much damage will be caused by the risk, and 3) taking appropriate measures to reduce the

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risk and damage. Given the first and second parts, finding high-risk areas and predicting actual damage is an important process for appropriately distributing the finite resources that are necessary for disaster response. All three processes are integral, but the last step must consider the efficacy of different strategies. The best possible coastal management measures considering cost and effectiveness will be essential in the future to optimally use limited resources (Jongman, 2018; Ferreira et al., 2019). These efforts can proactively facilitate risk mitigation before a disaster (FEMA, 2018; Reguero et al., 2020).

Past studies have investigated the effectiveness of measures and strategies to reduce the risk of coastal flooding. Reguero et al. (2018) quantitatively evaluated the cost-effectiveness of natural-based solutions (NBS) and structural techniques by comparing the effects of reducing the risk of coastal flooding in the Gulf Coast region at the county level. They found that applying NBS has a risk-reduction effect of 3.5 times compared to the investment. Ferreira et al. (2019) used a numerical model to compare the performance of beach nourishment with shelter removal and movement for reducing the impact of storms in 55-km coastal areas. It was found that using both options together or nourishment alone could avoid almost all observed effects. Vousdoukas et al. (2020) considered composite events with respect to climate and developed analytical tools to optimize adaptation strategies (ASs) and assess their impacts during the present century. They revealed that the use of dykes could reduce the economic effect of European flood damage by 23.7–32.1%. Tiggeloven et al. (2020) proposed a framework that considered different flood risk factors to assess the future benefits and costs of structural protection measures related to coastal flooding on a global scale at the country level. The benefits of the application of dykes were calculated according to four objectives, including maintaining the current protection level, and all showed positive effects. Creach et al. (2020) compared the implementation cost and efficiency of different housing ASs when exposed to flood risk to mitigate the level of risk in La Guérinière, France. Relocation reduced the risk by 100%, but was expensive while protection (dykes and seawall) reduced risk by 26–46% with an investment of 3.8 billion €. Therefore, numerous studies have been conducted to compare and evaluate the effectiveness of strategies for mitigating and reducing the risk of coastal flooding, although with different spatiotemporal extents. However, previous studies often did not consider spatiotemporal downscaled analysis. A study of the smallest spatial units was carried out by Reguero et al. (2018) at the county level. Additionally, a predictive study using future climate change scenarios (Tiggeloven et al., 2020) at the country level did not consider downscaled spatial range. The impact of and vulnerability to climate change may vary owing to the spatiotemporal characteristics of nations, under both current and future climate conditions (IPCC et al., 2007; 2014, 2022). It is thus necessary to consider spatiotemporal downscaled analysis to compare and evaluate the effectiveness of ASs in mitigating the risk of coastal flooding.

Therefore, this study aimed to explore the risk of coastal flooding driven by heavy rain and sea-level rise through detailed spatial and temporal modeling. To answer the question of how ASs for coastal flooding will be effective in the face of climate change, we examined the effects of green space and seawalls according to the geographic locations and urbanization intensities of cities along the South Korean shorelines.

To achieve the first goal, risk was defined as the possibility of coastal flooding and calculated by multiple machine learning techniques using large-scale spatial data modeling. Grey infrastructure such as seawalls and levees, which have historically been constructed to reduce the risk of coastal flooding, are expensive and have already been pointed out as limitations in terms of sustainability (Jones et al., 2012; Kitha and Lyth, 2011). As an alternative, experts suggest NBSs as eco-friendly strategies. Many studies related to the effectiveness of NBSs are being conducted, but more research on various NBS approaches is needed (Kumar et al., 2021). This study therefore selected seawalls, represented by concrete artifacts, and green space, which can be called a part of NBS (Ruangpan et al., 2019), to compare the effect of reducing the risk of coastal flooding. The projected long-term precipitation trajectories for Representative Concentration Pathway (RCP), developed by the Intergovernmental Panel on Climate Change (IPCC), were used to consider the impacts of climate change. To compare the performance of the two ASs, two adaptation pathways were developed and their risk reduction effects according to the degree of application were compared.

2. Materials and method

2.1. Study area

The study sites included the coastal areas of South Korea (33–38 °N, 125–131 °E). Following the "coastal management law" in the country, the spatial scope of this study was set to a 1 km inland buffer area from the coastline at a resolution of 250 m. The total length of the coastline of South Korea is 14,962.8 km and Fig. 1 shows the locations of 68 weather stations and 46 tide stations in the nation.

For the past 106 years (1912–2017), the average annual temperature in South Korea has been 13.2 °C and the annual precipitation has been 1237.4 mm (National Institute of Meteorological Science, 2018). In general, summer precipitation (June–August) is 710.9 mm, accounting for 54% of the annual precipitation. In addition, South Korea, which is exposed to Typoons at the end of summer, which are powerful storms caused by strong low pressure. Typoon Maemi (2003), which caused the most damage on record in the past 30 years, caused severe damage to 11 quay cranes and flooded container yards, rendering the port inoperable for three months (Lam et al., 2017). Also, over the past 30 years, the amount of precipitation during summer has increased by an average of 0.11 mm per year. The frequency and intensity of extreme rainfall on the Korean Peninsula have also been gradually increasing since the mid-1990s (Korea Meteorological Administration, 2020).

2.2. Data

To analyze the risk of coastal flooding, a total of six variables, including the flood trace map, were used with reference to Park and Lee (2020) (see Table 1). These variables have diverse data types and resolutions and were refined to match a resolution of 250 m. In cases of point data such as precipitation, the data was converted into grid-type data after interpolating it according to the coastal area. In addition, because traces of flooding existed from 2003 to 2018 and the associated climatic and environmental conditions on the days when flooding occurred were different for each event, a refinement process was performed to match the event-based time-series data. For example, in the case of flooding that occurred on September 1, 2003, the daily maximum precipitation and mean tide data for that date were coordinated. Thus, all data was converted into grid-type data and used to analyze coastal flooding risk using machine learning techniques.

2.3. Comparison of machine learning (ML) techniques and coastal flooding risk analysis

As shown in Fig. 2, to predict coastal flooding potentials, the undersampled dataset was divided into training (70%) and test (30%) sets and analyzed using three different machine learning (ML) techniques: k-nearest neighbor (kNN), random forest (RF), and artificial neural network (ANN). The reason for under-sampling is that coastal flooding trace data were imbalanced, with more non-occurrence than occurrence. Through more than 5000 iterations of training per technique, the average performance obtained for the techniques was compared. The performance of the techniques was evaluated by comparing the area under the receiver operating characteristic (ROC) curve (AUC), which is typically used to evaluate the performance of machine learning models (Huang and Ling, 2005). Coastal flood risk was then analyzed using the technique that presented the best performance. The probability results ranged from 0 to 1, with a higher probability value indicating a higher

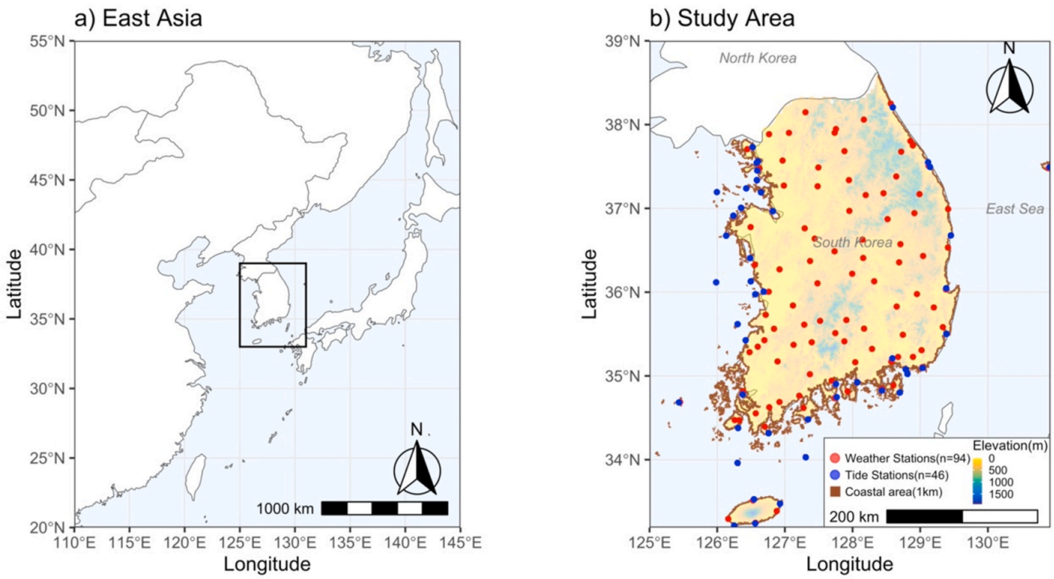

Fig. 1. (a) Countries in East Asia, (b) South Korea, and the study area (coastal area: 1 km from the coastline, resolution: 0.25 km, and geodetic datum: WGS84). Adapted from "Prediction of coastal flooding risk under climate change impacts in South Korea using machine learning algorithms" by Park and Lee (2020).

Table 1
Characteristics of the data used to analyze the risk of coastal flooding.

Category	Variable (unit)	Period	Data Type	Source
Marine	Mean Tide (mm)	2003–2018	Point	[a]KHOA
Meteorological	Daily Maximum Precipitation (mm)			[b]KMA
Geophysical	Elevation (m)	2010	Grid (250 m)	[c]ME
	Slope (°)			
	Urban Area (%)	2000, 2009	Polygon	
Coastal Flood Trace		2003–2018	Polygon	[d]LX
Adaptation Strategies	Seawall (m)	2020	Polyline	
	Green Space (%)	2013	Polygon	[c]ME

[a] KHOA: Korea Hydrographic and Oceanographic Agency (http://www.khoa.go.kr).
[b] KMA: Korea Meteorological Administration (https://www.weather.go.kr).
[c] ME: Ministry of Environment (http://me.go.kr).
[d] LX: Korea Land and Geospatial Informatrix Corporation (https://www.lx.or.kr).

risk of flooding.

kNN, proposed by Cover and Hart (1967), is a supervised learning ML algorithm that is simple and easy to implement. The setting of the k value that indicates proximity has a significant influence on the results of the algorithm (Bhavsar and Ganatra, 2012; Kim et al., 2012). The RF algorithm, described by Breiman (2001), is an ensemble learning method that constructs and operates several decision trees during the training period and is widely used in research along with ML techniques that use neural networks. ANNs are computational models inspired by the human brain (Yang, 2008). ANNs are used to model complex relationships between input and output information through a network of interconnected nodes to find patterns in the data. (Potdar and Kinnerkar, 2016).

2.4. Evaluation of coastal flooding risk with ASs

Using the ML technique that showed the highest performance, the effect of reducing the risk probability was computed under AS scenarios. As shown in Table 1, the seawall, representing the grey infrastructure installed to protect coastal areas, and the green space, representing the green infrastructure as well as can be called a part of NBS (Ruangpan et al., 2019), were compared. Green space and seawalls play an important role in protection against coastal flooding (Dong et al., 2020; Jeong et al., 2021). In this study, green space included artificially created and developed grasslands including city parks, open lawns, and waterside buffers. In previous studies, green infrastructure was found to be effective at reducing runoff by 3–47%. (Ahiablame and Shakya, 2016; Arjenaki et al., 2021; Li et al., 2021; Zhang et al., 2012). Therefore, the same reduction range was applied in this study to predict the potential of green spaces to mitigate surface flooding. Meanwhile, in the case of the seawalls, which are mainly installed along the coastline and serve to protect the land, seawalls were used to raise coastal elevation, and the associated slope was calculated and updated in the prediction model.

2.5. Potential coastal flooding risk depending on different adaptive pathways

Among the variables used in the analysis, daily maximum precipitation and mean tide are time-variant factors; therefore, future values were projected based on carbon emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). Using their fifth assessment report's RCP 8.5, which represents the "business as usual" scenario with a high-energy demand, a long-term precipitation trajectory was predicted by the middle of the century. We used five regional climate models (RCMs) provided by the Regional Climate Detailing Project in East Asia (CORDEX-EA: Coordinated Regional Downscaling Experiment, East Asia; source: http://cordex-ea.climate.go.kr/cordex): CCLM, HadGEM3-RA, RegCM4, SNU-RCM, and WRF. Ensemble methods using multiple climate models allow researchers to consider the uncertainty of different models (Parker, 2013). Time-series tide data from 46 stations located along the coast of Korea were used. As the observed mean value approximates a sine distribution, a Bayesian-influenced generalized additive model (GAM) was used to predict the future value for each station. The longitudinal data were then spatially interpolated onto the grid block for the input of the prediction model. The model was used to calculate the potential coastal flooding risk by extracting the space corresponding to the study site from interpolated data (see Fig. 2). In this study, we analyzed the potential coastal flooding risk probability, setting the year 2050 as the target. We selected 2050 because this is the year of the global target to achieve "net zero," meaning that net carbon emissions should be zero (IPCC et al., 2018).

Under the forecasted future climate conditions, two adaptive pathways were developed based on the flood mitigation techniques adopted

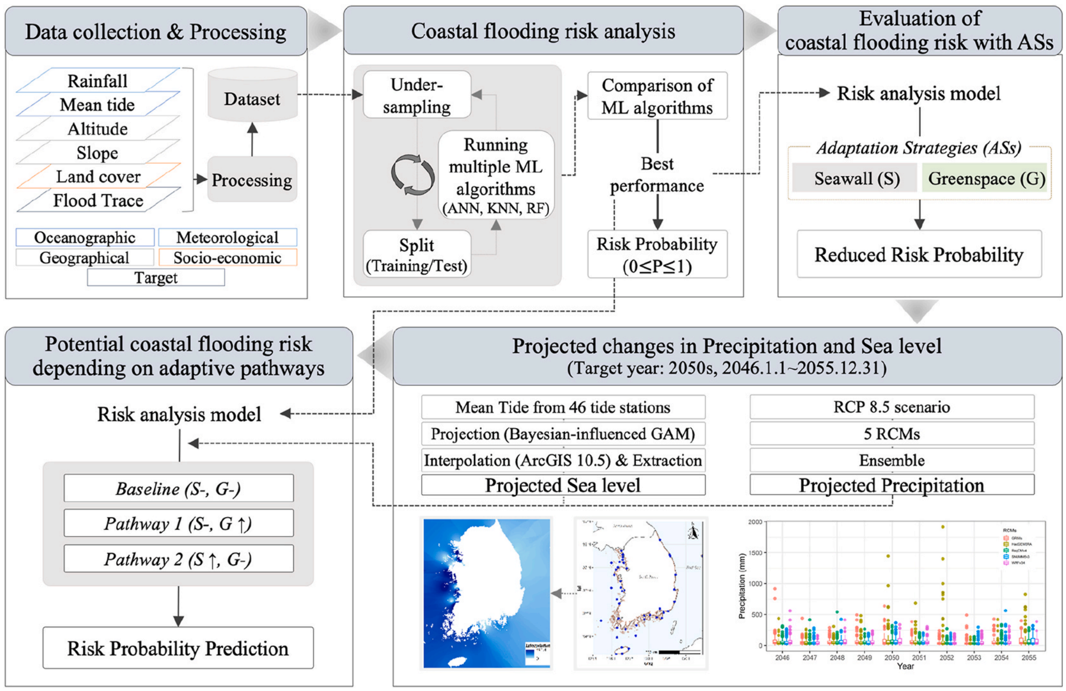

Fig. 2. Research flow consists of five processes: 1) data acquisition and processing, 2) risk analysis for coastal flooding using machine learning models, 3) evaluation of coastal flooding risk with adaptation strategies, 4) identification of projected precipitation and prediction of sea level, 5) potential coastal flooding depending on adaptive pathways.

and multiple scenarios were formulated for each pathway according to the intensity of application (see Table 2). The baseline pathway maintained the current level of ASs with no additional implementation. Pathway 1 hypothesized that green spaces were applied to 5–25% of the entire study area at 5% increments on a cell basis. At this time, the amount of green space increased on a cell-based means land that can be urbanized due to future development of land use in that cell. Pathway 2 applied seawalls with heights ranging from 1.5 to 7.5 m at 1.5 m increments. These application levels were determined using the standard construction cost per unit area for each technique. Regarding green space, the standard cost was 73,000 ₩ ($66.4 US dollars) per 1 m^2 according to the "national land planning and utilization act" in South Korea. For seawall, the cost was 500€ ($550 US dollars) per 1 m in height and length (Creach et al., 2020). In other words, 1% of the area of green space equated to 625 m^2 (considering the resolution of the analysis), with corresponding construction costs of $41,500. With the same amount of money, a seawall with a length of approximately 75 m and height of 1 m (=$41,500/$550) can be built. Thus, the construction costs of 75 m × 1 m (length × height) of seawall were equivalent to those for a 250 m × 0.3 m seawall in a unit cell. That is, a 1% increase in green space corresponded to a 0.3 m increase in seawall height (i.e., 5% is equal to 1.5 m of seawall).

Table 2
Pathways according to the degree of application of adaptation strategy (Target of the period: RCP 8.5, 2050s).

Adaptive Pathways	Application of adaptation strategy	Degrees of application				
Baseline	No adaptation	–				
Pathway 1	Greenspace	5%	10%	15%	20%	25%
Pathway 2	Seawall	1.5 m	3 m	4.5 m	6 m	7.5 m

3. Results

3.1. Performances of ML algorithms

According to the results obtained through approximately 5000 runs using three different ML algorithms, the RF model performed the best, with an average AUC of 0.976, followed by kNN (0.938) and ANN (0.896) (Fig. 3a). Although the differences were not significant, the dispersion of AUC was the lowest when RF was used, implying that RF was the most stable model. Fig. 3b shows the ROC curve plot obtained using RF. The ROC curve is suitable to indicate the reliability of the model, and a more curvilinear shape towards the left or top indicates a higher reliability of the model.

3.2. Coastal flooding risk with ASs

The current level of coastal flood risk was probability calculated using the best-performing algorithm, RF, and the change in risk probability was analyzed when two spatially distributed ASs were applied (Fig. 4). The average risk probability was 0.117 in the absence of ASs. When green spaces and seawalls were applied at the current level, the average risk probabilities were 0.066 and 0.056, respectively. Finally, when both were applied together, the average risk probability was 0.051. There was no significant difference in the average risk probability between the two strategies, applied separately or together.

Despite the insignificant reduction rates of the strategies applied, the spatial analysis demonstrated their varying performances by geographic location. Fig. 5 a, b, and c show the mapping results of the coastal flood risk probability when AS was not applied (a), when AS was applied (b), and when the risk probability was reduced by more than 0.9 (c). The blue dots in Fig. 5 c represent the points where coastal flooding occurred, as shown in Table 1. Although the average reduction in risk probability may seem low for the entire considered area (below 1%), regions disproportionally benefitted from AS; areas where the actual flood occurred particularly experienced a greater reduction in risk probability than other areas. Thus, it is important to use an adaptation

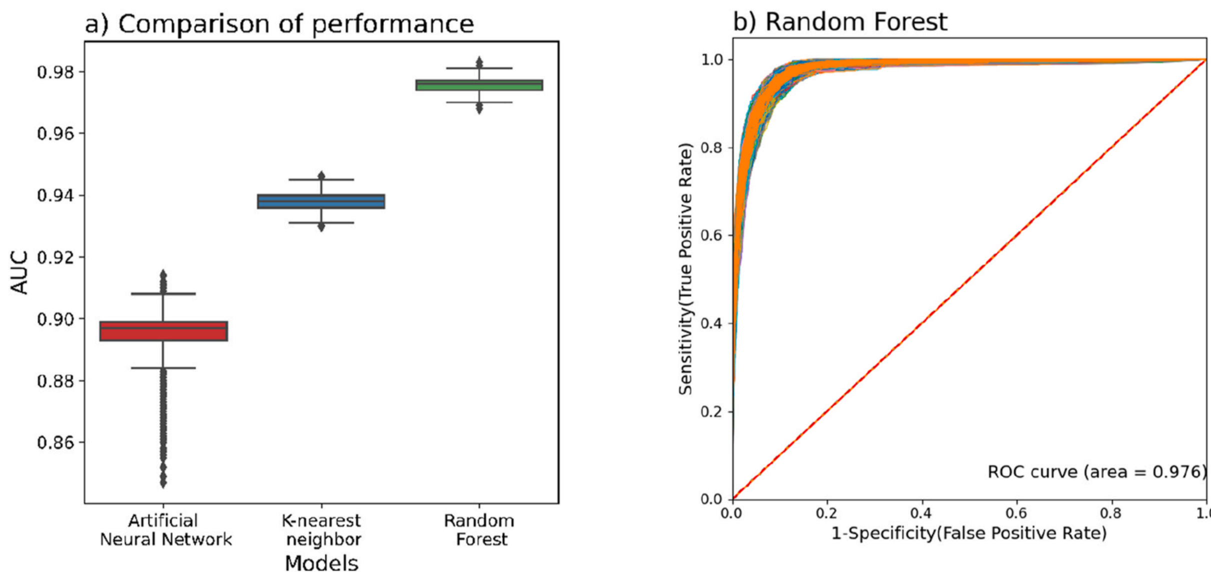

Fig. 3. Comparison of machine learning algorithms' performances. (a) Comparison of performances among three machine learning techniques. (b) Receiver operating characteristic curve plot using random forest.

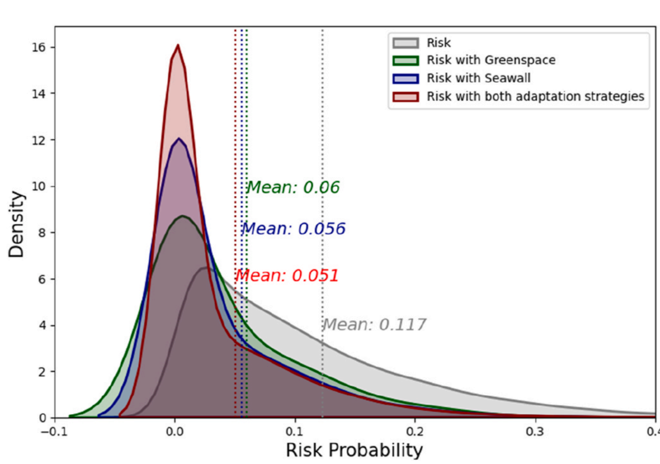

Fig. 4. Comparison of coastal flooding risk probability with respect to adaptation strategies.

strategy to reduce coastal flooding risk.

3.3. Potential coastal flooding risk according to different adaptive pathways

As shown in Fig. 6, the results of applying varying intensities of ASs in the two pathways revealed that green spaces generally have a better reduction effect than seawalls. The effect of green spaces improved slightly as the coverage area increased, and the effect was noticeable when it was expanded from 5% to 10%. However, for seawalls, the average risk probability did not change significantly when the height was increased, even though the frequency of high extreme values tended to gradually decrease. Ultimately, seawalls were less effective than green space, but they reduced the degree of risk to some extent for high-risk areas.

Nevertheless, seawalls can be an effective and economical structural strategy that are primarily considered for reducing the risk of coastal disasters (Duvat, 2013) and can be used in combination with green infrastructure, such as manmade green spaces, when federal and local budgets are restrained. A prioritized approach should be taken, implementing green spaces in the most vulnerable areas while applying seawalls as supplemental systems in moderate- or low-risk areas.

Next, to identify the spatial differences in risk probability, the spatial distribution according to the AS application scenario, targeting 2050, was compared for five different RCMs within the RCP 8.5 climate change scenario to determine the probability of potential coastal flood risk (Fig. 7). When no ASs were applied until 2050, HadGEM3RA and GRIMs showed a higher coastal flooding risk than the other three RCMs. This is because the result of the projected precipitation slightly differed according to the difference in the statistical techniques with which the RCMs are created (Déqué, 2007). Therefore, to consider the uncertainty of each model, the results of various models were assembled and the combined results were compared. As shown in Fig. 6, considering the ensemble of baseline, pathways 1, and 2, green space (25%) application showed a greatly reduced risk spatial distribution than seawall (7.5 m) application.

4. Discussion

4.1. Effect of AS according to spatial characteristics

Considering that the general opinion in climate change research is that the impact and vulnerability of climate change can vary greatly depending on the regional characteristics of climate change adaptation (IPCC et al., 2007; 2014, 2022), it is important to identify the differences in risk and vulnerability according to spatial characteristics. Therefore, a comparison of risk probabilities according to geographic and environmental differences was conducted to determine the differences in the application of ASs.

4.1.1. Differences in risk according to coastal geographical characteristics

In the case of South Korea, a peninsula-shaped country, the geographical characteristics of the east, west, and south coasts differ. The east coast has a monotonous coastline with a deep-water depth, while the west coast has substantial difference in tides owing to the low land and water depth. On the southern coast, there are numerous large and small islands with complex coastlines (Park and Lee, 2020). which respond differently to flooding (see Fig. 8). When AS was not applied, the risk probability of the southern coastal region was found to be the highest, on average. The probability between the 25th and 75th percentiles ranged from 0.09 to 0.25, a wider distribution than that for the other coasts. The southern coastline is characterized by an irregular

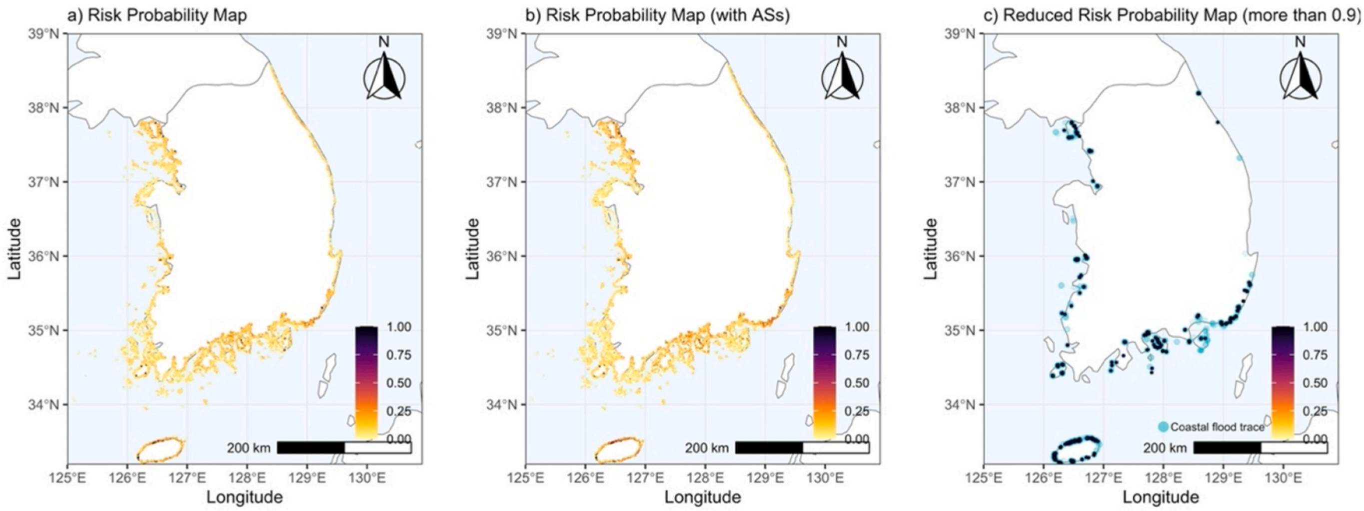

Fig. 5. Spatial comparison of coastal flooding risk probability with respect to adaptation strategies. Risk probability maps (a) without adaptation strategies, (b) with both adaptation strategies (seawall and green space), and (c) when probability was reduced by more than 0.9 (blue dots represent areas where coastal flooding occurred from 2003 to 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

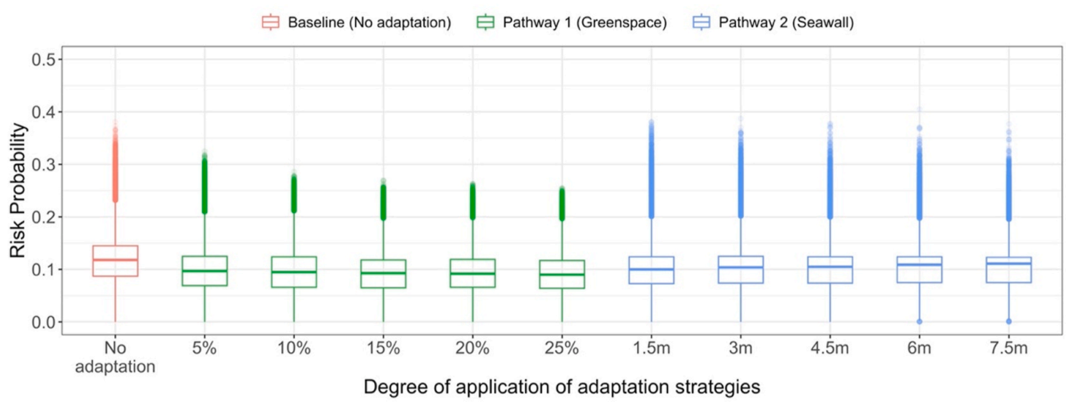

Fig. 6. Coastal flooding risk probability according to the degree of application of each adaptation strategy in the three adaptive pathways (RCP 8.5 climate change scenario targeting 2050).

pattern of low-lying lands and a high density of islands (see Fig. 8a). The region is the most vulnerable to flooding when tropical storms pass over the south coast during the typhoon season and reach landfall from June to September. However, when two ASs (green space and seawall) were applied, the probability decreased, with comparable interquartile ranges across the three regions. It is important to note that the high extremes of risk probability significantly reduced on applying ASs, demonstrating their importance.

4.1.2. Differences in risk by urbanization rate

Fig. 9 shows the change in the distribution of risk probability according to the urbanization ratio and AS type. Except for regions where the urban area ratio was less than 20%, the risk probability increased with the urban area ratio regardless of whether an AS was applied. It should be noted that when AS was not applied, the risk probability increased substantially as the urban area increased. On average, the risk probability for areas with more than 80% urbanization was 2.5 times greater than that for areas with 0–20% urbanization. This increase can be attenuated by the application of ASs. Comparatively, when comparing the risk probabilities depending on whether two ASs were applied, if only one was applied, green spaces had a greater mitigation effect than seawalls. Importantly, when these two techniques were applied together, the reduction effect increased as the ratio of the urban area increased; the slope of the baseline scenario (red) was steeper than that of the combined strategy (purple), and the difference between them increased as urbanization increased. This indicates the importance of investment in ASs in highly urbanized areas.

In summary, Fig. 9 implies that the risk in urban areas with high population density and socioeconomic activity may increase in the future. These results are consistent with the findings of other studies (Joo and Kim, 2021) and support the conclusion that South Korea needs to prepare for risks such as coastal flooding because many large urban infrastructures such as roads, power plants, and ports are located along the coast (Yum et al. al., 2021). Indeed, according to the forecast that more than one billion people will live in low-lying coastal zones by 2050 (IPCC, 2019), it is imperative to prepare for this.

4.2. Importance of nature-based solutions as ASs

To respond to the climate crisis, efforts by the international community to achieve carbon neutrality to not exceed a global temperature increase of 2 °C are being accelerated. However, despite the aim to achieve a carbon-neutral society, the increasing frequency and intensity of natural disasters due to rising global temperatures driven by emitted and accumulated carbon will continue and efforts must be made to adapt and respond to these. Therefore, climate change ASs are as important as reducing and absorbing carbon emissions.

NBSs have been emphasized for achieving goals in international

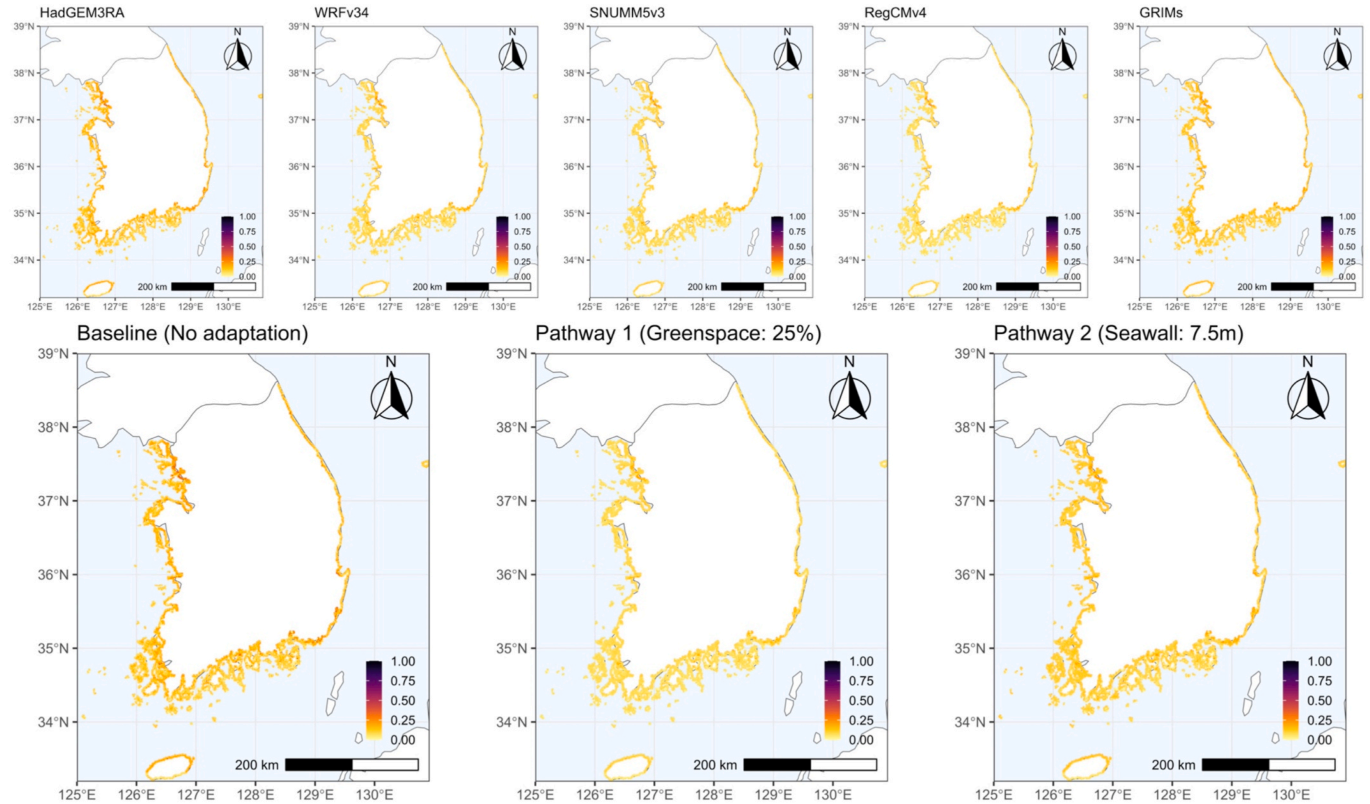

Fig. 7. Spatial distribution of coastal flooding risk probability using five different RCMs within the RCP 8.5 climate change scenario targeting 2050. Top: comparison of five RCMs without adaptation strategy. Bottom: comparison of ensemble with each adaptation strategy.

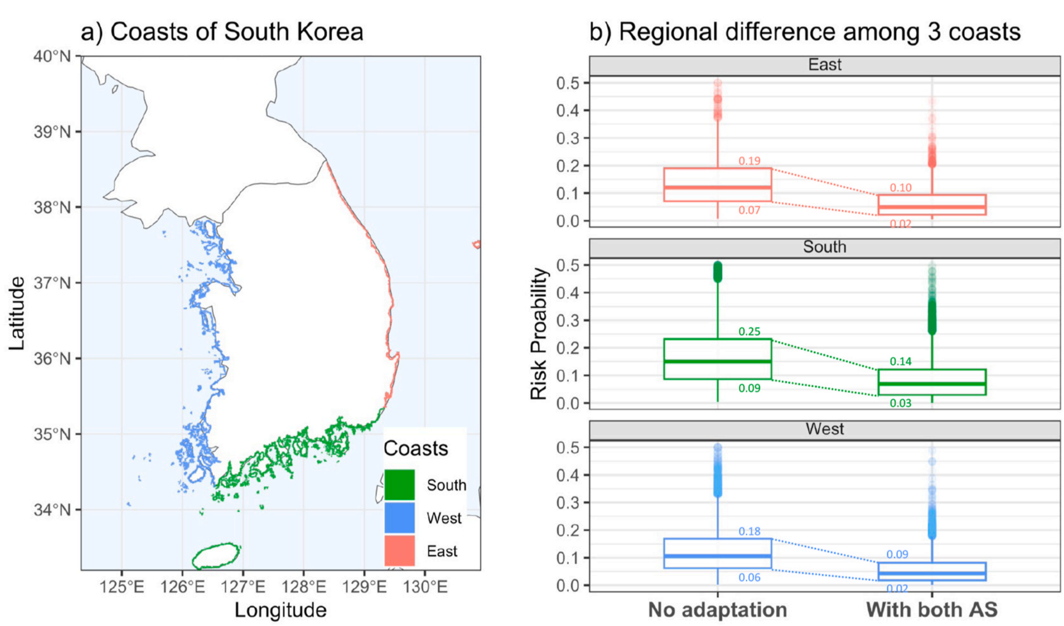

Fig. 8. (a) Regional differences among the three coasts of South Korea; and (b) coastal flooding risk probability among the three coasts of South Korea (with and without two adaptation strategies). Adapted from Park and Lee (2020).

communities, such as the Sendai Framework for Disaster Risk Reduction, Sustainable Development Goals (SDGs), and Paris Climate Agreement (Reguero et al., 2020). In particular, the importance and necessity of ecosystem-based ASs, such as green or natural infrastructure, have been emphasized among potential strategies to reduce flooding risk in coastal areas (Cheong et al., 2013; Ferreira et al., 2019; Jeong et al., 2021; Jongman, 2018; Kumar et al., 2021; Reguero et al., 2018, 2020; Spalding et al., 2014; World Bank, 2018), which is consistent with the findings of this study. In addition, NBSs can play an important role in realizing carbon neutrality. As they are based on nature, NBSs include ecological elements, such as vegetation and soil, which have the function of absorbing carbon (IUCN, 2012). Therefore, investments in NBSs are of utmost importance for increasing the resilience of urban spaces to climate change.

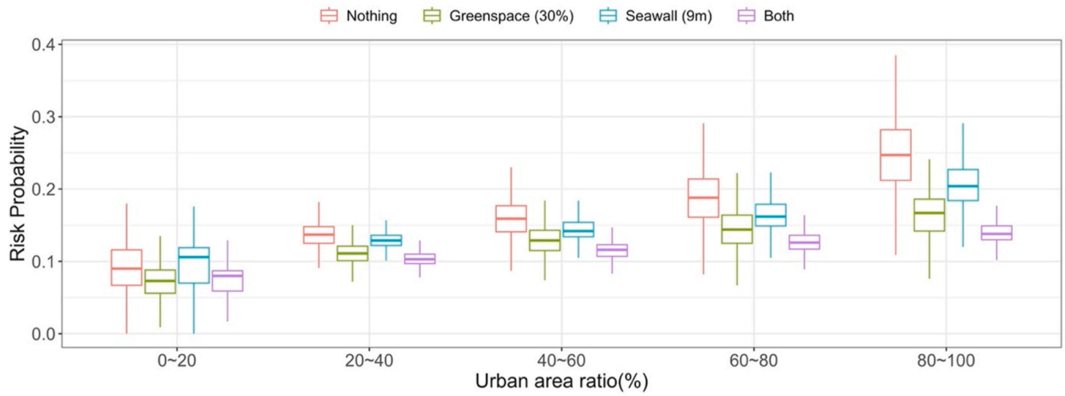

Fig. 9. Coastal flooding risk probability with respect to change in urban area ratio and circumstances of applying the four adaptation options that nothing, green space is applied as 30%, seawall is elevated 9 m, and both adaptation strategies are applied. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusions

This study predicts areas at high risk of flooding in coastal regions of South Korea because of climate change, which will likely cause extreme rainfall and sea-level rise, using spatial and temporal downscaling of future scenario values. Changes in risk probability according to the application or non-application of ASs were confirmed. To calculate the coastal flooding risk probability, the RF, which showed excellent performance, was utilized by comparing the performances of three ML techniques (RF, ANN, and kNN). To predict the potential coastal flooding risk probability in the future, the precipitation data were projected through an ensemble of five RCMs of the RCP 8.5 scenario provided by IPCC AR5. In addition, using real-time tide data from 46 tide stations on the coast of South Korea, the spatial and temporal data were projected by the Bayesian-influenced GAM. In this study, green spaces and "grey infrastructure" based seawalls were used as ASs (Kumar et al., 2021; Ruangpan et al., 2019). There was a clear difference in the risk probability distribution when ASs were applied or not applied and the effects of green space and seawall did not differ significantly (see Fig. 4). However, the effects of the two ASs on the future potential risk probability were somewhat different, and when 2050 was predicted as a target, green spaces were slightly more effective than seawalls (see Fig. 6).

However, this study had a limitation it did not utilize more diverse ASs. Several structural measures have been proposed to reduce the risk of coastal flooding, including sand nourishment, reefs, and dykes (Singhvi et al., 2022). In addition, aspects of economic sustainability, such as maintenance costs, were not considered in the performance analyses of ASs. Indeed, structural measures, such as large seawalls, levees, embankments, breakwaters, and concrete dams, are expensive and lack long-term sustainability (Jones et al., 2012; Kitha and Lyth, 2011). Their failures can have catastrophic impacts on societies and ecosystems (Debele et al., 2019). The importance of ecosystem-based NBS strategies was confirmed by utilizing the two contrasting strategies. In addition, this study only considered the effects of rainfall and sea-level changes as causes of coastal flooding. As in previous studies that considered coastal flooding through the interaction between rainfall and sea level (Eilander et al., 2020; Park and Lee, 2020), in coastal areas, like inland areas, inundation caused by heavy rains is just as important as flooding by storms and waves. These limitations will be supplemented in future studies on the application of adaptation strategies considering actual socio-economic conditions.

However, this study has several notable aspects. The impact of climate change differed spatially and different adaptation measures are required according to the characteristics of the region. Therefore, it is necessary to consider the characteristic differences of the coasts of Korea because there are differences in the geographical characteristics of the east, west, and south coasts and between urban and non-urban areas. As a result of comparing the coastal flooding risk probability of the east and west coasts of Korea, the risk probability of the south coast was slightly greater than that of the east and west coasts, with a comparatively wider distribution. This may be because of the geographical characteristics of the southern coast. Moreover, the risk probability increased as the urbanization rate increased. This means that a climate change response strategy is necessary for coastal cities, considering that the population and socioeconomic activities will increase in urban areas in the future.

Credit author statement

Sangjin Park: Conceptualization, Methodology, Investigation, Data preparation, Data curation, Writing- Original draft preparation, Visualization. Wonmin Sohn: Conceptualization, Methodology. Yong Piao: Investigation. Dongkun Lee: Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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