Future population exposure to flooding due to sea-level rise and storm surge in South Korea where the country's population is declining

Oh Seok Kim

Department of Geography, Graduate School of Korea University, Seoul, Republic of Korea

Department of Geography Education, College of Education, Korea University, Seoul, Republic of Korea

Institute of Future Land, Korea University, Seoul, Republic of Korea

Stephen A. Matthews

Department of Sociology and Criminology,

Department of Anthropology,

Penn State University, University Park, PA, USA

Jaeheon Jung

Department of Geography, Graduate School of Korea University, Seoul, Republic of Korea

Kee Whan Kim

Department of Big Data Science, Korea University, Sejong, Republic of Korea

Kwangwoo Cho

Division of Natural Environment, Korea Environment Institute, Sejong, Republic of Korea

Keun Hyung Hong

Ministry of Oceans and Fisheries, Sejong, Republic of Korea

Sunghwan Kim†

Construction and Economic Research Institute of Korea, Seoul, Republic of Korea

(† corresponding author)

Address of correspondence: 9th floor, 711 Eonju-ro, Gangnam-gu, Seoul, 06050, Republic of Korea, E-mail: sunghwan.gim@gmail.com

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South Korea's population is declining and its composition changing, associated with lowest-low fertility rates and super aging. When estimating changes in land and population exposure to future flooding due to sea-level rise (SLR) and storm surge (SS) events that are predicted to be intensified due to climate change, it is important to incorporate demographic dynamics. We analyze business-as-usual (BAU) population and SLR scenarios—where BAU refers to no significant change in current processes and trends in either domain—from 2025 to 2050 for South Korea. Data for both BAU scenarios, in addition to 50-year and 100-year frequency SSs, are spatially linked and used to measure and identify national and sub-national exposure to future flooding at the 500 m pixel level. The results reveal an increasing population exposure over time at the national level by 13.55–20.37%, but this varies widely within the country. At the sub-national aggregate-level, the population in the Seoul region will likely be most exposed to future flooding, followed by the Busan region. At a fine grained level (i.e., 500m pixel), more lands will get exposed to future flooding but because of population decline in some areas the number of residents exposed will decline. The coastal regions of the country are expected to become more vulnerable to future SLR and intensified SS. When designing a preventive policy to reduce the array of impacts of future flooding will bring, it will be important to identify the areas at risk of experiencing population decline as well as population growth.

Keywords: sea-level rise; storm surge; typhoon; gridded population; population projection; population decline; climate change.

Highlights:

- The population in South Korea will become increasingly vulnerable to future flooding due to sea-level rise and storm surge.
- The twinned processes of population change and SLR and SS varies spatially across South Korea.
- The population in the Seoul region will be most exposed to future SLR and SS, followed by the Busan region.

- In some areas experiencing SLR and more frequent SS, demographic change (i.e., population decline) will reduce the number of people exposed to future SLR and SS (i.e., More flooded lands do not necessarily mean that more people will be affected by the SLR and SS).
- Practicable policies should be developed based on a joint understanding of local demographic change and local SLR and SS risks.

1 Introduction

Sea-level rise (SLR) and storm surges (SS) represent critical global environmental challenges, with pronounced implications for coastal nations. South Korea, uniquely situated as a de facto island with its three sides bordered by ocean and its land borders impassable due to geopolitical circumstances (Kim et al., 2022), faces an elevated and distinct vulnerability to these coastal hazards. This geographical reality, coupled with the nation's historical susceptibility to frequent flooding from typhoons during monsoon seasons, underscores an urgent need for comprehensive risk assessment concerning future sea-level changes. Understanding the demographic context and related future trends is critical for a risk assessment. South Korea, is an important case study, as the country is losing population related to its lowest-low fertility rate and super aging (Kim and Kim, 2020). In 2023, the national level total fertility rate (TFR) was 0.72, the lowest in world history (Statistics Korea, 2024).

The environmental and demographic realties raise critical, yet unexplored, questions regarding how the dual pressures of increasing coastal inundation and a shrinking, aging population will interact and reshape South Koreans' exposure and vulnerability to climate events. Traditional assessments of SLR impacts often focus on the "population at risk" within a growing or stable demographic context (Curtis and Schneider, 2011; Hardy and Hauer, 2018; Hauer et al., 2016). However, the unique demographic trajectory of South Korea necessitates a more nuanced approach, one that integrates the dynamics of a declining population with refined projections of SLR. This research aims to bridge this critical knowledge gap by precisely quantifying the spatial and temporal impacts of projected SLR and SS on both land and population in South Korea. The three primary research questions are:

1. By 2050, how many lands and people will be exposed to future sea-level rise (SLR) and storm surge (SS) in South Korea, given its population decline?
2. Which regions in South Korea will be most exposed to future SLR and SS? What is the pattern of population exposure to future SLR and SS? And, how does this vary within-country?
3. If the government is to design a policy to prevent potential damages from future SLR and SS, what strategies are available and practicable?

Exposure is distinct from vulnerability (Adger, 2006; IPCC, 2014a, IPCC, 2022). In this paper we use definitions by the Intergovernmental Panel on Climate Change (IPCC). We argue that higher levels of exposure will amplify vulnerability and risk (both mortality and morbidity). Thus, understanding the population exposure to future SLR and SS is fundamental in terms of comprehending the associated vulnerability and risks; i.e., which populations *and* areas are at risks.

2 Material and Methods

2.1 Gridded Population Projection

2.1.1 Population projection

A small area population projection of South Korea was applied (Kim et al., 2022), which is based on the following sub-national population projection. Kim and Kim (2020) employed a cohort component method, where each demographic component was estimated using the following models: a generalized log gamma distribution model for fertility (Kaneko, 2003), Heligman and Pollard model for mortality (Heligman and Pollard, 1980), and a migrant pool model for gross migration (Kim and Kim, 2020). South Korea was divided into 37 regions based on commuting data and applied the cohort-component method using population registration data to project population by single-year of age and sex, which was then proportionally allocated to the municipal level to 162 small-areas by preserving the pycnophylactic property (Tobler 1979). This is based on the assumption that the most up-to-date age and sex ratios for each area would remain the same for the entire projection horizon, 2025–2050 (Kim et al., 2022).

2.1.2 Dasymetric mapping

Before applying Categorical Boosting (CatBoost), an ensemble machine learning model, to generate gridded population estimates, South Korea was categorized into urban and non-urban regions to address the significant spatial heterogeneity in population distribution. In the model development and downscaling, separate models for urban and non-urban regions were trained, tested, and verified, where they generated pixel-level population density estimates that serve as weights for dasymetric mapping. Urban regions (e.g., Seoul and Busan) exhibit substantially higher population density and nighttime lights compared to non-urban regions. Previous research showed that machine learning models underestimated non-urban population density when the regional differences were not considered (Stevens et al., 2015; Sinha et al., 2019).

CatBoost is a gradient boosting-based machine learning model specializes in analyzing categorical features using a permutation-driven alternative. The model is designed to address prediction bias issues by preventing overfitting through improved boosting techniques. Further, it supports graphics processing unit (GPU)-accelerated training, enabling efficient learning even with large datasets (Prokhorenkova et al., 2018). CatBoost worked best for the South Korean case study when compared with other predictive quantitative models verified by various measures (e.g., r-squared and root mean square error) and data sources (e.g., mobile phone data) (citation redacted), hence applied in this research to produce gridded population projections.

Using CatBoost, the urban model was trained using 83,819 census blocks and predicted population density for 45,688 pixels, while the non-urban model was trained with 20,093 census blocks and predicted population density for 372,651 pixels, where one pixel is equivalent to 500 m by 500 m. Small islands in remote areas (equivalent to 6 census blocks and 250 pixels) were excluded due to missing values in the input features. Specifics regarding the model training, testing, hyperparameter combinations, etc. are explained in detail in another methodology paper (citation redacted). After developing CatBoost-based population density estimates for the urban and non-urban regions, the population projection was downscaled to 500m-level pixels, while zero values were assigned to water bodies.

2.2. Sea-level rise and storm surge

2.2.1 Climate change scenario (RCP 4.5 and 8.5)

RCPs are the climate change scenarios used in the IPCC's 5th assessment report (IPCC, 2014b, Moss et al., 2010). RCP 4.5 indicates that the future radiative forcing is stabilized at 4.5 W per square meter (hence, RCP 4.5), and accordingly, the mean temperature will rise by 2.4 °C and 2.9 °C at the global and Korean peninsula levels, respectively, by 2071–2100 (Korea Meteorological Administration, 2018). This scenario assumes that global and national climate change mitigation policies are implemented and working effectively to some extent and that the carbon dioxide level in the atmosphere does not increase more than 538.4 ppm by 2100 (IPCC, 2013a). It is important to note that IPCC regards RCP 8.5 as business as usual (BAU), the scenario with no mitigation activities by the global community, resulting in the most radical climate change.

SLR is only meaningful for the year 2050 as no SLR was assumed for the year 2025 in this research. Developed by the government agencies (the Rural Development Administration and the Korea Environment Institute), SLR and storm surge (SS) polygons were constructed based on the averaged trend of representative concentration pathway 4.5 (RCP 4.5) and 8.5 (RPC 8.5) as for the year 2050 because this scenario is considered BAU in South Korea, while these climate change scenarios were developed by the Korea Meteorological Administration (KMA) (Cho et al., 2017).

While the government SLR and SS projections were available for 2050 and 2100 with multiple RCPs, only the 2050 projections with one RCP were used in this research in order for the time scale of the SLR and SS data could align with that of the gridded population projections. This averaged RCP 4.5 and 8.5 SLR projection indicates national average SLR of 34.1 cm by 2050 compared to current levels (Cho et al., 2017). Note that the IPCC (2013b) projected global average SLR of 47 cm and 63 cm under the RCP 4.5 and the RCP 8.5, respectively, by 2100. According to the KMA (2012), national average SLR by 2100 of the Korean Peninsula was projected to be 65.0 cm and 83.8 cm under the RCP 4.5 and the RCP 8.5. In other words, the Korean Peninsula will experience more severe SLR than the global average.

2.2.2 Storm surge scenario (50- and 100-year)

In the Korean Peninsula, it is important for the 50-year and 100-year frequency SS scenarios to factor in typhoons during monsoon seasons. To characterize these hypothetical typhoons, central pressure values for 50-year and 100-year frequency were driven by analyzing central pressure values from 1970 to 2010, provided by the Korea

Hydrographic and Oceanographic Agency (KHOA). With respect to changes in terms of typhoon intensity getting stronger due to temperature increase, additional 10 hPa difference was also added to typhoon's central pressure as for the year 2050 (Oh and Moon, 2013; Yoon et al, 2012). The typhoon's maximum wind speed and radius of maximum winds were determined by analyzing the Best Track data (2001–2014) of the Joint Typhoon Warning Center of the United States. As for typhoon paths, in total four paths were designed based on the work of Park et al. (2006) and also by considering the west and south coast of the peninsula. Regarding the typhoon's path for the west coast, two paths were designed based on the actual typhoons in the past, namely, Kompasu in 2010 and Bolaven in 2012; as for the south coast, the other two paths were determined based on the typhoons, Rusa in 2002 and Maemi in 2003. Further, 0.2-degree buffer was added to those four paths to guarantee robustness of typhoon paths (Cho et al., 2017).

2.2.3 Modeling sea-level rise and storm surge

After specifying the scenarios of SLR and SS these were applied to a series of models to simulate different levels of flooding and to map flooded areas in the study area. The models include: (a) ADvanced CIRCulation (ADCIRC), (b) Sea, Lake, and Overland Surges from Hurricanes (SLOSH), and (c) Bathtub models, for a hybrid modeling approach, leveraging the strengths of ADCIRC for reclaimed coastal areas and a combined SLOSH-Bathtub model for broader land coverage across South Korea. The ADCIRC model was specifically applied to reclaimed coastal areas. Developed by Luettich et al (1992), ADCIRC is a widely recognized robust tool for simulating coastal circulation and SS and also is well-suited for this research as it can detail complex coastlines, particularly along the intricate southwest coast of the Korean Peninsula (Choi et al., 2019; Suh et al., 2015). The model's previous applications in the peninsula further validates its suitability in this research and also often utilized by the Federal Emergency Management Agency (FEMA) of the United States. Modeling floods along the reclaimed coastal areas is crucial for the South Korean case because land reclamation has been popular and ongoing for decades (Ministry of Land, Infrastructure and Transport, 2024), so the country has many reclaimed lands for diverse purposes particularly on the southwest coast (Cho et al., 2017).

The SLOSH-Bathtub models were utilized for the entire inland area of South Korea, including coastal farmlands and the east coast. Developed by the National Weather Service of the United States, SLOSH model is adept at estimating potential flooding by factoring in atmospheric pressure, typhoon size, speed, and track data to estimate SS heights (Jalensnianski et al., 1992). A total of 600 hypothetical scenarios for SS heights, taking into account both SLR and changes in typhoon intensity were simulated. Using these scenarios, the maximum SS height values were calculated for individual locations along the entire coast of South Korea. The application of SLOSH model allows for the generation of inundation maps, which are essential for identifying areas vulnerable to flooding. The Bathtub model simplifies flood prediction by assuming that water will fill up to a certain elevation. We then overlaid the results, to map a detailed analysis of inundation and damage areas caused by flooding. Ultimately, the results from the hybrid approach of ADCIRC and SLOSH-Bathtub models were integrated to produce a comprehensive and refined final projection with respect to SLR and SS scenarios (Cho et al., 2017).

Bathymetry data for reclaimed coastal areas and coastline and topographic elevation data for land areas were required for this hybrid modeling approach. 5 m spatial resolution digital elevation model (DEM) data were acquired from the National Geographic Information Institute (NGII) and used as primary land elevation data in this research. As for the reclaimed farmlands, 1 m spatial resolution light detection and ranging (LiDAR) data were acquired from the KHOA. While existing nautical charts and the DEMs may include some information of coastline, it was necessary to supplement these by introducing additional coastal data primarily from KHOA's national survey and NGII's aerial photographs. This is because often did not timely reflect coastlines altered by frequent coastal constructions, e.g., land reclamation (Cho et al., 2017).

Unifying vertical reference datums of topography, bathymetry, and coastline data were crucial, as the data were produced and distributed by different national agencies of South Korea, their vertical reference datums for land and sea are inconsistent, hence merging these data without considering such inconsistency would result in unnecessary errors in modeling. By definition, an altitude zero in land was referenced to the mean sea-level of Incheon, the largest harbor city neighboring Seoul. Therefore, vertical reference datums of all raw data were adjusted to match with Incheon's msl, establishing a unified reference for this research (Cho et al., 2017).

Data on coastal agricultural and reclaimed lands across the country were merged into a GIS format using the following sources: soil maps (National Institute of Agricultural Sciences), boundary of reclaimed land (Korea Rural Community Corporation), DEM (NGII), cadastral maps (Ministry of Land, Infrastructure and Transport), and land-cover maps (Ministry of Environment). As a result, the data identified reclaimed areas distributed along the coastal regions of eight major metropolitan cities and provinces: Incheon, Gyeonggi, South Chungcheong, North Jeolla, South Jeolla, South Gyeongsang, Busan, and Jeju. In terms of total reclaimed area, South Jeolla Province covers the largest area at approximately 30.8%, followed by South Chungcheong and North Jeolla Provinces accounting about 22.1% and 21.7%, respectively. Overall, reclaimed lands were primarily concentrated along the west coast (Cho et al., 2017).

2.3 Exposure to sea-level rise and storm surge

Exposure to SLR and SS are measured in two ways: land exposure and population exposure, and only the population exposure is mainly analyzed and discussed in this paper. Land exposure primarily concerns physical damage to infrastructure, natural ecosystems, and economic assets tied to the land. Only the area of inundation of coastal lands are quantified and studied in this paper. Damage to infrastructure, such as roads, buildings, industrial facilities, and agricultural fields (reclaimed farmlands), and impacts on environmental degradation, such as saltwater intrusion into freshwater aquifers and agricultural soils, erosion of beaches and coastlines, and loss of wetlands and critical habitats, are not scope of this research.

Land exposure was measured by calculating the areas of the polygons of SLR and SS in square kilometer. That is, flooded areas without sea-level rise (in 2025) with 50-and 100-year scenarios, and flooded areas with sea-level rise (in 2050) with 50-and 100-year scenarios are represented in GIS polygons. Their changes are also tabulated. Future land reclamations was not considered due to lack of data. Population exposure was measured by overlaying gridded population pixels with those SLR and SS polygons. Only the pixels that were overlaid were later summed up to result in the number of people affected by the SLR and SS. This in total, four cases were driven, and the changes were calculated.

3 Results

3.1 Land exposure

The 100-year scenario will result in more severe SS and hence larger flooded areas than the 50-year scenario, with or without the SRL considered. When no SLR was assumed for the year 2025, 4,205.31 km^2 was expected to get flooded by the 100-year scenario, while 3,816.65 km^2 was expected by the 50-year scenario at the aggregate national level (Table 1). At the pixel level, the land exposure is mostly distributed in the west and south coast of South Korea, where many coastal wetlands are located (Figure 1). More land exposure is a result of relatively flat and low elevation areas. By 2050, the land exposure will increase by 19.18% and 24.80% for the 100- and 50-year scenarios, respectively, driven by the SLR (Table 1).

[Insert Table 1 and Figure 1 near here]

3.2 Population exposure

At the aggregate national level, population exposure shows a similar pattern. It is predicted that 3,684,398 people will be affected according to the 100-year scenario, while 3,237,453 people will get affected by the 50-year scenario. By 2050, the population exposure will increase by 13.55% and 20.37% for the 100- and 50-year scenarios, respectively, driven by the SLR (Table 2). In sum, it is evident that SLR will intensify SS in South Korea hence exposing more land and people living there.

[Insert Table 2 near here]

At the pixel level, geographical patterns of the population exposure are more complicated than the land exposure, as population dynamics needs to be considered. Unlike the land exposure, SLR and SS do not affect population in a linear fashion because some regions will have smaller population in the future than today. Those regions are color-coded in blue (Figure 1). That is, blue shows that the regions will be flooded due to 50-year (Figure 1a) and 100-year (Figure 1b) frequency SS, when with or without SLR is considered. However, the population exposed to the SLR and SS will be smaller in the future because of the regional population decline. Lighter red indicates the regions will be flooded with or without considering SLR, and there will be more people affected because it is expected that their regional populations will increase by 2050 (Figure 1). Lastly, brighter red illustrates the additional flooded regions when SRL is considered in addition to the given SS. The population in these regions will likely be exposed to future flooding regardless of their decline in regional populations between 2025 and 2050 (Figure 1a and 1b). In sum at the aggregate level, more people will get exposed to future SLR and SS even though there will be regional population decline by 2050 (Figure 2). It is important to note that the regional population decline will offset the additional exposure due to the SRL. If there was no population decline, there will be about 1 million additional people exposed to the SLR in both 100- and 50- year scenarios (Figure 2).

[Insert Figure 2 near here]

Two major urban areas, namely Seoul and Busan, are compared at the regional level because they host the most population along the coastal regions (Figures 1 and 3). Under the 50-year scenario, for instance, it is expected that there will about additional 1 million people exposed to the SLR at the national level (Figure 2). Under the same scenario, the Seoul and Busan regions alone will experience an additional 0.76 million people exposured by 2050 (i.e., 76% of the national exposure). Even when the 100-year scenario was considered, the two major urban regions will worth 74% of the national exposure (Figures 2 and 3).

Population exposure that is expected to increase by 2050 due to SLR and SS will be somehow compensated by the regional population decline resulting in less exposure when no population was considered (Figure 3). The 100-year scenario will be more affected by the population decline than the 50-year scenario (Figure 2). This pattern stays the same for the Seoul and Busan regions (Figure 3). The rest of the study area, primarily on the southwest coastal region (Figure 1), is constituted with small cities and rural villages, as opposed to Seoul and Busan, may have more lands flooded in the future, but a smaller number of people will be affected by such flooding.

[Insert Figure 3 near here]

4 Discussion

Our South Korean case study started with a simple question: What will happen to population exposure to SLR and SS when a country's population begins to decline in an era where there is an anticipated increase in SLR and more severe SS? One might anticipate that population exposure will decline as population declines but if the SLR increases rapidly then this can offset the population decline. Our results show that the overall population exposure to SLR and SS in South Korea is expected to increase in the future even with the anticipated population decline. However, it also shows that more flooded lands do not necessarily mean that more people will be affected by the SLR and SS.

Generally, when comparing two floods: one with more areas affected under a more extreme 100-year scenario, as opposed to the other fewer areas affected under a less extreme 50-year scenario, one can easily expect that more people will get exposed to SLR and SS under the 100-year scenario. Also, it is expected that an increment in population exposure will be more substantial under the 100-year scenario than the 50-year scenario when the SLR is additionally considered. However, that was not the case for South Korea. The 100-year scenario resulted in a larger population exposure, as opposed to the population exposure with the 50-year scenario with or without the SLR considered (Table 2 and Figure 2), but when comparing the population exposure over time, the 100-year scenario shows only 13.55% increase, while the 50-year scenario shows 20.37% (Table 2). That is, under the less extreme 50-year scenario the impact of future SLR could turn out much larger than the more extreme 100-year scenario because less exposure in the beginning does not always guarantee that the future exposure will be also less. Thus, it is crucial to note that an outcome of less extreme scenario may not always indicate that its impacts are smaller. When the regional population decline is taken into account, the 100-year scenario is more affected by it, as shown in Figures 2 and 3. In all cases, at both the national and regional scales, the aggregate of population exposure decrease due to population decline (blue bars) was larger than that of the 50-year scenario (Figures 2 and 3).

Population in small cities and rural areas are expected to be relatively less exposed to SLR and SS; however, it is important to stress that this does not necessarily mean the rural population would be less vulnerable to SLR and SS or are at minimal risk. As noted earlier, risk is a function of exposure and vulnerability (IPCC, 2022), and it is probable that the rural population may be at more risk. Characterizing vulnerability to SLR and SS is not the scope of this research, and very few studies analyzed vulnerability or risks along the Korean coastal areas by considering population. A recent study by Kim et al. (2024) estimated that population aged ≥65 will increase from 22.2% (2023) to 31.8% (2030) of the total population in fishery villages and coastal urban areas. If one is to extrapolate this increasing pattern to the years of 2040 and 2050, the ratios of population aged ≥65 are 42.8% and 50.6%, respectively. In sum, it is not only about how many people will be more exposed to future SLR and SS, but also about these people are getting older so potentially weaker health conditions when they are to be exposed to climate risks. The most up-to-date national climate change adaptation plan of South Korea does not take such population dynamics and composition into account when designing adaptation measures with respect to future climate risks (Ministries of Republic of Korea 2020).

In a study such as this it is important to discuss modeling uncertainties, and the research outcomes must be interpreted with some caution as the present research has employed multiple modeling approaches, each with associated uncertainty. To quantify a population exposure to SLR and SS in a spatially explicit fashion, it is necessary to have gridded population data to match with the existing SLR and SS research outcomes (Cho et al., 2017) for this South Korean case study. However, such data or the relevant literature regarding South Korea's downscaled future population has not yet been made available. Although the approach is sometimes criticized for oversimplification and its accuracy not comprehensively assessed (Wilson et al., 2021), the existing climate change literature confirms and justifies that our population data are suitable for quantifying exposure. In the literature, the downscaling and disaggregation approach is applied at a pixel (grid) level because this spatial scale is meaningful in climate change research (Jones et al., 2015, Jones and O'Neill, 2013, O'Neill, 2005, O'Neill et al., 2001).

5 Conclusions

The population in South Korea will become increasingly vulnerable to future flooding due to SLR and SS. However, the population-level exposure surface is not even within a country and nor will it be only determined by the increase in SLR and intensified SS. The rapidly changing demographics of South Korea, particularly the emergence of super aging populations will elevate the health and mortality risks. The twinned processes of population change and SLR and SS varies spatially across South Korea. Coupling climate change scenarios with population dynamics and paying close attention to composition in a spatially explicit manner can reveal areas and populations at high (and lower) risk. The population in the Seoul region will be most exposed to future SLR and SS, followed by the Busan region. In rural areas experiencing SLR and more frequent SS, demographic change (i.e., population decline) will reduce the number of people exposed to future SLR and SS. More flooded lands do not necessarily mean that more people will be affected by the SLR and SS.

Practicable policies should be developed based on a joint understanding of local demographic change and local SLR and SS risks. To date, the national adaptation plan regarding climate change risks has not fully incorporated demographic futures, and this may hinder designing and implementing an effective adaptation measure in terms of coping with climate change risks in South Korea.

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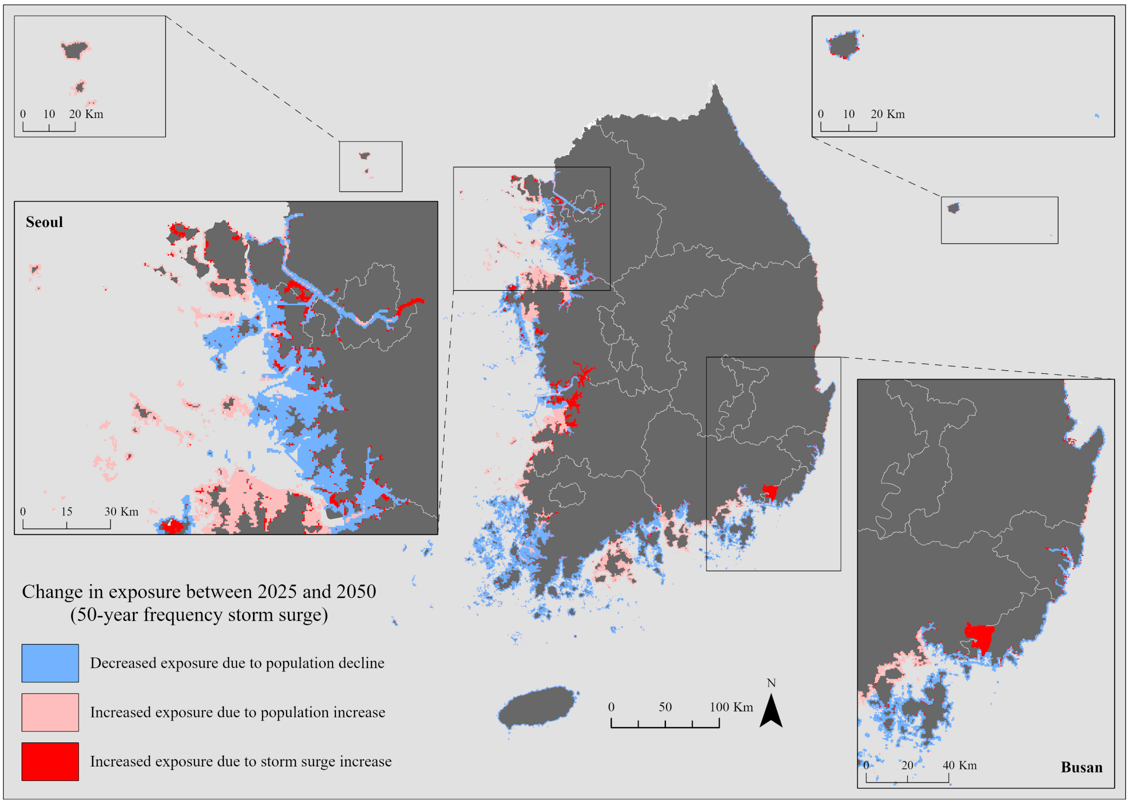
Table 1. Land exposure due to sea-level rise and storm surge in 2025 and 2050 and the percent changes.

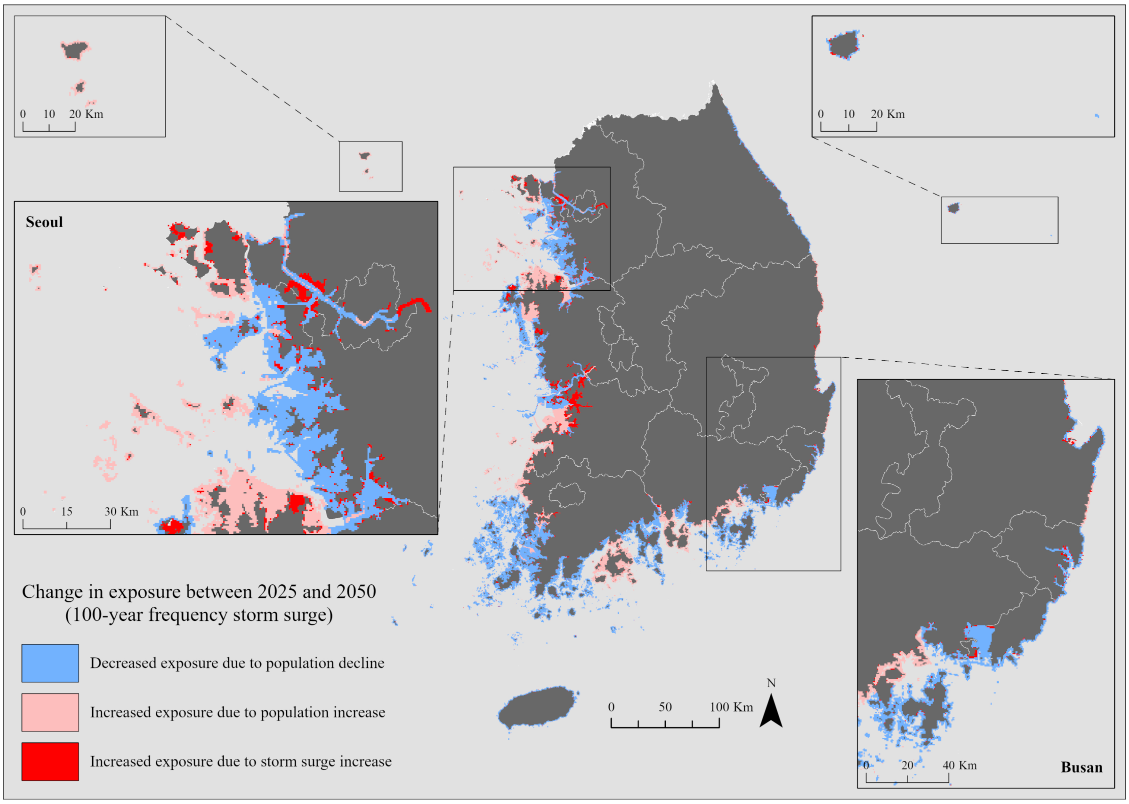
Year	Scenario	Flooded area (km^2)	Percent change compared to 2025
2025 (without sea-level rise)	50-year	3,816.65	
	100-year	4,205.31	
2050 (with sea-level rise)	50-year	4,763.02	+24.80%
	100-year	5,011.82	+19.18%

Table 2. Population exposure to sea-level rise and storm surge in 2025 and 2050 at the national aggregate level.

Year	Scenario	Population exposure (no. of persons)	Percent change compared to 2025
2025 (without sea-level rise)	50-year	3,237,453	
	100-year	3,684,398	
2050 (with sea-level rise)	50-year	3,896,765	+20.37%
	100-year	4,183,814	+13.55%


Seoul
0 15 30 Km
0 10 20 Km
0 10 20 Km
Change in exposure between 2025 and 2050
(50-year frequency storm surge)
Decreased exposure due to population decline
Increased exposure due to population increase
Increased exposure due to storm surge increase
0 50 100 Km
N
0 20 40 Km
Busan

1 (a)


Seoul
0 15 30 Km
0 10 20 Km
0 10 20 Km
Change in exposure between 2025 and 2050
(100-year frequency storm surge)
Decreased exposure due to population decline
Increased exposure due to population increase
Increased exposure due to storm surge increase
0 50 100 Km
N
0 20 40 Km
Busan

2 (b)

Figure 1. Population exposure to sea-level rise and storm surge and their changes in 2025 and 2050 based on (a) 50-year and (b) 100-year frequency storm surge scenarios.

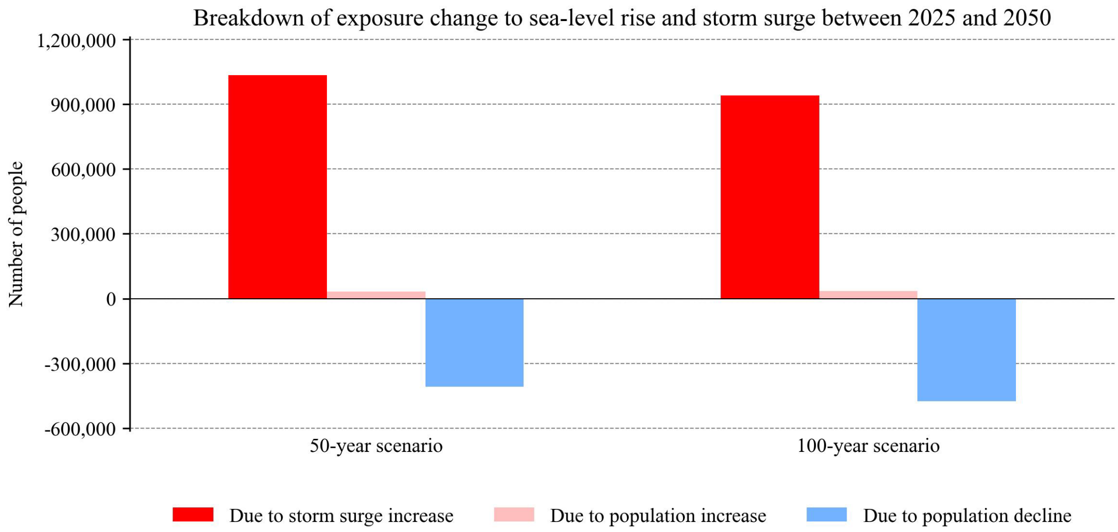


Figure 2. Breakdown of population exposure change to sea-level rise and storm surge between 2025 and 2050.

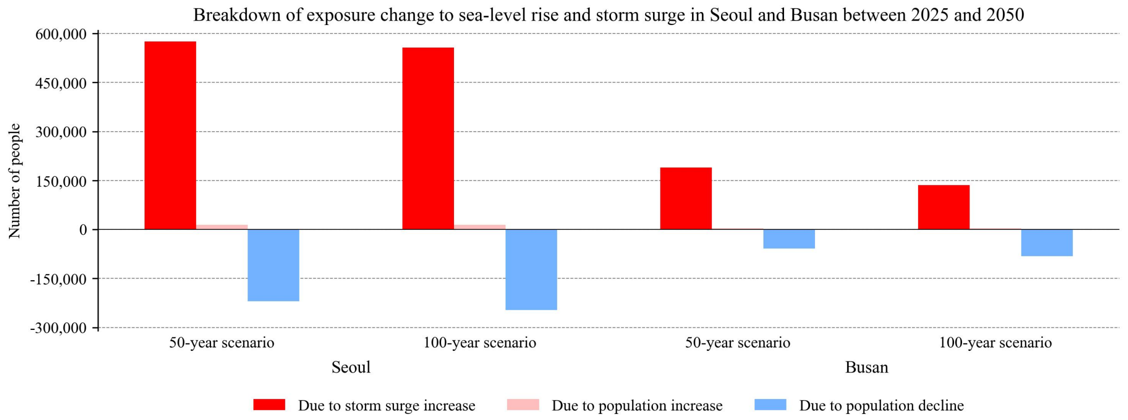


Figure 3. Breakdown of population exposure change to sea-level rise and storm surge in Seoul and Busan urban regions between 2025 and 2050.