Research Paper

Flood resilient scenario modelling (FReSMo):

Dynamic assessment of climate-induced effects on land use

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Abstract

Globally, the unprecedented mean sea level rise (SLR) is observing a devastating impact in terms of coastal inundation and high tide flooding. The high frequency of such incidents is likely to jeopardize coastal sustainability, especially in Southeast Asian countries, due to their relatively high exposure. The population density within the 100 km of coastline is expected to increase in the future, with India having the maximum number of people, about 14 million, exposed to coastal flooding by 2070. The east coast of India is worse affected due to the prevalence of extreme poverty, unregulated change in land use land cover, the absence of robust climate policies, and the volatile nature of the Bay of Bengal that is adding to the regional vulnerability. Sagar Island, West Bengal, is the largest habited part of the Sundarbans Islands, cleared for cultivation in the late 1800s. Without natural protection from mangroves, the island continues to face recurring damages due to climate extremes such as high tide flooding. Hence, coastal resilience from climate-induced flooding requires a dynamic assessment of flood exposure and regional sensitivity. The current research analyses the land use changes in the study region for the last two decades along with parameters for understanding the flooding scenario. The study then uses a 'Futures' model for land use prediction. The model ranked the growth parameters based on their spatial behavior in facilitating temporal change. The parameters were assigned weights using logistic regression, eliminating biases prevalent in the other multi-criteria-based models. The return period for high tide flooding was calculated using a Peak over Threshold (POT) model from long-term tidal data. The relative sea-level rise for the region was predicted using PSMSL (Permanent Service for Mean Sea Level) datasets and global mean sea level values. The total flood exposure was determined by spatially mapping the flood extent under the estimated SLR for different return period scenarios. The flood exposure was overlaid on the predicted land use map of 2050 to understand the flood sensitivity in a business as usual scenario (BAU). Henceforth, the risk map can be a visual tool for policymakers to channel informed decisions toward sustainable development.

Keywords

Coastal sustainability, Futures Model, High Tide Flooding, Peak over Threshold, Sea level rise

1. Introduction

1.1. Coastal flood risk

The climate-induced change in the global mean sea level has enhanced the coastal flood susceptibility of low-lying and densely populated coastal regions around the globe (Kirezci et al., 2021). The relative sea level rise around the Southeast Asian coastlines augments the probability of frequent and intense extreme sea floods, moving further inland (Gornitz et al., 2001; McGranahan et al., 2007). The estimated extreme sea level rise in Bangkok by 2030 can put 10.45 million people and 96% of its GDP at constant risk of high tide flooding (Kim & Wang, 2021). The flood risk within the South Asian region is critical as the region exposes an exceptionally large underequipped and economically diffident population to prolong inundation, causing significant damage to the built infrastructure (Edmonds et al., 2020; Hanif et al., 2021). Over the last few decades, the observed increase in the building damage data embarks the dominating influence of physiographic and economic parameters in advancing development over the flood-exposed region.

Regardless of flood exposure, coastal regions act as a sole source of livelihood, primarily for rural populations dependent on primary sector activities (Neumann et al., 2015; Narendr et al., 2022). Although, the loss of built infrastructure due to recurring floods will continue to affect the overall well-being, adding a recursive burden on resource-crunched rural economies. Furthermore, since the dynamics related to exposure and regional sensitivity are likely to enhance, the built-up location and flood extent are critical elements for the spatial assessment of coastal flood impact and formulating related policy for climate adaptation.

The studies have used temporal land use modelling (Xu et al, 2021; Chandrashekar and Aithal, 2021) as an essential indicator for analyzing present and future flood risk scenarios. However, the concern for realistic outcomes is hardly prioritized (Aithal et al., 2018; Al Rifat & Liu, 2022). It is relevant to mention that physiographic, socio-demographic, economic infrastructure, and accessibility is a few prominent parameters affecting the present and future regional growth (settlement/ built-up) (Tripathi et al., 2017). Hence, the proposed method of FreSMo uses a patch-growing algorithm (PGA) based open-sourced FUTURES model for simulating built-up through a holistic representation of the criteria mentioned above using a high-resolution (spatial) dataset. It integrates the model output (built-up growth) with predicted high water flood extent under different climate change scenarios. Finally, the model quantifies the built-up growth trend and deliberates its sensitivity in the business-as-usual scenario (BAU). Moreover, a discussion regarding the implication of nature-based solutions as a workable adaptation strategy is put forward.

2. Study Area

2.1. Sensitivity of West Bengal coast

The Indian coastline has experienced several episodes of high tide coastal flooding accompanied by tropical cyclones. West Bengal is predicted to have the highest rate of relative sea level increase, with about 5.16 mm recorded in Diamond Harbour, far ahead of the national average. The state also has the maximum population density (500-1000 persons per sq. km) residing below 10 m Low elevation coastal zone (Columbia University, 2007). Apart from this, the gently sloping continental shelf, volatile nature of the Bay of Bengal, unregulated change in land cover and absence of robust climate policies in most rural areas around the coastline brings the urgent need for intervention.

Sagar Island (282 sq km), located at the southern tip of the state, is entirely rural with a population of about 2 lakh people. The Sagar block comprising 47 villages has been repeatedly affected by coastal water intrusion due to tidal anomalies and storm surges. It has been a shelter for the population living in the adjacent parts of the drowning Sundarban estuary, highlighting the necessity to explore its susceptibility.

3. Data and Method

3.1. Flood resilient scenario modelling (FReSMo)

The first step of FreSMo is to investigate/ establish the growing threat of coastal floods on the built infrastructure. This is estimated by means of analyzing the spatial vulnerability of present and predicted (upcoming) development in the flood prone Sagar Island. The study further details the possible solutions integrated into the process of FReSMo to analyze their effectiveness in reducing flood susceptibility. The proposed analysis is limited to the initial step of FReSMo.

Table 1 describes the various datasets and their sources required for running FReSMo.

Table 1: Dataset and its description required for the analysis

Data type	Content	Usage	Source
Satellite data/ Remote sensing data	LISS IV (2012, 2014 , 2018 & 2020) Spatial resolution 5.6 m	• Landuse map • Predicted landuse	National Remote Sensing Centre (NRSC)
	Stereo pair of Cartosat Spatial resolution 2.5 m	• Digital Elevation Model • Slope Map • Coastal flood modelling	
	Spatial distribution of buildings, socio-economic, infrastructure and accessibility growth seeds	• Landuse map • Predicted landuse • Exposure analysis of coastal floods	Google earth, Open street Maps, Bhuvan (India)
Hydrological data	Mean Sea Level data (1974 -2006) for Ghagra station	Future relative SLR forecast	PSMSL (Permanent Service for Mean Sea Level)
	Daily records of high water and low water data	Return period analysis of high tide floods	Kolkata Port Trust, West Bengal, India
Census Data	The administrative boundary for Sagar Island	• Landuse and predicted landuse map	Govt. of West Bengal, Census of India 2011
	Village-wise population data for 1991, 2001 and 2011	• Landuse prediction • Land demand calculation	District census handbook for 24 South Paraganas, Census of India 2011

3.1. Description of Futures model and growth parameters

The growth of built-up in Sagar Island is simulated using a patch-growing algorithm-based FUTURES model. The simulation is based on three integral modules, namely, (a) Suitability module, (b) Demand module, and (c) PGA module. In the first module of FUTURES, the model identifies the likelihood of an area to be converted into built-up based on the influence of growth parameters. Unlike the typical CA models, the parameters were ranked based on logistic regression eliminating the biasedness of multi-criteria decision tools. The Demand module of FUTURES calculates the percapita demand based on present and predicted population input. The PGA module simulates the built(paved) dynamics based on the suitability, growth parameters and land demand estimation.

The growth parameters considered for the analysis have been categorized into physiographic, socio-demographic, economic infrastructure, and accessibility. Table 1 below highlights the significance of each parameter in seeding growth within Sagar Island. The temporal landuse map for the years 2012, 2014, 2018 and 2020 were extracted based on standard methods using Gaussian Maximum Likelihood Classifier (Aithal et al., 2017; Narendr et al., 2022). The landuse was classified into the following classes: water, agriculture, vegetation, built-up, mangroves and others. The landuse and other parameter described in table 2 were used to predict total built-up in 2050.

Table 2: Description of parameters used for prediction of built-up

Si No.	Parameters	Category	Description
1	Landuse landcover	Physiographic	Temporal change in landuse landcover determine the upcoming growth in the region as people tend to settle in communities
2	Slope	Physiographic	The communities tend to crop up in valley regions or gentler slopes rather than the peaks.
3	Mangroves	Physiographic	The mangroves are protected regions as they act as a natural buffer to cyclonic storms
4	Distance from tidal creek	Accessibility/ economic	Source of economic activity such as fishing, crab and prawn farming
5	Distance from the amenities	Accessibility/ economic/ socio-demographic	Amenities here are schools, religious places, banks, bus stops, docks, hospital and police station
6	Distance from the shoreline	Accessibility/ economic	Shorelines are source of attraction due to the facility for trade and commerce
7	Distance from the road	Accessibility/ economic	Distance to roads aids regional development by enhancing connectivity to educational, health care and business activities.
8	Population and exponential projection of population for 2050	Socio-demographic	The population size is used to estimate the residential land demand in coming years based on the area of current housing. The exponential increase is best suited for Indian subcontitent based on its past trend analysis

3.2. Calculating the flood area extent

The flood area extent presents a holistic impact of high tide flooding and sea level rise under the various climate change scenario. The flood return period for high water flooding was calculated based on long-term analysis of tidal data for Sagar Island using Peak over Threshold analysis. The long-term tidal data for Sagar Island were obtained from Kolkata Port Trust. The high tide value was separated from the daily tidal data. The high tide values were then plotted in a Pareto distribution as per the extreme value theory (Duo et al., 2020). The return period for 10, 100 and 1000-year data was calculated as a part of the final flood extent map.

The climate-induced variation in relative or local sea level was analyzed using MSL data from PSMSL. The MSL data for Sagar Island tidal station was highly distorted when compared to the sea level captured by TOPEX/ Poseidon, Jason 1 & 2 (Elkins, 2015). Therefore, the MSL data from Ghagra station (within 15 km of Sagar Island) was assumed to have the same historical trend as Sagar Island. The Ghagra MSL data was then extrapolated using the direct method upto till 2005 (Dastgheib & Ranasinghe., 2014). Beyond the year 2005, the global MSL trend were used to project the sea level variation and flood extent under

Socioeconomic Pathways (SSPs) 2.6 and 8.5 using the ratio method (Xu et al., 2021; Masson-Delmotte et al., 2021) Finally, a DEM based bathtub model (Shivamurthy et al., 2022) was used to map the total inundation due to the high tide flooding and the scenario impact.

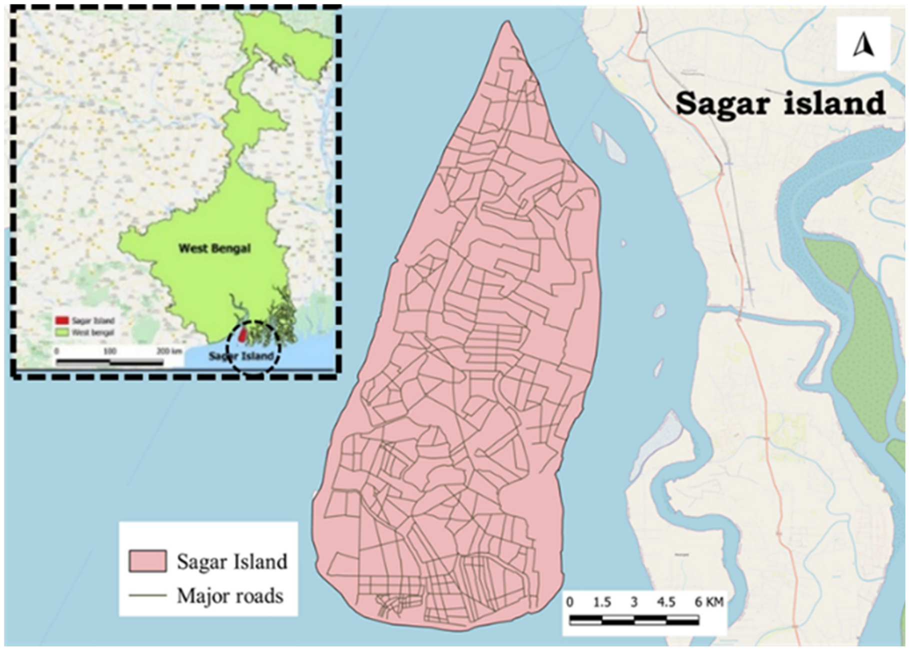


Figure 1: Sagar Island

3. Result and Discussion

Land use analysis: Figure 2 showcases Sagar Island's present and predicted landuse map. The validation accuracy obtained for the model was 98%. The built-up value for the year 2050 is predicted to rise about 4.73% from 2020. The rise in built-up has been mostly observed around the coastal villages within the Sagar block. The coastal area and tidal creeks have been active source of livelihood for the population as pisciculture and prawn farming provide all-year employment given the seasonal nature of agriculture. Coasts are also significant due to theirs geographical importance of facilitating connectivity from Sagar to mainland India (World Bank, 2014).

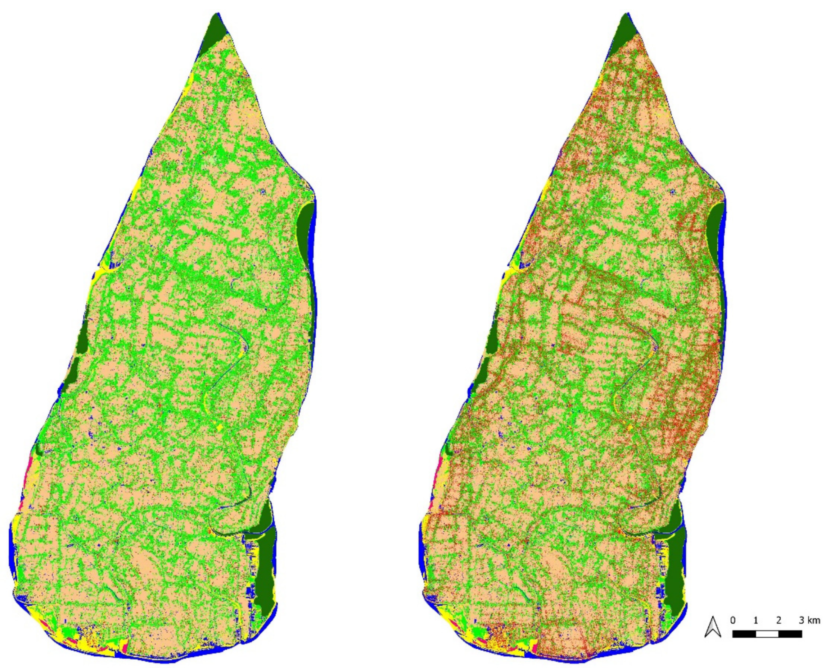
Similarly, roads have been observed as the second most active parameter attracting built-up growth in the region. The settlements within the Sagar block's coastal villages have been mostly on either side of the main roads. In addition to rising built-up, the region has observed a 2% decrease in inland vegetation, 0.17% decrease in water and about 2.5% decrease in the area belonging to its agriculture class. The decline in inland vegetation can have a detrimental effect on the flood situation.

Flood extent analysis: Figure 3 highlights the total flood extent above the high water line (HWL) within the Sagar region due to the tidal return period and the Shared Socioeconomic Pathways (SSPs) 2.6 and 8.5. The HWL is the geographical boundary demarcated due to regular action of high tides. The coastal floodings occour when the tidal water extends beyond the HWL and moves further inland. The table 3 describes the percentage of island area inundated due to coastal floods under the analyzed scenario. The area under inundation is classifed based on its elevation, as lower elevation would mean deeper and prolonged water standing against the built-up. The elevation upto 4 m is marked to have high susceptibility of floods in climate change scenario. Figures 4 and 5 highlight a significant increase in flood extent (between SSP1 2.6 and SSP5 8.5) which enhances the susceptibility of builtup pixels located within 2-3 m and 3-4 m. The results also indicate an interesting pattern of built up development in year 2050. There has been an overall increase in the built-up area but the most prominent variation can be noticed across the elevation 3-4m, where 40% of additional buildings will be affected in 2050 (SSP5 8.5, 1000 year rp) when compared to the same extent value in 2020. The 0-1 m elevation zones also showcase a considerable amount of rising in vulnerable buildings in 2050 (for all three return periods) compared to the year 2020. Further, for the 1000-year return period (SSP5 8.5), the flood extent building pixels present up to the elevation of 5 m for both 2020 and 2050.

Table 3: Area inundated under (a) SSP1 2.6 and (b) SSP5 8.5 for the given flood return period

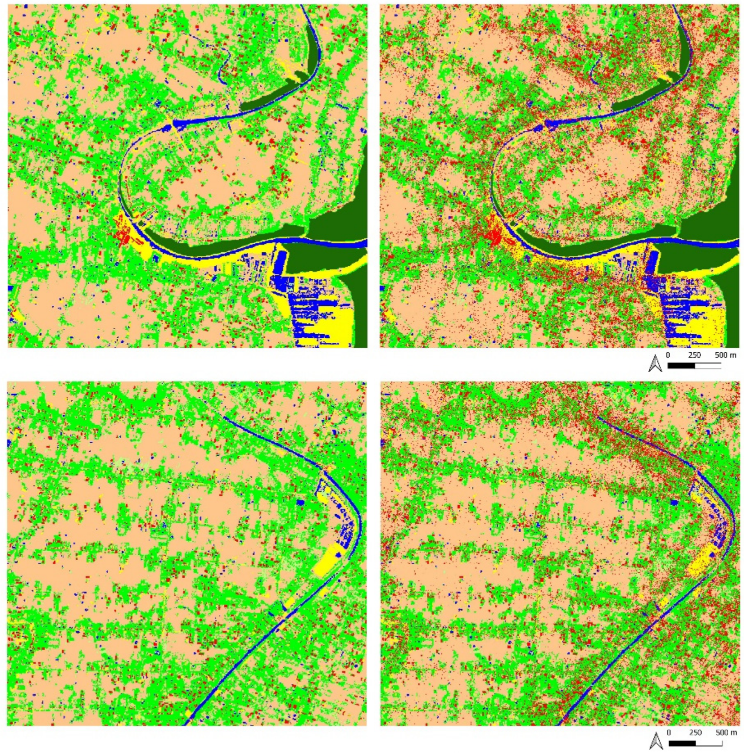
Scenario	Area in sq. km	% of Island area	Scenario	Area in sq. km	% of Island area
2.6 - 10 years	42.76	0.15	8.5 – 10 years	50.03	0.17
2.6 – 100 years	55.14	0.19	8.5 – 100 years	66.14	0.23
2.6 – 1000 year	70.89	0.25	8.5 – 1000 year	82.62	0.29

Nature-based solution-possible spatial intervention: In line with the consideration made by Albert et al., (2021), the development of mangroves around coastal zones within the high water zones can be considered as a workable and pragmatic solution for reducing the overall flood risk. The solution addresses the well-identified challenge of coastal flooding that the society is suffering from and can add various socio-economic co-benefits to the region.



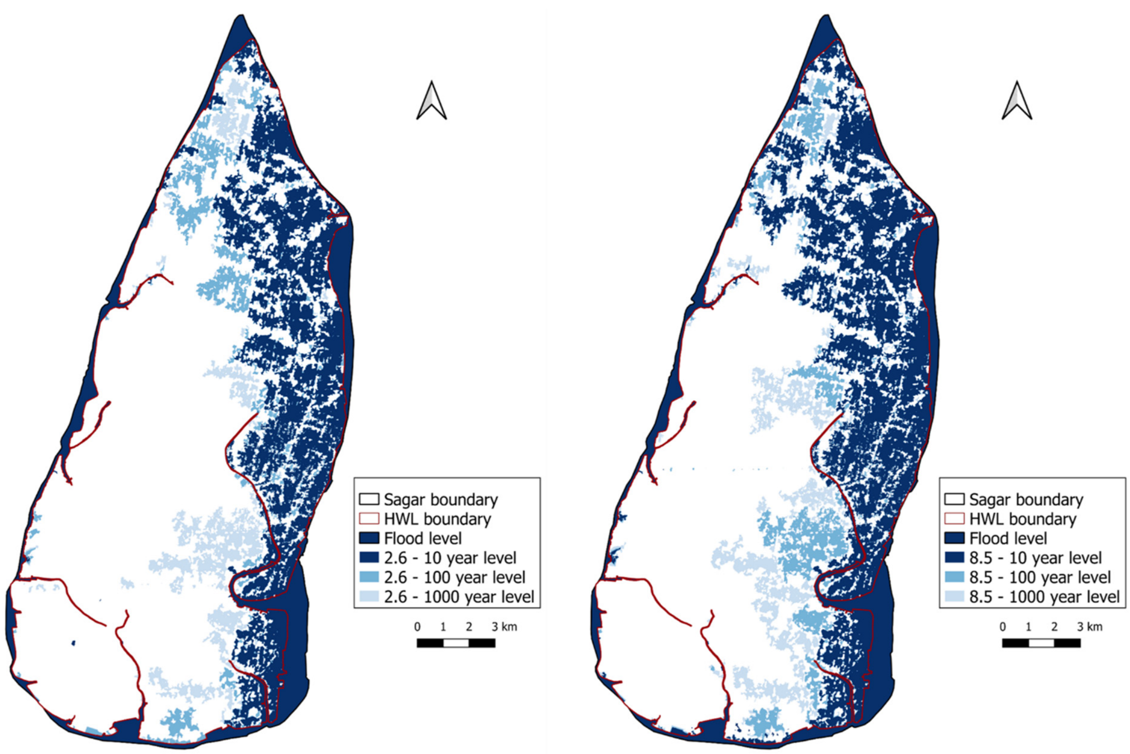
(a) Existing - 2020 (b) Predicted - 2050

Landuse Legend Agriculture Water Vegetation Others Built up Casurina Mangroves



(a) Existing - 2020 (b) Predicted - 2050

Figure 2: (a) Existing-2020 and (b) Predicted- 2050 landuse map of Sagar



(a) SSP1 2.6 (a) SSP5 8.5

Figure 3: Coastal inundation due to high tide flooding under various SLR scenarios,

4. Conclusion

The paper suggested a dynamic method FreSMo, for analyzing the coastal flood impact on land use, built-up primarily. The built-up correlates to the basic need for survival within the rural setting of Sagar Island. Hence, a realistic calculation of built-up growth by integrating various physiographic, socio-demographic, economic infrastructure, and accessibility features have been attempted, which is also one of the inventiveness of the proposed method. Later the test of built-up susceptibility against the scenario-based flood extent reveals that development up to elevation 3.5 m is highly susceptible to flooding in climate change scenarios. The area also shows significant built-up growth in the 0 to 1 m and 3- 3.5 m elevation zones that may be exposed in case of 1000-year flood incidents. The application of a high-resolution dataset makes the analysis one of its kind, providing micro-level insights on the scale of impact. Therefore, best suited for deciding solutions for resilience.

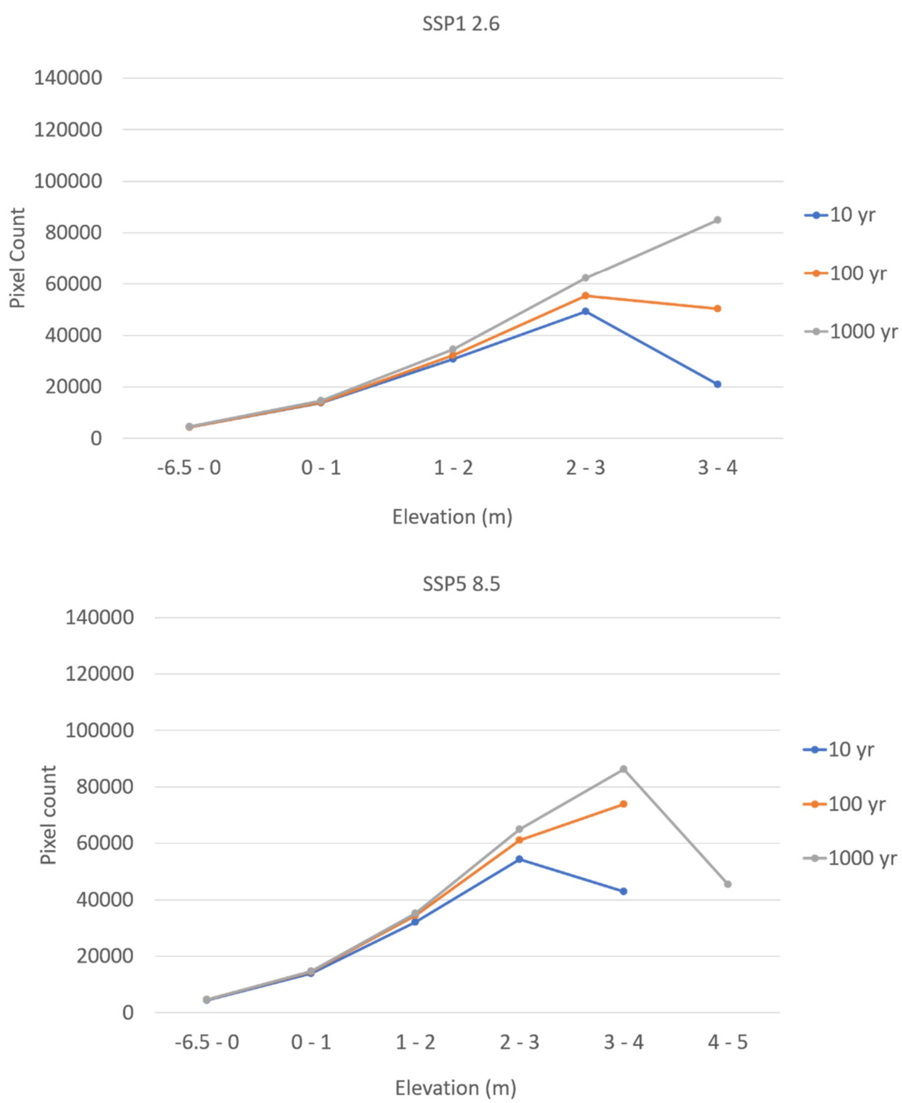


Figure 4: Susceptibility of building pixels under various inundation scenarios in 2020

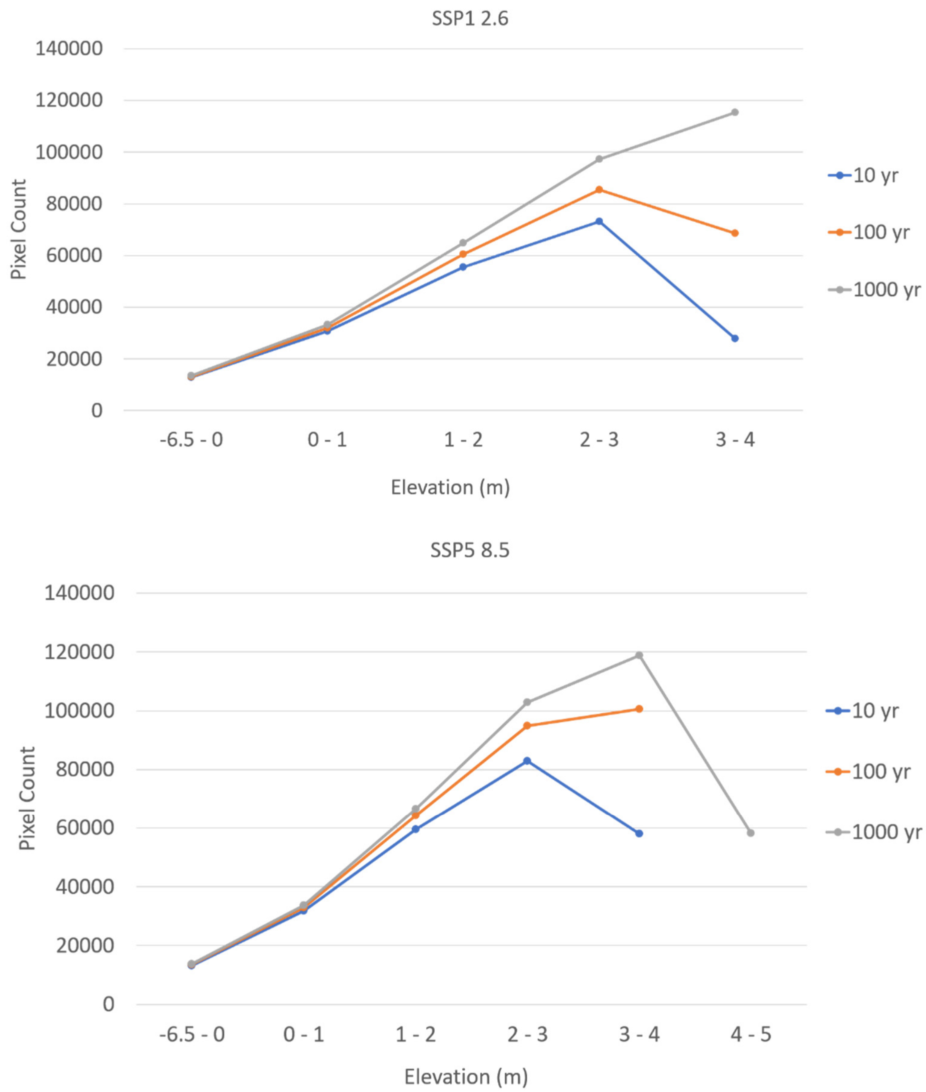


Figure 5: Susceptibility of building pixels under various inundation scenarios in 2050

5. Acknowledgement

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