Large-scale risk analysis and urbanisation amidst coastal flooding in Jakarta, Indonesia: Assessing exposure in future buildings

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Abstract - In 2022, 1500 floods occurred in Indonesia. Floods have worsened recently, injuring and displacing thousands. Jakarta's low topography and excessive groundwater pumping mean most of the city will be below sea level by 2100.

We turn to large-scale risk analysis to study the risk of large cities like Jakarta to climate-related hazards. The paper has three aims: (1) develop a large-scale coastal flood risk analysis for Jakarta, Indonesia using an urban growth model, (2) analyse the trends in urban exposure between new and existing developments and (3) demonstrate the impact of a flood protection policy on future flood risk.

The main inputs include a coastal flood inundation model that accounts for climate change, urban growth extents for 1995, 2001, 2006, 2018 and 2030, and flood damage functions for typical buildings in Indonesia. To generate future urban extents, we use SLEUTH, a cellular automata model with the acronym comprising of its input files - slope, land cover, excluded regions, urban extent, transportation and hillshade. These inputs were combined in a QGIS and Python environment to estimate expected urbanisation trends for Jakarta in 2030.

The results show by 2030, new buildings in Jakarta built from 2020 onwards will be significantly more exposed to extreme coastal flooding. This implies that most of the new development is likely to be in zones of high flood risk. Additionally, we simulated a hypothetical flood protection policy within the dynamic risk framework and quantified how the policy of elevating building heights can reduce new buildings' future flood risk. This work highlights that besides climate change, exposure and vulnerability are significant drivers of increasing risk and hence, key in large-scale disaster risk analysis. With rising urban growth, calculating large-scale climate risk is crucial for developing proactive policies for disaster risk management.

Keywords – Risk Analysis, Coastal Flooding, Urban growth model, Building exposure.

1 INTRODUCTION

Modelling future risk on a global scale is increasingly crucial amidst our changing climate, which introduces dynamic risk and uncertainties in our future. Globally, 1.8 billion people are exposed to floods with an intensity of 1 in 100 years (Rentschler et al., 2023). 1.3 billion people are projected to live in hazardous zones by 2050 with approximately 158 billion USD worth of assets exposed to flooding (Jongman et al., 2012). This increasing exposure is especially severe in coastal cities, where urbanisation and population growth still rise steadily. Rising uncontrolled development and exposure requires the pressing need for more research in large-scale disaster risk management, as backed up by the 2015-2030 Sendai Framework for Disaster Risk Reduction (SFDRR). Economic growth and urbanisation are expected to continue expanding over the years, and the risk in future buildings can be reduced with proper quantifying of risk. Risk analysis tools like probabilistic models of extreme sea levels, physically based climate models and LiDAR-based elevation modelling (Vousdoukas et al., 2018; Bilskie et al., 2014; Trepekli et al., 2022) have been developed to model future risk analysis in a diverse number of study areas.

Risk analysis for various hazards has been conducted but the different aspects of risk and the subsequent projected losses remain highly uncertain (Hemmati et al., 2020). Most risk analysis frameworks currently do not account for dynamic variations in exposure and vulnerability in large-scale risk analysis (Cremen et al., 2022). Coastal flooding studies also lack time-variations in exposure and vulnerability for large-scale risk analysis, with research mainly focusing only on future years (Schuerch et al., 2018; Beck et al., 2018) or the present (Muis et al., 2017). Additionally, rapid urban growth in flood zones has only been studied on a global scale, considering only one flood return period (1 in 100 years) (Rentschler et al., 2023).

This research study makes the following contributions: (1) Modelling a city-scale risk analysis that accounts for time variations using an urban growth model, (2) highlighting the risk that new buildings will experience as urban growth continues and (3) a dynamic risk framework that accounts for multiple coastal flooding return periods, when most studies only consider one. This work focuses on the hazard of coastal flooding, the vulnerability of buildings, and the rising exposure of buildings in Jakarta, Indonesia. Such research is significant especially since Jakarta is one of the largest coastal cities facing rising sea levels and intensifying coastal flooding. Besides climate change, urbanisation is another factor that will worsen coastal flooding. It is thus important to know which areas of Jakarta are most badly affected by this hazard for disaster risk reduction planning.

This dynamic risk framework was conducted in a QGIS and Python environment. 3 main aspects of hazard, exposure and vulnerability were included in this framework. This process was repeated for 12 return periods for the years 2020 and 2030. The framework has two applications – showing the number of significantly damaged buildings with and without policy. Jakarta is experiencing an increasing risk of coastal flooding and this increasing exposure is especially severe in coastal cities, where urbanisation and population growth rise steadily. Indonesia has more than 1000 flood events yearly. One notable flood in 2013 associated with a 30-year return period affected 124 villages, damaged 98,000 houses, displaced 40,000 people, and claimed the lives of 20 people, leaving damages of US$775 million (Wijayanti et al., 2017). These severe consequences can be reduced by analysing its risks and constructing a more resilient built environment. In this paper, we cover the inputs and methodology of risk analysis on a city scale in Jakarta accounting for time-variation. We find the number of buildings exposed to coastal flooding in the present and future, the implications of policy on new buildings, before a village-specific discussion on the more exposed areas.

1.1 STUDY AREA

Jakarta, the administrative capital of Indonesia, is situated on a deltaic plain in one of the world's most seismically and volcanically active regions, at coordinates 6.1944° S, 106.8229° E. (Figure 1). The city lies on a relatively flat topography with 13 major rivers running through. Jakarta frequently experiences coastal flooding, defined as seawater inundation of the land areas along the shoreline (Asnan et al., 2022). Coastal flooding happens when windstorm events and high tide occur concurrently or when both wave set-up and swash produce a powerful runoff together. In northern Jakarta, coastal flooding occurs due to high tides along the low topography land and is accelerated by rising sea levels. These hazards are not due to climate change alone. Anthropogenic issues like groundwater extraction and the densification of buildings increase Jakarta's susceptibility to coastal flooding. The city faces a myriad of environmental concerns such as land subsidence where its northern areas experience 15 - 25 cm of sinking annually (World Bank, 2016), heavy road traffic and spatial planning of its population, all of which are worsened by rising urbanisation.

Figure 1: Study area of North Jakarta, Indonesia, and its villages. Administrative cities include North Jakarta, East Jakarta, Central Jakarta, South Jakarta, and West Jakarta.

We focus on North Jakarta as its proximity to the coast, low elevation and dense informal settlements render the region the most exposed to coastal flooding. North Jakarta is 146.66 km2 with a population of 1,808,985 as of 2023 (Statistics Indonesia, 2023). Jakarta was planned for the spatial capacity of 12.5 million people, in which North Jakarta can host up to 18.6% of (Baumeister et al., 2023). The region has 418,026 buildings, 13.56% of the 3,082,884 buildings in Jakarta and is used for residences, industrial work, tourism, and transportation. The population's demographic is mostly low-income residents comprised of fishermen and migrant workers from rural areas of

Indonesia, who migrated there for better job opportunities and higher minimum wage in the city than in rural regions.

2 METHODOLOGIES

Risk is comprised of 3 aspects: hazard, exposure, and vulnerability. Hazard is defined as “a process, phenomenon or human activity that may cause loss of life, injury, or other health impacts, property damage, social and economic disruption or environmental degradation” by the United Nations Office for Disaster Risk Reduction (UNDRR, 2020). Exposure is the quantity of elements that could be affected by a hazard. It encompasses the location and value of assets important to the communities. Vulnerability is the likelihood that the assets will be damaged when they are exposed to a hazard. These 3 aspects are used in the framework as inputs to study the risk of coastal flooding to communities for building damage in North Jakarta.

2.1 HAZARD INPUT

Coastal flooding is defined as the hazard, using flood depth maps for 12 different return periods for the years 2020 and 2030 generated using the Flow-tub model**.** Flood depth maps show projected flood risks, providing insights into affected areas and appropriate management of those risks. Hydrodynamic models are process-based models often used in generating flood risks for flood risk assessments, but they are computationally intensive. Cheaper alternatives include a static version of hydrodynamic models - the simple Bathtub model (sBTM) is widely used for coastal flood modelling on a global scale.

The sBTM is a simplified version of coastal inundation, where the water level represents the sea level rise, and the bathtub is the coast. It considers all surfaces below a specified depth uniformly flooded regardless of surrounding topography (Williams, L. L., & Lück-Vogel, M, 2020) and calculates the difference between water elevation and ground surface level for a certain period. When the sea level rises, the bathtub is analogous to being filled up. However, with extreme events like storm surges or increased precipitation, the bathtub level rises quickly and causes flooding on the coast. Due to its static nature, the sBTM does not account for coastal processes during water flow and frequently overestimates flood depth and the extent of flooding inland. Overestimation of flood risk in flood modelling is due to the overlooking of hydraulic connectivity and path-based attenuation, which can inaccurately allocate resources when mitigating such risks. Hydraulic connectivity means that a pixel can only be flooded if it is linked to other flooded pixels. The sBTM occasionally shows unconnected flooded pixels because they are at the same elevation as the flood depth. Path-based attenuation is the decrease in water level as it travels away from the coast further inland.

Considering the main limitations of sBTM which does not account for path-based attenuation and hydraulic connectivity, the flooding extents in this paper were generated using the Flow-Tub model (Kasmalkar et al., 2024) (Figure 2). Hydraulic connectivity is ensured by imposing the condition in the model that for a pixel in the flood map to be considered flooded, it needs a path of flooded pixels leading up to it. An attenuation factor is assigned to each pixel in the flooding model. Based on its corresponding attenuation factor, the flood depth will be adjusted accordingly. The Flow-Tub model requires four inputs - water level, elevation, flood protection and attenuation factors. This improved model can produce flooding extents more accurately than the sBTM.

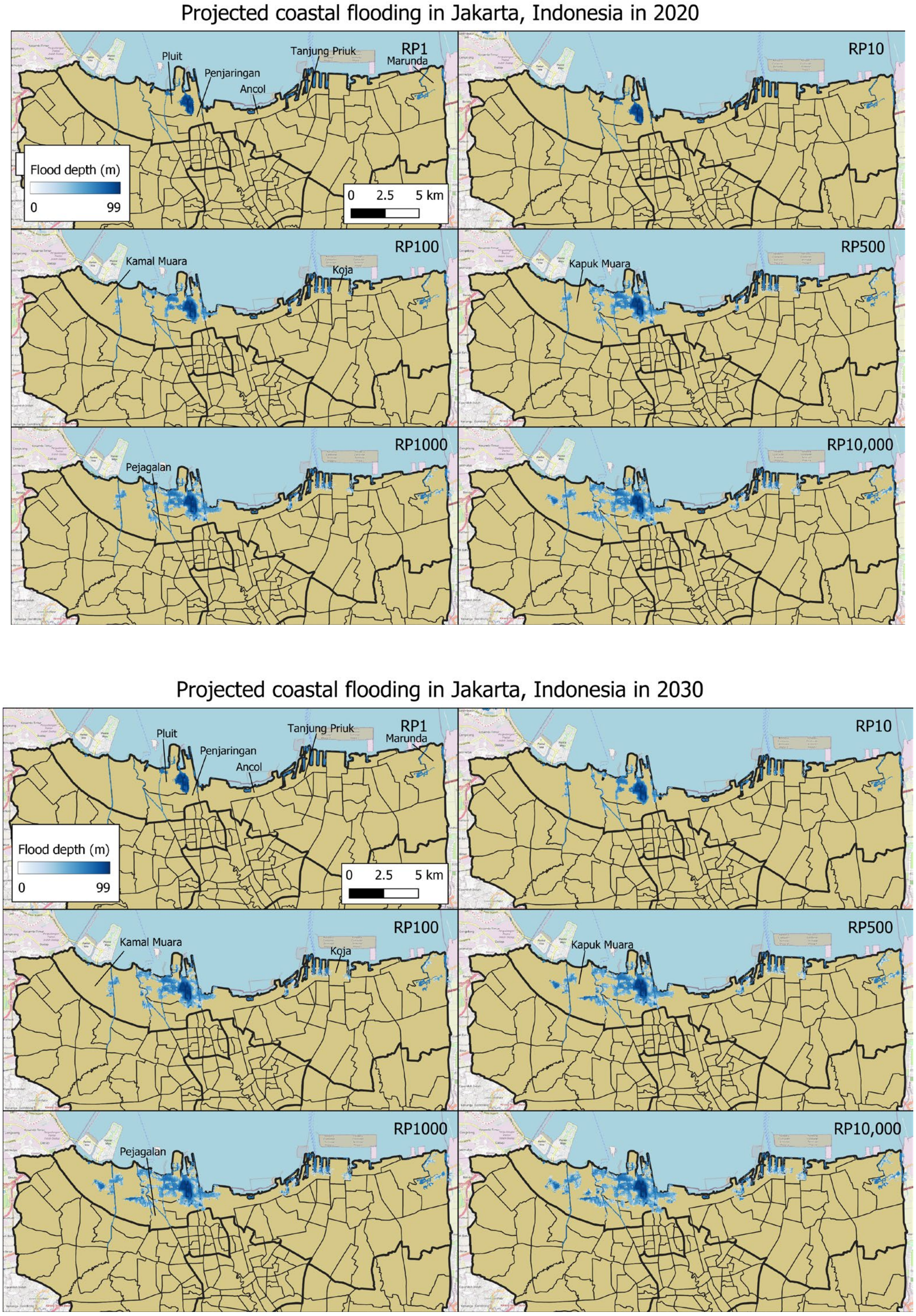


Figure 2 (a) and (b): Coastal flooding maps for different return periods for the years 2020 and 2030.

2.2 EXPOSURE INPUT

The number of significantly damaged buildings shows the exposure of buildings to coastal flooding. We use an urban growth model SLEUTH to map areas of predicted urban growth for the years 2020 and 2030, with the inputs obtained from Mestav Sarica et al. (2020). SLEUTH is a cellular automata-based urban growth model created by Keith C. Clarke that uses historical maps to forecast the expansion of future urban areas. Its name is an acronym for its input files: Slope, Land Use, Exclusion, Urban, Transportation and Hillshade. The input files of SLEUTH are greyscale GIF files of slopes, excluded areas, road networks, urban development and hillshade (Figure 3).

The slope input is a Digital Elevation Model (DEM) of the study area, where the cell values are in % slope (not degree slope, a common unit in GIS software). Land Use is classified into 4 types: urban, agriculture, range land and forest. In every land use layer, each land cover type is assigned to its own RGB values (e.g. urban land uses' RGB is 1,1,1). Excluded areas are areas resistant to urbanisation like water bodies or protected national parks. Areas that are impossible to urbanise have pixels with values of 100 or more. Locations with a slim or possible chance of urbanisation have pixels with values between 0 to 100. Urban extents are the seed of the SLEUTH model. The earliest urban extent year is used to start the model and later years of urban extent are calibrated against the initial year. At least four urban extent layers are required to run the model (Figure 4). In this model, urbanised and non-urbanised pixels have a value of 1 and 0 respectively. Transportation is another factor influencing urban growth - more connected and accessible areas have a higher weightage to the pixels assigned. Like urban extents, pixels with the presence and absence of roads are assigned values of 1 and 0 respectively (Clarke, 2017).

SLEUTH calibrates the best-fit coefficients for 5 control parameters – diffusion, breed, spread, slope, and road growth. These coefficients influence the 4 growth rules in the SLEUTH model – "spontaneous growth", "new spreading center growth", "edge growth" and "road-influenced growth" (Clarke et al., 1996). Spontaneous growth refers to the number of times a pixel is randomly selected for urbanisation. New spreading center growth is the probability a recently urbanised cell will become another urbanised center, where 3 or more adjacent urbanised cells are present. Edge growth is the growth that propagates from existing spreading centers. For Jakarta, edge growth is the most prominent growth type (Mestav Sarica & Pan, 2022). Lastly, road-influenced growth depends on the existing transportation infrastructure. Based on the dispersion coefficient, cells will travel along the existing roads and form a newly urbanised cell. (Project Gigalopolis, n.d.). The prediction of urban growth depends on the best-fit coefficients and growth rules. This study uses the brute force method to find the best-fit coefficients for the model. Three different sets of input files with different pixel sizes (30m, 60m, 120m) were used to calibrate SLEUTH, starting with a coarse resolution (120m) to a finer resolution (30m).

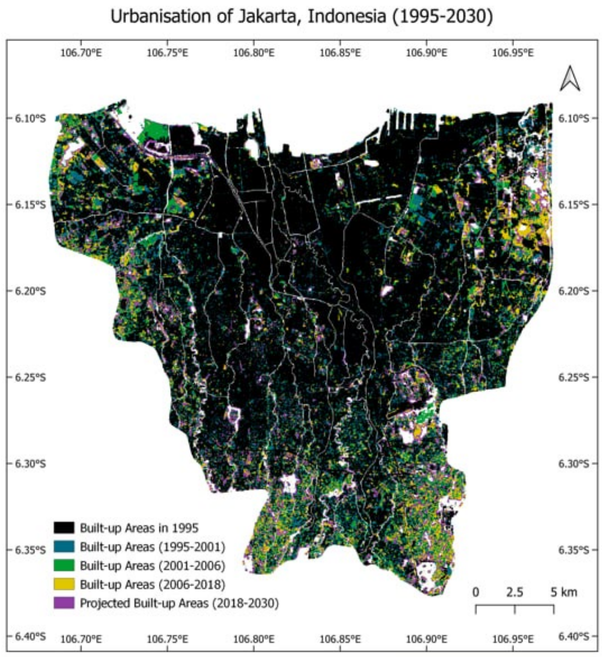


Figure 4: Built-up areas over time in Jakarta, Indonesia generated using SLEUTH.

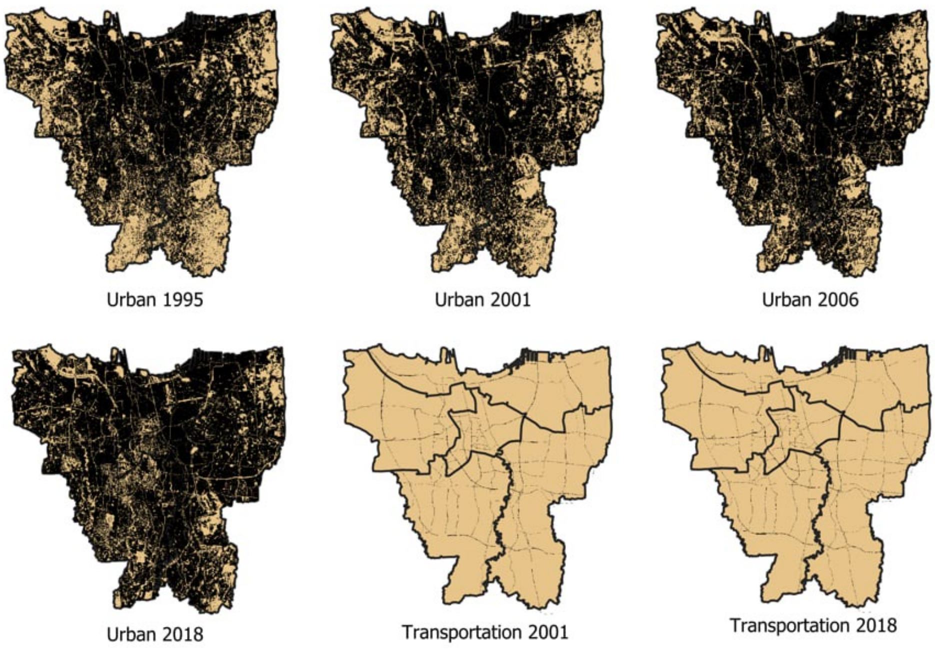


Figure 3: Urban extents (1995, 2001, 2006 and 2018) and transportation extents (2001 and 2018) used in SLEUTH.

Building count maps show the number of buildings present within a set perimeter. We created building count maps for Jakarta using data from Google Open Buildings (Sirko et al., 2021) using the World Bank 10m high resolution. This map's data represents the number of buildings for 2020 in this study. For newly urbanised buildings after 2020, we assume that each new pixel has 5 buildings. This value is based on the average number of buildings per pixel in Jakarta from the building count map.

2.3 VULNERABILITY INPUT

Vulnerability curves show the corresponding building damage at different flood depths. This paper uses the curve for a two-story single-family residential building with no basement exposed to short durations of saltwater flooding from FEMA HAZUS (FEMA, 2018) (Figure 5). This building type is most commonly observed in villages like Pluit, Penjaringan and Ancol from Google Maps Street View (see Appendix for photographs of buildings). The corresponding damage at each pixel is extracted and assigned to different areas of the coastal flooding model. If the building's damage percentage crosses the 50% threshold, it is considered significantly damaged. We note that despite structural similarities, the building materials of houses in different neighbourhoods and settlements vary greatly in resilience and such differences are not captured within this vulnerability curve. Another vulnerability curve is used for new buildings elevated by 0.45m in this framework, where the buildings receive significantly less damage at the same flood depth. The revised curve is used for the policy application in the results section to represent the vulnerability of new buildings by 2030.

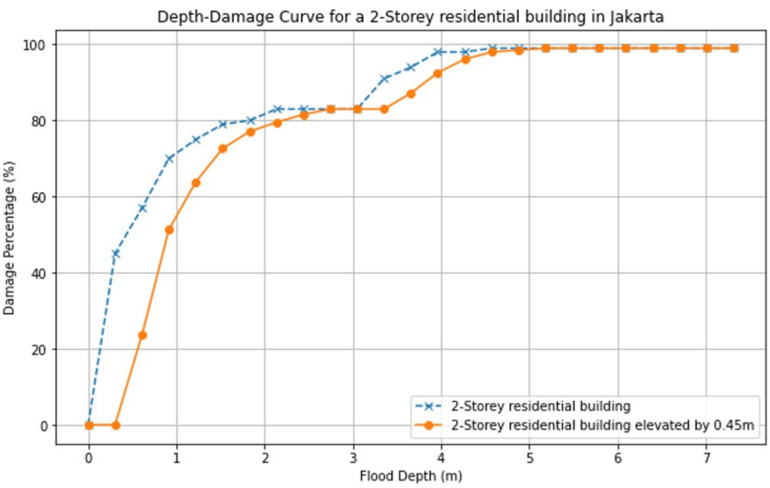


Figure 5: Depth-damage curve for a building type in Jakarta, compared to a depth-damage curve with policy.

2.4 RISK ANALYSIS FRAMEWORK

The following framework is used to analyse risk, and shows the number of exposed buildings, with and without policy (Figure 6). This process was repeated for 12 return periods in 2020 and 2030, in a QGIS, R and Python environment. Firstly, I incorporated the coastal flood model in different return periods with a vulnerability (damage) curve to show the corresponding damage values at flooded pixels. Then, I extracted those damage values at urbanised areas by overlaying the raster with SLEUTH's urban extents, with the assumption that non-urbanised areas don't receive any structural damage. Afterwards, the building is considered significantly damaged if its damage value is 50% or more. Pixels with a damage percentage value of 50 and above were then counted and I obtained the area of significantly damaged urbanised areas in km^2. A building count raster of all buildings in a 30m resolution was also utilised to show the sum of buildings significantly damaged by coastal flooding.

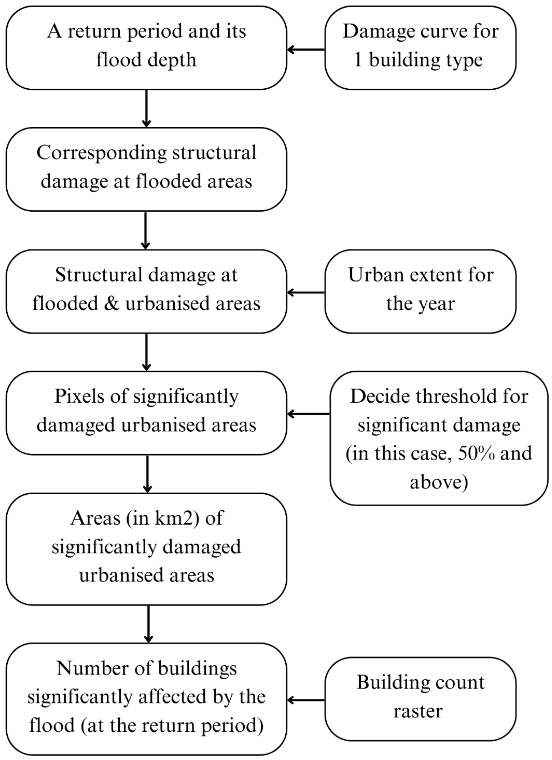


Figure 6: Risk analysis framework in a QGIS and Python environment.

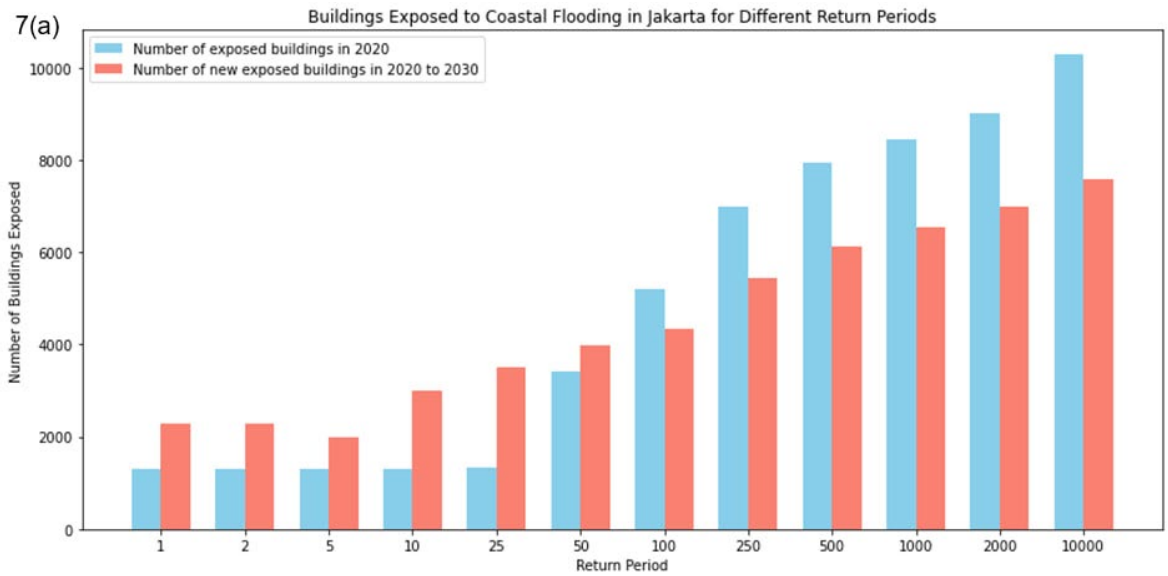
This framework was then repeated using a revised vulnerability curve, which elevated the building heights of future buildings by 0.45m. This hypothetical policy was designed to protect buildings from significant damage (i.e. 50% damage) from a 100-year return period flood. Elevating building heights is a common solution and even a traditional way of constructing buildings in parts of Southeast Asia like Cambodia, Indonesia, and Malaysia. Residents will build their homes on wooden stilts to avoid contact with the flood-prone ground, keeping these residents and their homes safe from flooding (Evers, 2015).

3 RESULTS

Using the methodology described above, we draw two conclusions. Firstly, new urban growth is increasingly exposed to more extreme events. More buildings are projected to be developed from 2020 to 2030 in flood-prone areas (Figure 7a). Since these buildings are still being constructed, future building developers, construction companies, urban planners and the government should enact policies or build the buildings to be more protected from coastal flooding.

Secondly, this framework can be adopted for policy implementation (Figure 7b), aimed at decreasing the number of new significantly exposed buildings. We elevated the building heights by 0.45m and reran the framework for the same return periods and years. With the policy, the number of new exposed buildings built from 2020 to 2030 noticeably decreased for every return period. The decrease in numbers proves the effectiveness of elevating the building height.

These buildings are in areas as seen in Figure 8. Maps of significant damage (>50%) in the years 2020 and 2030 show the villages most affected by coastal flooding. Areas like Pluit, Penjaringan and Kapuk Muara were particularly affected, even in less intense return periods.



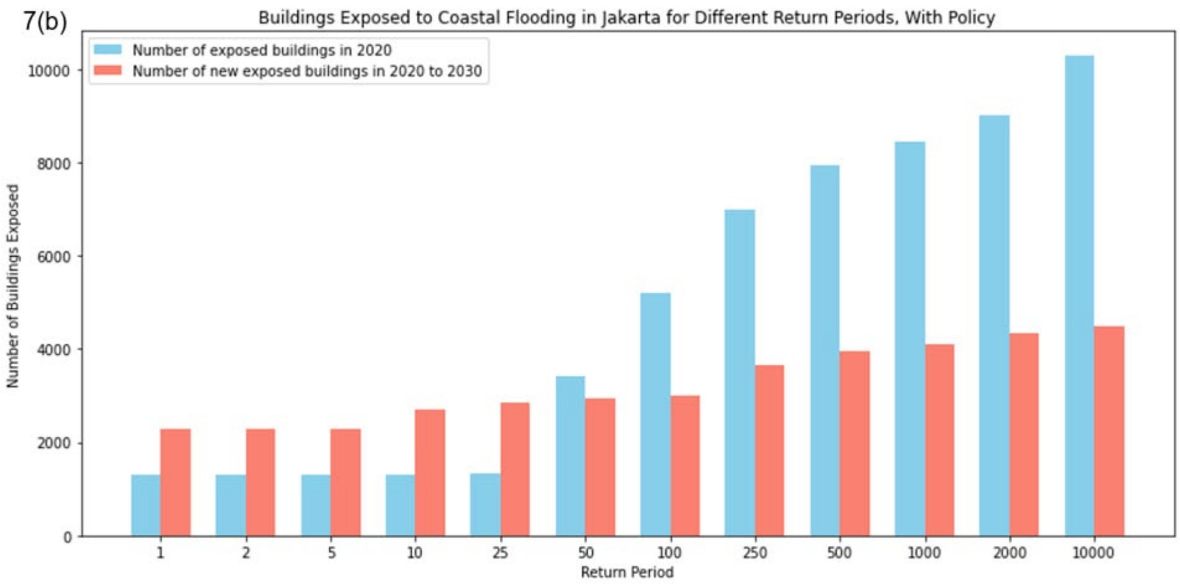
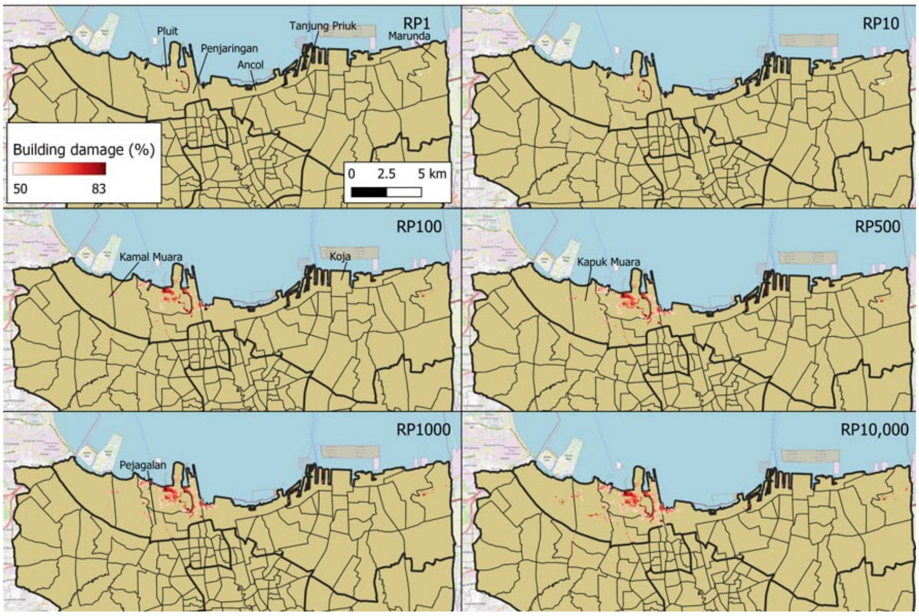
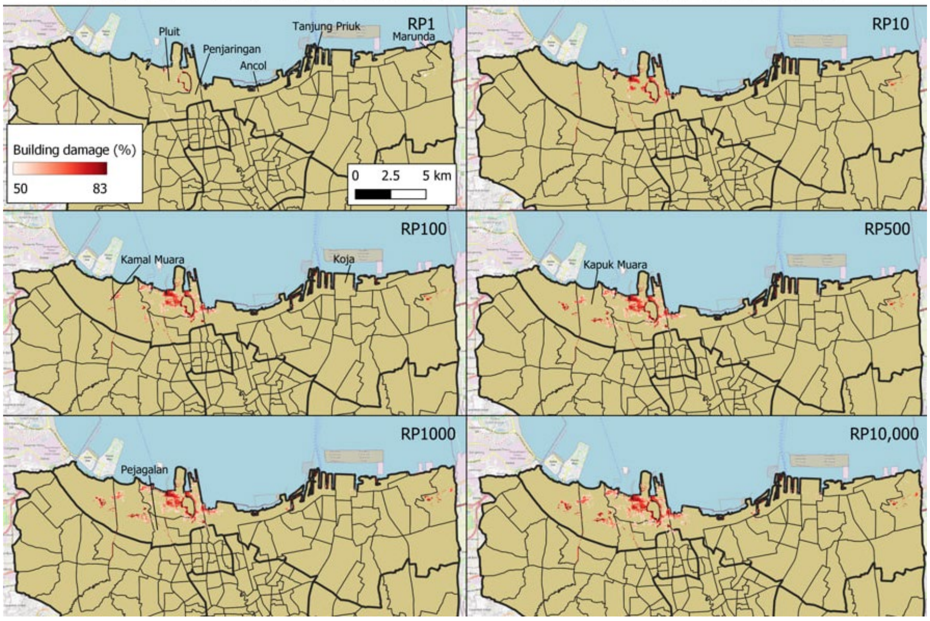


Figure 8 (a) and (b): Projected significant building damage (>50%) for different return periods for the years 2020 to 2030.

Projected building damage from coastal flooding in Jakarta, Indonesia in 2020



Projected building damage from coastal flooding in Jakarta, Indonesia in 2030



4 DISCUSSIONS

4.1 BUILDINGS EXPOSURE

The building is considered significantly exposed to coastal flooding if its pixel intersects the coastal flooding hazard and has crossed the threshold of 50% damage. We compare the exposed building numbers in 2020 with those of the new exposed buildings (that were built between 2020 and 2030). In 2020, the number of buildings exposed to coastal flooding ranged from 1295 to 10301 buildings. The projected number of new buildings built from 2020 to 2030, exposed to coastal flooding ranges from 2275 to 7590 buildings. For return periods 1 to 50, the number of new buildings exposed from 2020 to 2030 is significantly higher than that of buildings in 2020. For return periods 100 to 10,000, the new exposed building numbers are lower than that of 2020's exposed buildings. The number of buildings may plateau due to space constraints. However, with the policy of elevating the building height by 0.45m, the number of new exposed buildings decreases substantially. This decrease in exposure for future buildings shows the effectiveness of relevant flood risk management policies. Below is a table of the values obtained using the risk analysis framework (Table 1).

Table 1: Year VS average annual buildings of significant exposure (>50% damage).

Return Period	2020 Number of buildings significantly exposed	2020-2030 Original number of buildings significantly exposed	2020-2030 With policy, number of buildings significantly exposed
1	1295	2275	2275
2	1300	2275	2275
5	1300	1985	2275
10	1300	2990	2715
25	1322	3510	2860
50	3422	3970	2935
100	5212	4325	3010
250	7003	5440	3655
500	7950	6125	3945
1000	8453	6545	4095
2000	9002	7000	4335
10,000	10301	7590	4490

4.2 FORECASTED AREAS OF URBAN GROWTH

The urban extents from the SLEUTH model in Jakarta for 2030 are rasters of 30m resolution. Comparing 2018 and 2030, the urbanised areas that seem to be expanding in coastal regions include Ancol (resorts, amusement parks), Kamal Muara (high-end residential estates, golf course), Kapuk Muara, Pluit and Marunda. The SLEUTH model prediction of future development overlaps with the construction of Pantai Indah Kapuk in Kamal Muara, Pantai Mutiara in Pluit and Ancol recreational and residential development in Ancol (Wiryomartono, 2020). Little projected urbanisation occurs in Tanjung Priuk, Penjaringan and Koja. While some urbanisation occurs, the built-up extent is smaller than in other villages. Some reasons for decreasing rates of urbanisation can be the lack of space for future development due to the current overcrowding of buildings.

Table 3: Percentage (%) of buildings significantly exposed in the different scenarios.

Village	2020	2020-2030 (original)	2020-2030 (policy)	2020-2030 (reduction after policy)
Pluit	12.11	7.43	4.69	2.74
Penjaringan	13.94	3.00	1.03	1.97
Ancol	1.96	0.823	0.433	0.39
Kapuk Muara	0.416	4.27	2.19	2.08
Marunda	0.525	7.68	7.39	0.29

These 5 villages had the highest exposure to coastal flooding; thus, we examine and rank the number of buildings significantly exposed in each one (Table 2). All villages experience increased flood exposure in the future. Policymakers should note the new development in Pluit and Kapuk Muara with 1545 and 800 new buildings respectively, which will likely be significantly exposed to coastal flooding. Overall, the number of significantly exposed new buildings from 2020 to 2030 decreased with the policy of elevating the heights of the buildings, showing its impact on reducing exposure to coastal flooding (Table 3). Pluit has the most significantly exposed (>50% damage) buildings across the 3 different scenarios, ranking first in exposure while Marunda and Ancol have comparatively low exposure to coastal flooding. A notable finding is that the number of exposed buildings in Marunda and Kapuk Muara increase from 2020 to 2030, suggesting that more buildings are flood-prone in those areas. Pluit, Penjaringan and Ancol all decrease in significant exposure from 2020 to 2030 implying that the growth of future flood exposure is relatively less in these areas.

Areas names	Total building number	2020	2020-2030 original	2020-2030 policy	Ranking (2020)	Ranking (original in 2020-2030)	Ranking (policy in 2020-2030)
Pluit	20784	2517	1545	975	1	1	1
Penjaringan	14019	1954	420	145	2	3	4
Ancol	11537	226	95	50	3	5	5
Kapuk Muara	18751	78	800	410	4	2	2
Marunda	5140	27	395	380	5	4	3

Table 2: Number of buildings significantly exposed (>50%) in each village during a 100-year return period flood.

4.3 FORECASTED AREAS OF COASTAL FLOODING

Most coastal flooding is predicted to occur along Jakarta's northwestern coast. The most affected villages are Pluit, Penjaringan and Kamal Muara. In later return periods, coastal flooding may affect Marunda, a region located along the northeastern coast. Most of these regions are more flood-prone than others due to lower elevation, more severe land subsidence, higher building density and lesser flood defenses. The slow drainage rate of floods in these areas could be attributed to the waste that blocks the drains (Priambodo et al., 2018). Kamal Muara has subsided 133.08mm over 4 years, at a rate of 33.27mm/year (Hakim et al., 2020), making this area more prone to flooding. Pluit also has a reservoir located in its village, hence when coastal flooding occurs, more water tends to build up and may increase the intensity of the damage in buildings nearby.

5 CONCLUSIONS

5.1 LONG-TERM DRIVERS

Population growth and changing building vulnerabilities are drivers of long-term risk and we have demonstrated an approach to capture these time-dependent changes in a dynamic risk framework. Such changes must be considered to accurately capture the consequences of natural hazards, of which coastal flooding is one.

5.2 SIGNIFICANCE OF RESULTS

For Jakarta, on the governmental level, existing flood risk management measures fall under 2 main initiatives. Firstly, preparations are currently underway for the relocation of the capital to Nusantara, East Kalimantan. Secondly, proposals for the "Great Garuda Project" involving the 48.27 km Giant Seawall have been ongoing since 2011 in collaboration with the Dutch government and is projected to cost US$40 billion over the next 30 years (Wiryomartono, 2020). This plan halted in 2017 and resumed in 2024, with construction aimed for completion by the end of 2030.

At the community level, inhabitants are elevating their floors, substituting materials like wood or bricks for their homes and building additional storeys. Other adaptations include moving valuable household items to higher levels, hanging electrical devices above ground and placing clamshells on the ground which cleanses the floodwaters and renders them less susceptible to waterborne diseases (Marfai et al., 2015). Certain districts also construct flood protection structures like in Pluit, where they built a concrete dyke (an embankment to prevent seawater from entering inland) in the early 2000s (Takagi et al., 2017). In Cilincing, residents also built elevated pathways, pump houses, flood gates and drainage systems to adapt to coastal flooding (Baumeister et al., 2023).

Higher-income populations tend to stay further inland, away from the coast. The demographic of those exposed to coastal flooding tends to be poorer – exposure increases with slum density, where buildings are overcrowded and compactly built together. This social division creates issues where migrants living in the slums are unwilling to move out because it is their only home, whereas the well-to-do are not as heavily affected by the coastal flooding and have no incentive to solve it (Legarias et al., 2020). More regulations and solutions are needed in coastal locations, where the exposure of coastal flooding is the highest. Given the building materials of slums compared to high-end residential estates, the vulnerability of lower-income populations is undeniably higher than that of higher-income populations.

5.3 LIMITATIONS AND FUTURE WORK

Some limitations of this study are that the vulnerability curves used only account for one building type. Future works can include using this framework for more building types and other types of policies. By accounting for Gross Domestic Product (GDP) data, we can also calculate future economic losses when buildings are exposed to coastal flooding. Other work can include adopting the framework for other hazards and replicating these results for more cities across the globe as well. This large-scale risk analysis suggests the current and future risk of urban development to coastal flooding, particularly in North Jakarta. It demonstrates the impact of a possible flood protection policy, which the DKI Jakarta Provincial Government can use to construct more resilient buildings in less flood-prone areas.

6 ACKNOWLEDGEMENTS

I would like to thank my supervisors Associate Professor David Lallemant and Dr. Maricar Rabonza for their unending patience, time, invaluable expertise, knowledge, and feedback imparted during the many brainstorming meetings and presentations held for this URECA project. I acknowledge Indraneel Kasmalkar and Gizem Mestav Sarica for their contributions to the hazard and exposure inputs respectively, for which I am most grateful. Lastly, I would like to acknowledge the opportunities and funding support from Nanyang Technological University – URECA Undergraduate Research Programme for this research project.

7DATA AVAILABILITY

The codes used are here: https://github.com/ntu-dasl-sg/DynamicRisk-Jakarta

8APPENDIX

Figure 9: Houses in (a) Penjaringan District, (b) Pluit District, (c) Ancol District, (d) Pluit District. (Google

9 REFERENCES

Asnan, T., Anidah, Hartati, R., & Widodo, S. (2022). Extreme Climates in Coastal Cities. *BIODIVERS - BIOTROP Science Magazine*, *1*(1), 43–48. https://doi.org/10.56060/bdv.2022.1.1.1974

Baumeister, J., Giurgiu, I. C., Linaraki, D., & Ottmann, D. A. (Eds.). (2023). *SeaCities: Aquatic Urbanism*. Springer Nature Singapore. https://doi.org/10.1007/978-981-99-2481-3

Beck, M. W., Losada, I. J., Menéndez, P., Reguero, B. G., Díaz-Simal, P., & Fernández, F. (2018). The global flood protection savings provided by coral reefs. *Nature Communications*, *9*(1), 2186. https://doi.org/10.1038/s41467-018-04568-z

Bilskie, M. V., et al. (2016). Dynamics of sea level rise and coastal flooding on a changing landscape. *Geophysical Research Letters*.

Clarke, K. C., Hoppen, S., & Gaydos, L. J. (1996). *Methods and techniques for rigorous calibration of a cellular automaton model of urban growth*. 21–25.

Clarke, K. C. (2017). Improving SLEUTH Calibration with a Genetic Algorithm: *Proceedings of the 3rd International Conference on Geographical Information Systems Theory, Applications and Management*, 319–326. https://doi.org/10.5220/0006381203190326

Cremen, G., Galasso, C., & McCloskey, J. (2022). Modelling and quantifying tomorrow's risks from natural hazards. *Science of The Total Environment*, *817*, 152552. https://doi.org/10.1016/j.scitotenv.2021.152552

Evers, H.-D. (2015). Kampung Air: Water Settlements on the Island of Borneo. *Journal of the Malaysian Branch of the Royal Asiatic Society*, *88*(1), 79–85. https://doi.org/10.1353/ras.2015.0004

FEMA (2018), HAZUS – Multi-hazard Loss Estimation Methodology 2.1, Flood Model Technical Manual, Federal Emergency Management Agency, Washington D.C., 569p

Google maps (n.d.). [Buildings in Penjaringan District, Jakarta]. Retrieved June 27, 2024, from https://maps.app.goo.gl/CZ9nkG4HbnfTyGsUA

Google maps (n.d.). [Buildings in Pluit District, Jakarta]. Retrieved June 27, 2024, from https://maps.app.goo.gl/UjtmA33ZePWrtBpr5

Google maps (n.d.). [Buildings in Ancol District, Jakarta]. Retrieved June 27, 2024, from https://maps.app.goo.gl/Hta8ntpbxKkzmekx7

Google maps (n.d.). [Buildings in Pluit District, Jakarta]. Retrieved June 27, 2024, from https://maps.app.goo.gl/DTN77gKGSupYEh1p7

Hakim, W. L., Achmad, A. R., Eom, J., & Lee, C.-W. (2020). Land Subsidence Measurement of Jakarta Coastal Area Using Time Series Interferometry with Sentinel-1 SAR Data. *Journal of Coastal Research*, *102*(sp1). https://doi.org/10.2112/SI102-010.1

Hemmati, M., Ellingwood, B. R., & Mahmoud, H. N. (2020). The Role of Urban Growth in Resilience of Communities Under Flood Risk. *Earth's Future*, *8*(3), e2019EF001382. https://doi.org/10.1029/2019EF001382

Jongman, B., Ward, P. J., & Aerts, J. C. J. H. (2012). Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change*, *22*(4), 823–835. https://doi.org/10.1016/j.gloenvcha.2012.07.004

Kasmalkar, I., Wagenaar, D., Bill-Weilandt, A., Choong, J., Manimaran, S., Lim, T. N., Rabonza, M., & Lallemant, D. (2024). Flow-tub model: A modified bathtub flood model with hydraulic connectivity and path-based attenuation. *MethodsX*, *12*, 102524. https://doi.org/10.1016/j.mex.2023.102524

Legarias, T. M., Nurhasana, R., & Irwansyah, E. (2020). Building Density Level of Urban Slum Area in Jakarta. *Geosfera Indonesia*, *5*(2), 268. https://doi.org/10.19184/geosi.v5i2.18547

Marfai, M. A., Sekaranom, A. B., & Ward, P. (2015). Community responses and adaptation strategies toward flood hazard in Jakarta, Indonesia. *Natural Hazards*, *75*(2), 1127–1144. https://doi.org/10.1007/s11069-014-1365-3

Mestav Sarica, G., & Pan, T.-C. (2022). Seismic loss dynamics in three Asian megacities using a macro-level approach based on socioeconomic exposure indicators. *Communications Earth & Environment*, *3*(1), 101. https://doi.org/10.1038/s43247-022-00430-9

Mestav Sarica, G., Zhu, T., & Pan, T.-C. (2020). Spatio-temporal dynamics in seismic exposure of Asian megacities: Past, present and future. *Environmental Research Letters*, *15*(9), 094092. https://doi.org/10.1088/1748-9326/ababc7

Muis, S., Verlaan, M., Nicholls, R. J., Brown, S., Hinkel, J., Lincke, D., Vafeidis, A. T., Scussolini, P., Winsemius, H. C., & Ward, P. J. (2017). A comparison of two global datasets of extreme sea levels and resulting flood exposure. *Earth's Future*, *5*(4), 379–392. https://doi.org/10.1002/2016EF000430

Priambodo, I., Tambunan, M. P., & Kusratmoko, E. (2018). Spatial and statistical analysis on the cause of flooding in Northwest Jakarta floodplain (Kapuk and Penjaringan Districts). *MATEC Web of Conferences*, *229*, 04008. https://doi.org/10.1051/matecconf/201822904008

"Project Gigalopolis." (n.d.). Www.ncgia.ucsb.edu, [www.ncgia.ucsb.edu/projects/gig/About/dtInput.htm. Accessed 4 June 2024](www.ncgia.ucsb.edu/projects/gig/About/dtInput.htm).

Rentschler, J., Avner, P., Marconcini, M., Su, R., & Strano, E. (2023). *Global evidence of rapid urban growth in flood zones since 1985.*

Schuerch, M., Spencer, T., Temmerman, S., & Kirwan L, M. (2018). Future response of global coastal wetlands to sea-level rise. *Nature*, *561*(7722), 231–234. https://doi.org/10.1038/s41586-018-0476-5

Sirko, W., Kashubin, S., Ritter, M., Annkah, A., Bouchareb, Y. S. E., Dauphin, Y., Keysers, D., Neumann, M., Cisse, M., & Quinn, J. (2021). *Continental-Scale Building Detection from High Resolution Satellite Imagery* (arXiv:2107.12283). arXiv. http://arxiv.org/abs/2107.12283

Statistics Indonesia. (2023). *BPS Provinsi DKI Jakarta*. Jakarta.bps.go.id. https://jakarta.bps.go.id/indicator/12/1316/1/population-by-age-group-and-regency-city-in-dki-jakarta-province.html

Takagi, H., Fujii, D., Esteban, M., & Yi, X. (2017). Effectiveness and Limitation of Coastal Dykes in Jakarta: The Need for Prioritizing Actions against Land Subsidence. *Sustainability*, *9*(4). https://doi.org/10.3390/su9040619

Trepekli, K., Balstrøm, T., Friborg, T., Fog, B., Allotey, A. N., Kofie, R. Y., & Møller-Jensen, L. (2022). UAV-borne, LiDAR-based elevation modelling: A method for improving local-scale urban flood risk assessment. *Natural Hazards*, *113*(1), 423-451.

United Nations Office for Disaster Risk Reduction [UNDRR]. (2020). Hazard Definition & Classification Review: Technical Report.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., & Feyen, L. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications*, *9*(1), 2360. https://doi.org/10.1038/s41467-018-04692-w

Wijayanti, P., Zhu, X., Hellegers, P., Budiyono, Y., & Van Ierland, E. C. (2017). Estimation of river flood damages in Jakarta, Indonesia. *Natural Hazards*, *86*(3), 1059–1079. https://doi.org/10.1007/s11069-016-2730-1

Williams, L. L., & Lück-Vogel, M. (2020). *Comparative assessment of the GIS based bathtub model and an enhanced bathtub model for coastal inundation. Journal of Coastal Conservation, 24(2), 23.*

Wiryomartono, B., & Wiryomartono, B. (2020). Capitalist Agenda behind the Seawall development in Jakarta Bay, Indonesia: The marginalization of urban poor. *Traditions and Transformations of Habitation in Indonesia: Power, Architecture, and Urbanism*, 223-245.

World Bank. (2016, January 8). *Keeping Indonesia's Capital Safer from Floods*. World Bank. https://www.worldbank.org/en/news/feature/2016/01/08/keeping-indonesias-capital-safer-from-floods#:~:text=A%20capital%20prone%20to%20flooding&text=Certain%20areas%20of%20North%20Jakarta