Title

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Assessment of Increasing Flood Risks and Application of the Sponge City Concept to Increase Flood Resilience in Ho Chi Minh City

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Abstract

This study assesses the increasing flood risks in Ho Chi Minh City due to climate change and urbanization, and proposes the implementation of the sponge city concept as a solution to enhance flood resilience. Through a comprehensive analysis of literature, data, and models, coupled with GIS techniques, the study reveals the escalating flood risks in the city, both from inland and from the coast. The sponge city concept, which integrates nature-based solutions such as green spaces and water storage facilities, is presented as a means to improve flood resilience. The study analyzes the opportunities and constraints in the application process, provides recommendations to utilize opportunities and overcome constraints, and suggests some potential locations for implementation. The findings highlight the importance of incorporating nature-based solutions into urban planning and development strategies to create sustainable and resilient cities. While focusing on Ho Chi Minh City, the study's recommendations can be applicable to other urban areas facing similar flood challenges. Further research and feasibility studies are recommended to fully implement the sponge city concept.

Keywords: flood risks, climate change, urbanization, resilience, sponge city concept, nature-based solutions, Ho Chi Minh City.

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Chapter 1: Introduction

Climate change is defined as “long-term shifts in temperatures and weather patterns” (United Nations), which can be caused by both natural and anthropogenic factors. Earth’s climate has always been changing throughout its formation history, but the current climate change we are observing has proven to be dominantly caused by human activities such as burning fossil fuels and deforestation. The consequences of human-induced climate change include heatwaves, droughts and floods, sea level rise, and intensified hurricanes among other extreme weather events. These climate hazards have been and will continue to pose significant risks on all species on the planet, including humans. More than half of the world’s population lives in cities (IPCC, 2022), and this proportion is expected to increase to two thirds by 2050 (UN DESA, 2018). According to the World Economic Forum, 80% of cities worldwide, which is about 1.4 billion urban dwellers, are currently experiencing extreme climate-related events (Aki-Sawyerr et al., 2023), one manifestation being increasing flood risks. Human settlements often took place in deltas and alluvial plains adjacent to coastline since early days (Griggs, 2017), due to milder temperatures and abundant resources on the coast. As a result, cities are often developed in these extremely flood-prone areas. According to the most recent IPCC Assessment Report, coastal regions around the world are seeing more flooding from sea level rise, which has caused more frequent coastal flooding as well as chronic flooding at high tides, and from heavy precipitation events, which increases water from inland (IPCC, 2021). Flooding poses significant challenges to the lives and livelihoods of coastal communities, ranging from disruption of transportation to hygiene problems, spread of diseases, injuries, and loss of properties and lives. Increasing flood risks is disproportionally felt among coastal cities, with those in developing countries struggling due to limited adaptive capacity.

Vietnam is a developing, economically robust country in Southeast Asia, with its population estimated at 97.5 million as of 2021 (World Bank, 2022). The nation is ranked among the five countries most susceptible to climate change (Arndt et al., 2015), the impact of which cost Vietnam an estimate of $10 billion in 2020, or 3.2 percent of GDP (World Bank, 2022). The country will lose about 12 percent to 14.5 percent of GDP a year by 2050 if no proper adaptation and mitigation measures are implemented (World Bank, 2022). Flood is the most prevalent climate-related risk in Vietnam, as the nation is ranked joint 1st with Bangladesh as those with highest exposure to flooding, including riverine, flash, and coastal flooding (World Bank and ADB, 2021). Vietnam is also among the most exposed to tropical cyclones and their associated hazards (World Bank and ADB, 2021). These climate change impacts will not only set back the ambitious goal of the Vietnamese government to reach high-income status by 2045 but also pose significant risks to the lives and livelihoods of nearly 100 million people, especially when major cities with large populations and great shares of the country's economy will be facing major climate change induced issues.

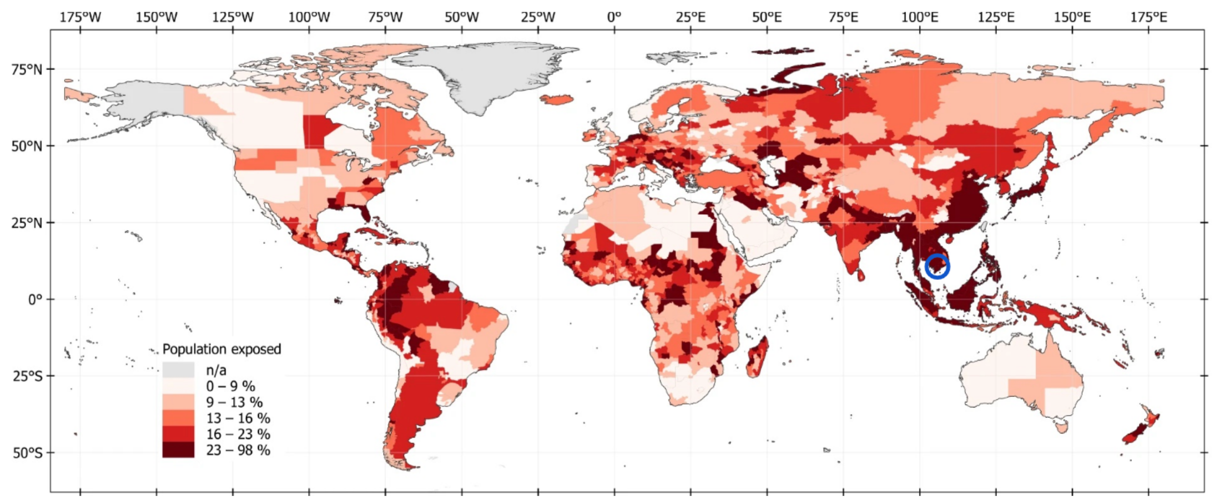

Figure 1: Population exposed to floods (Rentschler et al., 2022), with the Ho Chi Minh City area circled

Ho Chi Minh City is Vietnam's biggest population hub - an emerging megacity with a population of over 9 million people, and it is also the economic center that holds a quarter of the country's GDP (Pham, 2022). Meanwhile, the IPCC has concluded with high confidence that Ho Chi Minh City faces great risk of climate-driven flooding, sea level rise, and extreme rainfall (IPCC, 2022). The city is located in a tropical monsoon climate with two distinct seasons: rainy and dry, of which the rain season that spans from May to November is responsible for over 90 percent of annual precipitation (Figure 2a). It is built on low-lying marshland that is only 5 meters above sea level on average, of which nearly half the area lies less than 1 meter above sea level (Katzchner et al., 2016), and is situated in close proximity to major water bodies, including the Saigon River, Dong Nai River, and South China Sea, as well as various minor channels and canals (Figure 2b). Due to its geographic location and natural conditions, the city has always been prone to flooding, but the frequency and intensity of these events have been on the rise in recent years due to climate change and urbanization (Paulo and Rivai, 2021): climate change causes sea level rise and more frequent and intense extreme rainfall events, while urbanization leads to urban flooding and land subsidence.

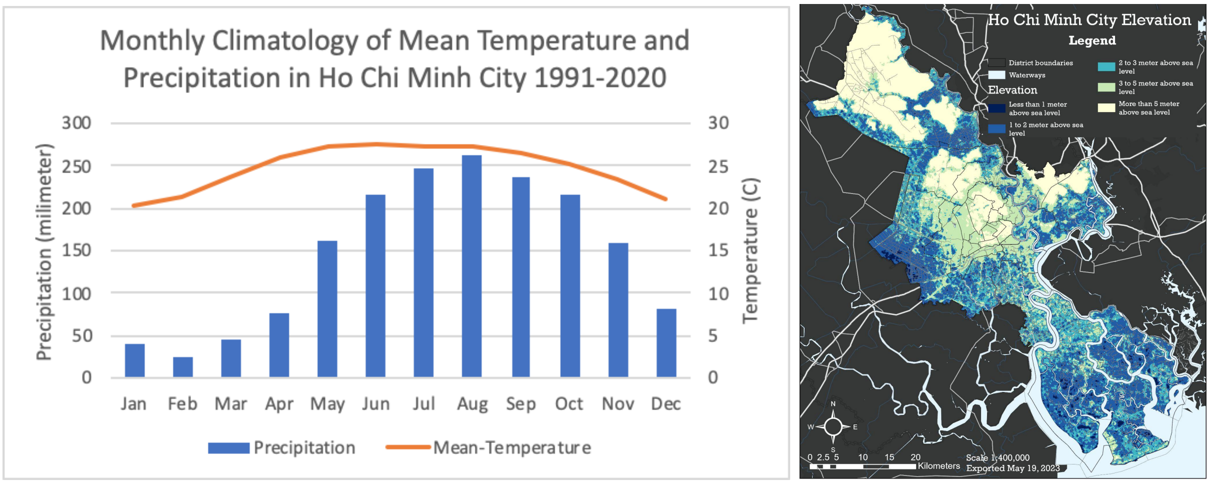

Figure 2: (a) Monthly Climatology of Mean Temperature and Precipitation in Ho Chi Minh City (World Bank Climate Change Knowledge Portal, 2021) and (b) Elevation of Ho Chi Minh City

As climate change and urbanization proceed, the situation will likely worsen in the upcoming future if no appropriate measures are taken. One way to increase a city's resilience to flooding is the improvement of stormwater management, which can take the forms of gray or green water infrastructure. Gray stormwater infrastructure such as gutters, sewers, and tunnels built with concrete are meant to move water away without absorption and filtration, therefore posing issues of pollution and flooding when overwhelmed. Meanwhile, green infrastructure is nature-based solutions such as lakes, plants, soil, and other permeable natural surfaces that can effectively filter, collect, and divert water, while also providing ecological services. Overall, green infrastructure was found to be more cost-effective than gray infrastructure (Daigneault et al., 2016). The “sponge city” is one type of system of green stormwater infrastructure, a concept developed and implemented in China. This concept involves using abundant natural landscapes to carry out three main functions of absorption, flow adjustment, and outflow into oceans or sinks (Thornett, 2023). There are multiple co-benefits associated with this model, including mitigation of climate change and its effects, improvement of biodiversity, providing recreational and cultural space, reducing pollution, and countering both floods and droughts. The concept not only exists in theory but also in practice: China has made a national initiative to implement this model in 30 cities, a prime example of which is Shenzhen - a coastal megacity with a lot of similarities with Ho Chi Minh City in Vietnam. The sponge city concept therefore provides great opportunities for Ho Chi Minh City to tackle increasing flood risk, and referring to the projected elevation and general land-use, this project will identify areas that can benefit from green flood solutions and propose some type of sponge city infrastructure that may be suitable for these areas. While there are multiple benefits and opportunities in implementation of the sponge city concept, the process also faces significant constraints related to funding, geography and technology, and socio-economic and institutional structures, which will be identified in this study, along with some recommendations to overcome these challenges.

Chapter 2: Methodological Approach

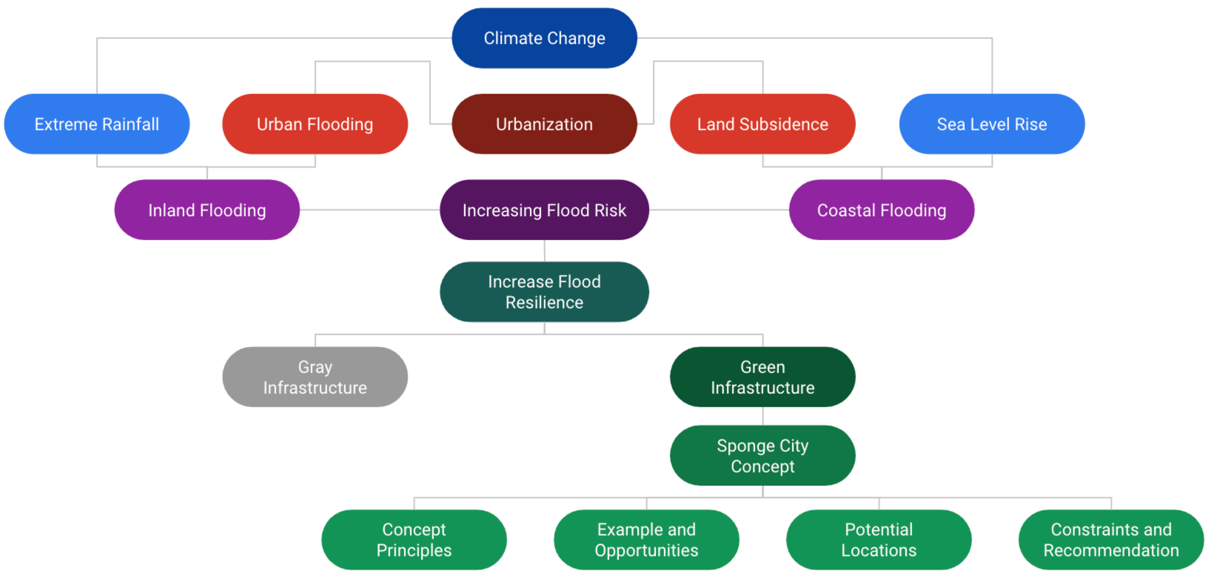

Figure 3: Outline of the methodological approach

The two main themes of this study are assessment of increasing flood risk and application of the sponge city concept as measures to increase resilience to flooding, in the context of Ho Chi Minh City.

Increasing flood risks in Ho Chi Minh City are caused by climate change and urbanization. Climate observations and projections of the region show more frequent and intense extreme rainfall events as well as sea level rise, both of which contribute to more flooding, while urbanization enhances flooding through land subsidence and urban flooding phenomenon. The study will review literature to understand the mechanism by which each of these factors contribute to the increase in flood risks, and how the impacts may couple with one another. Urban concrete non-permeable infrastructure will make the city more likely to be flooded from inland in the context of more frequent and intense extreme precipitation events. Sea level rise in combination with land subsidence means lower elevation relative to sea level, which will make the city more exposed to coastal floods, and this part of the study will be visually displayed by projection and mapping of the future elevation of the city with GIS tools. Flooding from inland and flooding from the coast together has posed great difficulties for the city and the risk will continue to grow in the future.

This situation calls for the need to increase resilience to flooding in Ho Chi Minh City. A brief comparison of gray and green infrastructure will be done in order to show the superiority of nature-based solutions. The study will specifically draw attention to the sponge city concept, first explaining the principles, then providing an existing example in Shenzhen and pointing out opportunities for application in Ho Chi Minh City. Certain types of infrastructure with the potential to mitigate flooding in areas identified as vulnerable in the previous chapter will also be proposed. The last part will identify some challenges in the application process and recommend some possible solutions.

Chapter 3: Assessment of Increasing Flood Risk

3.1. Inland Flood Risk

3.1.1. Climate change and extreme rainfall

Global warming will intensify the Earth's water cycle, therefore making more rain in some areas while drying up others (NASA Global Precipitation Measurement). Climate change will also affect the ENSO cycle, increasing the frequency of extreme El Niño and La Niña events, therefore altering precipitation patterns around the globe (NOAA, 2020). Observations from the previous century in Ho Chi Minh City did not show a consistent trend in annual average precipitation: while annual precipitation fell by an average of 21.16 mm per decade between 1971 and 2020, there are increasing trends when looking at a longer period of 1951-2020 or a shorter more recent period of 1991-2020 (Figure 4). Future projections are at variance with one another due to uncertainties in cloud and precipitation modeling, but the median result across climate models yields a slight decrease in annual rainfall in the low emissions scenario SSP 1-1.9, neither increase or decrease in the medium-high scenario SSP 3-7.0, and a slight increase in other scenarios (Figure 5a). According to monthly projections for the 2060-2079 period (Figure 5b), minor anomalies can be expected from December to April, which is during the dry season, while changes are more pronounced from May to December. More specifically, less rain is expected in May - the beginning of the rainy season in all climate scenarios, implying a later start of the rainy season. The rest of the rainy months from June to November will likely see less rain in SSP 1-1.9, fluctuating anomalies in SSP 3-7.0, and more rain in other scenarios, which may suggest that the rainy season will be shorter.

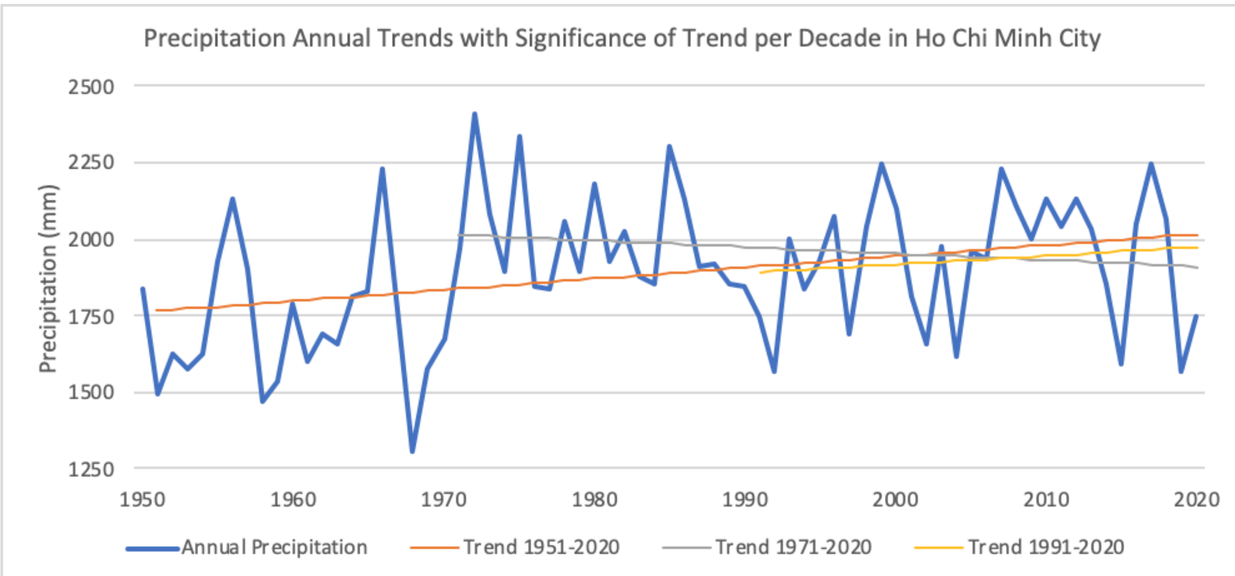

Figure 4: Precipitation Annual Trends with Significance of Trend per Decade in Ho Chi Minh City (World Bank Climate Change Knowledge Portal, 2021)

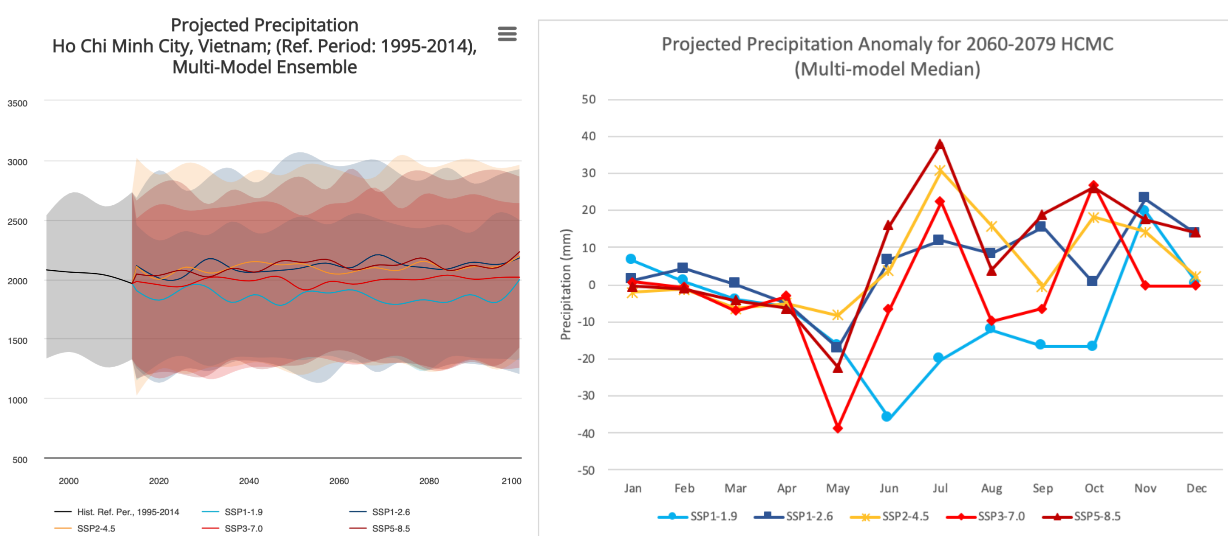

Figure 5: (a) Projected Annual Precipitation to 2100 and (b) Projected Precipitation Anomaly for 2060-2079 in Ho Chi Minh City (World Bank Climate Change Knowledge Portal, 2021)

Climate change not only affects the distribution of precipitation and the total amount of annual or seasonal rainfall at each location, but also the occurrence of extreme rainfall. Extreme rainfall refers to heavy precipitation concentrated in a short period of time (in a few hours or a day) that exceeds what is considered normal (average over month or year). Global warming can increase the intensity and frequency of these events, as warmer oceans enhance evaporation of water into the atmosphere, and this more moisture-laden air can produce heavier rain as it moves over land or converges into a storm system (US EPA, 2022). Ho Chi Minh City is located by one of the warmest waters of the world, and it is also within the impact zones of extreme El Niño and La Niña episodes (NOAA, 2020). It has been forecasted that the region will likely see more frequent and extreme rainfall events as well as tropical cyclones because of climate change (World Bank and ADB, 2021), and such events will pose significant risks of wind damages, landslides, and floods.

Fluvial flooding is the overflow of rivers onto the surrounding banks, shores and neighboring land, which is often caused by excessive precipitation quickly draining into rivers and raising water levels. In Ho Chi Minh City, river floods can occur under two main mechanisms: (1) extreme precipitation occurring in the upstream of Saigon River and Dong Nai River, increasing the volume of water flow towards the downstream floodplain where the city is located; and (2) extreme precipitation occurring within the city boundaries itself, directly adding to water levels in rivers and canals in the city. Another type of flooding that can unfold after extreme precipitation events is pluvial flooding, which can occur anywhere, notwithstanding the proximity to water bodies, whenever water accumulates on the land surface faster than it is absorbed or drained. Two common types of pluvial flooding are flash floods, which are raging torrents that move at great speed toward downstream within a short period of time after heavy rainfall events, and surface water floods, which occur gradually when urban drainage systems are overwhelmed and allow water to flow out into streets (Zurich, 2023). Due to their abrupt and robust nature, flash floods are extremely hazardous and even fatal. The intensity of flash flood is dependent on various factors besides rainfall, including the energy that floodwaters derive from the topography and soil saturation (Zurich, 2017). Flash floods are generally more likely to occur in steep terrains than in vast flatlands where Ho Chi Minh City is situated, but certain areas of the city that have more complex topography such as Thu Duc City (Ho Chi Minh City's sub-city) can still initiate flash floods (Le Phan and Chau Tan, 2022). Flash floods will be accelerated and more violent if water cannot permeate through soil. On the other hand, surface water floods are relatively less dangerous due to their slow-paced accumulation and often shallow submergence, but they still pose significant economic damage and health concerns. Surface water floods are also more substantial on impermeable surfaces. This phenomenon, known as urban flooding, will be discussed in the following section.

3.1.2. Urbanization and urban flooding

The history of concrete dates back to thousands of years ago, but modern use of concrete only began about three centuries ago (Science Museum, 2021). Due to its durability and high compressive strength, and later improved tensile strength with the creation of reinforced concrete, this composite material quickly became the foundation of not only infrastructure projects and civil engineering, but also the whole built environment in Europe in the 20th century, and subsequently in the whole world. Concrete represents human's ambition to tame nature, acting as a "rock-hard second skin" that protects us from rain, cold, and the natural world in general (Watts, 2019). The gray color of concrete buildings, roads, pavements, and other infrastructure has become what characterizes the urban landscape today. However, it is precisely the water resistant characteristic meant to keep us dry in the rain that is making our cities more prone to flooding. Unlike on vegetation cover where water permeates and travels through the soil towards sinks, water runs off of concrete structures and accumulates when drainage systems are overwhelmed. This phenomenon is referred to as urban flooding, and it is a common problem in almost all cities around the world.

Urban flooding will make cities already at high risk due to more frequent extreme rainfall caused by climate change even more prone to get flooded. Risks of river floods will increase as stormwater can move more rapidly into water bodies, therefore consistently raising water levels and causing overflow to the floodplain. Pluvial floods are also expected to occur more often and last longer as water can quickly accumulate on the surface without natural absorption. Flash floods are often less serious in areas of flat topography, but the likelihood and velocity of flash floods are especially heightened in urban areas due to the easiness of water to move on top of gray materials without absorption and friction, such as in the situation in Thu Duc City mentioned above. Urban flooding will add to the already growing flood risks from more frequent and intense extreme rainfall events due to climate change, putting Ho Chi Minh City into an even greater dilemma.

3.2. Coastal Flood Risk

3.2.1. Climate change and sea level rise

Another major consequence of climate change is sea level rise. The warming of the planet is causing land ice and mountain glaciers to melt, adding fresh water into the ocean and therefore causing sea level to rise. Thermal expansion, where sea water expands as it gets warmer, also adds to the process. Melting of sea ice, which was initially thought to have no impact on sea level, was also recently found to contribute a small amount to sea level rise (Huang, 2023). According to NASA, global mean sea level has risen by 98 millimeters since 1993, and the process has been accelerating in recent years at unprecedented rates. Observations at Hon Dau Oceanographic station off the shore of Ho Chi Minh City have shown that sea level rose at a rate of 3 mm/year between 1993 and 2008 (Katzschner, 2016), which is consistent with the global rate. The IPCC AR6 projects a rise of 200 to 250 millimeters relative to the 1995-2014 baseline by 2050, and the rate would increase to 4.4 to 8 mm/year between 2040 and 2060, depending on different climate scenarios (Garner et al., 2021).

The most noticeable impact of sea level rise is coastal flooding, which is the submergence of low-lying coastal lands by seawater. Should sea level exceed the land elevation, coastal lands can be permanently inundated and become submerged landscapes. This would be the case for about 66 percent of Ho Chi Minh City's area if sea level were to rise by 1.8 meters (McKinsey Global Institute, 2020). While such an extreme scenario is yet to come by the end of this century (Garner et al., 2021), given that 40 to 45 percent of the city area is 0 to 1 meter above sea level (Katzschner, 2016), many parts of the city will still be underwater by the next decade. Permanent inundation is not the only form of coastal flooding caused by sea level rise. Tidal flooding refers to the temporary inundation of low-lying areas during exceptionally high tide events. This applies not only to areas directly on the ocean coast, but also those by rivers as high tides add to the water levels near river mouths. With higher sea level, flooding can occur even on days with less extreme tides and flooding will be even more intense on days with more extreme tides. For Ho Chi Minh City, this means that half of the land that is barely above sea level will experience this type of nuisance flooding more frequently. Storm surge is another type of coastal flooding that occurs when high-speed wind associated with tropical cyclones pushes water towards the coast over a long fetch (Yin et al., 2020).

Storm surges will become more frequent and intense as the ocean warms and generate more and stronger hurricanes, and will be even higher due to sea level rise. Unlike permanent or tidal floodings which allow time to adapt and can be more predictable, storm surges are much more dangerous to coastal population and infrastructure due to uncertainty in forecasting, shorter warning time, and more damaging strength.

3.2.2. Urbanization and land subsidence

Land subsidence is the sinking of the Earth's surface, which can occur due to a variety of reasons, both through natural geomorphological processes such as sinkholes or thawing permafrost and human activities such as underground mining and aquifer-system compaction (USGS Water Resources Mission Area, 2019). Ho Chi Minh City is located away from major subduction zones, so the causes of land subsidence have been identified to be dominantly anthropogenic, with the most prevalent being groundwater extraction (Tay et al., 2022). Although groundwater is a renewable resource, its availability is unfixed. The stock of groundwater, according to Roumasset and Wada (2012), is dependent on recharge, natural leakage, and extraction, and it would stay in equilibrium should the sum of extraction and leakage be in parity with recharge. When such equilibrium is broken by over-extraction and slow recharge rate, the aquifer system will be compacted, leading to the sinking of land, and this is exactly what has been happening in Ho Chi Minh City. A study by Tay et al. (2022) recently found that Ho Chi Minh City is sinking faster than any other coastal city in the world, at a much more rapid rate than previously estimated vertical land motion (Figure 6).

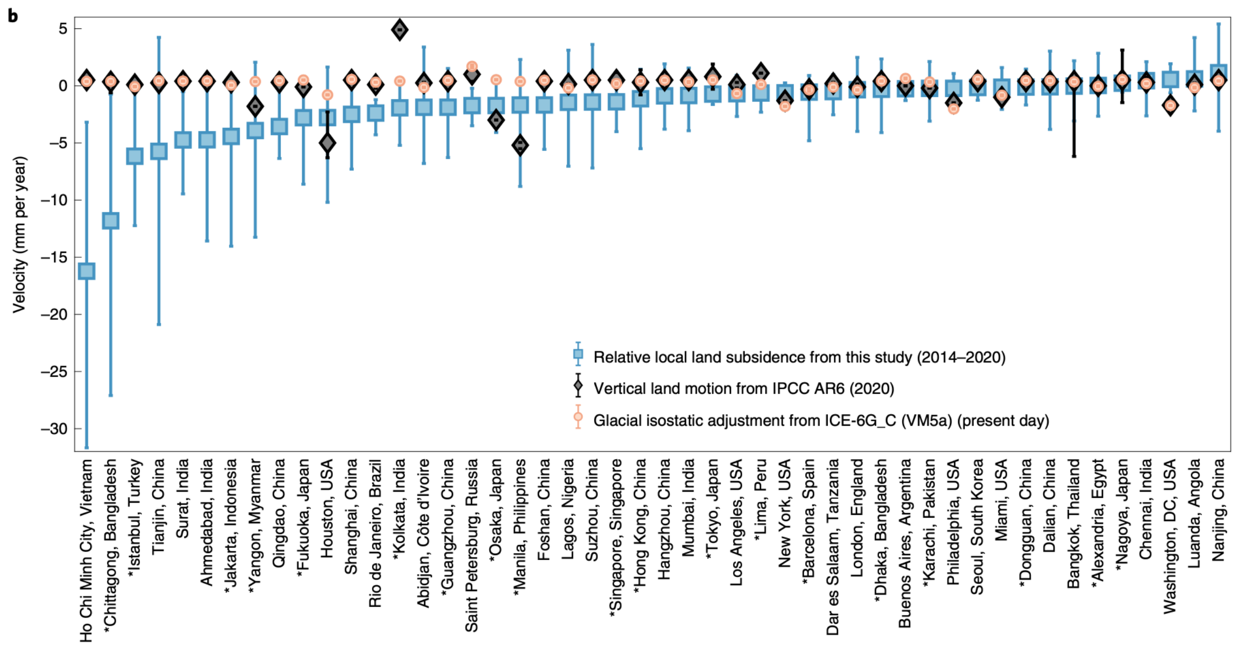

Figure 6: Relative local land subsidence across 48 coastal cities (Tay et al., 2022). Ho Chi Minh City has the highest sinking velocity among cities in this study, majorly diverging from previous assumptions.

Groundwater abstraction began in Ho Chi Minh City in 1920, when the French colonizers began to develop the then-called Saigon as a major city of Indochina, and has since served as a supplemental source for surface water from rivers. From 1990, following Vietnam's new economic policy and under the new world conditions as the Cold War ended, Ho Chi Minh City saw rapid industrialization and urbanization. Accompanying such growth was an increase in water demand from both industry and domestic sectors that surface water resources alone could not meet, so extraction of groundwater was intensified throughout the next two decades. Vuong et al. (2016) found that from 2006 to 2010, the number of wells almost tripled and the rate of extraction increased by over 20 percent. By 2010, almost half of the city's water supply came from groundwater, so at this point, abstraction exceeded recharge by nearly 30 percent. Statistics have proven that as the population grows, so does water demand. Urbanization further amplifies the issue as a city dweller uses 1.5 times more water than a rural person. Industrial activities and tourism also increase water stress. As population and urbanization are projected to continue to be on the rise, while industry and tourism are priorities in the city's economic development plan, Ho Chi Minh City will be even under more water pressure, hence facing critical challenges in managing the rate of groundwater extraction.

Meanwhile, the rate of groundwater recharge depends on multiple reasons. The city receives around 1800 to 2000 millimeters of rainfall annually, of which over 90 percent comes from the rainy season, which only lasts half of the year (Ho Chi Minh City Power Corporation, 2014), and Vuong et al. (2016) has found considerable seasonal fluctuations in groundwater head levels. Furthermore, less than 30 percent of rainfall goes to recharge aquifers, due to both natural properties such as elevation of land, surface of water bed, soil type, etc. as well as land use. Specifically, concrete urban landscape prevents water permeation through the soil down the aquifers. The heavy weight of concrete infrastructure and buildings also insert more pressure on the aquifers and enhance leakage. Over-extraction of groundwater, slow recharge rate, and more leakage cause aquifers to shrink, making land subside as a consequence.

Beside groundwater abstraction, Nguyen (2016) identified other reasons for the fast rate of land subsidence in Ho Chi Minh City, including mismanagement of underground infrastructure such as water pipelands electricity cables, and former minings, and pressure from heavy urban constructions combined with the area's weak soil and high groundwater geological structure. Urbanization processes together with the geological characteristics of the land has caused Ho Chi Minh City to become the fastest sinking city in the world, making it more exposed to flooding, especially in the context of climate change and sea level rise.

3.2.3. Lower elevation as a result of sea level rise and land subsidence

While local land subsidence has become a widely recognized problem, this factor has hardly been included in research on sea level rise at global scale due to significant regional variations. However, in the case of low-lying and fast-sinking coastal areas such as Ho Chi Minh City, failure to take into account local land subsidence can result in underestimation of exposure to sea level rise. The lower the land elevation relative to sea level, the more susceptible the city is to flooding impacts of sea level rise discussed above.

The methodology of this study is inspired by the "bathtub model" described by Tay et al. (2022) in the supplementary section on potential applications of their results of relative local land subsidence. Using CoastalDEM v2.1 (Kulp and Strauss, 2021), a 3 arcsecond horizontal resolution digital elevation model for ocean coastal areas developed by Climate Central, as the base digital elevation model (DEM), this study brought in the rate of local land subsidence in Ho Chi Minh City found by Tay et al. (2022) and sea level rise projection from IPCC AR6 to calculate future scenarios of relative elevation compared to sea level. Ho Chi Minh City is not located near any major natural subduction zone, so the model uses a steady rate projection of subsidence into the future. The full methodology is provided in the supplementary section. The result of this study is a series of maps of Ho Chi Minh City's elevation in the future under five different Shared Socioeconomic Pathways (SSPs) in years 2030, 2050, 2070, 2100, and 2150. The maps produced in this study by themselves can be used to identify areas that will be under sea level in the nearer and further future, thereby informing urban planning of the necessity for short-term or long-term adaptation and mitigation measures. The result of the study can be improved by further research into the response of land subsidence in different socioeconomic factors such as the escalation in groundwater extraction due to rising water stress or construction of more infrastructure, instead of assuming no major changes and therefore steady rate of subsidence. While this model predominantly only indicates soon-to-be submerged landscapes, it can be used in combination with storm surge or tidal forecast models to better understand the flood risks of each area in the city.

In particular, parts of Binh Chanh district to the west of the city center will be under sea level as soon as 2030, and most of the district will likely be underwater by 2050, so it is urgent that the city come up with flood mitigation measures for the short term while considering relocating vulnerable communities and infrastructure for the longer term. Rural districts of Cu Chi, Hoc Mon, and Nha Be, as well as the newly formed sub-city Thu Duc to the east of the center, will also soon have areas under sea level. Can Gio district in the south, which is the city's gate to the ocean where few people currently reside and home to natural mangrove ecosystems, will see its land under sea level almost immediately; therefore, the situation may suggest revision of the city's plan to develop Can Gio into a center for tourism, especially in additional consideration of impacts of hurricanes.

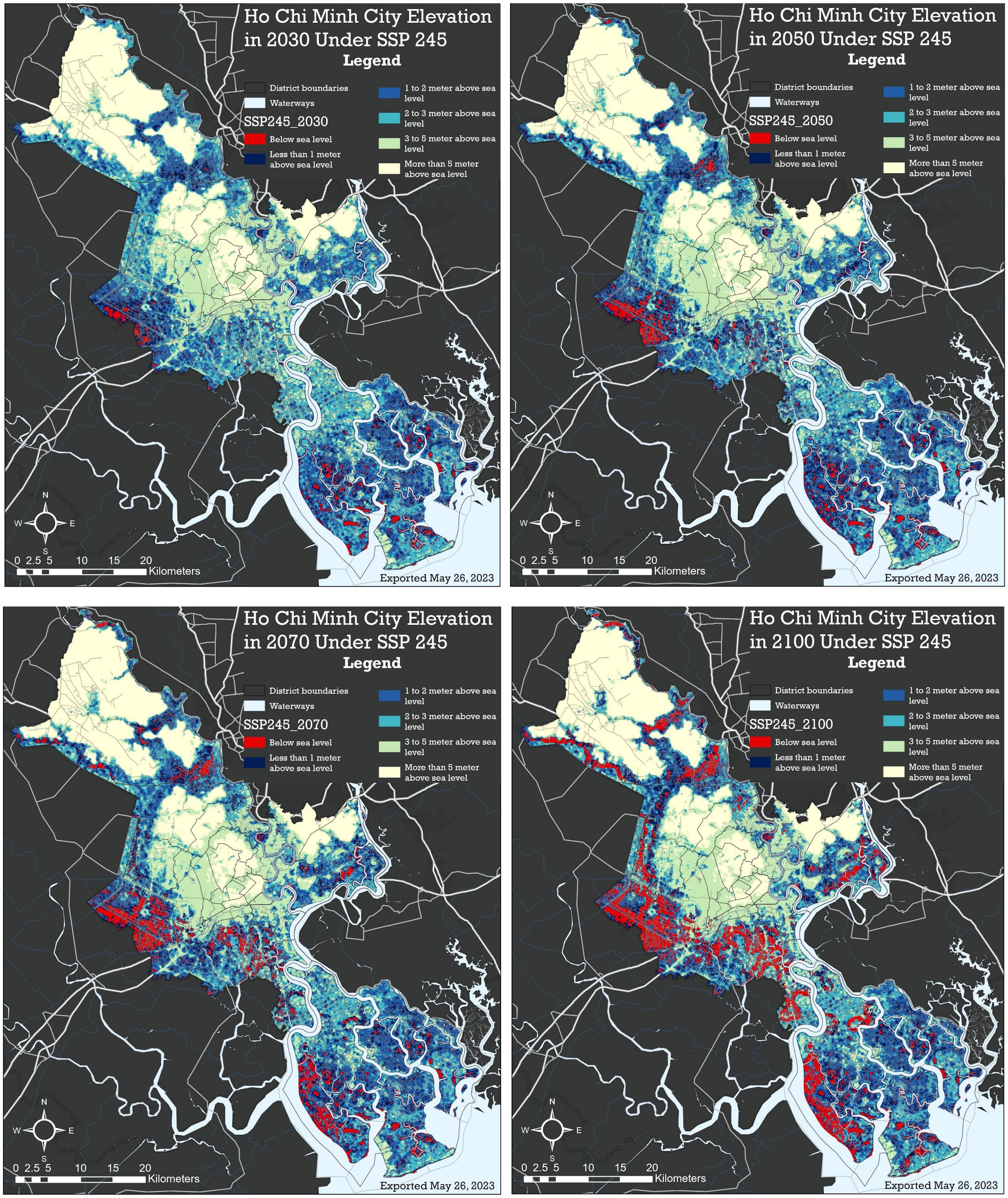

Figure 7: Projected elevation of Ho Chi Minh City under SSP 2-4.5 in (a) 2030, (b) 2050, (c) 2070, and (d) 2100

3.3. Summary

Due to climate change, Ho Chi Minh City will suffer from both heavy precipitation events and sea level rise. While each of these factors contribute to all different types of flooding, including coastal, river, flash, and urban floods, in different ways. Together these factors will enhance flooding even further, such as lowering of elevation due to sea level rise and subsidence, or more flood events due to extreme rainfall and urban impermeable surfaces. The impacts will even become more severe as all of these elements add up: escalating sea level pushes ocean water up while more frequent and intense extreme rainfall adds to water inland, closing two sides of the pincer and causing substantial flooding as a result (Muangsri et al., 2023). This dilemma calls for urgent development of flood mitigation measures for the short term, and potentially relocation of parts of the city for the longer term.

Chapter 4: Application of the Sponge City Concept to Increase Flood Resilience

4.1. Gray vs. Green Stormwater Infrastructure

Stormwater management solutions can be categorized into gray infrastructure and green infrastructure. Gray infrastructure is the “traditional” method of stormwater management in the built environment, which includes gutters, drains, pipes, and retention basins (US EPA, 2023). Green infrastructure, on the other hand, is inspired by how nature originally captures rainwater to incorporate that into the built environment. Examples of green infrastructure are permeable pavement, rain gardens, bioretention cells, vegetative swales, infiltration trenches, green roofs, rainwater harvesting, urban tree canopies (US EPA, 2023), as well as natural landscapes such as forests, wetlands, and mangroves. A report by the World Bank and the World Research Institute indicates that traditional human-built gray infrastructure would put costs at the higher end of that spectrum and would no longer be sufficient to provide the climate resiliency and level of services required in the 21st century (Browder et al., 2019). Gray infrastructures are originally engineered to prevent flooding by directing stormwater away, but in many cases, these solutions generate more problems. Upstream dam operations and levees meant to regulate river flow and control flood water turn out to disconnect floodplains from rivers and reduce capacity to capture and store water and attenuate peak flows, which leads to more river floods. Insufficient urban stormwater management systems occasionally fail and overflow, flooding cities with stormwater mixed with unhygienic sewage discharge. The situation calls for the need to integrate green infrastructure in the scene, which can deliver a triple-win for the economy, communities, and the environment (Browder et al., 2019). A group of researchers from New Zealand has found through cost-benefit analysis and comparison that green infrastructure options are more cost-effective than gray infrastructure in flood mitigation, especially when both avoided damages from floods and ecosystem service co-benefits are considered (Daigneault et al., 2016). The World Economic Forum has deemed nature as “the most resource-efficient solution to help build resilient, vibrant and future-proof cities” (Aki-Sawyerr et al., 2023).

4.2. Principle of the sponge city concept

Sponge city is a nature-based concept for urban water planning (Nguyen et al., 2019). This concept was invented by professor Kongjian Yu of Peking University in 2013 to refer to a city with natural landscapes intended to prevent flooding by absorbing water rather than having concrete infrastructure channel water away (Sagris, 2022). Sponge city design is based on three fundamental principles: (1) absorbing water with sponge holes of lakes, vegetation and permeable surfaces; (2) slowing and guiding the flow with winding rivers and vegetation wetlands surrounding water bodies; and (3) allowing water to flow into the ocean by turning coastlines into natural sinks and avoiding constructions along waterways (Thornett, 2023). Examples of sponge city infrastructures include wetlands, waterfront parks, lakes, ecological parks, permeable pavement, green streets, and so on. This nature-based solution not only absorbs, stores, filters, and purifies rainwater to prevent flooding, but it is also expected to solve droughts by releasing water for usage when needed (Figure 8). The sponge city concept can also reduce pollution thanks to water infiltration, restore biodiversity with abundant natural landscapes, provide cooling effects to counter urban heat island effects, and mitigate climate change by increasing natural carbon sinks. Beside ecological and climate co-benefits, the sponge city concept also delivers social and economic co-benefits. Green parks provide aesthetics for the city landscape and cultural and recreational spaces for residents, encourage creativity and love for nature, attract tourism, among many others.

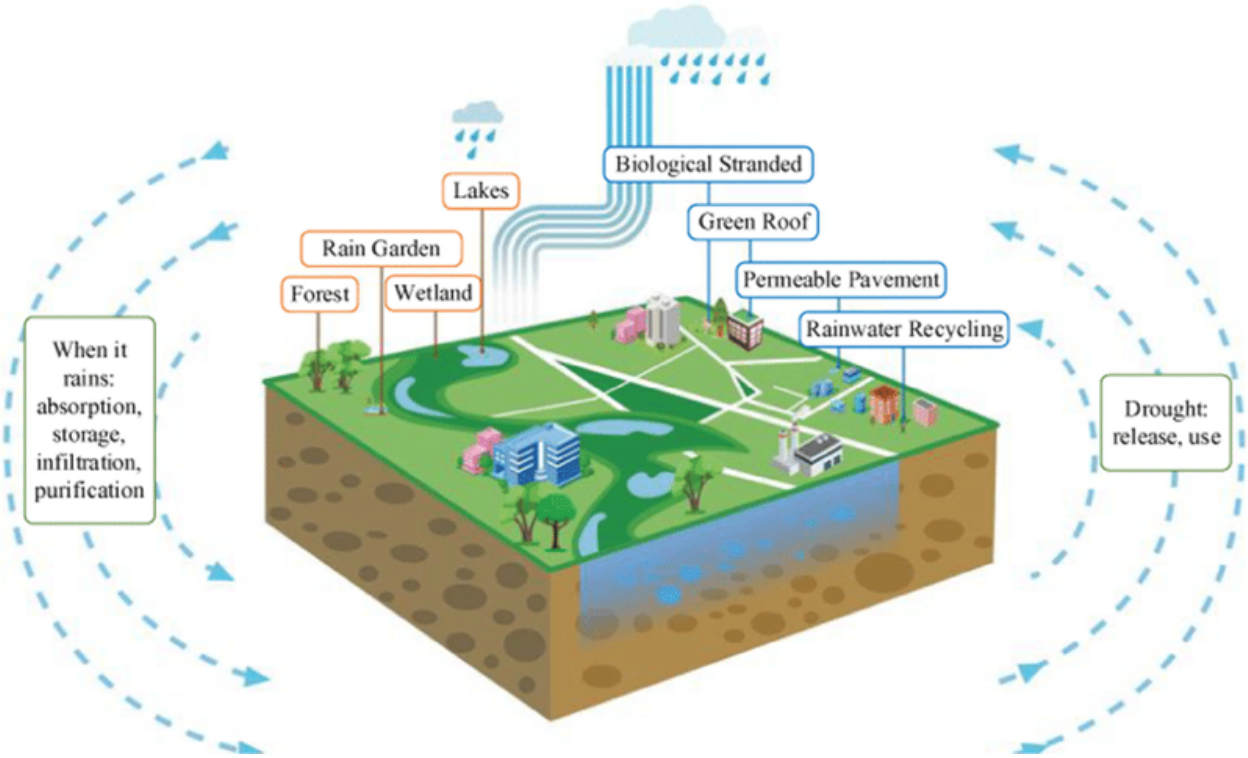

Figure 8: Diagram of sponge city mechanism (Zhao et al., 2022)

4.3. Example of Shenzhen and Opportunities for Ho Chi Minh City

While the idea may sound idealistic, it has already been adopted by the government of China since 2015, with the aim to transform 80 percent of urban areas in 30 chosen sites into sponge cities by 2030 (Thornett, 2023). One of the most preeminent examples of China's Sponge City Program (SCP) is Shenzhen City in Guangdong province, a megacity and special economic zone that is dubbed "the Silicon Valley of China" (Murphy, 2017). "Shenzhen speed" is a term that refers to the fast pace at which infrastructure construction and economic development took place in Shenzhen to transform a small fishing village into a major technological hub of the world, and the term is now used to address its transformation into a sponge city. The city was chosen as one of the first 16 pilot SCP sites in 2016, and after seven years of implementation, Shenzhen has made significant achievements.

The city has an interconnected greenway network that totals 2,377 kilometers in length, serving the "three-legged stool" purposes of transportation, conservation, and recreation (Liu et al., 2020). These greenways run in various traffic corridors, parks, and forests of the city, consisting of permeable pavements and pathways to allow slow absorption and filtration, and direct runoffs to desirable sinks or to the ocean. Shenzhen Bay Park, which runs 13 kilometers along the city's southern coastline, together with the adjacent Futian Mangrove Nature Reserve, releases stormwater to the ocean and shields urban infrastructure and residential areas from sea level rise and storm surge. Shenzhen Bay Park project also restores 24.83 acres of coastal mangrove and tidal mudflats, thereby sequestering an estimated 934.13 tons of carbon annually and providing habitat to over 50 bird species, and stabilizes temperatures along the coastline (Shannon and Hood, 2016). The city also opened two lakeside parks – Talent Park and Xiangmi Park – with green spaces surrounding water bodies, and converted an ecologically dysfunctional area with frequent flooding and water pollution – Fenghuangcheng – into a forest park with abundant green space, permeable surface, and a water treatment plant. The sponge city construction in Fenghuangcheng area completely solved the waterlogging problem at six residence estates and industrial zones and eliminated water pollution of seven branches of different rivers (General Office of Guangming District People's Government, 2019). Floodplain parks in Shenzhen not only serve environmental objectives of flood mitigation, air condition, and so forth, but they are also beneficial to the society: Shenzhen Bay Park hosts various cultural events, Talent Park displays creative art pieces and seasonal flowers throughout the year, and Xiangmi Park opens a Science Library within the nature scene.

The empirical experience of the implementation of the sponge city concept in Shenzhen provides valuable opportunities to other coastal cities facing increasing flood risks due to climate change such as Ho Chi Minh City. Ho Chi Minh City and Shenzhen share multiple natural and social characteristics such as their coastal locations, hence facing the same risks from sea level rise and intense rainfall events, and urbanization and industrialization patterns, hence suffering from pollution and ecological degradation. Therefore, the benefits Ho Chi Minh City can receive from implementing Shenzhen's sponge city model is apparent, ranging from the main purpose of flood prevention to accompanying benefits such as reduction of pollution, revival of ecological function, improvement of biophilic recreation facilities, among others. Ho Chi Minh City also has a mangrove forest buffering between the city center and the ocean, which can be utilized for storm surge barriers and flood mitigation measures. Vietnam and China are neighboring countries with a cooperative relationship and the two countries are quite similar in terms of political structure with the Communist party as the leader of the one-party regime, which may imply equivalent capacity of governmental agencies in enforcing developmental plans. Ho Chi Minh City and Guangdong province specifically established a twinning agreement in 2009 (HCMC Foreign Affairs Office, 2015), and the close relationship between the two cities may further facilitate favorable conditions for inter-city learning. Given these advantages, the sponge city model potentially has high applicability to the case of Ho Chi Minh City.

4.4. Potential Locations for Application

The types of sponge city infrastructure and the extent to which they can be applied depend on the topography, population, and land-use function of each location. From the projection in the previous chapter, Can Gio district, Thu Duc City, and Binh Chanh district are some of the areas most likely to be under sea level. Each of these areas have very different characteristics and therefore are compatible with different green infrastructure solutions.

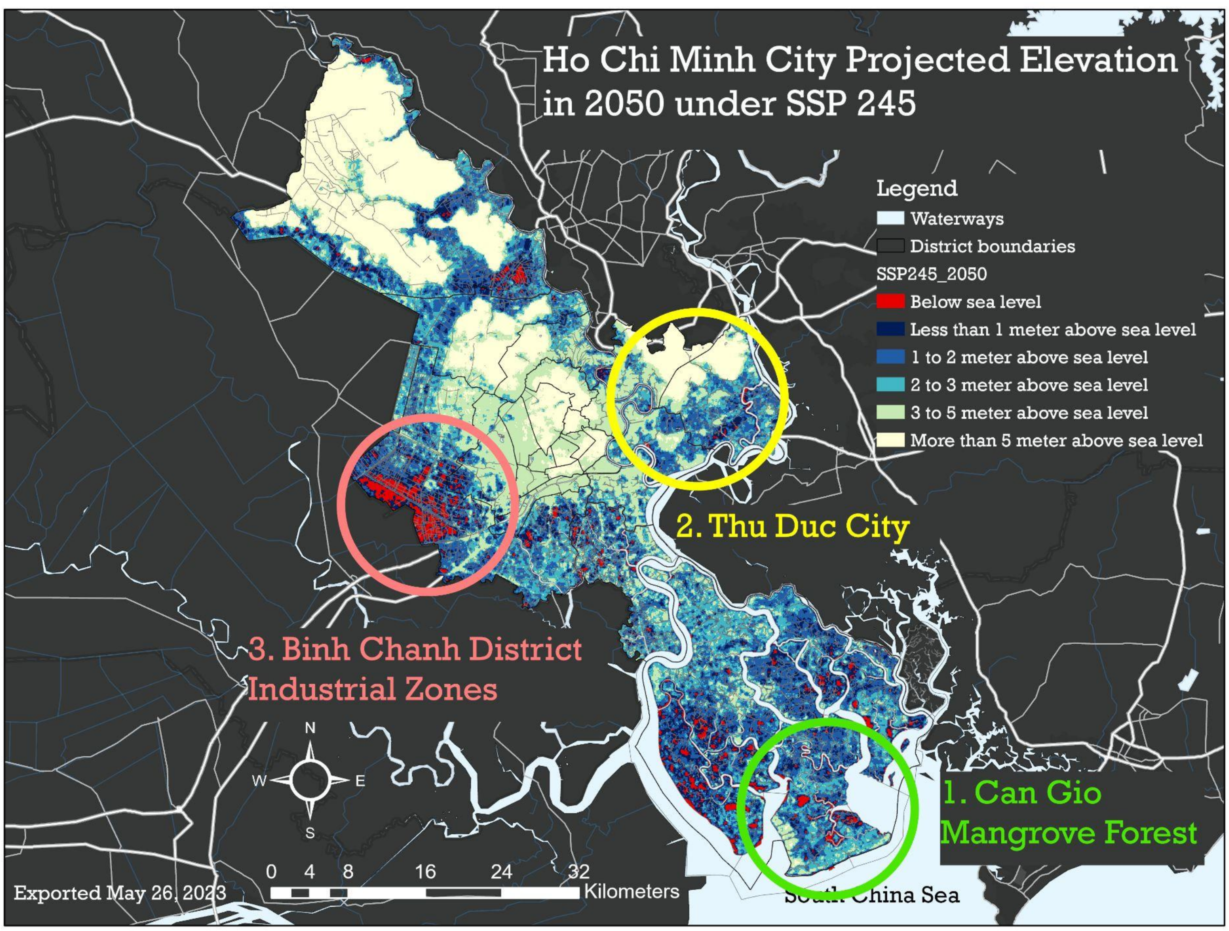

Figure 9: Potential locations for sponge city infrastructure in Ho Chi Minh City

4.4.1. Nature reserve - Can Gio district

Mangrove forests are not only rich in biodiversity, they also play major roles in mitigation of climate change and climate-related risks. According to UNESCO, mangrove ecosystems are effective carbon sinks, each hectare of which can sequester 3754 tons of carbon; on the other hand, mangrove deforestation is a major source of carbon emissions, accounting for up to 10 percent of emissions from deforestation despite making up less than 1 percent of land coverage. Located in the coastal intertidal zone between land and sea, mangroves act as natural protection against storm surges, rising sea levels and extreme coastal events for coastal communities worldwide: a 500-meter mangrove strip can reduce wave heights by 50 to 99 percent. However, they are quickly disappearing hence typically coming up as rare ecosystems in need of conservation, with multiple international and intergovernmental agencies advocating for and regulating their protection (UNESCO, 2022).

Can Gio Mangrove Forest is a UNESCO-designated biosphere reserve. Administratively, Can Gio district, where the mangrove forest is located, is a rural district with the smallest population in Ho Chi Minh City. The district lies between the ocean and the city center, moderating impacts of storms and extreme coastal events on the most populous areas. The city's plan is to develop Can Gio District into a high-quality eco-tourism and resort city by the year 2030 (Vietnamese Government Electronic Portal, 2022). The greatest challenge to this plan is how to achieve the triple goals of developing an attractive resort city, making it resilient to climate change and sea level rise, and preserving the mangrove forest. The story of Shenzhen has shown how mangrove forests can serve its ecological and disaster risk reducing functions while facilitating recreational, cultural, and even economic benefits. A major difference between Futian Mangrove Forest in Shenzhen and Can Gio Mangrove Forest is that the former has all residential areas and roads behind the forest. Meanwhile, although Can Gio District has the smallest population in the city, this population is concentrated in the outermost peninsula that directly borders the ocean, and the city's plan is to further expand this area toward the ocean with a man-made island that has an iconic skyscraper, an amusement park, shopping and conference centers, and so forth (PLO, 2023). While this edge may not become submerged landscape thanks to its higher elevation compared to surrounding landscapes, the area is still at risk of higher storm surge and frequent extreme coastal events from climate change. Since the mangrove forest is between this planned city and Ho Chi Minh City's center, it can only protect the inner Ho Chi Minh City and not the newly planned infrastructures. Without any natural buffer between these planned urban infrastructures and the ocean, residents and properties would be upfront exposed to storms and tides. It is therefore not ideal to develop residential infrastructure right on the man-made beach like in the current plan, rather a coastal ecological park with abundant permeable surfaces like Shenzhen Bay Park to act as a natural barrier for these infrastructures could be a more appropriate idea.

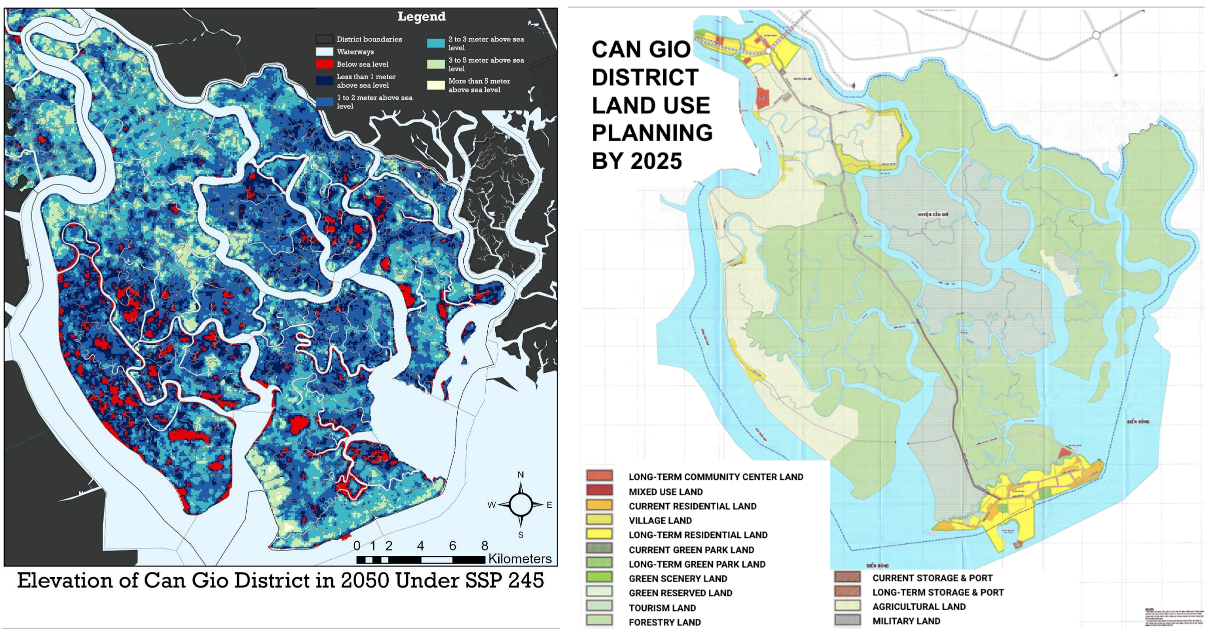

Figure 10: (a) Projected elevation of Can Gio district in 2070 under SSP 2-4.5 and (b) Can Gio district land use planning by 2025

4.4.2. Smart city development - Thu Duc City

Thu Duc City was formed by merging three districts on the east of Saigon river as Vietnam's first city-within-city (Standing Committee of the National Assembly, 2020). The overall objective of the establishment of Thu Duc City is to develop an interactive and innovative urban area, becoming a technology-based economy, innovation ecosystem, regional transportation, and home to resilient communities. Planning for the new municipal city includes various tech hubs specialized in finance, education, ecology, and manufacturing, sports and recreational centers, ports and traffic hubs, and startup centers. Notably, since the city was very recently formed and the planning for the city began in the era of accelerating climate impacts and frequent flooding, flood mitigation measures are among the highlights of the city planning. The city is divided into four risk zones: (1) safe zone with high elevation and therefore not majorly affected by river floods but are at risk of flash floods from extreme rainfall, (2) protection zone with low elevation and high concentration of population and properties, therefore in need of immediate protection as water levels rise, (3) ecological zone with low elevation and frequent flooding, also the green lung of the area, (4) adaptation zone with low elevation and currently less developed, but will have high concentration of population and properties in the future, planned for nature-based solutions (Figure 11b, Thu Duc City People's Committee, 2023). The objectives of flood mitigation in Thu Duc City encompass protection against present flooding, adaptation to climate change by flood mitigation, and disaster risk reduction in case of extreme flooding events (Thu Duc City People's Committee, 2023).

The development plan for Thu Duc City is similar to the development path of Shenzhen: a "smart city" that encompasses high technology and ecological values. The municipal city's open space plan includes various sponge city infrastructures such as urban parks, ecological parks, street parks, river corridors, green streets and walkways, and reservoirs (Figure 11c). Comparing the open space plan (Figure 11c) with the projected elevation (Figure 11a), the city seems to have made good efforts to identify low-lying areas to plan for green stormwater infrastructure. Nevertheless, probably because the previous studies mainly discussed sea level rise without land subsidence, some areas that would be under sea level earlier were not identified and emphasized in the city's planning. Instead, all low lying areas below 5 meters were grouped together as protection zones without any indication on priorities. The maps produced in this project can serve as reference for city planners to highlight areas that are most in need of flood mitigation measures and to adjust the open space plan accordingly. Particularly, the area bordering a tributary to Dong Nai River to the central south of the city is shown to be soon underwater according to the calculations of this study, but this area is to be developed for housing. Further assessments will be needed to decide whether nearby riverfront parks and reservoirs will be sufficient to mitigate flooding in this area, otherwise it may be better to place sponge city infrastructure at these specific locations.

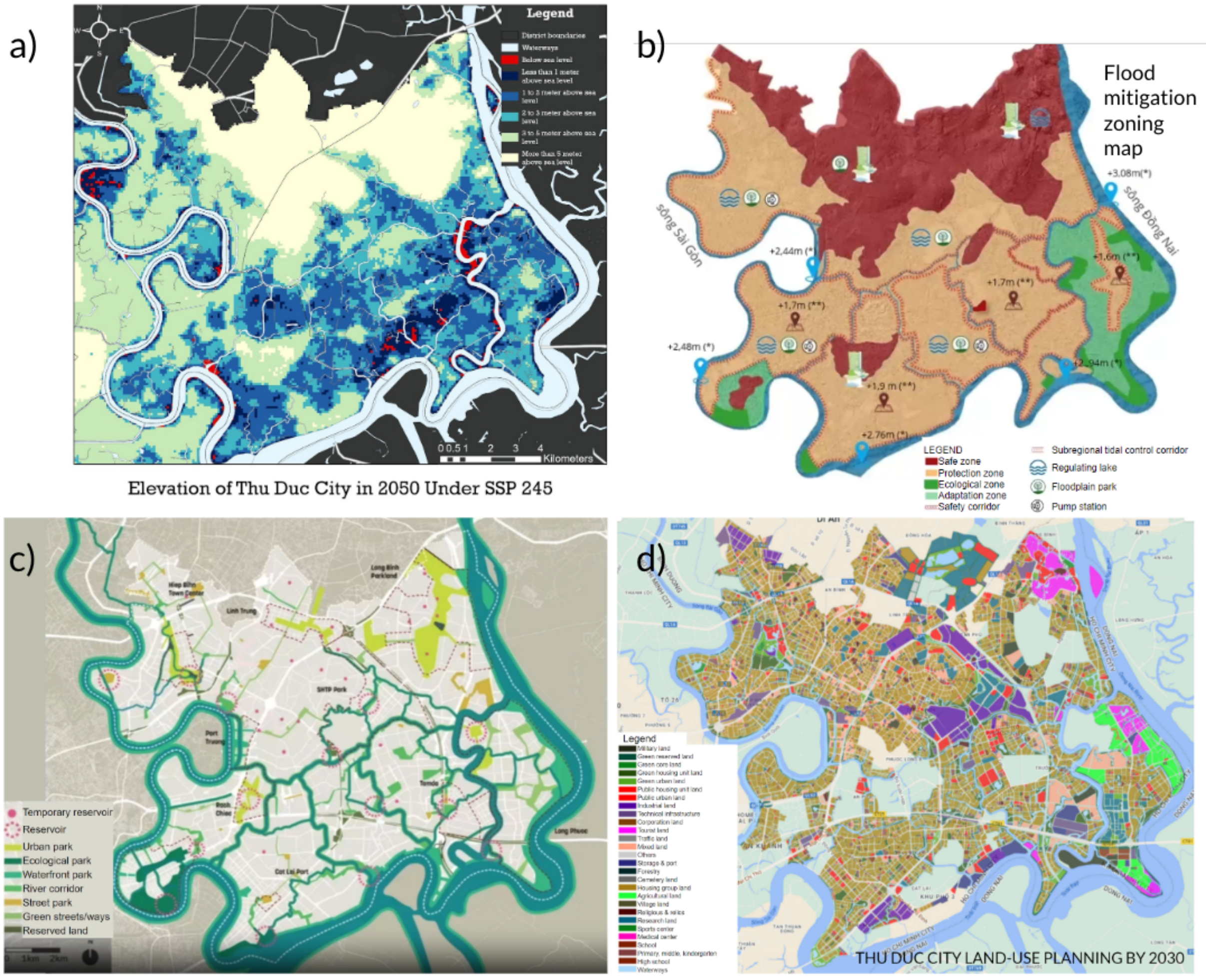

Figure 11: (a) Projected elevation in 2050 under SSP2-4.5, (b) Flood mitigation zones (Thu Duc City People's Committee, 2023), (c) Open space plan (Thu Duc City People's Committee, 2023), and (d) Land use planning by 2030 (Thu Duc City People's Committee, 2023) of Thu Duc City

4.4.3. Industrial zones - Binh Chanh District

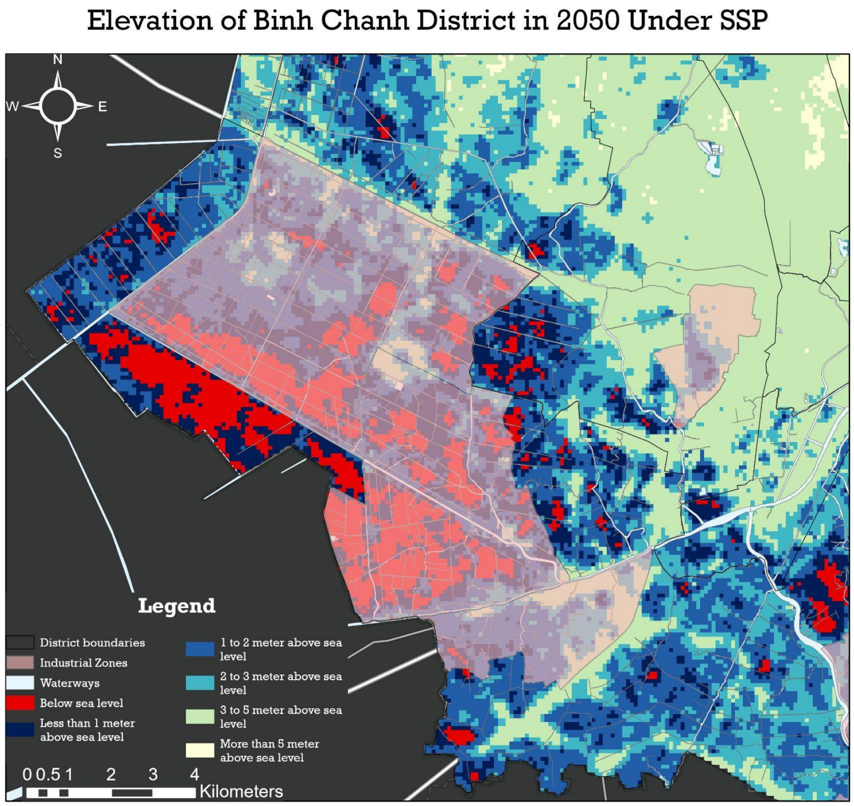

Figure 12: Projected elevation in 2050 under SSP2-4.5 of Binh Chanh district with industrial zones highlighted

Binh Chanh district will be the first to be lower than sea level due to its low-lying topography and its extreme rate of subsidence, and the area under sea level will rapidly expand over time. The majority of Binh Chanh district land area is designated as industrial zones (Figure 12). Unlike ecological or residential zones, industrial zones often pose significant concerns for industrial pollution and ecological dysfunction, but as seen in the example of Fenghuangcheng in Shenzhen where the former industrial park with frequent flooding and water pollution has been converted into a forest park with abundant green space, permeable surface, and a water treatment plant, the sponge city concept may be the solution to mitigate all these problems. The Fenghuangcheng model is highly applicable to inactive industrial areas, infiltrating existing pollution, reestablishing ecological functions, and providing recreational values for residents in the area. There are multiple industrial land pieces that either have not been developed or have been abandoned, especially due to economic difficulties after the pandemic (Chuong, 2022), so there could be opportunities for development of large-scale green floodplain parks in place of these wasted land.

However, only inactive industrial parks can take such a transformational approach, while smaller scale infrastructure such as bioswales, tree canopies, or permeable roads and parking lots would be more suitable for active industrial facilities. These infrastructure can be integrated into the existing landscapes to create eco-industrial parks. This integration of green stormwater infrastructure into industrial landscapes not only serves the purpose of flood risk mitigation but it is also beneficial to the environment, the community, and industries (Muangsri et al., 2023). Eco-industrial parks can improve water quality and enhance biodiversity, provide aesthetic recreational spaces and encourage love for nature, while also helping industrial facilities meet water quality standards, green certifications, and sustainable commitments. Furthermore, workers at these facilities can benefit from the biophilic design, becoming healthier and more productive (Sturgeon, 2020, in Johnson & Wilkinson, 2020, page 166-169), which would in turn improve productivity of these factories and help retain and attract more workers.

4.5. Constraints in the application process

While the benefits of the sponge city concept are visible and the opportunities for realizing the concept are great, there are obstacles to implementing this model in Ho Chi Minh City. Various challenges may arise in the application process, specifically concerning the source of funding for projects, and suitability of land to locate green infrastructure based on natural as well as social conditions.

4.5.1. Financial constraints

Funding is a major barrier in the execution of any project. Being one of the most vulnerable countries to climate change, it is estimated that Vietnam will need around $254 billion from 2022 to 2040 to implement adaptation measures to protect the country's assets, infrastructure, and people (World Bank, 2022), and flood resilience in Ho Chi Minh City is just one of the various areas that must be addressed. China is the world's largest economy and a leader in the field of green technology and innovation with abundant financial resources to fund its own sustainable development projects, hence Shenzhen's transformation into a sponge city at “Shenzhen speed”. Vietnam as a small developing country, however, does not have a huge budget for investments - funding from the public sector alone is far from sufficient to cover the climate financing needs (World Bank, 2022). Furthermore, despite the Vietnamese government’s strong commitments to address climate change at COP26, the pledge primarily involves the decarbonizing pathway rather than the resilience pathway; therefore, the adaptation to climate change is not emphasized in the climate agenda even though Vietnam is a highly vulnerable country. As a result, this imbalance between attention to climate change adaptation and mitigation is posing great challenges to the needed actions to prepare for climate risks, such as implementation of flood resilience actions in Ho Chi Minh City. Public finance will need to pay more attention towards climate resiliency as well as be distributed more effectively, and the government should also make efforts to utilize the two following external resources in order to alleviate this difficulty.

International cooperations and foreign aids and loans are additional resources that developing countries like Vietnam can turn to. While whether globalization is good or bad is debatable, it is undeniable that globalization brings great chances for international cooperation. Although at some points foreign loans can be problematic, such as how the IMF and World Bank policies toward the end of the 20th century caused increased debts, weakened economies, environmental degradation, social injustice, and economic inequality in many developing nations instead of economic prosperity for all like the developed world envisioned, globalization can work if it is done right, if the voice of developing nations can be heard (Stiglitz, 2002, in Blewitt, 2018, page 26-28). On one hand, foreign aid and loan distributors of developed countries and international banks need to take a more “more comprehensive approach to global development”, which includes increasing foreign assistance from the rich countries to the poor and canceling or relieving of foreign debt. After all, the current climate change is marked by the Anthropocene, which some even argued should instead be referred to as the “Capitalocene” since it was dominantly caused by industrial activities in the West (Davison, 2019), yet the issue is not restricted by national borders. In fact, the poorer are the ones more vulnerable to the impacts of climate change. Therefore, it is reasonable for developed countries to provide financial and technical aid to the more climate vulnerable developing world in building climate resilience. On the other hand, developing nations also need to perform reforms within their financial infrastructure to limit corruption, attract investment, and make the most use of the funding they receive. This means improving transparency in the flow of funds to project implementation and preparing thorough and practical proposals for climate resilient projects that can be turned into action immediately after funding is received. With improvements in the mechanism of aid granting and receiving, globalization can be favorable for addressing climate risks, especially when climate change has been placed emphasis on the international discussion table in recent years. Specifically, the COP27 in 2022 marked a ground-breaking agreement on the establishment of new funding arrangements known as the “Loss and Damage” Fund (UN Climate Press Release, 2022) that opens up new opportunities for climate impact mitigation in vulnerable developing countries like Vietnam.

The private sector is another option to mobilize for climate finance. While the country’s government has made strong commitments to address climate change, the private sector is unevenly prepared for the impacts of climate change and therefore they have not played active roles in climate projects funding (World Bank, 2022). Extractives, manufacturing, agriculture, wholesale and retail, and hotels/accommodation sectors are the most vulnerable to climate-related disaster risks, but the financial sector also suffers (World Bank, 2022). However, the risks are not systematically and comprehensively addressed, so the private sector has not been deeply involved in funding for climate change mitigation and adaptation. The World Bank (2022) suggests that the private sector will need to “allocate a quarter of its current savings (3.4 percent of GDP per year) toward resilient and low-carbon investments”, which is more than the contribution of the public sector in order for Vietnam to meet its financing needs. Achieving this goal will require higher expertise in green finance assessment, as well as public policy to facilitate favorable conditions for the green financial market. Vietnam will need to encompass all available financial resources in order to fund climate change adaptation and mitigation, among which is flood resiliency in Ho Chi Minh City.

4.5.2. Geographic and technical constraints

Limited funding means that Ho Chi Minh City cannot emerge into a fully-realized sponge city at once - the city must be mindful of under or over-investment and identify areas to prioritize for infrastructural development. These objectives can be geographically and technically obstructed: while it is quite straightforward to install front-line sponge city infrastructure such as waterfront parks or permeable walkways by rivers and the ocean, it would be more complicated to determine the compatibility of the land with stormwater infrastructure for locations further inland such as Binh Chanh district. Muangsri et al. (2022) identified three characteristics that would decide flood mitigation capacity of land: amount of runoff from drainage areas, the area for rainwater collection, and the groundwater level. The more runoff reaches the land piece (due to topography) and the larger the area to collect rainwater, and the lower the groundwater level, the more water green infrastructure would be able to store and therefore the more effective they are at flood mitigation. Based on evaluation of these factors, the city can focus their funding and resources on developing sponge city infrastructure in the most critical areas first, then expand to supplementary areas later on. Few published studies are specialized in this type of assessment for the case of Ho Chi Minh City, but there are general methodological researches as well as specific case studies of other cities that can be valuable resources for carrying out similar analysis. For example, the Hydrology-based Land Capability Assessment and Classification (HLCA+C) Methodology developed by Muangsri et al. (2022), which encompasses all the factors mentioned above to classify stormwater management zones, is a toolset that can be utilized to study areas for sponge city development in Ho Chi Minh City. Nevertheless, each case is still distinct, so there should be policies to encourage research on flood mitigation capacity with the specific case study of Ho Chi Minh City in order to compensate for knowledge and technical constraints.

4.5.3. Socio-economic and institutional constraints

Socio-economic and institutional constraints are majorly tied to land-use conflicts. Land is an extremely valuable resource, especially to densely populated cities like Ho Chi Minh City, which results in the city's decisions to carry out urban expansion in highly vulnerable landscapes such as swampland and even ocean edge (Gravert & Wiechmann, in Katzschner et al., 2016). The project to develop Can Gio into an urban tourist-concentrated area towards the ocean conflicts with the benefits of the mangrove forest as a natural flood mitigation measure. Probably because the risks of sea level rise and changing intense storm patterns are not well understood and therefore underestimated, the city is willing to exchange climate resiliency for economic development. It should be recognized that considerable difficulties will arise in the process of building a polder city especially in the context of climate change, such as erosion by waves and landfalls of tropical storms among others that must be carefully considered in order not to end up with a costly and worthless investment. The erosion of Cua Dai beach in Quang Nam province in the past decade, during which multiple luxurious resorts were washed away and abandoned, should serve as a lesson for coastal development for Ho Chi Minh City.

Moreover, urban construction at the edge of the mangrove forest can negatively impact the ecosystem, which must be carefully assessed knowing that mangroves are not only the protector against natural hazards for Ho Chi Minh City and Vietnam but also one of the world's important sites for carbon sequestration and biodiversity conservation. There are also multiple other urban expansion plans that involve construction on flood-prone areas (Gravert & Wiechmann, in Katzschner et al., 2016). On the other hand, there are unused or abandoned lands as project contractors are unable to complete construction timely due to various reasons, two most prominent of which are lack of finance and slow duration. These "hanging projects" not only occupy the precious land but also become space for landfills and slums, therefore generating pollution and social problems. Policy measures to oversee and manage project progress, perform land acquisition when needed, and provide relocation for people living in slums would be able to minimize waste of land. The reacquired land can then be used for development of sponge city infrastructure to increase the city's flood resiliency, or at least be used for a more meaningful purpose than sitting there and causing problems. Facing such great risks of climate change, it is high time for Ho Chi Minh City to prioritize building a climate resilient society and facilitating sustainable development rather than pursuing immediate yet risky economic benefits.

Chapter 5: Conclusions and recommendations

Having always been a flood-prone city, Ho Chi Minh City will substantially become more exposed to floods as a result of climate change and urbanization. Inland flood risks caused by extreme rainfall due to climate change and urban flooding due to urbanization, in combination with coastal flood risks caused by sea level rise and land subsidence, will result in substantial flooding. The dilemma calls for measures to increase flood resilience, and the sponge city concept encompasses promising nature-based solutions that not only reduces flooding but also has the ability to mitigate droughts by releasing water when needed, regulate climate change as carbon sinks, relieve urban heat island impacts, lessen pollution, provide space for recreational and cultural activities, enhance sense of community and connection to nature, and deliver direct and indirect economic benefits, among others.

For an emerging megacity characterized by large population and industrialization, each part of Ho Chi Minh City will be suitable for installation of certain types and scales of green infrastructure.

- Areas that are ecologically functional, especially mangrove ecosystems, should limit urban development and preserve natural landscapes.
- Areas adjacent to water bodies should have waterfront parks and permeable corridors to prevent river or coastal flooding. Areas directly bordering the ocean should not have major urban infrastructure due to risks of storm surges.
- Inactive industrial zones and abandoned or overdue land development projects can be converted into large-scale floodplain parks.
- Active industrial zones can incorporate small-scale solutions such as bioswales, tree canopies, and permeable parking lots to become eco-industrial parks.
- Areas highlighted as soon-to-be under sea level in the map series in this study should not be sites for residential development unless carefully calculated flood mitigation measures are in place.

Despite opportunities and benefits, various constraints may arise but are not insurmountable. Financial constraints can be addressed by a combination of more effective public funding, utilization of international cooperation and aids, and mobilization of private sectors. Geographic and technical constraints, such as different capacity for flood mitigation that have not been thoroughly studied in the case of Ho Chi Minh City, will require the city to review existing methodologies and learn from other case studies, as well as encourage research on the city's specific case. Socio-economic and institutional constraints, such as land-use conflicts and economy vs. well-being dilemma, also demand more attention than ever. The city must recognize the risks of urban development in vulnerable areas and prioritize a climate resilient society and sustainable development over immediate economic benefits. Some current plans undermine flood resiliency, but the city needs to recognize the risks associated with urban development in vulnerable areas and prioritize building a resilient community and sustainable development rather than pursuing immediate economic benefits. Given the extremely high risks of flooding due to climate change, it is high time for Ho Chi Minh City to incorporate solutions to alleviate current and future flooding, the sponge city concept being one recommendation.

Appendix: Methodology for mapping impacts of land subsidence and sea level rise

1. GIS Layers

CoastalDEM v2.1 (Kulp & Strauss, 2021) is a 3 arcsecond horizontal resolution digital elevation model for ocean coastal areas developed by Climate Central. This DEM is based on NASADEM, a near-global satellite radar dataset derived from SRTM satellite radar during a NASA mission in 2000. This raster is used as the base DEM for calculation of future scenarios. City boundaries obtained from Humanitarian Data Exchange by United Nations OCHA (2020) are used to cut the DEM raster to include only the city. Rate of local land subsidence in Ho Chi Minh City raster from Tay et al. (2022) study, which is calculated from the period 2014-2020, is used to produce future DEM prior to consideration of sea level rise. Sea level rise projection from IPCC AR6 (Garner et al., 2021) comes in the form of an Excel file, with projection by years and Shared Socioeconomic Pathways (SSPs) compared to the baseline of 1995-2014, and it is used to map elevation relative to sea level in these different scenarios. Waterways shapefile from HCMCGIS Portal is laid on top of DEMs so as to cover up waterways on the DEM. Population distribution by district from General Statistics Office of Vietnam (2019), are added to the attribute table of the district boundaries shapefile in order to map population distribution, and together with industrial zones polygons from HCMGIS OpenData are used to compare with the elevation as implications of potential impacts on urban dwellers.

Data	**Format**	**Source**	**Purpose**
CoastalDEM v2.1	Raster	Climate Central	Original DEM
City and district boundaries	Shapefile	Humanitarian Data Exchange	Clip DEM raster
Rate of local land subsidence	Raster	Tay et al., 2022	Calculate future DEM
Sea level rise projection	Table	Garner et al., 2021	Calculate future DEM

Waterways	Shapefile	HCMGIS Portal	Exclude waterways from DEM
Industrial zones	GeoJSON	HCMGIS OpenData	Map industrial zones

2. Procedures

CoastalDEM v2.1 comes in tiles of 1 degree x 1 degree, and to cover the area of Ho Chi Minh City, which ranges from 10.5°N to 11°N and 106.35°E to 107°E, would require three tiles N11E106, N10E106, and N10E107. These three tiles are imported into GIS and merged together using the 'Mosaic to new raster' tool. Meanwhile, from the Vietnam admin boundaries layer, the Ho Chi Minh City feature is exported to get the city boundaries. The L-shaped DEM combine raster is then clipped to the city boundaries using the 'Clip raster' tool to yield the HCMC DEM raster.

'Raster calculator' cannot be performed on No data cells, so after the rate of local land subsidence raster is imported into GIS, the 'Is null' tool is used to identify the No data values in the raster, then the 'Con' tool is used to assign 0 value to No data, and keep the original value for cells with data.

The resulting DEM raster and land subsidence velocity raster are then brought into the raster calculator. Since the DEM is constructed from imagery taken in 2000 and the land subsidence velocity is measured as annual average within the period of 2014 to 2020, it is assumed here that there is no change in elevation due to land subsidence from 2000 to 2014, the rate of land subsidence is consistent from 2014 to 2020, and that rate is projected into the future of 2030, 2050, 2070, 2100, and 2150. The elevation due to land subsidence in 2030 is the sum of the original DEM and the land subsidence velocity times 16 years (from 2014 to 2030). Similarly, the elevation due to land subsidence in 2050 is the sum of the original DEM and the land subsidence velocity times 36 years (from 2014 to 2050), 56 years for 2070, 86 years for 2100, and 136 years for 2150.

The 'raster calculator tool' is used to subtract sea level rise from the elevation due to land subsidence to yield the elevation due to both land subsidence and sea level rise. Sea level rise projection data is processed in Excel. Since the vertical land motion factor contributing to sea level rise should already be included in the local land subsidence rate, a new spreadsheet of sea level rise without the impacts of vertical land motion is calculated by adding all other factors. Sea level rise projections used in this study are the 50 percentile of all the medium-confidence scenarios. The symbology of all the DEMs are changed to 'classify' and 'manual interval'. The original DEM has 5 classes: less than 1 meter, 1 to 2 meter, 2 to 3 meter, 3 to 5 meter, and more than 5 meter above sea level. The color scheme used here is blue-green-yellow. It should be noted that the original DEM does not contain any value below 0, meaning no area is currently under sea level yet. The projected DEMs have an extra class of below sea level, and it is color coded red for more emphasis. The other classes are customized with the eyedropper tool to have the same colors with those in the original DEM. Waterways shapefile is added to cover up the waterways from the DEM, and the eyedropper tool is used to match with the ocean color in the base map.

Geo-reference data on industrial zones is obtained from HCMGIS OpenData, but the only download option available is GeoJSON, so the file has to go through an online converter tool before being downloaded as a shapefile and imported into GIS. The industrial zones shapefile is then used as reference for which industrial areas are at high risk of being under sea level. This reference is specifically aimed to demonstrate industrial areas as possible locations for sponge city infrastructure in Chapter 4.4.

The maps used for presentation and analysis in Chapter 3 of the main content of this project is for the SSP2-4.5, which is the "most likely scenario" (Tay et al., 2022). The maps used in Chapter 4 are taken from the SSP2-4.5 in the year 2050, because this is the most appropriate time stamp for vision of city planning.

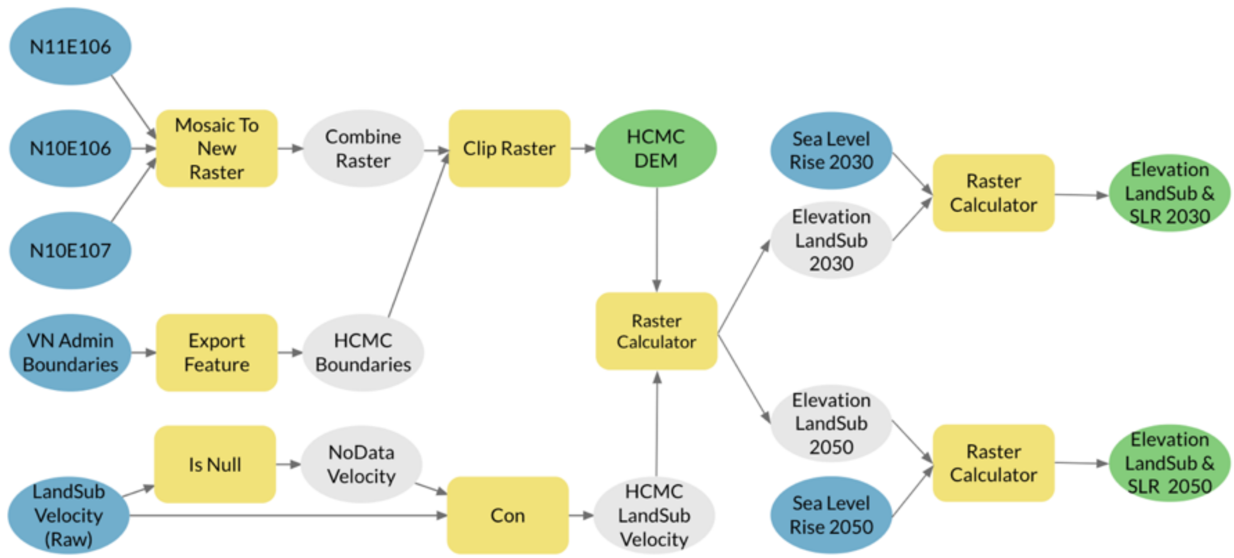

Figure 13: Flowchart of procedures in GIS

3. Limitations

The study assumes a steady-state rate of subsidence, which implies no major socio-political changes and their responses to climate change (e.g. more groundwater extraction as a result of water stress from urbanization and climate change) that can affect this rate, so this method can therefore underestimate the rate of subsidence. Tay et al. (2022) also acknowledged this limitation in the supplementary section on proposed applications of their rate of land subsidence rate, and suggested that a model to predict future groundwater extraction and relation to land subsidence can improve the accuracy of future projections. Moreover, this project only shows the areas that could be permanently inundated due to elevation below sea level, without considering the proximity to water bodies, tide patterns, extreme sea level events, or storm surge. An inclusive model that encompasses all these factors would be able to identify vulnerable areas more correctly and therefore inform city planning with more certainty.

The map series produced in this project are openly accessible at this link.

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