Understanding the Non-Technical

Challenges of Gray Flooding Solutions in Coastal Cities

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Adriel Kim

Spring 2022

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor

Kathryn A. Neeley, Associate Professor of STS, Department of Engineering and Society

Introduction

Flooding is an imminent threat to coastal cities, such as Ho Chi Minh City (HCMC), due to sea-level rise caused by climate change and land inundation. There have been various attempts and proposals to mitigate the problem of frequent flooding. Some of these solutions include building a dike, raising roads, and lifting buildings to a higher elevation. These solutions involve gray infrastructure, which typically refers to man-made, concrete structures. According to the EPA, these are structures such as "gutters, sewers, and tunnels we use to move water away from homes and businesses" ("Leaving the Gray Behind" , 2016). However, they could be cost-prohibitive or even detrimental to the environment. In addition, many of these solutions are only short-term fixes that either interfere with the natural processes of the environment or do not address the root of flooding. It is important to look at these existing solutions critically and their impact on non-technical dimensions such as society and the natural environment. A destabilizing condition that will be discussed in the paper is that many of these existing gray solutions are incredible works of engineering and are effective at addressing the immediate problem of flooding. It is likely that the effectiveness of these solutions would have to be compromised in order to accommodate other criteria such as lower cost or reduced environmental impact. Overall, this research aims to show that city officials must analyze specific details of their environment and the broader non-technical context before implementing flood mitigation or prevention measures.

In this paper, I argue that existing proposals and solutions to mitigate flooding in coastal cities (mainly HCMC) are insufficient in addressing the problem and may instead cause long-term societal and environmental harm. This paper will assess various approaches to flood response and their benefits but with a greater focus on their shortcomings. Examples of such shortcomings are their prohibitive monetary costs or their harm to surrounding ecosystems. This STS research will help me establish the purpose of my technical project, FloodWatch, which aims to improve flood response and decision-making through crowdsourced data. By assessing the negative societal and environmental impacts of current solutions, I will be able to better guide the direction of my project and focus on what is most relevant to solving the problem.

Shortcomings of Gray Solutions in Ho Chi Minh City and Venice

Flooding is a major problem in coastal cities due to factors such as the sea-level rise and land subsidence. For the purposes of this paper, Ho Chi Minh City (HCMC) and Venice will serve as the main case studies for assessing current solutions to flooding. For HCMC, flooding is a regular occurrence with 40 to 45% of the land being less than a meter above sea level (Paulo, 2021). This disrupts local businesses, damages real estate, and slows down traffic. The primary response to flooding in HCMC has involved changes to physical infrastructure such as roads and buildings. Specifically, this involves raising the level of roads as well as homes. These solutions fall short because of their slow time to implement, prohibitive costs, and lack of long-term impact. Additionally, they fail to address other major factors of flooding such as land inundation/subsidence (Paulo, 2021) and lack of green space to absorb water ("Saigon's urban green", 2019).

One drastic proposal by HCMC authorities was to build a sea dike, which is an onshore artificial wall, in order to prevent flooding altogether (Paulo, 2021). However, this solution can potentially disrupt the surrounding ecosystem, be prohibitively costly, and take a long time to complete (Rivai, 2021). This could take an economic toll on HCMC and may not even solve the problem due to the rapid pace of sea-level rise. By 2050, the sea level could rise another 28 to 33cm which would completely inundate the city (Takagi, 2016). Due to the sea dike's cost and lack of long-term effectiveness, there has been pushback from HCMC inhabitants on its construction. According to Thu (2020), the impact of sea dike construction in Can Gio Bay would be detrimental to the mangrove forests as it would decrease the salinity of the bay. However, mangrove habitats thrive under greater salinity levels. As a result, mangrove forests would diminish as they have been in other areas such as Phu Xuan station due to man-made structures (Thu, 2020). In addition to environmental impacts, the construction of sea dikes could negatively impact others living in surrounding areas. For example, the existing dikes in the Mekong River Delta, built to protect the surrounding agricultural land, have resulted in the displacement of flooding to urban areas (Rivai, 2021).

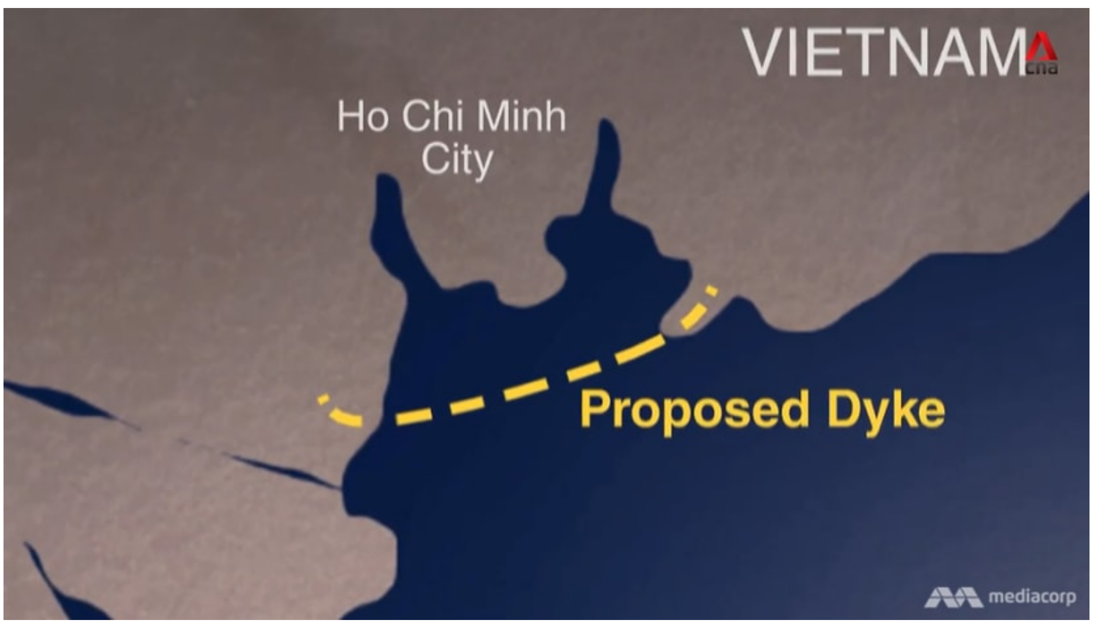

Figure 1: Proposed sea dike/dyke surrounding Can Gio Bay and Ho Chi Minh City (Paulo, 2021).

Flood barrier systems that have already been implemented in other coastal cities also suggest that invasive, man-made solutions may be ineffective and impractical. Venice is a coastal city that has already implemented a mobile flood barrier system, called MOSE, which has fallen very short of expectations. This system had high hopes as a novel flood barrier system that could be raised and lowered by operators depending on the level of the tide. The system consists of a series of barriers that can be raised independently of each other. When raised together, they form a continuous barrier along a stretch of water. The system is located along three inlets that lead into a lagoon within which Venice resides ("MOSE System", n.d.).

Figure 2: The Modulo Sperimentale Elettromeccanico (MOSE) system is a series of retractable barriers which cover the inlets of Lido, Malamocco and Chioggia ("MOSE System", n.d.).

The MOSE flood barrier system is regarded as a failure by Venetians primarily because of its high cost, interference with economic activity, lack of long-term effectiveness, and detriment to the surrounding ecosystem. The upfront cost of building the system was around 6 billion euros (Bello, 2018). Not only that, it costs tens of millions of euros just to maintain the system. In addition, it costs around 300,000 euros just to raise the flood barriers due to electricity and specialist engineers (Hughes, 2020). Other costs are incurred from the interference with economic activity that the flood barriers cause. The frequency at which these flood barriers are raised is a significant concern for Venice's port activity, which accounts for 27% of the economy of the Commune of Venice (Hughes, 2020).

According to Bello (2018), the MOSE flood barriers would have to be closed for up to half a year with an estimated sea-level rise of 50 centimeters. With the sea level continually on the rise, this problem is only likely to worsen. Not only would it disrupt economic activity, but it would also pose a risk to the lagoon ecosystem surrounding Venice by depleting its oxygen levels (Bella, 2018). This in turn would result in the depletion of populations of fish and bird species in the area (Bella, 2018). One solution that has been proposed is to only activate MOSE when the water level rises to 110 centimeters above average (Bella, 2018). However, this is unlikely to prevent Venice from flooding since lower water level rises have often resulted in flooding as well. Like HCMC, Venice is also suffering from land subsidence (Tosi, 2013). In the long term, there is no way for the MOSE system to address this problem.

Alternatives to Gray Infrastructure

As we've discussed, MOSE is a real-world example of a flood mitigation solution that has fallen short in many of the ways that researchers predict the HCMC sea dikes will. The commonality with these previously discussed approaches to mitigating floods is that they attempt to fight against and control nature with artificial structures. As we've seen, this is impractical and likely harmful to the environment. Instead, should residents of flood-prone cities develop solutions that adapt to and work with nature? This is already being done to an extent in coastal areas that experience regular flooding. According to Takagi (2016) residents in the Mekong Delta have traditionally lived with floods which developed their resilience to small, regular flooding. Unlike strictly gray solutions involving completely man-made structures, this approach is much less invasive and involves understanding and working with nature rather than counteracting it. For instance, my research project, FloodWatch, aims to notify residents of real-time flooding events in order to enable residents to more effectively adapt to floods. FloodWatch can collect flooding data over time to develop a greater understanding of flood patterns in the area while providing immediate benefits to its users. In the long term, our goal is to use this data to inform non-invasive, mitigative solutions that are backed up by a deep understanding of the environment. Although FloodWatch is a non-permanent software solution to flood mitigation, it's a critical first step in understanding flooding in coastal cities and informing long-term physical solutions.

Green-blue infrastructure is an example of a non-gray, physical solution that has been part of the discussion for possible solutions to flooding in HCMC. Rather than working against nature, these types of solutions aim to provide environmental co-benefits while also addressing flood mitigation. The planting of more green spaces within the city is an example of green-blue infrastructure. This not only adds the benefits of incorporating nature into the city, but it also can serve as a sponge to absorb floodwater. The diagram below describes the methodology for informing green-blue-gray solutions for flood mitigation. It illustrates the various tradeoffs and considerations that must be taken before implementing such a solution. These considerations are the objectives and feasible solutions available to address the problem. The solutions assessment part of the diagram indicates the tools being used to analyze trade-offs between the solutions with respect to the objectives. As illustrated in the diagram, Alves et. Al (2019) specifically uses hydrodynamic modeling and multi-objective optimization in order to visualize trade-offs between flood management strategies. From the solutions assessment, researchers are able to make an informed decision.

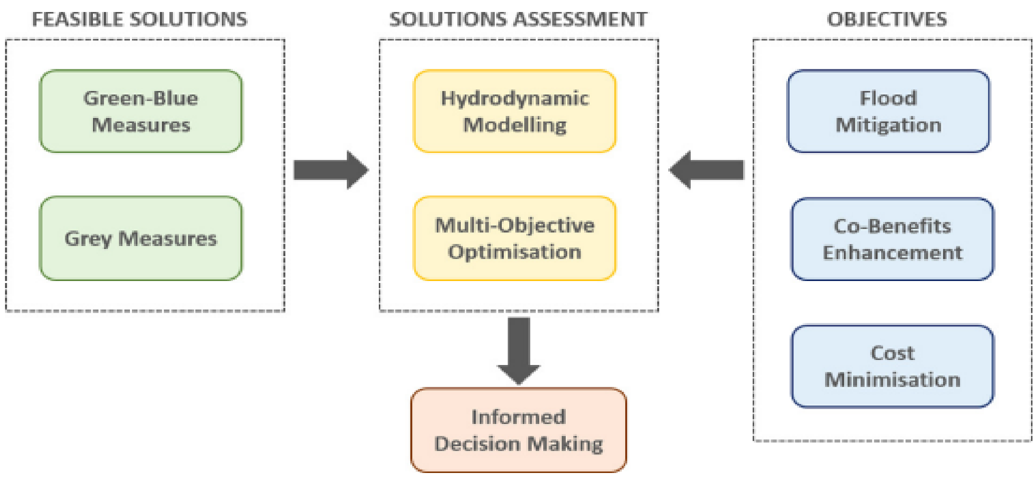

Figure 3: Visualization of the tradeoffs and considerations when implementing green-blue-gray solutions for flood mitigation. Green-blue refers to measures involving natural processes while gray refers to traditional man-made approaches (Alves et. al, 2019).

Although the above approach can achieve multiple objectives, it may be more difficult to follow without compromising the main objective of flood mitigation (Alves et. al, 2019). Attempting to implement green-blue-gray solutions may distract from the original goal and lead to a less effective flood mitigation solution than a completely gray solution — even if the overall impact is positive. However, urban areas such as HCMC and Venice that may have multiple goals in addition to flood reduction would benefit the most from green-blue-gray solutions. According to Alves et. al (2019), “In urban spaces, where space is limited, the combination of green, blue and grey measures allows to maximize the efficiency with some measures performing best at flood risk reduction.” The combination of green space, such as open detention basins; and gray infrastructure, such as pipes, is one example of an optimal flood reduction solution mentioned in the paper by Alves et. al. The green-blue-gray approach may not always be optimal, but it is a promising way of approaching flood mitigation with the broader context in mind.

Research Methods

The method for approaching this research topic was largely inspired by Bijker (2007) in *American and Dutch Coastal Engineering: Differences in Risk Conception and Differences in Technological Culture*. Here, Bijker compares the differing perspectives on flood risk between Americans and the Dutch. In particular, he explains why Americans focus on flood prediction and mitigation while the Dutch focus on complete flood elimination. Bijker's approach involved looking into the history and the environmental and political differences between the USA and the Netherlands. One insightful piece of history Bijker mentions is the "1953 storm surge disaster, generally known in the Netherlands as 'De Ramp' - 'The Disaster' " that had a traumatic effect on the Netherlands, drowning 1835 people in just a week. By explaining this history, Bijker makes it very clear why the Dutch have a drastically different policy from the U.S. on flooding. Bijker also mentions environmental differences, speculating that one cause of the differing perspectives on flood risk is because "The Netherlands is just a more watery country than the USA, with more sea coast and more river borders per square mile."

Using an approach similar to Bijker's, I was able to take into account a variety of factors, such as the environment or flooding history, which may affect the impact of various flooding solutions in HCMC and Venice. With these factors in mind, I am able to look at existing or proposed flooding solutions more critically. In other words, I was able to determine whether or not these flooding solutions were appropriate for these cities based on factors such as their surrounding environment or residents' tolerance to flooding. For example, the environments these cities reside in introduce major challenges for gray solutions. As mentioned previously, the mangrove forests around HCMC could be negatively affected because a sea dike would reduce the salinity levels of the water. And in Venice, the MOSE flood barrier system could negatively impact marine life by depleting the water's oxygen levels. Regardless of the engineering quality of these flood prevention solutions, their effectiveness is limited by their negative impacts on the surrounding environment. Bijker's approach involves taking a step back by not assessing the quality of these solutions from a pure engineering standpoint.

In relation to my technical research, Bijker's approach helped me gain an understanding of the different factors involved in making a flooding solution effective. Understanding these factors and the challenges they pose can help the FloodWatch research team develop a more effective flood response solution. Areas which are more tolerant or acclimated to regular floodings, such as HCMC, may be more receptive to less invasive solutions that involve major infrastructure changes. For this reason, these types of areas might be better off developing solutions to coexist with flooding or compromising with green-blue infrastructure as opposed to implementing completely gray solutions. On the other hand, areas with more resources or less tolerance to flooding may be more receptive to more expensive, gray solutions. Depending on the severity of the impacts that flooding may have in these areas, it may be worth the environmental risk that gray solutions pose. The FloodWatch project can take into consideration these different factors to enable city officials to make more informed decisions on flood mitigation of prevention measures.

In addition to Bijker, I decided to take a case study-like approach by narrowing my research to Ho Chi Minh City (HCMC) and Venice. This approach "allows in-depth, multi-faceted explorations of complex issues in their real-life settings" (Crowe et. al, 2011). I use the case-study approach to gain a real-world understanding of the problems that existing flooding solutions face. In addition, it helps me recognize patterns, such as the significance of the environment on flooding solutions. More broadly, Crowe et. al (2011) says, "case studies can be used to explain, describe or explore events or phenomena in the everyday contexts in which they occur." This research paper specifically aims to use case studies to explore the shortcomings of various flooding solutions from a broader, societal and environmental perspective.

When it comes to selecting a case, Crowe et. al (2011) outlines several different ways to do so. For this research paper, multiple *intrinsic* case studies were selected. According to Crowe et. al, an *intrinsic* case "is selected not because it is representative of other cases, but because of its uniqueness, which is of genuine interest to the researchers." HCMC was particularly interesting because of its regular flooding, proposed sea dike solution, and environment. In addition, HCMC city is the current focus of the FloodWatch project. Venice was also intrinsically interesting because of its frequent flooding and the MOSE flood barrier system that is already mostly completed. Venice served as a good example of a coastal city that has already tried solutions similar to the ones proposed by HCMC. Studying Venice has allowed me to gain a better understanding of the impacts of gray infrastructure solutions. Along with HCMC, Venice bolsters the claim that gray solutions are often invasive and impractical because of their prohibitive costs, time to implement, and impact on the environment and residents.

In addition to the different case studies one can select, there are different ways the case study method can be approached, as presented by Crowe et. al in the table below.

Table 6 Example of epistemological approaches that may be used in case study research

Approach	Characteristics	Criticisms	Key references
Critical	Involves questioning one's own assumptions taking into account the wider political and social environment.	It can possibly neglect other factors by focussing only on power relationships and may give the researcher a position that is too privileged.	Howcroft and Trauth [30] Blakie [31] Doolin [11,32]
	Interprets the limiting conditions in relation to power and control that are thought to influence behaviour.		Bloomfield and Best [33]
Interpretative	Involves understanding meanings/contexts and processes as perceived from different perspectives, trying to understand individual and shared social meanings. Focus is on theory building.	Often difficult to explain unintended consequences and for neglecting surrounding historical contexts	Stake [8] Doolin [11]
Positivist	Involves establishing which variables one wishes to study in advance and seeing whether they fit in with the findings. Focus is often on testing and refining theory on the basis of case study findings.	It does not take into account the role of the researcher in influencing findings.	Yin [1,27,28] Shanks and Parr [34]

Figure 2: Table describing the various approaches that can be used when conducting case study research. It describes the advantages and disadvantages of each approach (Crowe et. al, 2011).

The approach taken in this paper is primarily interpretive, seeking to understand the challenges involved in implementing various flooding solutions in the context of the social and environmental factors involved in each case. Understanding these challenges can prompt the exploration of other approaches to flooding such as green-blue infrastructure or a data-driven approach such as the FloodWatch project. Although this paper only focuses on two cities, the hope is that the insights gleaned from this research can be applied to all types of flood-prone areas. For the FloodWatch project, these insights can enable the research team to develop a general-purpose solution that enables city officials or planners to determine the best flooding solution.

Preliminary Results

The main contribution of this paper is that it provides a deeper understanding the non-technical challenges with gray flooding solutions. In addition, the paper motivates the FloodWatch project by suggesting the need for a multifaceted approach to developing flooding solutions, such as the green-blue-gray infrastructure approach discussed by Alves et. Al (2019). Although the gray flooding solutions discussed in this paper may be effective from an engineering standpoint, this paper exposes complicating factors such as environmental and societal. As previously discussed, although sea dikes around HCMC may address the problem of flooding itself, it would pose threats to the surrounding mangrove forests, be too cost-prohibitive, and shift the problem of flooding to neighboring areas. And the MOSE system in Venice has already been cost-prohibitive and may hinder economic activity and endanger marine life. For both HCMC and Venice, land inundation and sea-level rise are other factors that diminish the long-term effectiveness of gray solutions. These factors illustrate the challenges that arise when implementing technical solutions in the real world which is a complex system of society and technology. Approaching these challenges requires careful decision-making that considers the broader context, such as the kind of decision-making that would be supported by the FloodWatch application.

By discussing the non-technical challenges with developing flooding solutions, this research has revealed a fourth, data-driven category of solutions. Crowdsourcing is an example of this, involving gathering data from a large number of people through a decentralized network. Although this approach would not directly address the problem of flooding itself, it is a critical first step that informs decisions that address flooding. A critical realization I've had through the course of this research is that there is no single best solution to flooding. This does not mean a solution is inherently bad from a technical standpoint. Rather, this means that one solution alone may not be appropriate due to a variety of factors. One solution may work effectively in one area while being detrimental or impractical when implemented in another area. Sometimes it may be better to learn to coexist with nature as opposed to developing infrastructure to counteract it if possible. Other times, it may be best to use a combination of natural and gray structures. With the framework proposed by Alves et. al, we are able to converge to the optimal approach or combination of approaches based on multiple objectives.

Through a case study approach in combination with Bijker's methodology, this research provides an in-depth understanding of different flood response approaches and their advantages and disadvantages. From this research, I've inferred that societal and environmental factors play a large role in determining which flood response approach is most effective. As previously mentioned, a less invasive approach may be more beneficial to HCMC because of the city's pre-existing resilience to flooding. However, for a city such as Venice with a rich and unique historical and cultural significance, developing ways to coexist with flooding may not be a desirable approach. This research approach also provides stronger evidence for the claims presented in this paper. For instance, by exploring both HCMC and Venice in depth the reader is able to gain a better understanding of the problems with existing flood mitigation solutions. Both cities are actually fairly similar in terms of the types of flooding they experience, causes of flooding, and their approaches to flood mitigation. However, they are very much different in terms of geographical location and culture. In light of these similarities and differences, the reader is able to see how problems with current flood mitigation solutions are similar across different areas. Despite their differences, both HCMC and Venice face similar environmental and economic risks when implementing a major infrastructural solution, namely, artificial flood barriers.

Conclusion

Before implementing flood mitigation solutions, it is important for city officials or planners to look at them within an environmental and societal context. As discussed in this paper, some flood solutions are cost-prohibitive in both the long term and short term. They can disrupt economic activity and the well-being of residents by shifting flooding to other inhabited areas. Specifically gray, major infrastructural solutions, can have negative environmental impacts such as reducing oxygen levels or reducing salinity levels. Not only do some of these solutions have undesirable side effects, but they are also likely ineffective at mitigating flooding in the long term due to rapid sea-level rise and land subsidence. Green-blue-gray infrastructure may address the shortcomings of the previously discussed gray solutions. These solutions involve providing side benefits to the environment while addressing the main problem of flooding. Alves (2019) illustrates this with his illustration that models the trade-offs and considerations when developing green-blue-gray solutions. However, even these types of solutions require careful consideration in order to create the best balance between providing environmental benefits while also still effectively addressing flooding. A completely non-gray approach is a data-driven approach. This approach is being used in my technical research in order to more fully understand the patterns of flooding while also providing immediate impact to residents. However, it must be acknowledged that these types of approaches are more of a stepping stone to reaching a long-term solution (or combination of solutions) rather than a complete solution on its own.

The findings of this research can inform the development of new solutions which address the shortcomings of existing ones. It can also educate engineers to be more considerate of other factors such as environmental, cultural, social, etc. For the FloodWatch project, this research can help inform the team of what features they may want to include in order to develop the most comprehensive and generalized solution possible.

References

Alves, A., Vojinovic, Z., Kapelan, Z., Sanchez, A., & Gersonius, B. (2020). Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation. *Science of The Total Environment*, *703*, 134980. doi:10.1016/j.scitotenv.2019.134980

Bello, L. D. (2018, November 29). *Venice anti-flood gates could wreck lagoon ecosystem*. Nature News. Retrieved March 25, 2022, from https://www.nature.com/articles/d41586-018-07372-3#:~:text=Researchers%20now%20say%20that%20MOSE's,in%20just%20a%20few%20decades.

Bijker, Wiebe. (2007). American and Dutch Coastal Engineering: Differences in Risk Conception and Differences in Technological Culture. Social Studies of Science - SOC STUD SCI. 37. 143-152. 10.1177/0306312706069437.

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., & Sheikh, A. (2011). The case study approach. BMC Medical Research Methodology, 11(1), 100. doi:10.1186/1471-2288-11-100

Dittus, M., Quattrone, G., & Capra, L. (2017). Mass Participation During Emergency Response: Event-Centric Crowdsourcing in Humanitarian Mapping. *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*, 1290–1303. Presented at the Portland, Oregon, USA. doi:10.1145/2998181.2998216

“Leaving the Gray Behind.” *EPA*, Environmental Protection Agency, 24 June 2016, https://www.epa.gov/sciencematters/leaving-gray-behind.

Ng, J. (2020, September 14). *Udi Maps is a Saigon weather app that helps drivers avoid flood-prone areas this rainy season*. TheSmartLocal Vietnam - Travel, Lifestyle, Culture & Language Guide. Retrieved March 25, 2022, from https://thesmartlocal.com/vietnam/udi-maps-weather-app/

Maneriker, P., Vedula, N., Al-Olimat, H. S., Liang, J., El-Khoury, O., Kubatko, E., … Parthasarathy, S. (2019). A Pipeline for Disaster Response and Relief Coordination. *Proceedings of the 42nd International ACM SIGIR Conference on Research and Development in Information Retrieval*, 1337–1340. Presented at the Paris, France. doi:10.1145/3331184.3331405

MOSE System. MOSE Venezia. (n.d.). Retrieved March 25, 2022, from https://www.mosevenezia.eu/project/?lang=en

Paulo, D. A., & Rivai, I. (2021, February 8). *Under siege by climate, man-made problems, a sinking Ho Chi Minh City fights to survive*. CNA. Retrieved February 22, 2022, from https://www.channelnewsasia.com/cnainsider/siege-climate-man-made-problems-sinking-ho-chi-minh-city-floods-2052231

Sharma, P., Kar, B., Wang, J., & Bausch, D. (2021). A Machine Learning Approach to Flood Severity Classification and Alerting. *Proceedings of the 4th ACM SIGSPATIAL International Workshop on Advances in Resilient and Intelligent Cities*, 42–47. Presented at the Beijing, China. doi:10.1145/3486626.3493432

Takagi, H., Thao, N., & Anh, L. (2016). Sea-Level Rise and Land Subsidence: Impacts on Flood Projections for the Mekong Delta's Largest City. *Sustainability*, *8*(9), 959. https://doi.org/10.3390/su8090959

Thu, V. T. H., Tabata, T., Hiramatsu, K., Ngoc, T. A., & Harada, M. (2020). Assessing Impacts of Sea Level Rise and Sea Dike Construction on Salinity Regime in Can Gio Bay, South Vietnam. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *146*(6), 05020006. doi:10.1061/(ASCE)WW.1943-5460.0000608

Tosi, L., Teatini, P. & Strozzi, T. (2013). Natural versus anthropogenic subsidence of Venice. *Sci Rep* 3, 2710. https://doi.org/10.1038/srep02710

Urbanist Network. (2019, July 16). *Saigon's urban green coverage is poor, but little is done to speed up park projects*. Saigoneer. Retrieved March 24, 2022, from https://saigoneer.com/saigon-news/16954-saigon-s-urban-green-coverage-is-poor,-but-little-is-done-to-speed-up-park-projects#:~:text=Therefore%2C%20while%20the%20average%20green,per%20person%20in%20some%20spots.