The City of Annapolis Flood Mitigation Trade-off Study

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***Abstract*— Annapolis, the Capital City of Maryland, is routinely experiencing significant flooding events with nearly 40 floods a year and projections showing an increase. To minimize the probability of flooding and high cost in damages, the gap between the needed protection for high water elevations must be filled. By obtaining a protective barrier, the risk of flooding and its effects can be mitigated. Our analysis includes research on climate change models, a stochastic flood model to determine future water elevations, and a trade-off decision analysis between protective alternatives.**

I. INTRODUCTION

Annapolis, the Capital City of Maryland, is routinely experiencing significant flooding events. The City is one of the most historic cities in the country and is located on the south bank of the Severn River, near the mouth of the Chesapeake Bay. According to the Capital Gazette news, between the years of 1957 and 1963, Annapolis experienced 3.8 floods per year. In addition, between the years of 2007 and 2013, Annapolis experienced nearly 40 floods a year [1]. Its location as a coastal community presents a risk for tidal flooding. Additionally, climate change brings an increased risk of flooding due to heavier rains, higher tides and stronger storm surges. Current and past design studies have proposed a near term solution that does not consider the systemic climate change effects.

With the threat of rising sea levels, there is a need to reduce the effects of flooding on lives and property in the near and long term by investing in a systemic climate change design trade-off study. The flood mitigation project focuses on the low-lying areas of Annapolis (City Dock) and the King George Street intersection with Brownson Rd which is adjacent to the United States Naval Academy (Fig. 1 shows scoped area). To obtain greater protection for the City and minimize the probability of flooding and the related damage cost, the gap between the needed level of protection for water elevations can be filled by obtaining a protective barrier for the City. Our analysis includes research on climate change models, a flood model to determine future water elevations conditions, and a decision analysis between protective alternatives.

The main constraints on the system alternatives are cost and historical value to the City. The Annapolis Historic Preservation Commission (HPC) will limit the types of alternatives to consider due to the visual impact they may have on the City. Also, tourism brings a considerable amount of revenue and publicity to the City which must be considered. In order to narrow down the possible alternatives that can be recommended to the City, it is important to note that long-term is defined to be 30 years or by the year 2050.

Fig 1. Black lines represent the delimited scoped area. Red dots represent lowest elevation areas at the dock, with the left upper red marker being at a 1.5 ft NAVD88 elevation and the right most point at a 1.80 ft NAVD88 elevation. Blue solid lines represent the current concrete bulkheads (sea wall) at about 4.65 ft NAVD88. Dashed black line delimited the end of dock street. (Source image from Google maps).

Furthermore, to obtain the necessary level of protection needed by the City, the effects of climate change for components such as: sea level rise (SLR), precipitation, storm surges, and tides were analyzed. Ultimately, to develop the future scenarios of the total water surface in a given time, a relationship between these components must be determined. The models were calibrated using hourly tide gauge data from the National Oceanic Atmospheric Administration (NOAA) and sea level rise trends. Results show that in order to prove to be a long-lasting alternative, the solution needs to protect from at least 4.5 feet water elevation relative to NAVD 88 (3 to 6.5, 95% confidence interval bounds).

Currently, Annapolis is in the funding and designing process for a flood mitigation project that will account for the frequent tidal flooding and should protect at least 3.2 feet relative to NAVD 88. The project should resolve the current issue with the existing drainage system where the water can freely flow in any direction, thus creating a backflow problem. In order to prove to be protective against the threat of sea level rise and storm surges, our solution shall be readily available, prove to be a long-term solution, provide enough protection, and comply with city codes and guidelines. The alternatives for analysis will include the Self Closing Flood Barrier, TigerDam, AquaFence, and the GMU Dynamic Pneumatic Cofferdam. Each alternative has been evaluated against stakeholder constraints to obtain utility measures to perform a trade-off analysis between total cost and yield of utility, and to identify the long-term benefits and the return on investment for each of the alternatives.

II. UNDERSTANDING THE ECONOMIC IMPACTS

The most substantial portion of damage to the City is the closure of businesses due to severe flooding, causing a loss in revenue. Revenue is positively correlated by the amount of traffic of people. Hino et al. quantified the correlation between flooding levels (based on thresholds) and loss in visits. This study shows a 40%, 60%, and 90% loss in visits due to minor, moderate and major flooding, respectively [2]. It is estimated that all businesses combined around the city dock area (38 business in total) will lose about $100,000 per flood day [3].

Subsequently, flooding can cause structural damages to buildings. For instance, flooding due to Hurricane Isabel caused an estimated $116 million in Annapolis [4]. However, a protective barrier can minimize these costs. Although protective barriers can be expensive, it is likely to be offset by the savings of revenue and damage costs.

III. DATA

The observed mean sea level, from the years 1928 to 2018, was obtained from the National Oceanic Atmospheric Administration's (NOAA) using the tide gauge No. 8575512 to evaluate the sea level rise (SLR). Using the same Annapolis-located tide gauge, the hourly water levels were retrieved for the years 2000-2018 and were recorded in feet relative to the North American Vertical Datum of 1988 (NAVD88) [5]. Similarly, the historical daily weather and climate data were obtained from NOAA National Center for Environmental Information which includes precipitation, wind direction, and wind speed for the years 2007 to 2018.

IV. PROCEDURE

The preliminary step, for this study, was to identify the possible sources of flooding in the City of Annapolis. City officials have estimated about 95% of flooding events are due to high water elevation which is referred to tidal or nuisance flooding. The Hino et al (2019) study matched visual evidence with water elevations and precipitation data for the years 2016 and 2017 to confirm that flooding is indeed driven by water levels rather than precipitation [2]. Our analysis, with the exclusion of visual evidence, extends the study done by Hino et. al., with the addition of water elevations data from 2007 to 2018.

Fig 2. shows the relationship between precipitation and water elevations; a solid horizontal red line represents the minor flood threshold (1.83 ft, NAVD88) in which the City would begin to experience flooding. Data points in the top left quadrant of Fig. 2 (above threshold line) shows that the City still experienced flooding even with the absence of precipitation. Note, we cannot conclude whether flooding events would be driven by high water elevations the same way in the future as they do today. Although, precipitation is expected to increase, these changes will not be considered in this analysis. Emissions scenarios show increases in seasonal total precipitation in the winter and spring across the Chesapeake Bay watershed [6]. This study, however, focuses on the effects of sea level rise on high water levels and storm surges in the City of Annapolis, Maryland.

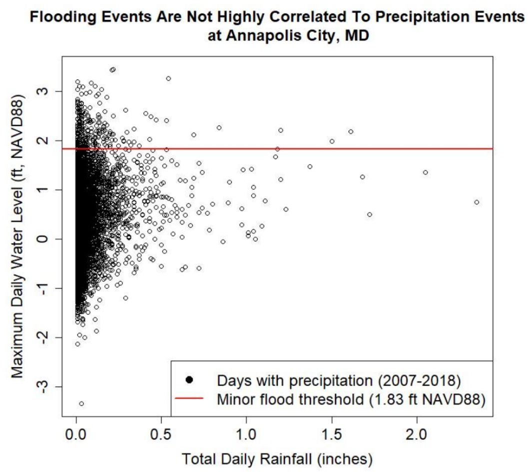

Fig.2 Precipitation and Water elevation comparison.

A. *Sea Level Rise Projections*

The mean sea level rise trends were explored by modeling NOAA's observed elevations of mean sea level from 1928-2018 with the average seasonal cycle removed. Original data was in meters relative to NAVD 88 but was converted into feet relative to NAVD88 for consistency. Different regression models were fitted to find the best performing model compared by their r-square values (goodness of fit). Therefore, a quadratic fit model was chosen to project the Relative Mean Sea Level change up to the year 2050, resulting in an elevation of 1.67 feet Above NAVD88, 95% confidence interval upper and lower bound at 2.4 and0.9 ft NAVD88, respectively.

Understanding that our predictions do not account for factors such as: greenhouse gas emission, thermal expansion, melting glaciers and ice sheets, we compared our own prediction on sea level rise using NOAA et al. (2017) sea level predictions. NOAA et al. SLR scenarios account for some, not all, of the uncertainty factors. For instance, NOAA's probabilistic analysis does not include ice-sheet melting rates currently. Evidence regarding the Antarctic ice sheet would increase the exceedance probabilities in the different scenarios, particularly for RCP8.5 projections based upon Kopp et al. (2014). We use the year 2000 as our zero value to begin examining the changes in sea level. Our model follows close to the intermediate scenario with the 95% confidence interval bounds reaching the intermediate high and intermediate low scenarios. To estimate the exceedance probability of our own prediction, we use the probability table in NOAA et al.'s Global and Regional Sea Level Rise Scenarios for The United States Technical Report (2017). The table is based upon Kopp et al. (2014), where the low scenario has a 94% to a 100% chance of being exceeded under the IPCC's greenhouse gas emission scenarios RCP2.6 and RCP8.5, whereas, the extreme scenario has a 0.05% to a 0.1% chance of being exceeded. Taking this into consideration, we estimate the exceedance probabilities for the central estimates of the quadratic regression projection to be at 2% to a 17%. Additionally, the chance of exceedance for the lower 95% confidence interval (CI) of the quadratic SLR model bound is 49% to a 96% and for the upper bound is 0.40% to a 1.30%. These are preliminary estimates to allow us to determine the probabilities for future extreme water elevations and storm surges at Annapolis City, MD.

B. Storm surges and Extreme Water Elevations

The frequency of coastal flooding has increased across much of the United States due to sea level rise [7]. Another cause of flooding along coastal areas is storm surges, which occur when the high winds of a storm (i.e., hurricane, tropical storm) push water inland. Future projections based on theory and high-resolution dynamical models indicate that greenhouse warming will cause the intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2–11% by 2100 and project a decrease in the globally averaged frequency of tropical cyclones, by 6–34% [8]. Annapolis is a hotspot for sea level rise [9], which poses a greater risk of flooding from storm events due to the likelihood of storm surges reaching further inland. For instance, it is predicted that a category 1 storm in the future will produce as much damage as a category 2 storm today [10].

The National Weather Service has a designated flooding threshold that estimates the level of inundation to be experienced in a given area based on water levels recorded by the corresponding tide gauge. Flooding thresholds designated to the Annapolis gauge No. 8575512 are: Minor 1.83ft, Moderate 2.53 ft, and Major 5.23 ft (all relative to NAVD88). Water levels in the past never surpassed a level of 4 ft NAVD88, except during Isabel (2003) where the maximum water elevation experienced was equal to 6.42 ft NAVD88. Thus, for the purpose of this study we have estimated our own thresholds based on our own analysis on water levels and inundation experienced. We determined thresholds to be as follows: Minor threshold 1.5 ft (lowest elevation where water begins rising over the City at Dinghy Dock), Moderate 2.0 ft and Major 2.45ft (all relative to NAVD 88). With that, we filtered out hourly water elevation by threshold and aggregated the data to obtain maximum and mean water elevations, per month and per year. To properly evaluate observed extreme water levels, historic mean sea level (MSL) was factored out to obtain a baseline to compare the water levels influenced only by tides, storms and seasonal shifts [11]. The City of Annapolis experiences semidiurnal tides; by filtering out the detrended data (data not including historic MSL) by the higher high tides, we obtain an average tide amplitude of 0.72 feet NAVD88. For simplicity, we assume that tide amplitude will remain unchanged in the future.

Using the fact that tides and surges have an additive relationship [12], we can calculate the future water elevations by using the calculated tide amplitude and the SLR quadratic model. By simple arithmetic, we analyze the relationship between high-water elevations and tide heights to obtain the average factor for surge heights. It is important to note that this study does not consider any future changes in storm frequency, intensity, or track. Results show a relationship between surges and water levels equal to a factor of two (2) relative to the tide height.

This study does not provide any specific amount of storm surges per year or the return period for them; instead this study provides a preliminary probabilistic analysis for future water elevations of a storm surge if it were to occur. Results show an elevation of 4.67 ft NAVD88 (± 1.25 ft NAVD88) for extreme-water levels by the year 2050 (Fig. 3). Based on these results, we set the recommended protection height to be at an elevation of 4.5ft NAVD88 all around the scoped area delimiting the water (Fig. 1).

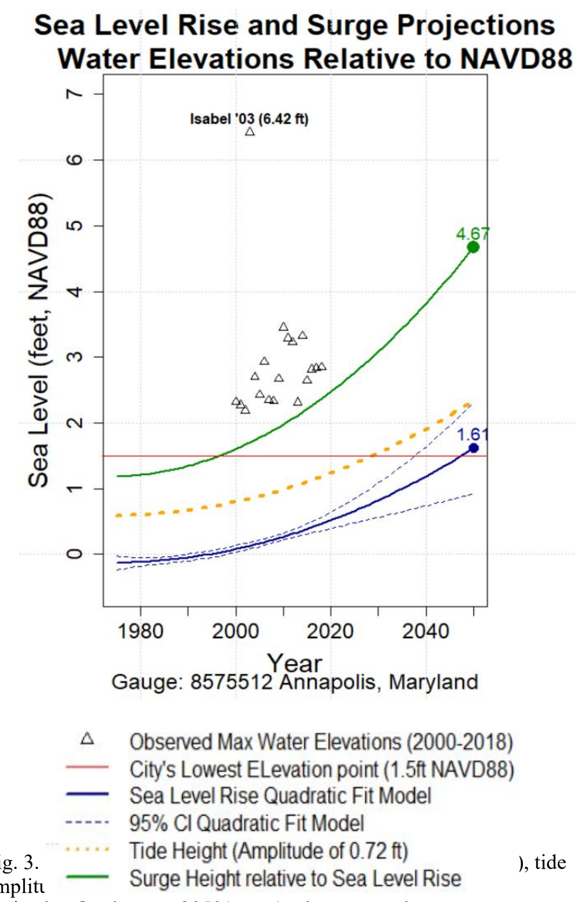

Fig. 3.), tide amplitı projection for the year 2050(green), observe maximum water elevation (black triangles), and threshold line for minor flooding (1.5 ft NAVD88).

V. Alternatives

Annapolis is currently attempting to mitigate the frequent tidal flood damage through an improved drainage system which will be installed with backflow preventers and two pumping stations. The current storm drain system relies on free-flowing water to expel water from the City, however, high water levels in the bay create a backflow issue. The backflow preventers allow water to move in only one direction thus preventing it from re-entering the City. Within each of the two pump stations, three submersible electric pumps and a wet well will be installed and constructed. After operation begins, it is expected that this system should protect at least 3.2 feet relative to NAVD 88 [13].

To reiterate, this study will focus on how to protect the City against storm surges on the frequent tidal flooding with the new drainage system. It has been determined that with climate change and sea level rise, storm surges will become stronger and begin at a higher elevation. The following considerations will help make a recommendation to the City to mitigate flooding and flood related costs. First, the alternative must be a "long term" solution. This means that the alternative will be used for the next 30 years or by the year 2050. Next, the alternative should be able to protect from at least 4.5 feet of water elevation relative to NAVD 88. Lastly, the stakeholders and their tensions must be adhered to while making decisions. The main tension, to account for, being visual impact to the City. Therefore, the flood mitigation alternatives that will be considered are: TigerDam, AquaFence, Self-Closing Flood Barrier, and the GMU Dynamic Pneumatic Cofferdam.

In order to provide a recommendation that will prove to be positively impactful to the City of Annapolis, a trade-off analysis was conducted. Firstly, a cost analysis was made to determine the life cycle for each of the alternatives for the 30-year time period.

The life cycle cost is based on the total cost for each alternative per year. This total cost is calculated differently depending on the alternative. For the TigerDams, AquaFences, and GMU Dynamic Pneumatic Cofferdams, the total cost can be calculated using the following formula: Total Cost = (Acquisition Cost * Number of Uses) + (Usage Cots *Length of Barrier). The usage cost accounts for and is the product of the installers required, installation time, and the installers' hourly wage. This product is doubled to account for the both the erection cost and the dismantle cost for each product. For the Self-Closing Flood Barrier, the total cost can be calculated using the following formula: Total Cost = (Length of Barrier * Height of Barrier) * Acquisition Cost.

With all variables accounted for, the total cost for the next 30 years was calculated using the following formula: Life Cycle = Number of Purchases * Total Cost. The number of purchases includes the initial acquisition cost and subsequent replacement purchases for the 30-year period. It is important to note that maintenance will not be accounted for in the life cycle or totals costs. This assumption is made on the basis that the alternatives will be replaced to avoid failures which is further based on its respective life expectancy and material durability.

Shown in Fig 4. below, is the proposed location for the alternatives, outlined in green, which will require approximate about 1500 linear feet in length of barrier. Areas in blue represent the existing concrete bulkhead that stands at about 4.65 ft NAVD88. Since this elevation is already above our recommended elevation, there is no need for extra elevation in this specified area. Generalizing, the necessary height of a given structure is to be at 3ft NAVD88, based on the lowest elevation point (1.5 ft NAVD88).

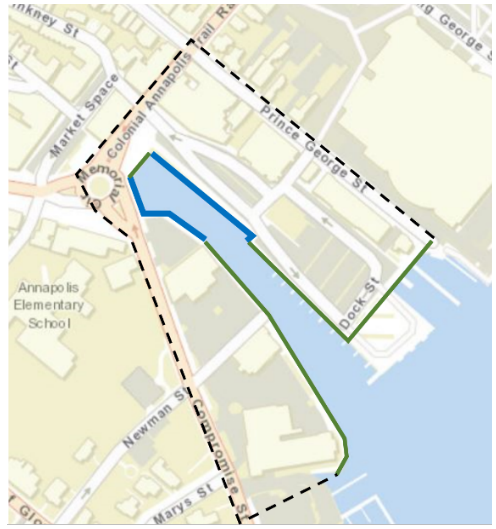

Fig 4. Map shows the proposed location for the alternatives in green (~1500ft). Blue lines show the concrete bulkheads (sea wall). Dashed line plus colored lines delimited the entire scoped area. (Source image from Google maps).

A. TigerDams

TigerDams are long flexible tubes which may be stacked quickly, joined end to end, and filled with water. Individual tubes come in varying heights, ranging from 1.5 to 3.5 feet with acquisition costs ranging from $35/ft to $80/ft. They may be constructed into a pyramid-shaped structure which will act as a barrier against flood waters and may be removed once the flood has subsided.

With a life expectancy of 5 years, TigerDams will need to be purchased 7 times during a 30-year time period [14]. Due to TigerDams being highly customizable to accommodate varying heights, an optimization analysis was made to minimize cost. If a height of 3.5-feet is desired, there are two options to choose for comparison. The first configuration consists a single TigerDam and does not include any stacking.

This 1-configuration of the FM Approved 42" Super Tiger Dam costs about $850,000 for 1500 feet and with an installation time of about 6 hours. The 2 to 1 (2-1) configuration consists of acquiring three of specific height of TigerDam, where two tubes are used for the base and the last tube is stacked on top to create the pyramid structure. A 2-1 configuration of the 2 ft Super Tiger Dam costs about $1.4 million for 1500 feet and with installation time of about 6 hours. Installation time was determined based on the flow rate and with an assumption that two fire hoses will be used to inflate each 50-foot long TigerDam. Given that the installation times are the same for either configuration, the 1 configuration of the FM Approved 42" Super Tiger Dam will be used for the final trade-off analysis.

B. Aqua Fence

AquaFence is a "fence-like" solution with a base that sits underwater during a flood. The panels, which come in sizes ranging from 4x4 to 8x4 feet and acquisition costs ranging from $315/ft to $750/ft, are joined together and secured to a surface before a flood. They may be used in multiple configurations and are fully removable after a flood event. For Annapolis, if AquaFence is chosen, the product will have to be replaced an estimated 4 times in 30 years, based on a reusability rate of 60 times per panel [15]. If the 4x4 feet panels are desired for installation, the life cycle cost is estimated to be about $2 million for 1,500 feet and with an installation time of about 1.7 hours (1 hour 40 minutes).

C. Self-Closing Flood Barrier

The Self-Closing Flood Barrier (SCFB) is a floating entrenching wall that remains recessed in-ground during normal non-flood conditions. When flood water begins to rise, the basin in front of the flood barrier will fill, thus causing the wall, which can be fully customizable to whatever height, to rise. Once the basin is filled, the barrier rises and locks in a watertight position [16]. The SCFB's wall is typically made of concrete and has a life expectancy of about 50 years. With a high life expectancy, this alternative will only be purchased and constructed once to accommodate the next 30 years of flooding. For a height of 3-feet tall and 15,000 long, the SCFB's life cycle cost equates to about $4.3 million.

D. Dynamic Pneumatic Cofferdam

Figure axis labels are often a source of confusion. Use George Mason University's Dynamic Pneumatic Cofferdam is an air-inflated cofferdam alternative with a provisional patent application in process. It will be readily available, can be rapidly deployed only when needed and will be a permanent solution that allows for a low visual impact. The design uses aluminum for the structure and is made to resemble a sidewalk. There is a hinge on one side that allows the aluminum "wall" to rise when the internal airbag is inflated. Steel cables will be secured on the protected side to hold the angle of the dam.

The standard size for the GMU Cofferdam, as shown in Fig. 5 below, will be 4 feet wide and 7.5 inches tall to fit a typical sidewalk when in it's in passive state. Due to the design and needs of Annapolis City dock, the height of the cofferdam will be standardized to 3 feet tall when active and will be split up in 50foot sections. This puts the angle of the dam at around 36 degrees with steel cables of length 2.5 feet. Due to only a small amount of force expected from the water on the cofferdam, any standard bolts would hold down the cofferdam.

For redundancy, bolts and steel cables will be placed at three-foot intervals along the length of the cofferdam. The airbag is the most delicate part of the design. Although it is likely to last the desired 30 years, the cost estimate will account for needing to replace it one time. With most of the cost coming from the aluminum sheets and airbag, the expected cost of acquiring 1,500 LF of the cofferdam is $720,000, which does not include installation or assembly costs. Installation is not expected to greatly affect the cost because the cofferdam ideally will sit on top of the ground.

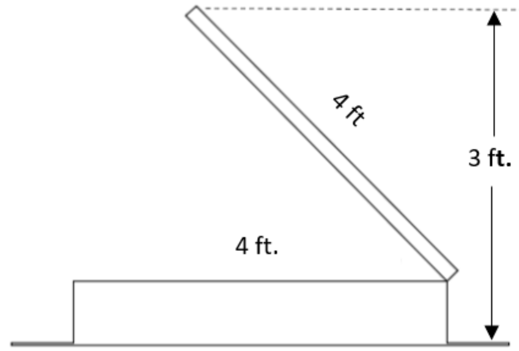

Fig. 5 George Mason University's Dynamic Pneumatic Cofferdam

VI. Trade-Off Analysis

We began by determining the evaluation criteria to be customizability, life expectancy, responsiveness, and aesthetics based on stakeholders' constraints. To evaluate the alternatives, we tested their utility based on these specified criteria. Customizability is defined as the measure of being able to correspond with the customers' desired height of the structure required.

Some of the alternatives are manufactured at a predetermined height, while others can be manufactured by customers' preference. Life expectancy refers to the time period in which the initial purchase lasts. Furthermore, aesthetics is the visual impact on the City. The City is considered a historic landmark thus, resulting in a constraint on construction and alteration of the structures of the City. Permanently installed structures must comply with the Historic Preservation Commission (HPC) guides and codes.

Finally, responsiveness corresponds to how fast an alternative can be configured or erected when needed. Alternatives that are permanently installed have a higher responsive time, while alternatives that must be stored and then installed in place have a lower responsive time. Each alternative is then ranked using a scale of 1 to 5, with 1 being "ok" and 5 being "excellent" depending on how they stand within a specific criterion; this will be referred to as an alternative matrix.

Once the criteria were determined, using the analytical hierarchy process (AHP) method, we rated each evaluation criteria in a "4 by 4" matrix (number of criteria) to rank the importance of a given criteria when compared to another. A scale of relative importance from 1 to 9 rating, 1 representing "equal importance" and 9 being "extreme importance," was also employed. Rates are then normalized by dividing the rating over the sum of the column. Once the matrix was normalized, the row was then averaged to obtain the weights. Derived weights and alternative matrix were then put into the Logical Decisions Software to calculate individual utilities for each alternative. Using the software, the utility yield for each alternative resulted in 0.743 for the SCFB, 0.573 for the Aqua

Fence, 0.550 for the GMU Dynamic Pneumatic Cofferdam, and 0.468 for the TigerDam.

A. Utility vs Cost

Based on the utility given to each of the alternatives, we can plot a utility vs cost graphic (Fig 6), to showcase the trade-off between the different alternatives' 30-year life cycle cost and the utility they yield. The overall cost for any given structure is constrained by the height required for the protection. As previously stated, our protection goal is an elevation of 4.5ft NAVD88 around city dock. The GMU Cofferdam yields the lowest cost with a respectable utility while the SCFB yields the highest overall utility but the most expensive alternative, as shown in Fig 6.

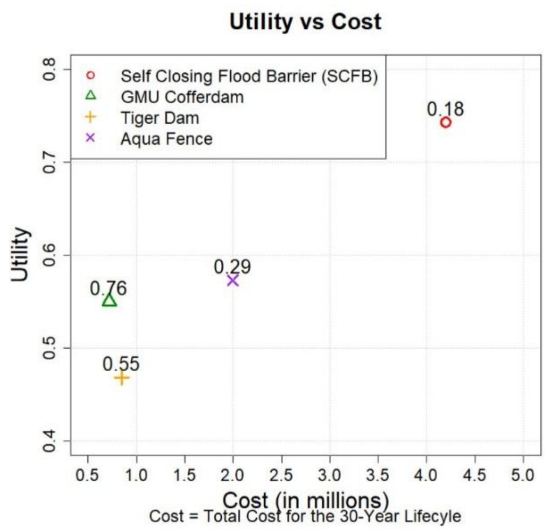

Fig. 6. Utility versus cost plot shows the relationship between different alternatives' yield in utility and life cycle cost. Point labels represent the result of diving the utility versus the cost.

VII. Recommendation and Conclusion

We recommend that the City needs to address the ever-changing climate change effects in their analysis when planning. The effects of climate change are drastically increasing at a fast rate and the City needs to properly prepare the city to become more resilient against the expected climate change. Although Annapolis is already investing in updating the current storm drain system, to best protect the City there needs to be additional tidal surge protection. If the improved storm drain system were to provide the needed additional protection, purchasing and adding a storm surge protective barrier will significantly improve the resilience for any flooding event.

Our recommendation is to protect against 4.5 feet relative to NAVD88 at any given location in the scoped area. The current sea wall already accounts for 4.65 feet relative to NAVD88, but some areas lay as low as 1.5 feet relative to NAVD88 (highlighted in green in Fig. 4). Any solution proposed above will be able compensate for the low elevation. However, based on the trade-off analysis the George Mason University's Dynamic Pneumatic Cofferdam yields the greater trade-off between utility and total life cycle cost. Investing in the Dynamic Pneumatic Cofferdam will cost about $720,000 for the 30-year period. In comparison, businesses are currently experiencing a loss of revenue greater than the cost of any of the proposed alternatives. Annapolis has experienced about 55 floods in 2018 (based on the National Weather Service minor thresholds, 1.83 ft NAVD88) that has cost business around City Dock about $5,500,000 in revenue loss last year alone. Not only would the acquisition of a protective barrier increase the resilience of the city, it does not present a major expense when compared to the current losses the city is facing.

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