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Exploring Real-time Control of Stormwater Systems for Sea Level Rise

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Highlights

- We assess the utility of model predictive control of three actuators in a coastal city for reducing flooding made worse by sea level rise.
- In addition to using a tide gate, model predictive control reduced overall flood volumes with an average effective percent reduction of 32%.
- Model predictive control also reduced maximum node flood volume by an average of 52% for sea level increases of 2.0 ft and above.

Abstract

Low-lying, low-relief coastal cities have seen increased flooding due to climate change. In these cities, stormwater pipe outlets can be inundated by coastal waters at high tide or from storm surge, making drainage impossible. The objective of this research is to assess the utility of model predictive control (MPC) of stormwater actuators to reduce flooding in a coastal urban setting made worse by sea level rise. The stormwater system and the control scenarios are simulated using the United States Environmental Protection Agency Storm Water Management Model (SWMM5) coupled with a Python library, swmm_mpc. The study area is Norfolk, Virginia, USA, a city which is particularly vulnerable to coastal flooding. A simulated 2-year 12-hour design storm and sea level rise scenarios up to 3.5 ft are applied to the model for three control scenarios: 1) a passive system, 2) a passive system with a tide gate (backflow preventer), and 3) a tide gate and three actuators (a pump, a valve, and an inflatable dam) controlled through MPC. Flooding in the passive system reached a tipping point and increased dramatically after a sea level rise of 1.6 ft. The addition of a tide gate greatly mitigated this increase in flooding. MPC further reduced overall flooding with an average effective percent reduction of 32%. The rate of the increase in flooding was significantly smaller with MPC than without. MPC also reduced maximum node flood volume by an average of 52% for sea level increases of 2.0 ft and above. In addition to the installation of a tide gate, our results suggest that the use of actuators controlled by MPC could significantly reduce overall flood volumes and reduce flood severity at individual nodes in coastal cities.

Keywords

Stormwater, Real-time Control, Smart Stormwater, Coastal Flooding, Sea level rise

1 Introduction

Coastal urban flooding is likely to increase globally in the coming decades. In addition to more intense rainfall (Berggren et al., 2012; Neumann et al., 2015), which can affect any city, expected sea level rise (SLR) (Church et al., 2013) makes coastal cities particularly vulnerable to increased flooding. In coastal cities, the water level of the receiving water body has a large impact on drainage and flooding. When receiving water levels are above the system outlets, system pipes cannot drain efficiently; when this happens during a storm event, backups can occur. In such cases, not only is there a decrease in the amount of volume available in the system, but the hydraulic head is also decreased, slowing the rate of drainage. If the receiving water levels are high enough, water can backflow into stormwater pipes, eventually reaching city streets and causing flooding even with no rainfall at all. SLR will make these problems worse as the average water level at system outfalls increases.

In addition to the magnitude of the tide cycle, the timing of the tide cycle can significantly influence flooding in coastal cities. For these cities, the stormwater outfalls could be inundated at high tide and completely free at low tide. Thus, the ability for the stormwater system to drain runoff from the city may be affected by the timing of the storm's runoff relative to the timing of the tide cycle.

One strategy for mitigating flooding in coastal cities is the use of real time control (RTC). RTC of stormwater systems consists of three major components: (1) real-time sensors, (2) system analysis, and (3) actuators. Sensors (e.g., rain gauges, water level sensors, flow meters) provide real-time information on system states. Given the real-time system states, a control decision is made based on either offline or online system analysis. The control decision selected through the analysis is then implemented by actuators (e.g., pumps, gates, valves) which affect the behavior of the system until the next control decision (Schütze et al., 2004).

Conventional stormwater systems are driven by gravity and behave statically. RTC systems, on the other hand, employ actuators to counteract gravity and control the storage and flow of water dynamically. Using RTC, a stormwater system can be managed in a more optimal way (Kerkez et al., 2016). For example, there may be under-utilized capacity in the system in the form of unused storage in a pond or in the pipes themselves that could be utilized with RTC devices. If the existing capacity is used more effectively, there is less need for expensive expansions of physical infrastructure.

RTC in urban drainage systems has been primarily explored, implemented, and evaluated for combined sewer systems (CSS) with the primary objective of minimizing combined sewer overflows (CSOs) (Meneses et al., 2018; Garofalo et al., 2017; Pleau et al., 2005; Schütze et al., 2004). Although the research on RTC for CSS has been well-developed in the literature, there has been a smaller but growing amount of research on the use and utility of RTC in separate sewer systems which are used in most modern cities (Wong and Kerkez, 2018). Research on benefits that RTC systems could provide for flood resilience in coastal cities is limited. It is, therefore, the intent of this paper to characterize the utility of RTC for flood reduction, specifically an implementation of model predictive control (MPC) (Puig et al., 2009; Cembrano et al., 2004; Schütze et al., 2004; Gelormino and Ricker, 1994) in a separated sewer system subjected to various SLR scenarios.

While the use of RTC systems could benefit coastal cities globally, the geographic focus of our study is the coastal city of Norfolk, Virginia USA. Norfolk is part of a region which is experiencing faster than average SLR due to land subsidence (Mitchell et al., 2013). Therefore, the conditions being seen now in Norfolk and its neighboring cities could be seen in coastal cities globally in the decades to come.

We will assess the current and future utility of MPC systems in Norfolk using a simulation model, the Environmental Protection Agency (EPA) Stormwater Management Model version 5 (SWMM5). In the SWMM5 model, three scenarios will be simulated with increasing sea levels: 1) the passive scenario (representing the current state of the system), 2) the passive scenario with the addition of a tide gate (a mechanical device used to prevent backflow into the system), and 3) the tide gate scenario with the addition of actuators controlled by MPC. The simulated flood volumes from the three system scenarios will be compared and flood reduction from MPC calculated. The increasing receiving water levels will then be related to SLR scenarios. In addition to increasing the sea level at the stormwater outfalls, we will also vary the timing of the tide cycle relative to the rainfall and assess the effect of this factor on flooding.

In the remainder of this paper, we present details about our methods including the study area of Norfolk, VA, the MPC scenarios explored, and the rainfall and tidal conditions used. We then present the results which demonstrate the utility of MPC (in terms of flood reduction) with increasing sea levels. Finally we discuss the results and relate the increasing receiving water levels to potential SLR scenarios.

2 Methods

2.1 Study area

Norfolk, VA USA served as the study area for this research (Figure 1). Norfolk is a peninsula with several inland streams and much of the city is within close proximity to a tidally-influenced water body. The city is low-lying with low topographic relief. Because of these geographic conditions, Norfolk experiences frequent flooding (Sadler et al., 2018; Ezer and Atkinson, 2014; Mitchell et al., 2013; Atkinson et al., 2012).

Given the size of the city and the complexity of the stormwater system with all its features (subcatchments, pipes, channels, junctions, ponds, etc.), our study focused on a subsection of the city: the neighborhood called the Hague. The Hague, approximately eight square km, is a key part of Norfolk. It is home to many of Norfolk's most historic buildings and cultural attractions. The Hague is also key to the city's connectivity as it is adjacent to the city government buildings and the regional hospital. In addition to its importance to Norfolk, the Hague area is one of the most flood-prone of the city.

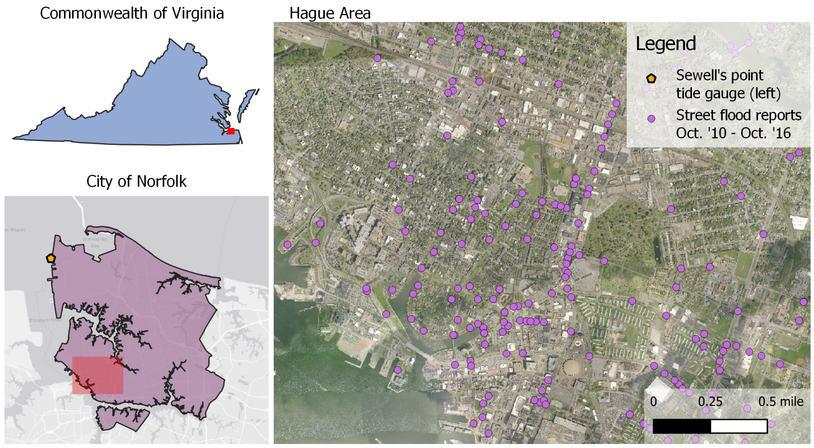

Figure 1: Study area - Hague neighborhood in Norfolk, VA USA

2.2 Storm event and base tidal conditions

There are two main factors that affect flooding in low-lying coastal cities: rainfall and tidal conditions. Because this paper is primarily focused on the utility of MPC over time given SLR, the rainfall event in all the simulations was kept constant and the tidal conditions were varied. The rainfall event we used was a 2-year 12-hour storm event (3.08 in) (Bonnin et al., 2018) with a SCS Type II temporal distribution (Mockus, 2012) (Figure 2). We chose a smaller event because we wanted the focus the analysis on an event that would occur more frequently and because flooding from an extreme event would be difficult to impact with RTC. Because simulations were for events lasting a day or less, other meteorological conditions such as evapotranspiration were not considered. Therefore, the absolute time of day of the simulated rainfall does not affect the simulation, as long as the timing relative to the tide is the same.

Observations from the Sewells Point tide gauging station (Figure 1), operated and maintained by the US National Oceanic and Atmospheric Administration (NOAA) (NOAA, 2019), served as the baseline tide conditions in the simulations. Hourly water level observations from a typical 24-hour tide cycle were taken as a base tidal boundary condition in the simulations. The tide cycle (Figure 2) was the hourly water level recorded at the Sewells Point station on August 8, 2018. This day was selected because the 24-hour tidal range (2.78 ft)

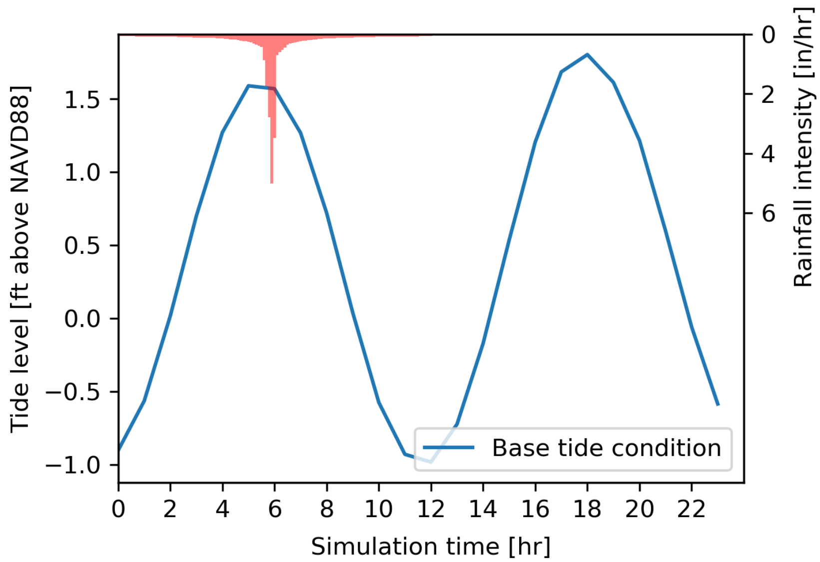

Figure 2: Design storm and base tide condition

was very similar to the station's all-time average 24-hour tidal range (2.76 ft) and because the day had a very typical tide cycle without unusual effects from wind or other factors.

2.3 Increasing tide levels

To estimate the utility of MPC with SLR, the baseline hourly tidal conditions were increased in magnitude. To cover a range of possible SLR scenarios, the hourly tide levels were increased by 0.5 foot increments up to 3.5 ft, for a total of seven elevated water levels. The increases in tide level were then correlated to region-specific SLR estimates from Mitchell et al. (2013) who adjusted global SLR estimates with local land subsidence rates.

2.4 Computational model

The computational model used to simulate the stormwater system in the study area was EPA-SWMM5. It was selected based on its general use as a 1D stormwater system model and its ability to simulate stormwater system actuators (Burger et al., 2014). SWMM5 solves the St. Venant equations numerically to simulate dynamic routing in a stormwater system. The use of dynamic wave routing is particularly important in simulating coastal systems because the systems often experience backflow from tidally influenced receiving waters. In a SWMM5 simulation, each node has a maximum depth (usually the distance from the invert elevation to the ground surface elevation). When the simulated water exceeds the maximum depth at a node, the excess water volume is recorded as flood volume by SWMM5. At the end of a simulation, both the accumulated flood volume at each node and the combined flood volume across all the nodes together is reported.

A SWMM5 model of the Hague neighborhood was obtained from the city of Norfolk (Figure 3). The city of Norfolk verified that the model behavior sufficiently represented the behavior of the physical system. The model consists of 208 nodes with a wall-clock time of approximately 0.5 minutes for running a 24-hour simulation of a 12-hour storm event on an 8-core desktop computer. The system drains to a tidally influenced water body and a water level boundary condition was implemented at the outfall to simulate the influence of the tidal water body at the receiving waters.

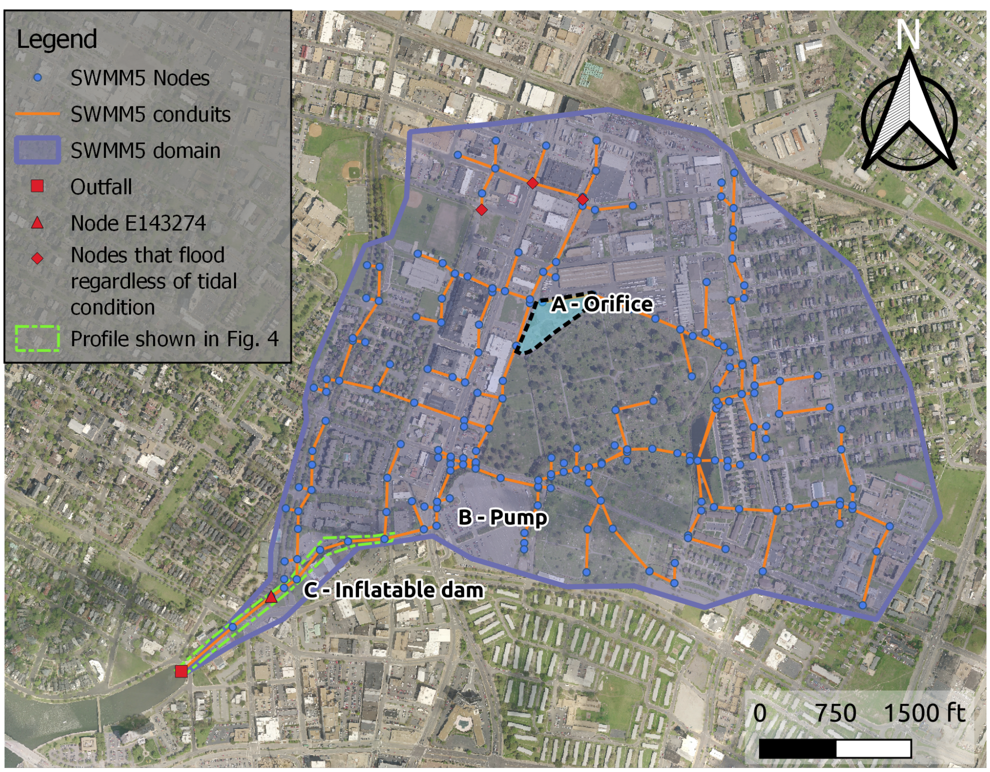

Figure 3: SWMM5 model of the study area and simulated actuators

Figure 4 shows the elevation profile of the nodes closest to the outfall of the system. This elevation profile is important to understanding the drainage system. When the sea water exceeds the surface elevation of the node with the lowest surface elevation in the system, 3.41 ft at node E143274, the sea water exits node E143274 causing flooding even without rainfall. This is referred in coastal cities as “sunny day flooding” (Sweet et al., 2016). This occurs in the Hague system at high tide when the base tide cycle is increased in magnitude by 1.6 ft.

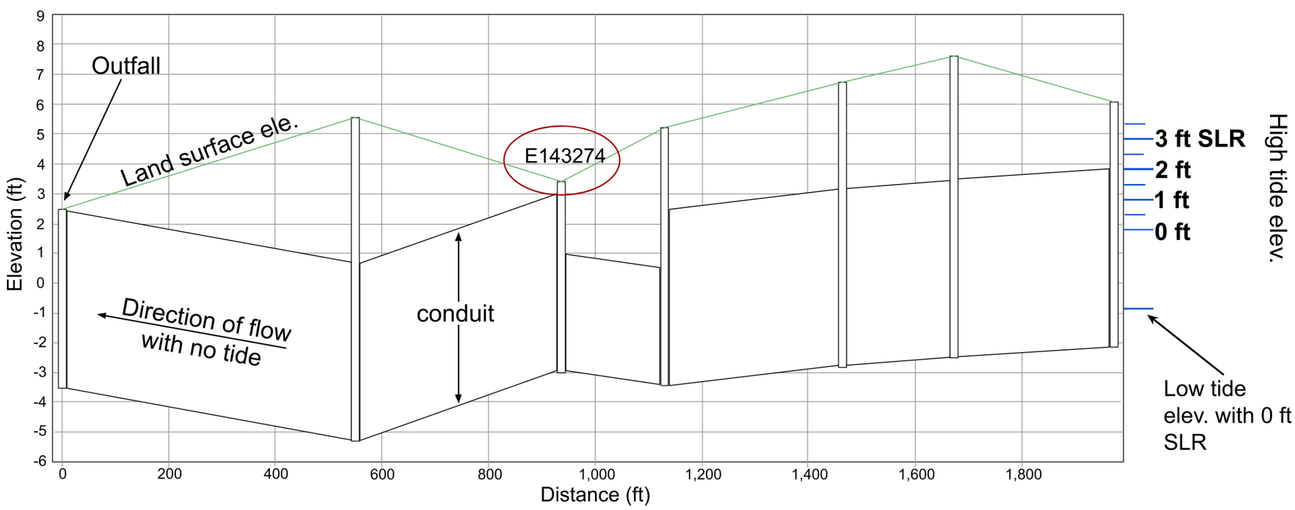

Figure 4: Elevation profile of the closest nodes to the outfall as shown in Figure 3. When the sea water level exceeds the surface elevation of the node with the lowest surface elevation in the system, E143274, flooding occurs even with no rainfall. Also shown are the high tide elevations with 0-3.5 ft SLR and the low tide elevation with 0 ft SLR.

2.5 Addition of tide gate

Before simulating MPC in the system, a tide gate was added to the outfall of the passive SWMM5 model. A tide gate is a passive device used to prevent backflow from a receiving water body. The use of a tide gate was explored because the installation of a tide gate could become an important approach for minimizing tidal flooding in coastal cities as the likelihood of backflow increases with SLR. In SWMM5 simulations, tide gates are assumed to be 100% effective at preventing backflow through the system outfall. That is, even when the tidal boundary condition exceeds the elevation of the outfall, water will not backflow into the system. Additionally, in a SWMM5 simulation, water cannot flow out of an outfall with a tide gate when the outfall is inundated.

2.6 Addition of MPC

Three actuators for mitigating flooding in coastal cities were simulated in the MPC scenario. First, a valve at the outlet of a simulated pond (Point A in Figure 3) was used to control the storage volume in the pond. Second, a pump (Point B in Figure 3) was simulated to increase the hydraulic head in the stormwater pipes. This is particularly important in a low-relief, coastal city because the contribution of elevation head to the total hydraulic head is very small. Third and finally, an inflatable dam was simulated to utilize inline storage in the stormwater pipes (Point C in Figure 3). Although these controls were simulated in the Hague area, such controls (or different combinations of controls) would likely be useful in many coastal cities globally since many coastal cities share similar geographic characteristics (low relief, low elevation).

The control approach in the MPC scenario was simulated using the swmm_mpc Python library (Sadler et al., 2019). The main parameters in running swmm_mpc include cost function parameters, genetic algorithm parameters, and control parameters. The cost function in these simulations was the total amount of flooding that occurred in the simulation as reported in the SWMM5 output. For the genetic algorithm, six generations were used (including the initial generation) with twenty individuals in the initial generation. The control horizon was 30 minutes and the control time step was 15 minutes, meaning that the algorithm was searching for two control settings for each actuator at every time step in the model (see Table 1).

We estimated the time of concentration from the passive SWMM model results to be 26 minutes. The control horizon of 30 minutes, therefore, should be sufficient to prepare for and respond to the runoff response from a rainfall event. Although the control time step is 15-minutes, the control algorithm still accounts for the rainfall at the 6-minute simulation interval. That said, the 15-minute control time step is perhaps coarser than ideal given the time of concentration and the potential for flashy runoff response in urban watersheds. To move to a finer resolution with the same control horizon, however, would have significantly increased computational expense. In MPC, the control strategy for each actuator is determined and can be changed at every control time step (15 minutes in this case). This makes the approach flexible, that flexibility, however, comes at a higher computational cost since the control strategy is determined by running many iterations of the simulation model at each time step. Given the computational cost of running this library, the MPC scenarios were executed on a high-performance computer with 20 computational cores and 128 GB of RAM.

Table 1: Control parameters for MPC scenarios

Parameter	Value
Control Horizon (hr)	0.5
Control Time Step (hr)	0.25
Num controls	3

2.6.1 Assessment of MPC with SLR

To assess the utility of adding MPC in the Hague stormwater system, the storm event and tidal conditions described above were input into swmm_mpc. For each of the tidal and gate scenarios, the amount of flooding that occurred in the MPC scenario was compared to the amount of flooding that occurred in the scenario with the tide gate. The percent reduction of total flooding and the maximum flooding at a single node between the MPC and the tide gate scenarios was also calculated. In preliminary simulations, it was found that the runoff from the rainfall event alone caused flooding at some nodes that were not affected at all by tidal conditions or MPC. The majority of this flooding occurred upstream of the controls at three nodes. Therefore, because the volume of flooding at these three nodes (in total $0.582\text{x}10^6$ gallons) could not be prevented with any MPC strategy, it was not taken into account when calculating the percent decrease in total flooding. Instead, an effective percent reduction of total flooding was calculated:

$$\text{effective percent reduction} = \frac{F_{G\_eff} - F_{R\_eff}}{F_{G\_eff}} \tag{1}$$

and

$$F_{G\_eff} = F_G - F_{uneff} \tag{2}$$

$$F_{R\_eff} = F_R - F_{uneff} \tag{3}$$

where F_G and F_R are the total simulated flood volumes in the tide gate and MPC scenario, respectively, and F_{uneff} is the flood volume unaffected by MPC and tidal conditions (0.582×10^6 gallons in this case).

2.7 Timing of tide cycle

In addition to the magnitude of the tide levels, the timing of the tide cycle relative to the timing of a rainfall event can impact drainage and flooding in a coastal stormwater system. Therefore, as well as analyzing changes in flooding with increasing the magnitude of tide levels (the main focus of this study), the timing of the tide cycle relative to the 2-year 12-hour design rainfall event was also varied. To assess the effect of the timing of the tide cycle, the timing of the rainfall event was held constant while base tide cycle was shifted in 1-hour increments from 0-11 hours. This was done under increases in sea level as above (up to 3.5 ft increase in 0.5 ft increments). In total, this resulted in 96 model runs (12 variations in timing x 8 increases in sea level).

For each increase in sea level the amount of flooding changed based on the timing of the tide cycle. To quantify the impact of this timing, the difference in flood volume was computed between the timing that caused the maximum flood volume and the timing that caused the minimum flood volume. The difference between the maximum flood volume and minimum flood volume for a given amount of SLR, i, is given as

$$\Delta F_i = \max_{j=0}^{T}(F_{ij}) - \min_{j=0}^{T}(F_{ij}) \tag{4}$$

where F is the total simulated flood volume, j is the shift in tide cycle timing, and T is the number of hourly shifts, in our case 12.

Because there is likely a significant increase in total flooding with increasing SLR, the normalized difference in flooding between the tide cycle timing that caused the maximum flooding and the timing that caused the minimum flooding was also found. The normalized difference for a given amount of SLR was found by dividing the difference by the average of the flooding across all tide cycle timings for that amount of SLR. For a given amount of SLR, i, this was computed as

$$\Delta F_i^{norm} = \frac{\max_{j=0}^{T}(F_{ij}) - \min_{j=0}^{T}(F_{ij})}{\frac{1}{T}\sum_{j=0}^{T} F_{ij}} \tag{5}$$

Because the timing of the tide cycle would affect both the MPC and passive systems similarly, the different timings were only simulated on the passive case.

2.8 Comparison with regional SLR scenarios and extreme water levels

To put the modeled scenarios of 0-3.5 ft of SLR in context, the results were compared to regional SLR predictions and locally-observed historic extreme water levels. The regional SLR predictions took into account both global SLR and regional land subsidence (Mitchell et al., 2013). These predictions were made for "high," "medium," and "low" scenarios emission scenarios. Local extreme water levels were obtained for comparison from the Sewells Point tide station (NOAA, 2020).

3 Results

3.1 Flooding with SLR in passive scenario

Figure 5a shows the amount of flooding in the passive system given increases in sea level. The amount of flooding remains fairly constant between no increase in sea level and an increase in sea level of 1.5 ft, however, there is a dramatic increase in flooding between increases of 1.5 ft and 2.0 ft. This occurs because with an increase of 2.0 ft, the elevation of

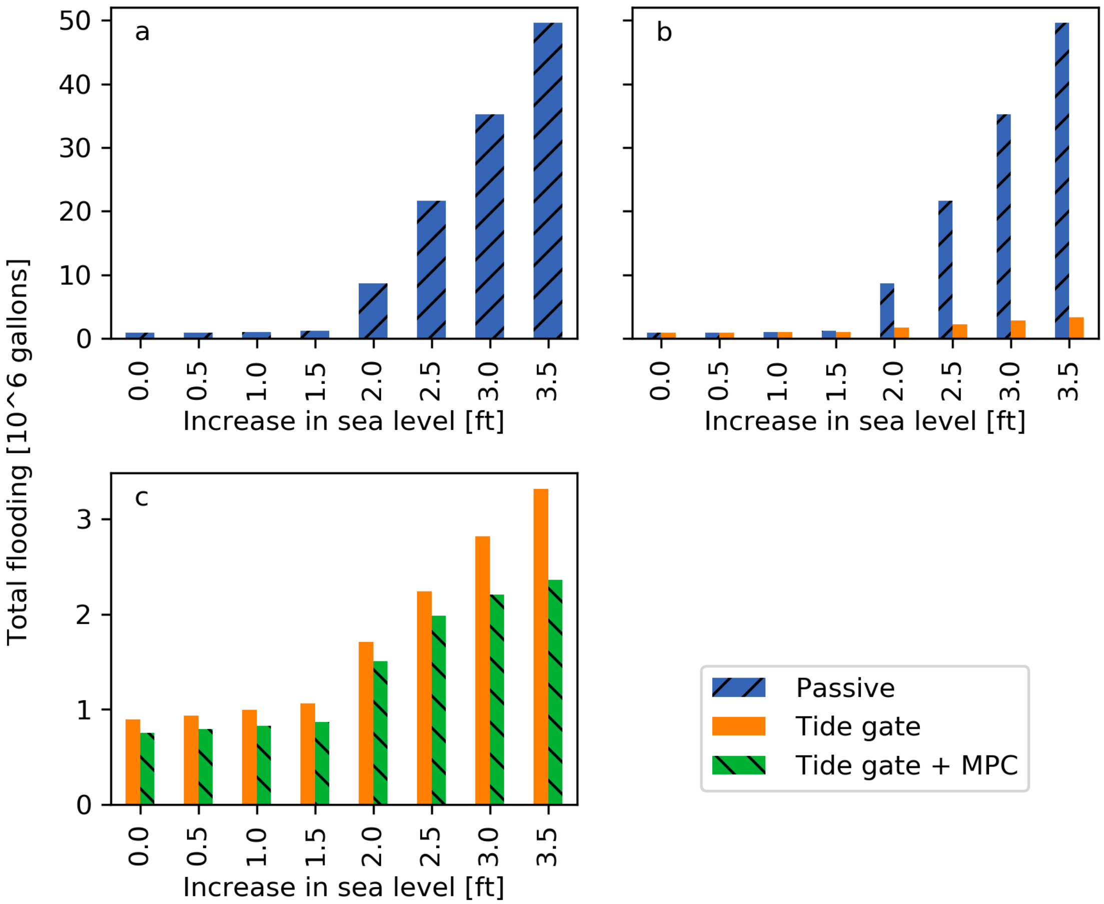

Figure 5: Flooding with sea level increases in (a) passive scenario, (b) passive compared to tide gate scenario, and (c) tide gate compared to MPC with tide gate scenario

the high tide (3.8 ft) exceeds the 3.41 ft land surface elevation at node E143274 (see Figure 4). A sea level increase of 1.6 ft therefore becomes a tipping point and any increase in sea level beyond this causes much more flooding. This is seen in the substantial increases in flood volume with each increase in sea level above 1.5 ft.

3.2 Flood reduction with addition of tide gate

The impact of adding a tide gate to the outfall of the system dramatically reduced flooding with increasing sea levels compared to the passive system (Figure 5b). This reduction was most evident with sea level increases of 2.0 ft and higher when the vast majority of the flooding was tidally driven. With lower sea levels, the effect was less significant. This is most striking between increases in sea level of 1.5 ft and 2.0 ft. The addition of the tide gate with a 1.5 ft increase in sea level reduced total flooding from 1.3x10^6 gallons to 1.1x10^6 gallons, a reduction of 15%. In contrast, with a sea level increase of 2.0 ft, the addition of a tide gate reduced the total flood volume from 8.7x10^6 gallons to 1.7x10^6 gallons, an 80% reduction. When sea level was increased to 3.5 ft, flooding was reduced from 49.6x10^6 gallons to 3.3x10^6 gallons, a 93% reduction.

3.3 Flood reduction with tide gate and MPC

Figure 5c shows the amount of flooding seen in the tide gate and MPC scenario given increases in sea level. Like in the tide gate scenario, the total amount of flooding increases with increasing sea level. However, the rate of increase is slower compared to flooding in the situation without MPC (see Figure 6). The actuators in the MPC are able to reduce flooding at a rate higher than the tide gate alone. For example, from a 3 ft to a 3.5 ft increase in sea level, the flooding increases by 18% without MPC; with MPC the increase is only 9%.

MPC reduced flooding by at least 40% for each of the sea level increases below 2.0 ft (Figure 7). Above 2.0 ft increases in sea level, the percent reduction generally increased with increases in sea level up to a 35% reduction in flooding with a sea level increase of 3.5 ft. In addition to reducing the total flood volume, MPC reduced the maximum node flood volume with sea level increases of 2.0 ft and above (Figure 8). The largest reduction of maximum node flood volumes was 70% at Node E143274 with a 3.5 ft sea level increase (from 2.2x10^6 gallons without MPC to 0.65x10^6 gallons with MPC).

Figure 9 shows the amount the three controls were utilized for the 0-3.5 ft SLR scenarios. In general, each of the three controls were utilized more as the SLR increased. The increase of use of the orifice was not as related to the amount of SLR compared to the inflatable dam and the pump. This may be because it is much further from the coast than the inflatable dam and the pump. The pump was utilized much more often and for longer with SLR of 1.5 ft and greater. The average pump run time with SLR of 0-1.0 ft was 5.25 hr, whereas the average for SLR of 1.5-3.5 ft was 18.45 hr. The pump time peaked at the 2.0 ft SLR and then decreased. This is correlated with the amount of time that the water had to drain between tide cycles which decreased with increasing SLR. It is possible that the use of the pump to send water more quickly downstream became less helpful with less time to drain that water.

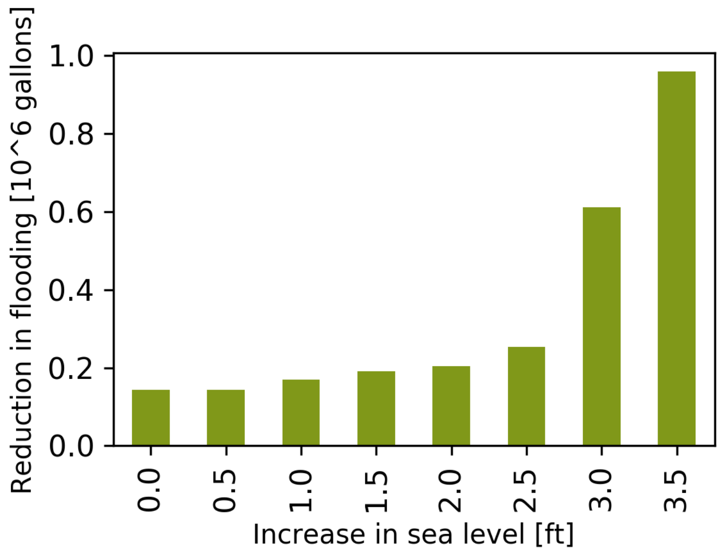

Figure 6: Flood reduction in MPC compared to tide gate scenario given increasing sea level

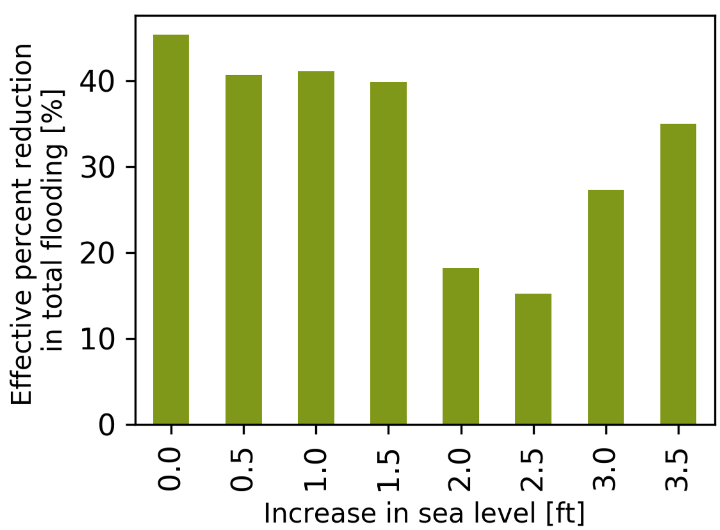

Figure 7: Effective percent total flood reduction in MPC compared to tide gate scenario given increasing sea level

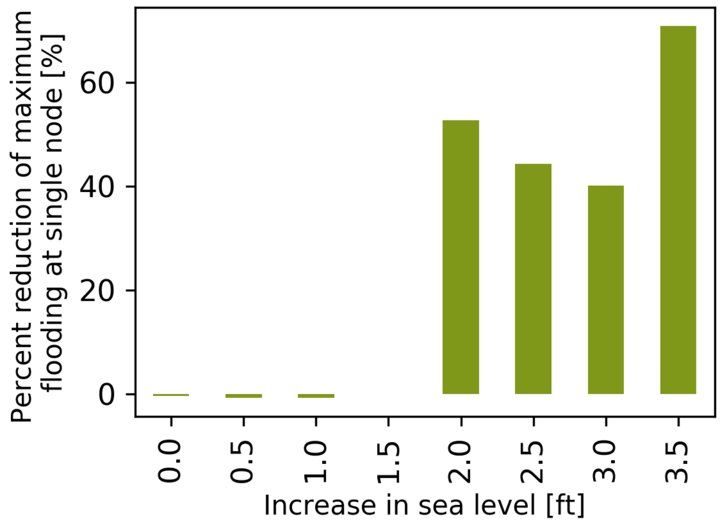

Figure 8: Percent reduction of maximum flooding at an individual node with MPC compared to tide gate scenario given increasing sea level

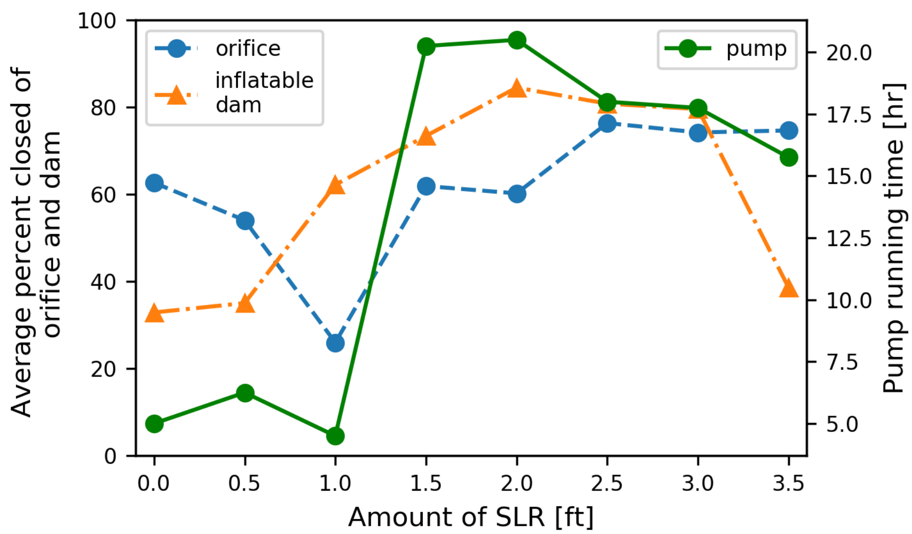

Figure 9: Use of controls in each of the SLR scenarios - the average percent closed of the orifice and inflatable dam and running time of the pump for SLR from 0-3.5 ft

3.4 Timing of tide cycle

In a similar trend to the increase in flooding with SLR, the difference between the maximum and minimum flood volumes from different timings also increases substantially starting with a sea level increase of 2.0 ft (Figure 10). The difference between the maximum and minimum flood volumes, however, does not follow the same trend when divided by the average flood volume at each sea level increase (Figure 11). The largest normalized difference, in fact, occurs at a SLR increase of 1.5 ft. These results suggest that following a sea level increase of 2.0 ft, the tidal flood volume is so large that the flood volume from the rainfall event, and thus the timing of the tide cycle relative to the rainfall, makes an increasingly smaller impact.

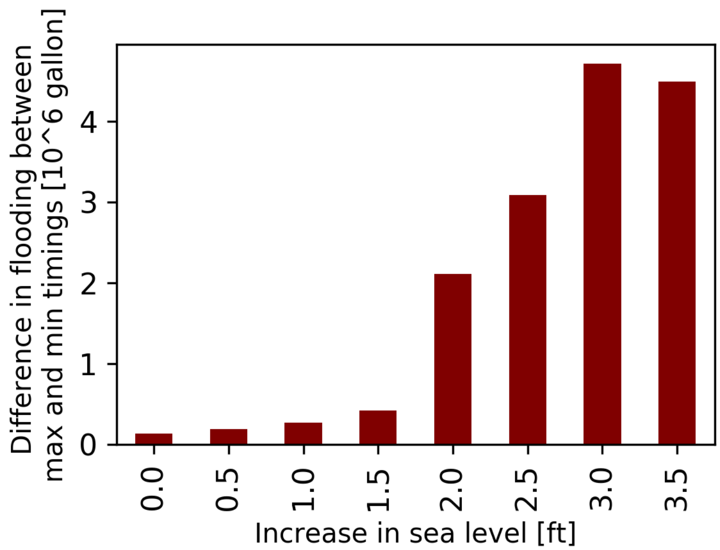

Figure 10: Difference between the flood volume caused by the worst-case scenario timing and the best-case scenario timing

3.5 Comparison with local SLR scenarios and extreme water levels

Figure 12 shows SLR estimates specific to south-east Virginia (Mitchell et al., 2013). As sea level increases with time, a normal tide cycle will become increasingly problematic for coastal cities. Based on our analysis above, there will be a dramatic increase in tidal flooding in this case study region once the high tide reaches 3.41 ft. This would be an increase of the base tide cycle in Figure 2 of 1.6 ft (shown as the dashed line in Figure 12). When this threshold is crossed, we would expect to see street flooding from a typical daily tide cycle at high tide. Based on the SLR estimates from Mitchell et al. (2013), the 1.6 ft threshold could

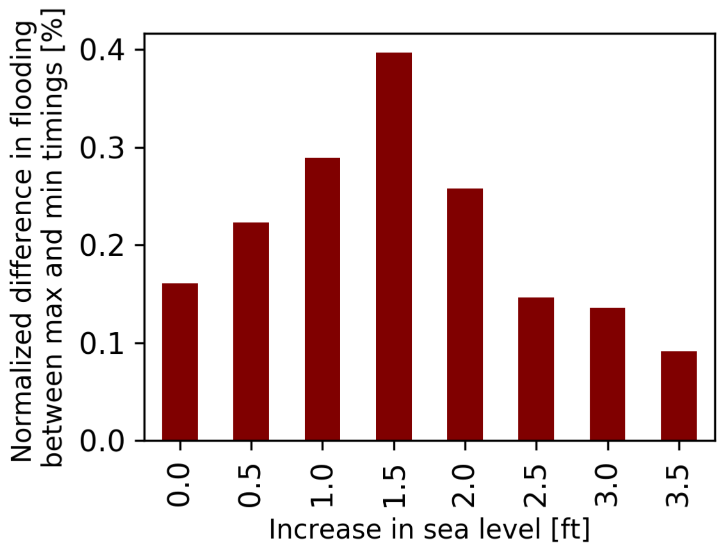

Figure 11: Difference between the flood volume caused by the worst-case scenario timing and the best-case scenario timing normalized by the average flood volume for each sea level increase

be crossed as early as the year 2035 for Norfolk in the high emission scenario and by 2060 for the low scenario.

The use of RTC for stormwater systems will become increasingly valuable with increasing average sea level in the coming decades. However, under current conditions storm surge and astronomical tides alone can already elevate sea levels temporarily to the point where RTC would be useful. For example, since 2000, four storms, Hurricanes Isabel (2003), Irene (2011), and Sandy (2012), and a powerful Nor'easter (2009) each caused storm surge that reached over 3.93 ft (1.2 m) in our study region. The astronomical tide alone has a 99% likelihood of reaching 2.85 ft (0.87 meters) each year in Norfolk (based on the 1983-2001 tidal epoch, see Figure 13). This is well above the 1.6 ft threshold, showing that Norfolk now experiences, and will continue to experience, flooding from the highest tide of each year. The results of this analysis suggest that with the addition of a tide gate, the introduction of active controls through MPC could significantly reduce flooding caused by similar storm surge and astronomical tide events.

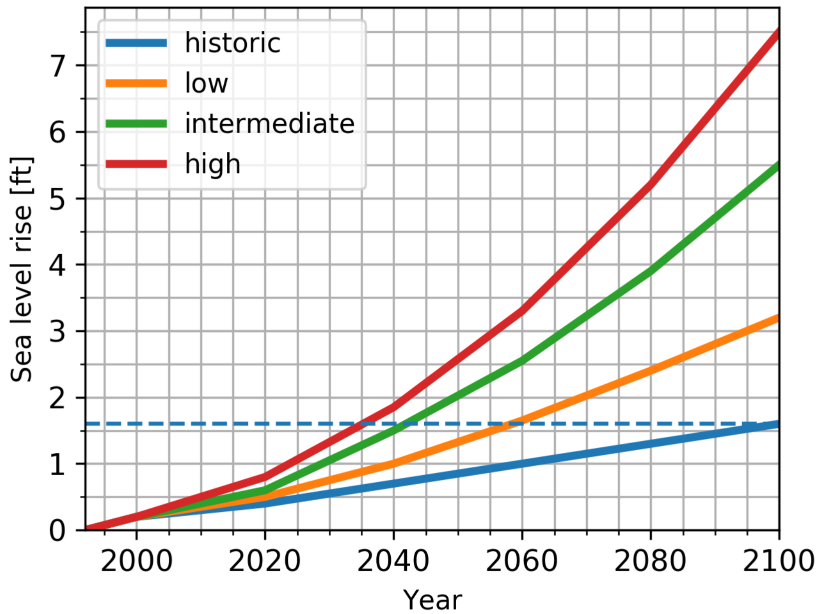

Figure 12: Region specific SLR scenarios for coastal Virginia. The "high", "medium" and "low" scenarios are different emission scenarios. The "historic" is an extrapolation of the existing tidal record. Adapted from (Mitchell et al., 2013)

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4 Discussion

Although the use of a tide gate makes a greater difference in overall flooding compared to the passive scenario, the use of MPC further improves the system performance. Not only does MPC reduce the overall volume of flooding, but it also reduces the maximum node flood volume, thus more evenly distributing the flood volume across the nodes in the system. Less severe flooding at any given node could mean less disruption and or damage to the community.

In our analysis, the utility of MPC, in terms of percent flood volume reduction and absolute flood volume reduction, generally increased with increasing sea levels. The largest increases in utility occurred with higher increases (3.0 ft and 3.5 ft). This suggests that as coastal cities consider investment and mitigation alternatives, the investment in RTC and MPC could provide a greater return on investment in coming years.

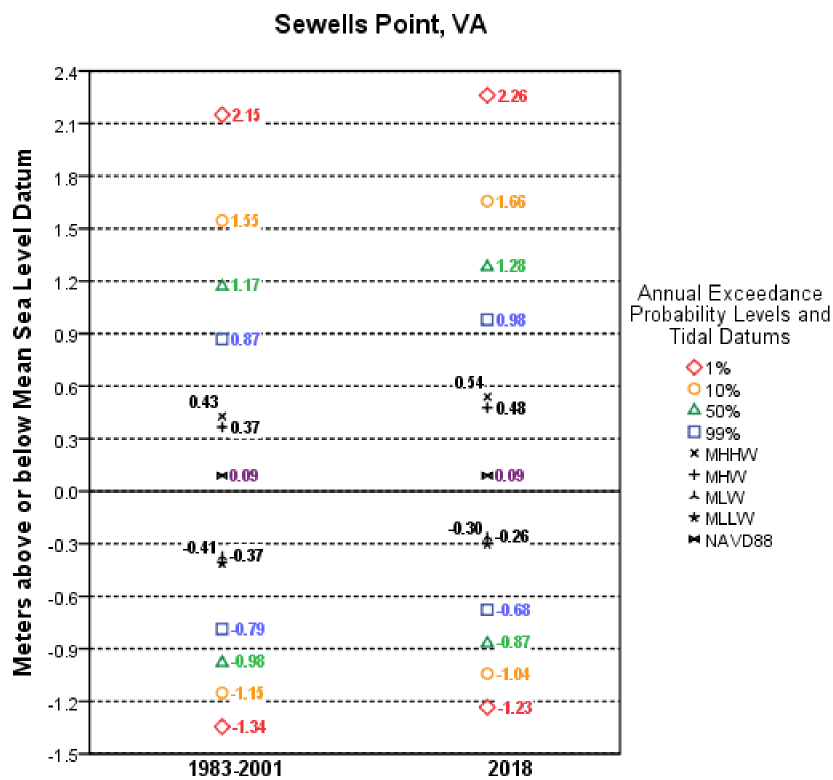

Figure 13: High and low exceedance probability levels for Sewells Point tide gauge in Norfolk, VA USA (NOAA, 2020)

To make the results and inferences more complete, future work should be done to quantify uncertainty in the results. One source of uncertainty in this analysis includes the model itself and how well it represents the physical system. SWMM5 is a 1D model and therefore cannot simulate some aspects of coastal flooding. For example, SWMM5 only records a volume of water that is flooded from a given node, and does not simulate the depth of flooding. Given detailed land elevation data, however, this could be calculated using the height above nearest drainage method (HAND) (Nobre et al., 2011) or a similar method. Knowing the depth of flooding, and the reduction of depth by MPC, would be another way to assess the utility of MPC.

Another uncertainty in the results is in the optimality of the control strategies found in the MPC scenario by swmm_mpc. The SWMM5 model is used as a black-box model without the optimizer having any knowledge of the underlying mathematical structure of the governing equations. Because of this, the control strategies found by swmm_mpc cannot be guaranteed to be optimal. Future work could be done to analyze the optimality of the strategies found through swmm_mpc.

In this analysis, we simulated three actuators. These were chosen in an ad hoc manner based on the behavior of the model and the constraints of the physical system. A methodology for systematically selecting which actuators should be used and where they should be placed would be a useful extension of this work. Such a methodology could be especially useful as coastal cities seek adaptation alternatives. The monetary cost for adding controls into the system could be added to the cost function as an important practical consideration for municipalities. Optimizing the placement and selection of controls could be an addition to the swmm_mpc software.

Because the focus of this study was on flooding impacts due to SLR, the rainfall magnitude and intensity were not changed. However, climate change, in addition to causing SLR, is anticipated to increase rainfall intensity (Berggren et al., 2012; Neumann et al., 2015). It would therefore be useful, in addition to increasing sea level in the simulations, to increase rainfall intensity and/or volume with time. A recent study in the region quantified increases in design storm rainfall volumes with climate change (Smirnov et al., 2018). By analyzing historic rainfall data and climate models the authors recommend 20% higher rainfall volumes for design storms. These projections could be used to adjust design storms and run additional scenarios using the methods of this study.

Barriers to adoption of RTC for stormwater systems by municipalities include costs and risk. Monetary costs include the costs of the equipment, installation, and maintenance. The cost of installation and maintenance can be especially high in cities with limited available space. For example, the location of the simulated inflatable dam in our study is a busy intersection near cultural attractions, government buildings, and the city's downtown area. The city of Norfolk would, therefore, have to take into consideration both the cost of the disruption to the community as well as the capital costs of construction when weighing against the benefits.

Less straightforward to estimate, and perhaps a larger barrier than monetary cost is that of potential risks of RTC systems in stormwater infrastructure. Although successfully deployed in some cities for combined sewer systems, the use of RTC in separated sewer systems is still new. Schütze et al. (2004) provide some suggestions for overcoming institutional barriers for adopting RTC systems. Although primarily focused on combined sewer systems, many of the suggestions apply to separated sewer systems as well. A key suggestion made by the authors in regards to safety and risk when implementing RTC is that in the worst-case scenario, the RTC system should perform as well or better than the system before the installation of the RTC. Additionally, Schütze et al. (2004) suggests that equipment failure should be considered inevitable and, therefore, redundancy should be built into the system. Finally, the authors emphasize the need to involve and educate municipality stormwater personnel from the beginning stages and potentially begin with an operator-in-the-loop approach until trust in the system is built.

Given RTC systems' reliance on real-time communications, costs and risks will include those associated with information technology infrastructure. Costs can include communication costs, data storage costs, and data access/display portal costs. Associated risks include breaches in cyber-security in which cyber-criminals could either disable the RTC system or use it to intentionally cause damage or disruption. As municipalities consider RTC systems, they must have personnel in place specifically trained to prevent and address such attacks.

5 Conclusions

In this research we assessed the utility of model predictive control (MPC) for reducing flooding in a coastal city with sea level rise (SLR). The study area was a neighborhood in Norfolk, VA, USA, a city particularly vulnerable to coastal flooding. A 2-year 12-hour design storm along with various tide scenarios were input into a SWMM5 model of the study area. This event was used because we were only considering non-extreme rainfall and tidal conditions (e.g., not hurricane-level events). To simulate a range of SLR scenarios, the base tide cycle was increased in 0.5 ft increments up to 3.5 ft.

The tidal increases were input for three scenarios, 1) a passive system (system as it currently behaves), 2) the passive system with the addition of a tide gate, and 3) the system with the addition of a tide gate and actuators controlled through MPC. Three actuators were simulated in the MPC scenario, a valve at the outlet of a pond, a pump to increase head, and an inflatable dam to utilize inline storage. The control strategies for the actuators were found using the swmm_mpc library with a genetic algorithm as the optimization method.

Flooding in the passive system increased dramatically after an increase in sea level of 1.6 ft. The addition of a tide gate greatly mitigated this increase in flooding. MPC further reduced overall flooding with an average effective percent reduction of 32%. The rate of the increase in flooding was significantly smaller with MPC than without. MPC also reduced maximum node flood volume by an average of 52% for sea level increases of 2.0 ft and above.

It is anticipated that SLR will make coastal cities more vulnerable to tidally- and rainfall-driven flooding. In addition to the installation of a tide gate, our results suggest that the use of actuators controlled by MPC could significantly reduce overall flood volumes and reduce flood severity at individual nodes in coastal cities. Transforming traditionally static, gravity-driven stormwater systems into dynamic, adaptive ones could reap large benefits in cumulative reduced flood volumes over the decades.

6 Data, model, and script availability

The data, models, and scripts used to produce the results of this study are available from HydroShare, (Sadler, 2020).

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