The Performance Comparison between RTC and GI to Mitigate Impacts of Climate Change and Urban Redevelopment on Urban Flooding

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The Performance Comparison between RTC and GI to Mitigate Impacts of Climate Change and Urban Redevelopment on Urban Flooding

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Abstract

Green stormwater infrastructure (GI) is widely adopted for addressing urban flooding challenges. Another rising solution that is complementary to, but distinguishable from GI, is smart real-time control (RTC). However, the outcomes of the battle between RTC and GI has been unknown. This research compares the performance of RTC and GI to mitigate the climatic and urbanized influences on historical and future urban floods; a case study located in Sugar House neighborhood of Salt Lake City, Utah, USA, was provided. Results show that RTC and GI have comparable performance to reduce the historical flooding severity from 2001-2015, but RTC outperforms GI for improving flooding resilience in the future. Especially from 2085 to 2099, RTC maintains the system service level against future climatic and urbanized disturbances better than GI. This work improves the understanding about how RTC brings benefits for controlling future urban floods.

Keywords: resilience analysis; future adaptation; urban flooding control; urban infill; climate change

1. Introduction

Urban flooding poses adverse influences on economic, social, and environmental perspectives. These impacts cause economical loss, life loss, traffic flow disruption, and infrastructure damage around the world. For example, urban floods across the United States notably increased the economic loss from US$ 1 to 7 billion from the 2010s to the 2020s (Brusentsev and Vroman 2016). The United Kingdom suffered from US$ 5 billion loss due to annual property damage caused by urban floods occurring from 2015 to 2016 (Miller and Hutchins 2017). In Beijing, China, a flash flooding event led to 79 deaths and approximately US$ 1.5 billion in economic loss in 2012 (Xie et al. 2017). In Mumbai, India, urban flooding has resulted in the destruction of mangroves in coastal areas (Pramanik et al. 2021). Urban floods are projected to be more frequent in the 21st century due to future urban redevelopment and rainfall variations because of climate change (Physical and Basis 2012).

Rainfall changes in time, especially due to climate change, may affect the frequency of urban stormwater flooding. The impacts of climate change can be quantified by using the downscaled precipitation projections from global climate models (Hansen et al. 2017; Li and Burian 2022). The downscaled precipitation represents possible shifts in frequency, duration, and intensity of storm events, which can then be translated to changes in surface runoff response and urban floods (Tao et al. 2016). For instance, it was found the frequency and duration of urban floods would increase in the future (2041-2070 and 2071-2100) due to changes in rainfall in the southeast of Sweden (Berggren et al. 2011). The urban flood volume would increase by 52% from the period of 1971-2000 to 2020–2040 because of changes in rainfall intensity in Hohhot City of northern China (Zhou et al. 2019).

Another driver of urban flood increase is the impact of land cover change due to infill development and redevelopment. Population growth spurs infill development and redevelopment in cities to accommodate a higher density of people, which leads to an increase in impervious land cover. As a result, stormwater runoff volume and peak discharge increase, and urban floods become more likely to occur and of higher magnitude (Panos et al. 2018). To accommodate the growing population, urban redevelopment typically involves replacing single-family housing and open space with denser multi-family housing (Li and Bortolot 2022). Urban redevelopment is common in the U.S., with nearly 75% of the large metropolitan regions experiencing some form (EPA 2014). The associated increase in impervious land cover over time leads to an increase in urban flooding frequency (Li et al. 2019). In the western cities of the U.S., a 1% increase in imperviousness percentage due to urban redevelopment produces a flooding volume increase from 0.5% to 1.6% (Li et al. 2023c; Panos et al. 2018). Flooding increases driven by redevelopment are likely to exceed the designs of urban drainage systems (UDSs) leading to increased frequency and magnitude of failure if existing stormwater infrastructures are not adapted (Li et al. 2021; Li and Bortolot 2022).

The combined impacts of rainfall and impervious land cover may compound the individual effects of urban floods. Many studies have found increases in flooding at larger spatial scales, such as river basins (Woltemade et al. 2020), due to a range of factors. Although (Zhou et al. 2019) discovered that land cover change elevated flood volume 172% more than rainfall modification due to climate change, their analysis did not consider the combined effect of changes in rainfall intensity and imperviousness. Facing these challenges of change, local utilities typically retrofit existing UDSs with structural enhancements (e.g., increase pipe conveyance capacity, add storage capacity, and introduce green infrastructure) (Chester and Allenby 2019; McPhillips et al. 2020).

The current Urban Drainage Systems (UDSs) are not well-prepared for future rainfalls and future imperviousness due to urban redevelopment. This is because traditional stormwater infrastructures are designed based on historical rainfalls for normal loadings, which are insufficient to absorb and resist future external disturbances, such as extreme rainfalls and impervious surface changes (Kim et al. 2017; Mohammadiun et al. 2020). Facing future conditions, UDSs lasting for several decades or longer might unpredictably fail to serve the local community due to performance deterioration and functionality loss (Egger and Maurer 2015). Even worse, flooding failures, such as manhole overflow, drainage blockage, and pipe collapse, can propagate through connected networks to cause unpredictable failures in other economic or social networks like disruptions in the public transportation network and damages to telecommunication and power grids (Li 2021a; Li et al. 2020a). Thus, the decision about improving the system resilience under future changing environments has become a priority in maintaining a satisfactory service level over the long-term period, while including this priority in building resilient UDSs is still obscure for local utilities.

Resilience, which is defined as the adaptive capacity to respond to, recover from, and adapt to intentional anthropogenic attacks, unpredictable natural events, and human-made disturbances (Li et al. 2020c), has been extensively introduced into stormwater engineering to minimize failure risks (Butler et al. 2017; Juan-García et al. 2017; Sweetapple et al. 2018). Enhancing future flooding resilience needs adaptation strategies. One prevalent adaptation strategy is green infrastructure (GI), which mimics the natural hydrological process to infiltrate and evaporate water, absorb excess discharge, and reduce the surface runoff volume (Li et al. 2019). (Dong et al. 2017) simulated green roofs and bio-retention for improving flooding resilience by over 30% under rainfall and impervious cover change. (Salerno et al. 2018) found that GI practices, including permeable pavement, rain gardens, and green roofs, can promote flooding resilience by 15%. However, (2021) revealed that utilizing GI practices, such as bioretention, as adaptation strategies can only handle increases in runoff and flooding volume from rainfall and imperviousness change alone, but not likely both. (Hou et al. 2020) also found that current stormwater gray and green infrastructures are insufficient for future resilient stormwater management.

Another adaptive solution is smart real-time control (RTC). RTC is a product of the Internet of Things (IoT), which can retrofit the UDSs with water level sensors, flow sensors, actuators, and moveable gates to achieve continuous monitoring and dynamic control (Li 2021b). Sensors provide real-time system states for actuators, which accordingly open or close gates to some extent until the next sensed information enters the RTC system. In this way, UDSs can be controlled in real-time to make full use of the available or under-used storage and conveyance capacity to selectively discharge water in the pipe during a storm or to retain water in the tank before the next storm comes (Li et al. 2023a). RTC has been widely adopted for various stormwater objectives. Prior studies intended to utilize RTC to reduce the drainage peak flow (Schmitt et al. 2020; Shishegar et al. 2019), alleviate stormwater runoff volume (Li et al. 2023b; Löwe et al. 2016), diminish urban flooding volume (Li 2020; Mullapudi et al. 2020; Wong and Kerkez 2018), control combined sewer overflow (Rathnayake and Faisal Anwar 2019), promote stream health (Xu et al. 2020), and improve water quality (Li et al. 2020b; Sharior et al. 2019; Sun et al. 2020; Troutman et al. 2020). However, employing smart stormwater RTC to improve flooding resilience under the combined rainfall and impervious surface changes due to urban redevelopment has been neglected in previous studies (Kerkez et al. 2016; Di Matteo et al. 2019).

This study seeks to answer the following question: can RTC outperforms GI in mitigating the impacts of climate change and urban redevelopment on urban flooding resilience? To that end, the objective of this study is to compare the performance of RTC and GI under effects induced by rainfall change and land cover change and to identify the suitable adaptation strategy for impact scenario planning. The novel point of this research is taking into account the effects of climate change and urbanization when exploring the performance of RTC and GI against future urban floods. This study separately simulates the RTC and GI, which is helpful for engineers to better understand which approach is more suitable for the local flooding control.

2. Methods

2.1 Case study and UDS modeling

We select the urban drainage catchment, which is located in the Sugar House neighborhoods, Salt Lake City, Utah, the US, as the case study shown in Fig.1 below. The region has an area of 0.8 km^2 with semiarid climates. One reason that we chose this area is the uncertain seasonality of the weather resulting in unpredictable hydrological regimes in the local neighborhoods. The second reason is that urban redeveloping projects have been rising due to economic and population growth in recent years. Urban redevelopment accelerates urban landscape changes from less dense to highly dense surfaces with many more shared driveways and extended decks, sheds, and patios, in the studied area. (Panos et al. 2020) illustrate how single-family housing is redeveloped into a multi-family housing lot that consequently increases the impervious area by approximately 40%.

Currently, Surga House is rebuilt for commercial or mixed-residential/commercial districts, including multi-family housing, high-rise apartment buildings, and shopping stores. Thirdly, most drainage pipes have ages from 20 to 70 years (Sugarhouse projects 2018). These old pipes can not keep the expected service level as the stormwater runoff volume is increasing due to the urban growth within the study case. The aging stormwater UDS is supposed for rehabilitation or replacement by local utilities. An SWMM (Storm Water Management Model) model 5.1 version (Rossman 2015) is used to simulate the UDS. This model is composed of 181 junctions, 184 conduits, and 28 sub-catchments. Table 1 shows the parameter settings for these structural components below.

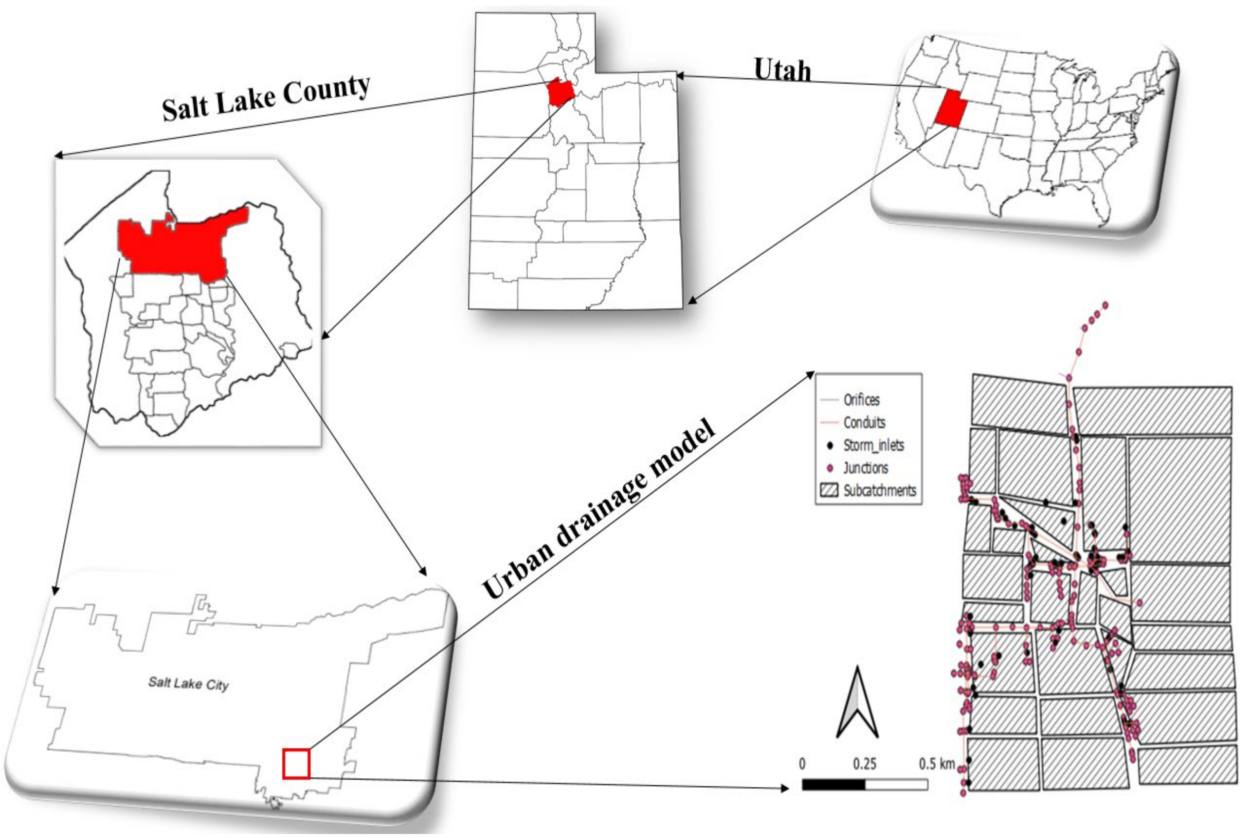


Fig.1 The study case with the modeled urban drainage network in Sugar House, Salt Lake City, Utah, USA.

Table.1 Parameter settings of the SWMM model

Subcatchments	
Area (km^2)	0.04 to 0.2
Slope (%)	1.6% to 6.2
Width (m)	128 to 311
Conduits	
Length (m)	10 to 100
Diameter (mm)	500 to 1500
Slope (%)	0.06 to 0.40
Roughness	0.01 to 0.016
Junctions	
Elevation (m)	4320 to 4371
Surcharge depth (m)	0 to 6.4

2.2 Impact scenarios development

Three combined impact scenarios with changes in rainfall intensity and impervious land cover are quantified to reflect climate change and urban redevelopment, respectively. Table 2 shows that three climatic scenarios are developed, in which the rainfall intensities are 165, 189, and 213 mm/hour, for historical (2001-2015), future mid-age (2035-2049), and future late-age (2085-2099) periods, respectively. These periods are selected because they are representative timelines for the early, middle, and late ages of the 21st century. The future rainfall intensities are scaled from a historical 100-year, 12-hour rainfall event based on the change factor derived from the simple

Delta Change approach (Choi et al. 2009; Graham et al. 2007; Jung et al. 2011). It can be seen that the rainfall intensity increased by 29% from 2001 to 2099. This growth agrees with the majority of case studies of future climate scenarios (Leandro et al. 2020; Salerno et al. 2018).

Table.2 Impact scenario design

Rainfall intensity (mm/hour)	**Imperviousness percentage**	**Impact scenarios**
165	56%	Historical (2001 to 2015)
189	71%	Future mid-age (2035-2049)
213	91%	Future late-age (2085-2099)

In terms of projecting the impervious surfaces, we adopt 56%, 71%, and 91% as the average impervious percentages for the historical, future mid-age, and late-age urbanized scenarios, respectively. These imperviousness changes indicate an about 0.35% increase per year, which is 0.05% lower than the prior findings in the projected urban impervious surface due to urban redevelopment (Cherry et al. 2019; Panos et al. 2018). DCIA (Directly Connected Imperviousness Percentage) for individual sub-catchments is calculated according to the average imperviousness percentage and area-weighted method from (Pond and Dietz 2006). Fig.2 shows a significant increase in the median, the first and second quartile, minimum, and maximum of DCIA of sub-catchments. These statistics present rapid growth in the impervious surface from the early stage to the late stage in the 21st century.

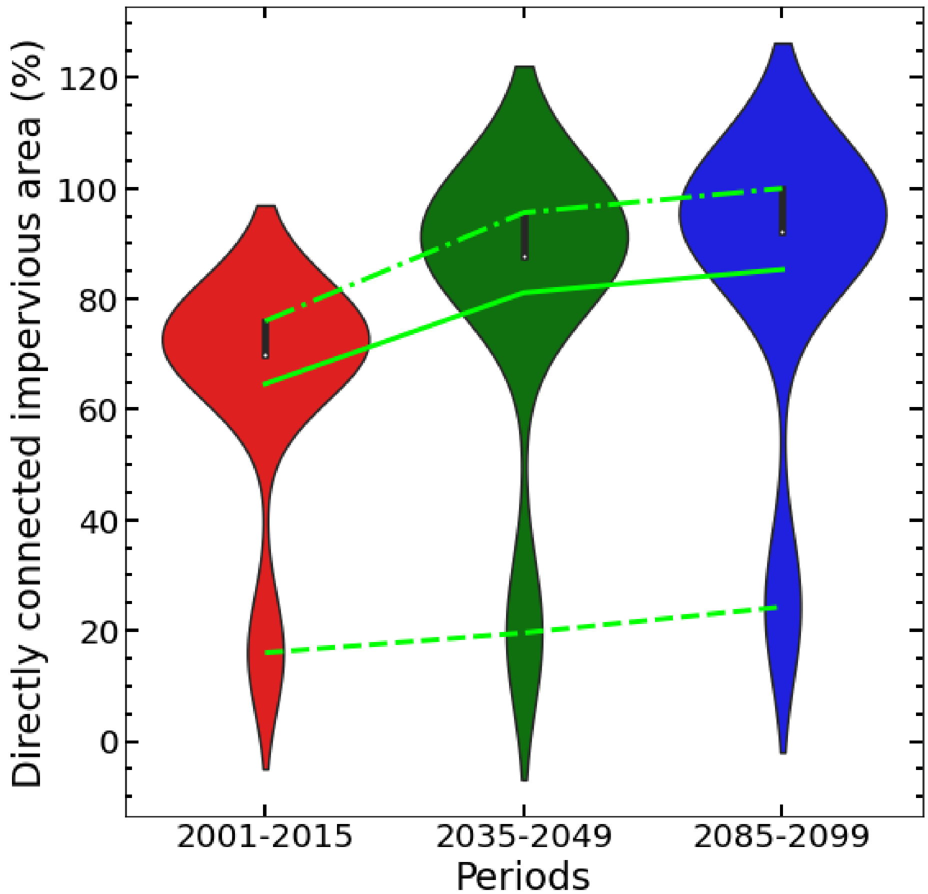


Fig.2 Violin plot of sub-catchment imperviousness percentage evolutions (the white dot in the center bar is the median value; the black bar in the center of the violin is the first and second quartile; the black line connects the mean values; the purple line connects the maximum values; the yellow line connects the minimum values; wider sections of the violin plot represent a higher probability of observations taking a given value, the thinner sections correspond to a lower probability).

2.3 Adaptation strategy design and implementation

Under each impact scenario, three types of adaptation strategies configured with different scales of GI and RTC practices are simulated, shown in Table 3 below. A total of 15 SWMMsimulation experiments are conducted to investigate the performance of the proposed adaptation strategies. These adaptation modelings are listed below.

Table.3 Adaptation strategy simulation set-up

Scenarios / Adaptations	Historical impacts	Mid-age impacts	Late-age impacts
BS	Simulation #1	Simulation #2	Simulation #3
GI (5%)	Simulation #4	Simulation #5	Simulation #6
GI (10%)	Simulation #7	Simulation #8	Simulation #9
GI (15%)	Simulation #10	Simulation #11	Simulation #12
RTC	Simulation #13	Simulation #14	Simulation #15

BS (Baseline Scenario) strategy means that UDS is under the 'business-as-usual' state. GI strategy represents that drainage catchment is distributed with bio-retention cell and permeable pavement. Bioretention cells are chosen because they can be installed in a variety of locations in Sugar House. The permeable pavement is selected because there are many low-use or low-speed pavement sites within the study area. A range of 5%, 10%, and 15% of the total area is implemented with GI. It is assumed that 50% of the impervious area of each sub-catchment is routed to its corresponding bio-retentions or permeable pavements. For the RTC strategy, three hypothetical storage units and sluice gates (square shape with 1 m^2 area) is added to the existing UDS. The size for these storage units is determined to be 4.5, 5, and 5.7 m^3, respectively, according to the stage-volume calculation under a 90% percentile storm event with 16.3 mm rainfall depth. In RTC simulation, these three storage units are controlled by regulatory gate orifices to represent the control adaptation strategy. All adaptation strategies are simulated by using PySWMM, which is a Python wrapper for dynamically controlling the SWMM model throughout a rainfall-runoff simulation step-by-step (McDonnell et al. 2020).

2.4 Flooding resilience computation

In this study, the flooding resilience is visualized by the system performance curve, an example shown in Fig.3. In Fig.3, the black solid horizontal line, P_o represents the original (design) performance level of service. The red dotted line, P_a stands for a lower but acceptable level of service. P_{mf} means the maximum system failure level resulting from the considered threat. The flooding severity Sev_{efs} is quantitatively represented as the shaded area (Fig.3) between the original system performance level, P_0 and the actual system performance curve, $P_i(t)$, at any time t after the occurrence of a given threat (extreme storm) that leads to system failure. The shaded rectangular area in Fig.3 can be calculated by equation 1, which has been simplified to equation 2 to approximate the flooding severity. The flooding resilience index Res_0 is estimated as one minus the computed volumetric flooding severity Sev_i, shown in equation 3, according to (2015). The initial resilience is 1 (no system performance deterioration), which decreases from t_{fs} as failure stressors (e.g., an extreme rainfall event) drive, reaches the minimum value of P_{mf} at t_{mf}, restores from t_{rs} and completely recovers to the initial level of service at t_r. The recovered system will be more successfully adaptive to new adverse failures between the period t_r and t_n . The distance from t_{fs} to t_r is the failure duration t_f and the distance from P_o to P_{mf} is the failure magnitude.

$$Sev_i = f\left[Sev_p, t_f\right] = \frac{1}{P_0}\int_{t_0}^{t_n}(P_0 - P_i(t))dt \qquad (1)$$

Where t_f is the failure duration; t_0 is the time of occurrence of the threat; t_n is the total modeling time.

$$Sev_i = \frac{V_{TF}}{V_{T1}} \times \frac{t_r - t_{fs}}{t_n - t_o} = \frac{V_{TF}}{V_{T1}} \times \frac{t_f}{t_n} \qquad (2)$$

$$Res_0 = 1 - Sev_i = 1 - \frac{V_{TF}}{V_{T1}} \times \frac{t_f}{t_n} \qquad (3)$$

Where V_{TF} is the total flood volume, $V_{T1}$the total inflow into the system, t_f the mean duration of nodal flooding and t_n the total simulation time. The Res_o ranges from 0 to 1. A zero Res_o indicates the lowest level of resilience, while one is the highest level of resilience to the considered flooding failure scenarios.

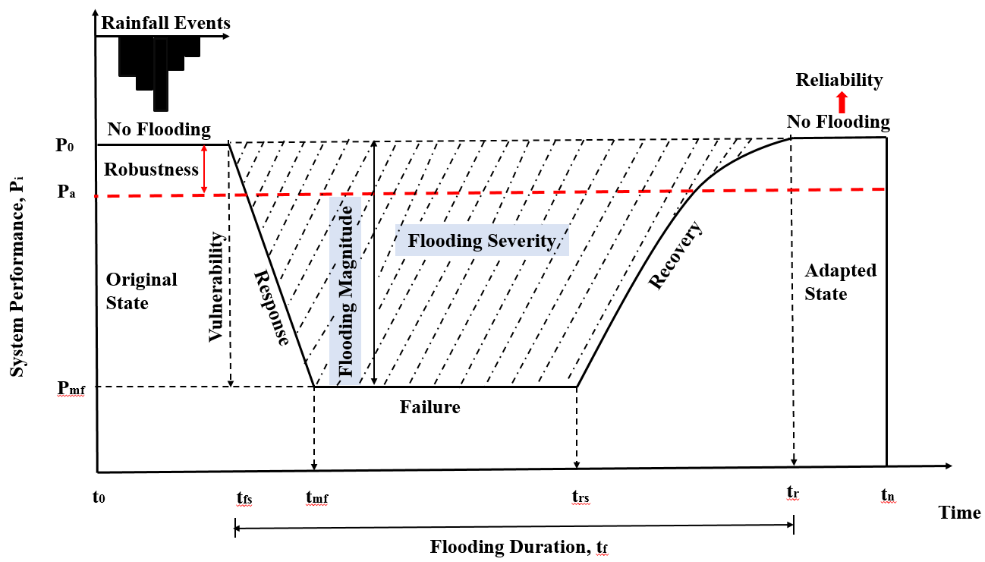


Fig.3 System performance curve for urban drainage system under rainfall event.

3. Results and discussions

3.1 Impacts of climate change and urban redevelopment on flooding severity

The flooding risks become severer from the historical period to the future periods for the baseline scenario without an adaptation strategy. Fig.4 shows that the mean flooding severity rises up by 150% from the historical to future periods. The flooding severity bounds ranging from minimum to maximum severity are also enlarged by around two times wider as future climatic or urbanized impacts increase from historical to future time. During the 12-hour modeling process, the flooding severity peaks after a 6-hour simulation and then keeps stable status. The flooding severity trend can also be detected with spatial flooding mapping. The increasing impacts from rainfall and land cover change mainly cause more flooding junctions located in the middle area of the urban drainage system from simulation #1 (historical period) to simulation #3 (future period). These extra junctions highlighted within red square areas in Fig.5 have high peak water depths, indicating a higher flooding risk from 2085 to 2099.

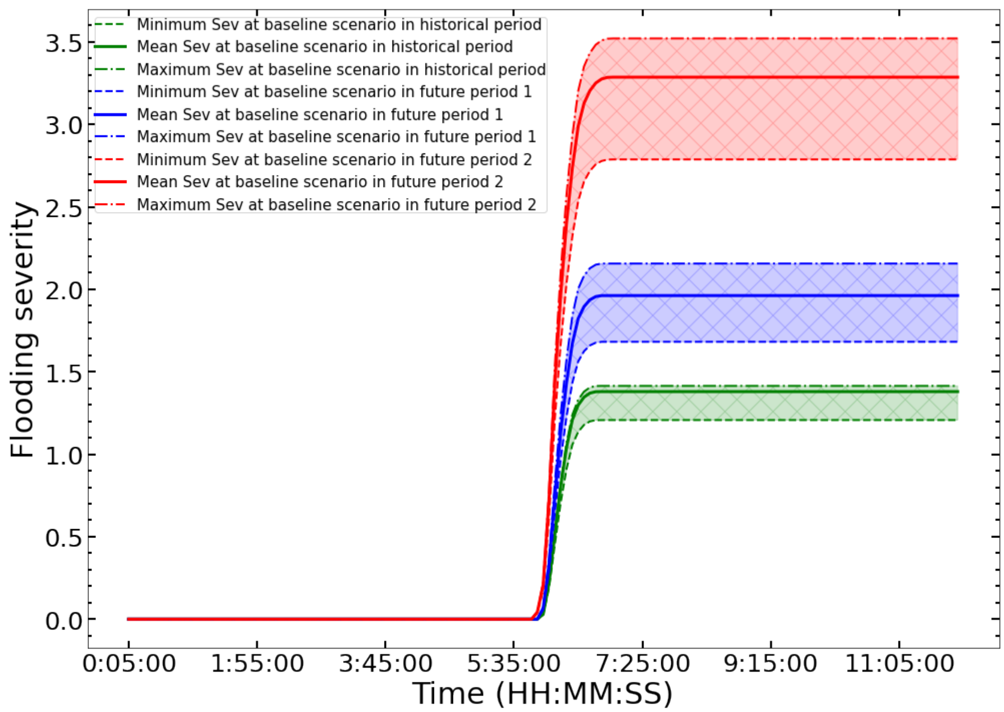


Fig.4 Flooding severity (maximum, mean, and minimum) under different climate change and urban redevelopment scenarios, corresponding to simulations #1 to #3.

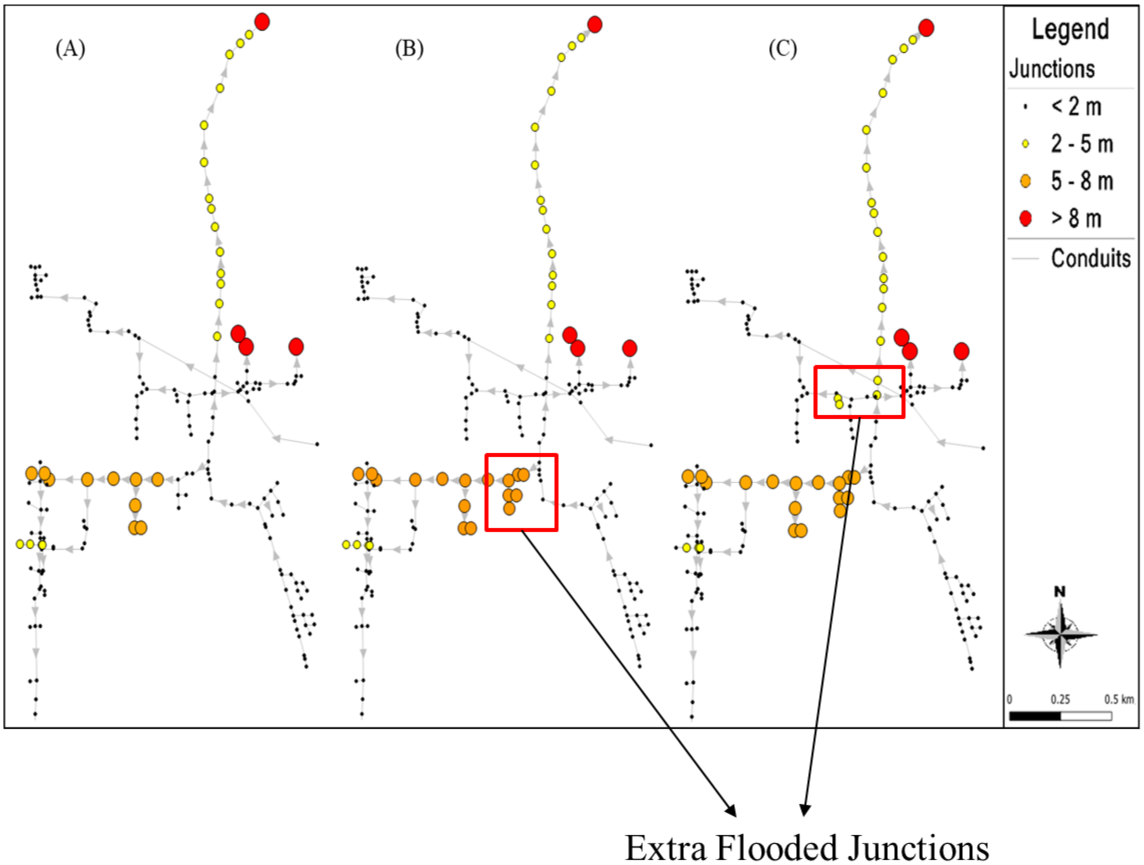
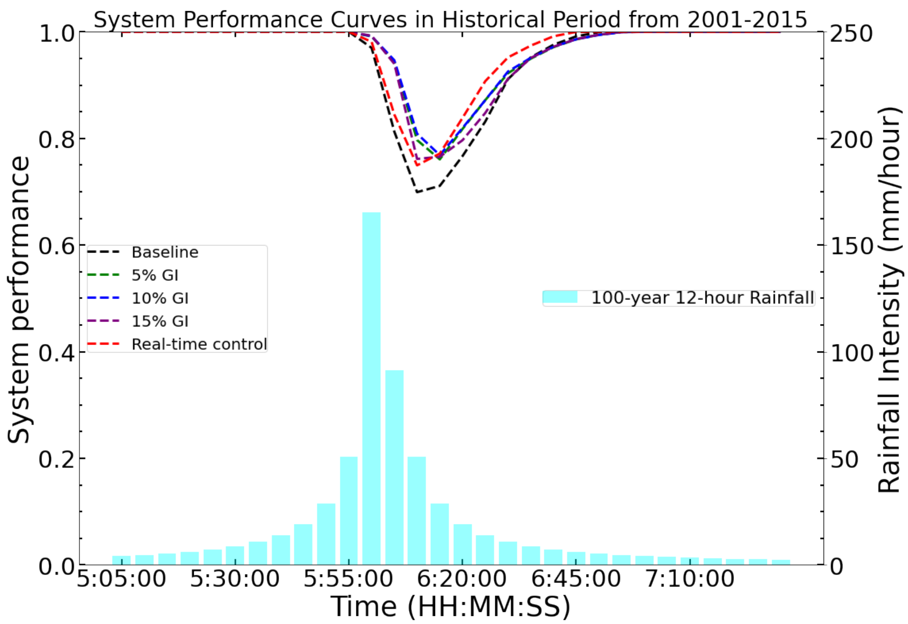


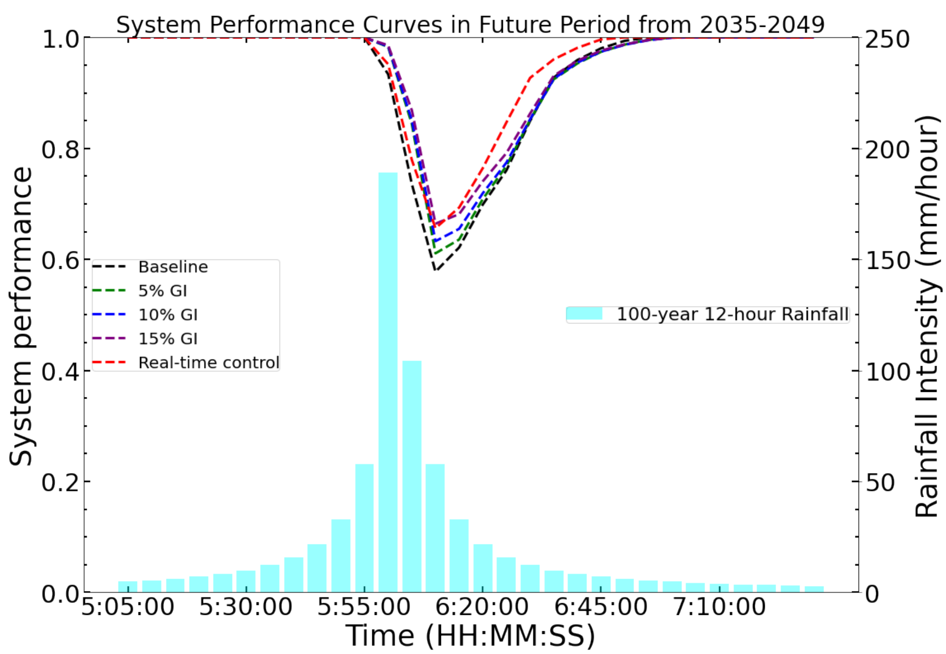
Fig.5 Spatial map of peak water depth by junctions under different climate change and urban redevelopment scenarios, corresponding to simulations #1 to #3.

3.2 RTC and GI to reshape system performance curves

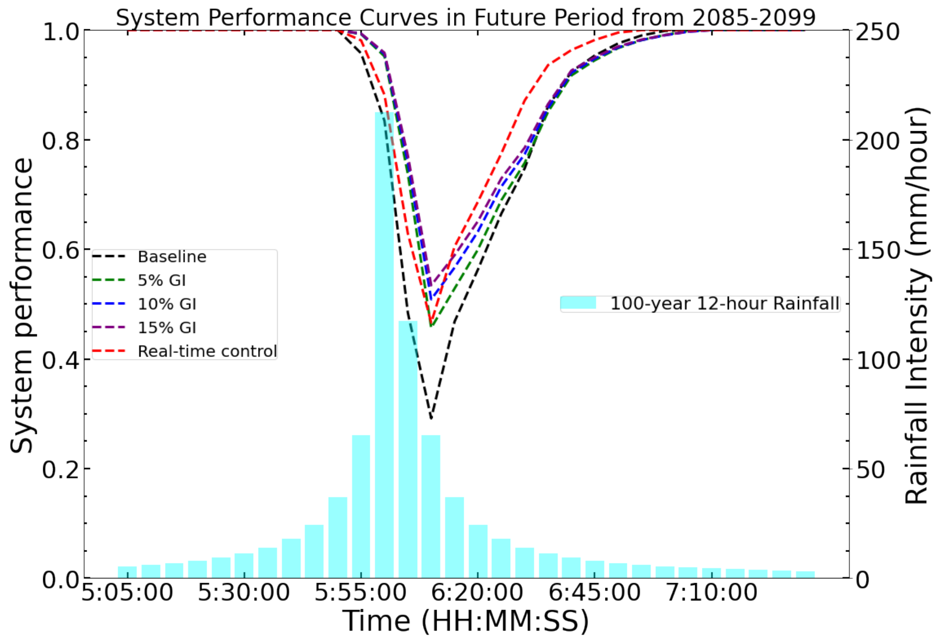
Both RTC and GI can reshape the system performance curves. For the historical period, the RTC has comparable performance for all GI configurations ranging from 5% to 15% implementation. RTC and GI improve the maximum failure level from 0.7 to 0.75 for the performance curves in Fig.6a. The improvement in failure level means the implementation of RTC and GI can reduce the flooding magnitude under disturbances from rainfall or land cover imperviousness changes. For the future period from 2035 to 2049, RTC shows a similar maximum failure level as the 15% GI implementation, higher than other GI adaptation strategies. In Fig.6b, RTC has a more steep recovery curve than GI. The fast recovery rate allows the system to be more resilient than the baseline scenario. The high recovery speed is also found in Fig.6c. In sum, RTC and GI improve the system failure level. RTC is more capable of enhancing the system recovery rate than GI when a system failure happens.



(a)



(b)



(c)

Fig.6 UDS performance curves comparison with different adaptation strategies under A) historical impact; B) future mid-age impact; C) future late-age impact.

3.3 RTC and GI to enhance flooding resilience

In general, RTC improves flooding resilience more than GI. Fig.7 compares the relative resilience changes from the baseline scenario to every adaptation strategy with GI or RTC. The RTC tops the resilience changes at 60% and 75% for future #1 and #2 periods, respectively, around 10% and 25% higher than the 15% GI adaptation strategy. For the historical period, the 10% GI implementation has the highest resilience advancement than other adaptation strategies. This can be explained by Fig.8, where the mean flooding severity (green solid line) in 10% GI is lower than in other GI historical scenarios. As the flooding resilience equals one minus the flooding severity value, the lower flooding severity generates a higher flooding resilience value. On average, the GI advances flooding resilience similar to what RTC can promote during the historical period. When the climatic and urbanized impacts are amplified during the future period, RTC would augment the resilience more significantly than GI adaptation methods.

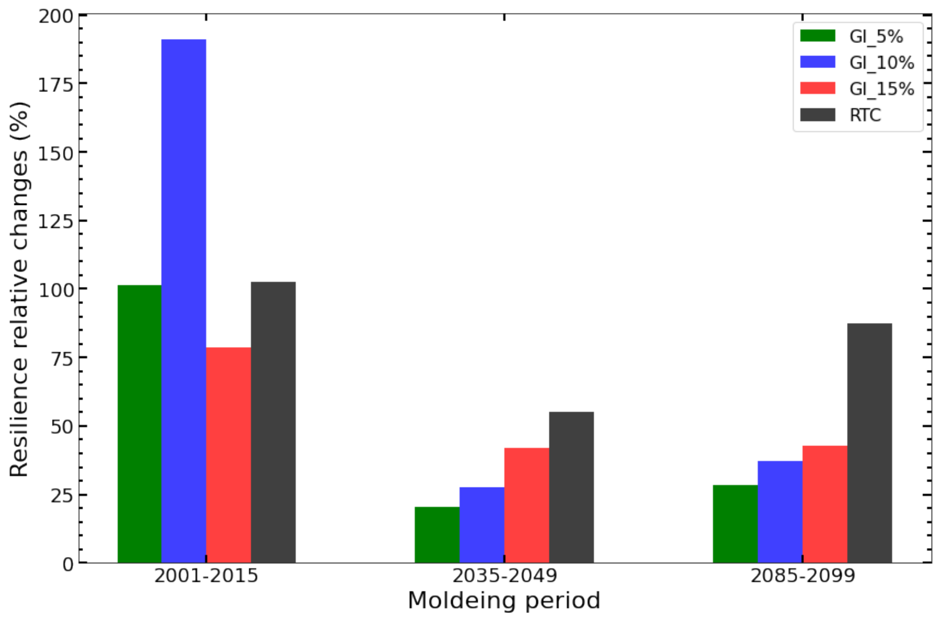
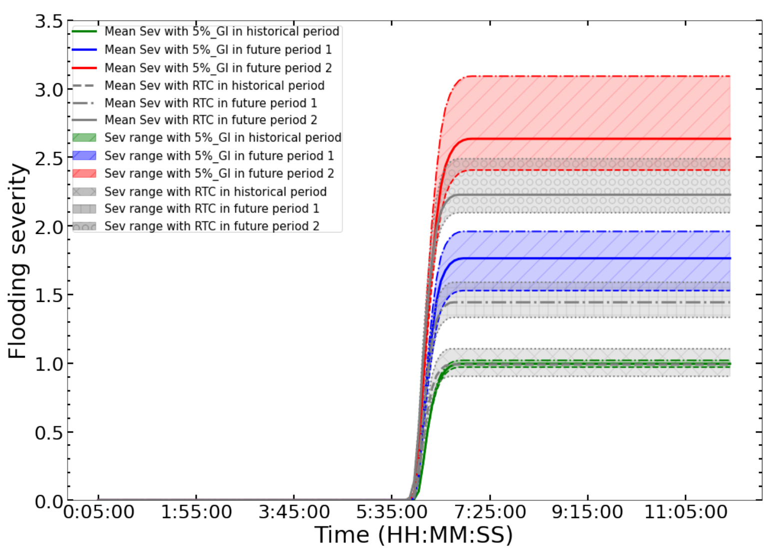


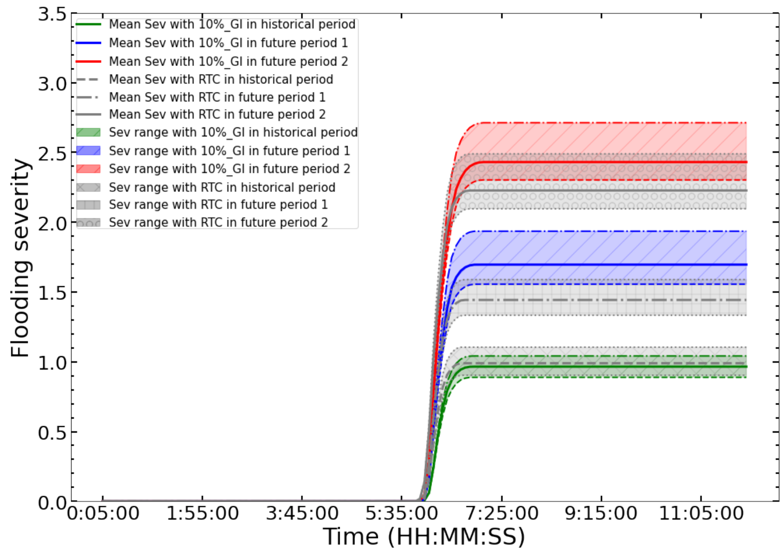
Fig.7 Barplot of relative changes in system resilience from adaptation scenarios to baseline scenario under the historical impact, future mid-age impact, and future late-age impact.

GI implementation expands the flooding severity more than RTC. In Fig.8a and 8b, the severity range is wider in 5% and 10% GIs than in RTC. Although there are limited differences between the RTC and 15% GI in the severity range in Fig.8c, it still can be observed that GI is less able to narrow down the flooding severity bounds than RTC. This observation indicates that RTC is more capable of handling flooding uncertainties caused by climate change and urban redevelopment. That is the reason why RTC can assist UDSs recovery faster from failure level than GI implementation discussed in section 3.2.

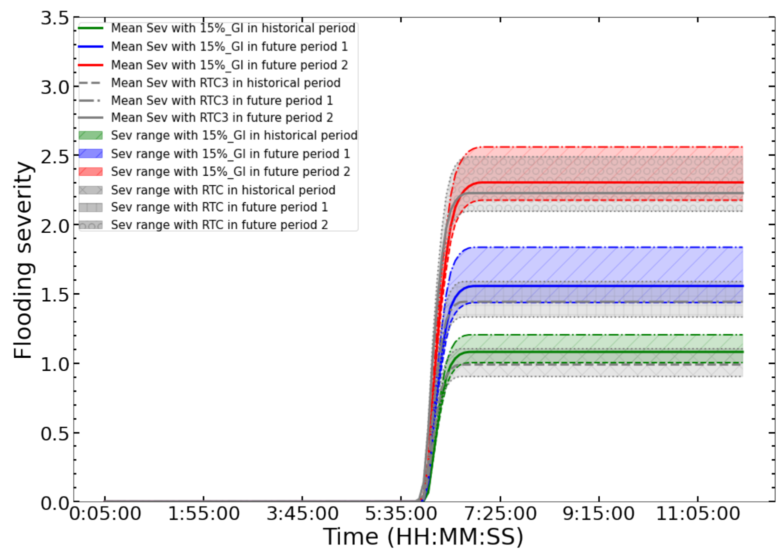
Climate change is the forcing factor on shifting hydrometeorological patterns, intensifying rainfall, sizing storm events, and increasing rainfall volume, which finally exposes stormwater infrastructures to exceptional flooding volume and peaks. For instance, a 1% increase in historical rainfall intensity improved the urban flooding volume by 1.8% in Salt Lake City, Utah, USA (Li and Burian 2022). Changes in the impervious urban surfaces due to urban redevelopment also contribute to urban flooding by aggravating the stormwater volume and peak runoff. In the same study area, a 1% increase in imperviousness due to redevelopment elevated the flooding intensity by 5% (Li and Burian 2022). Flooding changes driven by the redeveloping imperviousness are projected to exceed the UDS regulatory standards and cause UDS functionality loss if existing stormwater systems remain nonadaptive (Panos et al. 2021). The climatic and urbanized impacts on flooding would increase, while RTC is more adaptive to control the flooding severity within in smaller bound than GI.



(a)



(b)



(c)

Fig.8 Flooding severity under different adaptation strategies, A) 5% GI versus RTC; B) 10% GI versus RTC; C) 15% GI versus RTC, on flooding severity under historical, future mid-age, and future late-age periods.

4. Conclusions

This study compares the performance of real-time control (RTC) and green infrastructure (GI) to mitigate the impacts induced by rainfall change and land cover change on urban flooding from 2001 to 2099.The innovative point comes from considering the influences of future climatic and urbanized changes into the performance analysis. The system performance curves and flooding resilience are utilized as the target index to assess the RTC and GI implementation into the stormwater urban drainage system located in the Sugar House Neighborhood of Salt Lake City, Utah, USA. This research fills in the gap of the performance comparision between RTC and GI for future flooding mitigation. Three pieces of conclusions are drawn below.

1) GI has comparable performance with RTC in terms of improving the flooding resilience and system performance curves in the historical period. Implementing RTC or GI can improve system response and the recovery rate in response to system failures. From 2001-2015, A minimum of 5% GI implementation into the existing stormwater system can handle the extra flooding severity brought by the growths in the rainfall intensity and land cover imperviousness.
2) RTC outperforms GI to control the flooding severity bound and to improve flooding resilience during future periods (2035-2049 and 2085-2099). While flooding severity is significantly amplified by climate change and land cover change in the future period from 2085 to 2099, RTC shows more capability than GI to maintain the service of the urban drainage system in response to external climate and urbanization disturbances.

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