Extended Abstract Template

Quantifying the Performance of RTC to Enhance Urban Flooding Resilience under Climate Change

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Highlights

- The performance of RTC peaks at large-storm events.
- RTC can enhance urban flooding resilience by up to 17%.
- RTC is an effective solution to address climate-driven urban flooding.

Introduction

Resilience was first proposed in ecology and ultimately entered into engineering to characterize system failure (Holling, 1996). Engineering resilience is interperated by four basic phases, including preparation, withstanding, restoration, and adaptation. The stormwater research community gradually embraced resilience as a novel design criteria (Butler et al., 2017). In stormwater drainage engineering, resilience is to transfer the performance of stormwater infrastructure from 'fail-safe' (minimizing failure probability) to 'safe-to-fail' (minimize the failure consequences) (Ahern, 2011; Park et al., 2011). Therefore, resilience to improve stormwater system performance can be achieved through implementing external structural or nonstructural components, such as rehabilitating drainage pipes (Mohammadiun et al., 2020), building stormwater control measures (Leandro et al., 2020), and sitting green stormwater infrastructure (Dong et al., 2017; Panos et al., 2021; Salerno et al., 2018).

Recently, smart stormwater systems with real-time control (RTC) have re-emerged as potential strategies to address climate-driven urban flooding issues (García et al., 2015; Kerkez et al., 2016; Schütze et al., 2004). RTC is a product of the Internet of Things, which can retrofit the UDSs with water level sensors, flow sensors, actuators, moveable gates, and weirs to achieve real-time monitoring and dynamic control (Mullapudi et al., 2017). With RTC, UDSs selectively discharge water from pond to downstream catchments based on the control rules of gate operation. The performance of control rules can be optimized by using rainfall-runoff prediction (Shishegar et al., 2021). The RTC strategy could be further improved by reducing system failures caused by storm events (Sharior et al., 2019). However, the functionality of the controlled UDSs influenced by rainfall variations is seldom discussed in prior studies. Previous work ignores the impacts of climate change on RTC performance to enhance system resilience (Li, 2020; Rathnayake and Faisal Anwar, 2019; Sadler et al., 2020).

This study aims to address the gap in quantified stormwater RTC performance to battle climate change. First, this paper introduces the resilience computation, model and datasets, and RTC strategy. Second, this work provides results and discussion of the impacts of RTC on urban flooding resilience under varying rainfall events. Thirdly, this paper concludes with the implications and recommendations of utilizing RTC as a measure to advance smart and resilient stormwater systems.

Methodology

Flooding resilience

The definition of flooding resilience (Res) is a single quantitative index comprised of the magnitude and duration of the system's functional failure during storm events (Casal-Campos et al., 2018; Ouyang et al., 2012). Flooding resilience is calculated by the area between the original system performance curve and the actual performance curve at any time after the occurrence of a storm (Mugume et al., 2015). Figure 1 shows the time-dependent graph profile of the system performance curve, also called the resilience profile graph, for a failure-causing rainfall event. Failure is defined as the occurrence of a flooding event. For a given external disturbance like storm events, Res quantifies the UDS residual functionality as a function of total flooding volume and mean duration of nodal flooding. The Res ranges from 0 to 1. A value of 0 for Res indicates the lowest level of resilience, while 1 is the highest level of resilience.

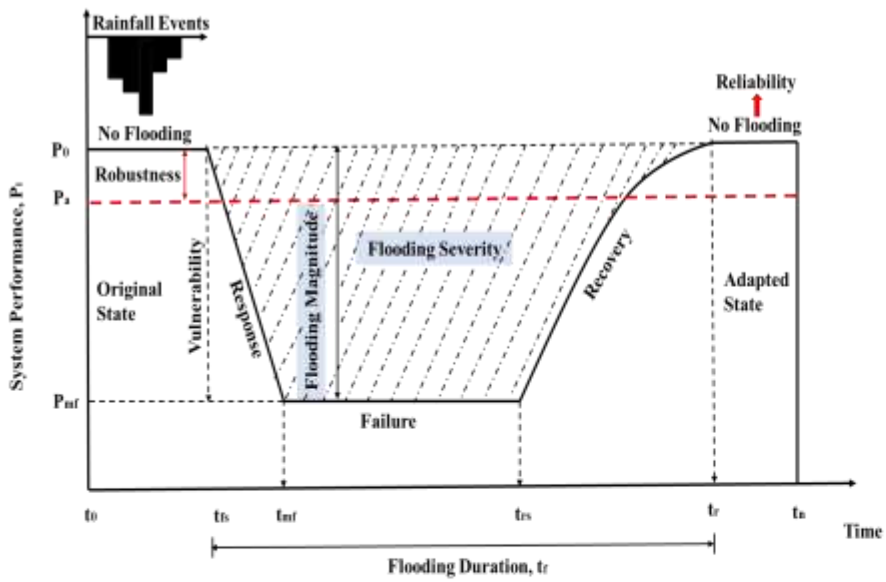

Figure 1. The system performance curve of an urban drainage system for a failure-causing rainfall event (The t_o is the time of occurrence of storms; The t_{fs} is the flood starting time; The t_{mf} is the starting time of maximum failure; The t_{rs} is the ending time of maximum failure; The t_r is the recovery ending time; The t_f is the flooding duration; The t_n is the total simulation time). This figure is adopted from previous work (Li et al., 2021)

Case study

The case study drainage catchment is located in Salt Lake City, Utah, USA. Salt Lake City has a semi-arid climate with an average annual precipitation depth of 412 mm, and more than 85% of the rainfall occurring during the spring and summer seasons (NOAA, 2010). Changes in rainfall intensity from climate change is projected to magnify runoff volume and worsen over-loadings in the local UDSs during rainfall extremes. For this study, a stormwater drainage model is built using the U.S. Environmental Protection Agency Storm Water Management Model (SWMM) Version 5.1 (Rossman 2015). The model includes 28 sub-catchments, 184 conduits, and 181 junctions, and one rain gauge (Li and Burian, 2021).

RTC design and implementation

An RTC adaptation strategy was developed to control three hypothetical orifice gates and three corresponding storage tanks (Li et al., 2021). The storage volume is designed to meet the capacity to accommodate the total stormwater runoff volume from the upstream contributing sub-catchments and to prevent the tanks' outflow from exceeding the predevelopment system peak flow under rainfall events. The RTC strategy automatically adjusts the gate opening to control the tank storage volume and outflow. Actions in gates (% openings of gates) are computed by the nonlinear control Equation (1).

$$GO_i = min\left(1,\ \frac{D_i * R_i}{A * \sqrt[2]{2 * g * Q_i}}\right) \times 100\% \tag{1}$$

Where GO_i is the gate percentage opening at the i^{th} time step; D_i is the tank water depth at the i^{th} time step; R_i is the rainfall intensity at the i^{th} time step; Q_i is the tank outflow at the i^{th} time step; A is the maximum opening area of the gate, and this study assumes the maximum area to be 1 m^2; g is the acceleration of gravity (9.8 m^2/s); min is to select the minimum value between the actual opening output and 1 as the final gate opening, which avoids the gate opening over 100%.

Modeling scenarios

RTC performance for enhancing flooding resilience was assessed under the following future climate scenarios: 1) BS: RTC simulation driven by historical design storms without climatic impacts; 2) RCP (Representative Concentration Pathway) 4.5: same as BS but with future design storms of RCP 4.5 of global climate model CCSM 4.1; 3) RCP 8.5: same as BS but with future design storms of RCP 8.5 of global climate model CCSM 4.1. These designed storm events with 3-hour duration and 2-, 10-, and 100-year return periods are presented in Figure 2 below.

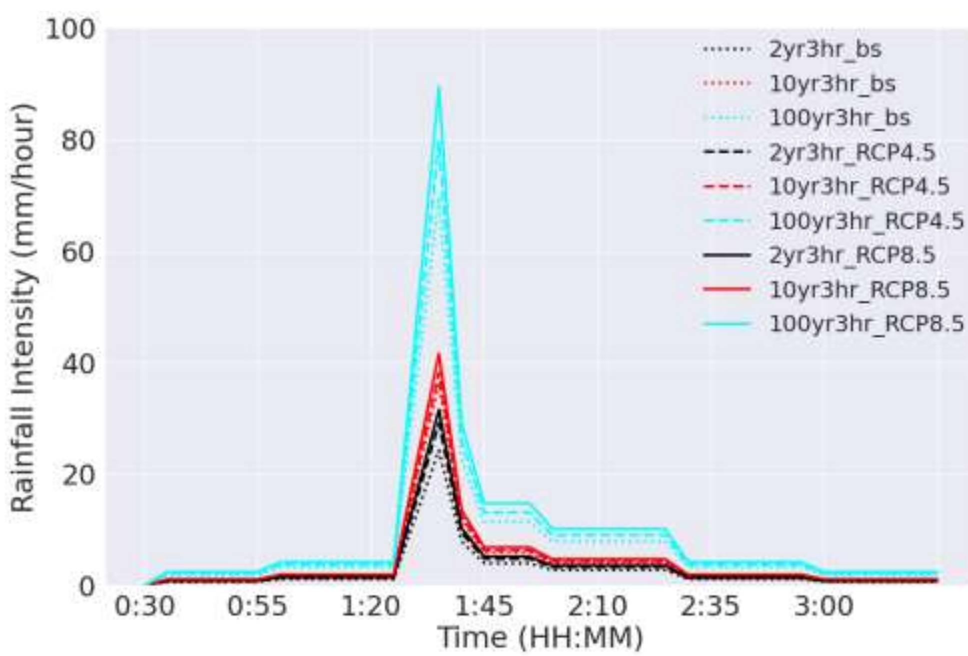

Figure 2. A graphic demonstration of baseline and future design rainfalls of 3-hour duration and 2-, 10-, and 100-year return periods.

Results and discussion

RTC shows the ability to mitigate future climatic impacts on urban flooding. Figure 1 exhibits that resilience improvements are positively correlated with the event return period. RTC enhances the flooding resilience up to 6% and 17% for RCP 4.5 and RCP 8.5, respectively. The largest resilience advancement occurs in the 100-year storm event. Differences in resilience improvements are few for the 10-year storm event. When the return period is over 10-year, the RTC shows greater performance for achieving higher resilience for rainfall events. Although RTC has shown significant benefits in reducing flooding and improving water quality in prior studies (Li et al., 2021, 2020, 2019), RTC to enhance flooding resilience is rarely studied. This result highlights that RTC retrofits can drive existing UDSs towards resilient stormwater management.

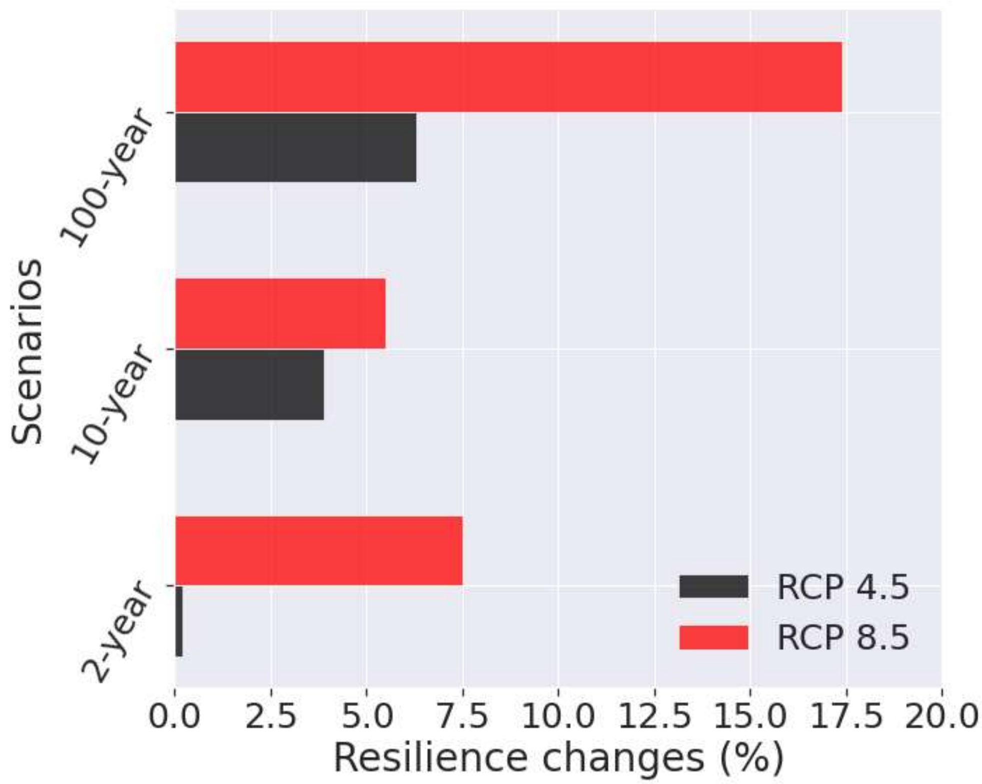

Figure 3. Resilience relative changes from RTC adaptation strategy to the baseline scenario under future 3-hour designed rainfalls of RCP 4.5 and RCP 8.5 climate scenarios.

Conclusions and future work

In the context of climate change, the present study contributes to resilience advancements in UDSs by smart stormwater RTC strategy. This research investigated the performance of RTC to mitigate the impacts of climate change on urban flooding. The RTC was tested in the UDS in Salt Lake City, Utah, USA. This research conducted modeling scenarios of the flooding resilience assessment under future single rainfalls, which is helpful to improve the understanding of the temporal dynamics in system performance and functionality loss. It was concluded that RTC is an effective adaptation strategy by improving resilience by up to 17%, respectively. As the storm size increases over the 10-year return period, RTC is more capable of enhancing system performance and resilience than under small-size storms. Future work will explore the performance of RTC in future long-term continuous simulations and also compare the performance of RTC with green stormwater infrastructure under ‘back-to-back’ storm events.

References

Ahern, J., 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landscape and Urban Planning 100, 341–343. https://doi.org/10.1016/j.landurbplan.2011.02.021

Butler, D., Ward, S., Sweetapple, C., Astaraie-Imani, M., Diao, K., Farmani, R., Fu, G., 2017. Reliable, resilient and sustainable water management: the Safe & SuRe approach. Global Challenges 1, 63–77. https://doi.org/10.1002/gch2.1010

Casal-Campos, A., Sadr, S.M.K., Fu, G., Butler, D., 2018. Reliable, Resilient and Sustainable Urban Drainage Systems: An Analysis of Robustness under Deep Uncertainty. Environmental Science and Technology 52, 9008–9021. https://doi.org/10.1021/acs.est.8b01193

Dong, X., Guo, H., Zeng, S., 2017. Enhancing future resilience in urban drainage system: Green versus grey infrastructure. Water Research 124, 280–289. https://doi.org/10.1016/j.watres.2017.07.038

García, L., Barreiro-Gomez, J., Escobar, E., Téllez, D., Quijano, N., Ocampo-Martinez, C., 2015. Modeling and real-time control of urban drainage systems: A review. Advances in Water Resources 85, 120–132. https://doi.org/10.1016/j.advwatres.2015.08.007

Holling, C.S., 1996. Engineering resilience versus ecological resilience, National Academy of Engineering, in: Engineering Within Ecological Constraints. pp. 31–44.

Kerkez, B., Gruden, C., Lewis, M., Montestruque, L., Quigley, M., Wong, B., Bedig, A., Kertesz, R., Braun, T., Cadwalader, O., Poresky, A., Pak, C., 2016. Smarter stormwater systems. Environmental Science and Technology 50, 7267–7273. https://doi.org/10.1021/acs.est.5b05870

Leandro, J., Chen, K.F., Wood, R.R., Ludwig, R., 2020. A scalable flood-resilience-index for measuring climate change adaptation: Munich city. Water Research 173. https://doi.org/10.1016/j.watres.2020.115502

Li, J., 2020. A data-driven improved fuzzy logic control optimization-simulation tool for reducing flooding volume at downstream urban drainage systems. Science of the Total Environment 732, 138931. https://doi.org/10.1016/j.scitotenv.2020.138931

Li, J., Burian, S., 2021. Effects of Nonstationarity in Urban Land Cover and Rainfall on Historical Flooding Intensity in a Semi-Arid Catchment. Journal of Sustainable Water in the Built Environment (Under Review).

Li, J., Burian, S., Oroza, C., 2021. Real-time control of an urban stormwater drainage system enhances flooding resilience of a semi-arid catchment against rainfall and land cover changes. Journal of Hydrology (Under Review).

Li, J., Burian, S., Oroza, C., 2019. Exploring the potential for simulating system-level controlled smart stormwater system, in: World Environmental and Water Resources Congress 2019: Water, Wastewater, and Stormwater; Urban Water Resources; and Municipal Water Infrastructure - Selected Papers from the World Environmental and Water Resources Congress 2019. pp. 46–56. https://doi.org/10.1061/9780784482360.006

Li, J., Oroza, C., Burian, S., 2020. Evaluating Real-time Control Performance on System-level Urban Flooding Reduction and Water Quality Improvement. EarthArXiv https://doi.org/10.31223/osf.io/y43j7.

Mohammadiun, S., Yazdi, J., Hager, J., Salehi Neyshabouri, S.A.A., Sadiq, R., Hewage, K., Alavi Gharahbagh, A., 2020. Effects of bottleneck blockage on the resilience of an urban stormwater drainage system. Hydrological Sciences Journal 65, 281–295. https://doi.org/10.1080/02626667.2019.1690657

Mugume, S.N., Gomez, D.E., Fu, G., Farmani, R., Butler, D., 2015. A global analysis approach for investigating structural resilience in urban drainage systems. Water Research 81, 15–26. https://doi.org/10.1016/j.watres.2015.05.030

Mullapudi, A., Wong, B.P., Kerkez, B., 2017. Emerging investigators series: building a theory for smart stormwater systems. Environ. Sci.: Water Res. Technol. https://doi.org/10.1039/C6EW00211K

NOAA, 2010. National Weather Service. National Oceanic and atmospheric administration.

Ouyang, M., Dueñas-Osorio, L., Min, X., 2012. A three-stage resilience analysis framework for urban infrastructure systems. Structural Safety 36–37, 23–31. https://doi.org/10.1016/j.strusafe.2011.12.004

Panos, C.L., Wolfand, J.M., Hogue, T.S., 2021. Assessing resilience of a dual drainage urban system to redevelopment and climate change. Journal of Hydrology 596, 126101. https://doi.org/10.1016/j.jhydrol.2021.126101

Park, J., Seager, T.P., Rao, P.S.C., 2011. Lessons in risk- versus resilience-based design and management. Integrated Environmental Assessment and Management 7, 396–399. https://doi.org/10.1002/ieam.228

Rathnayake, U., Faisal Anwar, A.H.M., 2019. Dynamic control of urban sewer systems to reduce combined sewer overflows and their adverse impacts. Journal of Hydrology 579, 124150. https://doi.org/10.1016/j.jhydrol.2019.124150

Rossman, L.A., Huber, W.C., 2016. Storm Water Management Model Reference Manual Volume I – Hydrology (revised)(EPA/600/R-15/162A). U.S. Environmental Protection Agency I, 231. https://doi.org/EPA/600/R-15/162 |

Sadler, J.M., Goodall, J.L., Behl, M., Bowes, B.D., Morsy, M.M., 2020. Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. Journal of Hydrology 583. https://doi.org/10.1016/j.jhydrol.2020.124571

Salerno, F., Viviano, G., Tartari, G., 2018. Urbanization and climate change impacts on surface water quality: Enhancing the resilience by reducing impervious surfaces. Water Research 144, 491–502. https://doi.org/10.1016/j.watres.2018.07.058

Schütze, M., Campisano, A., Colas, H., Schilling, W., Vanrolleghem, P.A., 2004. Real time control of urban wastewater systems - Where do we stand today? Journal of Hydrology 299, 335–348. https://doi.org/10.1016/j.jhydrol.2004.08.010

Sharior, S., McDonald, W., Parolari, A.J., 2019. Improved reliability of stormwater detention basin performance through water quality data-informed real-time control. Journal of Hydrology 573, 422–431. https://doi.org/10.1016/j.jhydrol.2019.03.012

Shishegar, S., Duchesne, S., Pelletier, G., Ghorbani, R., 2021. A smart predictive framework for system-level stormwater management optimization. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2020.111505