Flash Floods Exposure Assessment Model for DRR Oriented Adaptive Planning in High-density Urban Areas

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Abstract

Rapid urbanization in China is placing increased pressure on urban drainage infrastructure. Northeast coastal cities are susceptible to flood damage from typhoons and climate change is expected to produce more extreme weather events. Urban planners and local governments need better risk assessment tools to plan for future extreme events. An open data based exposure assessment model has been developed for disaster risk reduction (DRR) oriented adaptive urban plan making based on the understanding of flash floods risk in high-density urban areas under future climate scenarios. The proposed model is based on hydrological simulation, which accuracy is sensitive to the precision of input digital elevation model (DEM). A regression kriging based geo-interpolation method is employed to reshape ground surface by increasing precision of global coverage ASTER GDEM from 30m to 10m. Time component is introduced to the Horton's water permeation model. The parameter of permeation speed limitation is critical to this model; initial values are taken from published Land Classification Codes and adjusted according to the field surveys and observation records. Shekou community in Shenzhen is a case study to verify the proposed model. Two most common scenarios are tested. One is a storm at low-tide condition, with a fully functional urban drainage system. This scenario is simulated by using historical rainfall data from Meteorological Bureau. The other scenario is a typhoon occurring at high-tide, which means urban drainage system is partially malfunctioned. The simulation results show high agreement with both the historical record and satellite observations. Based on the understanding of flash floods exposure assessment and the temporal-spatial distribution of the risk, DRR oriented adaptive urban plans can be made.

Keywords

High-density urban areas, Flash floods, Exposure assessment model, DRR plans

1. Introduction

In recent years, urban floods caused by climate change, extreme weather, and rapid urbanization have been increasing both in severity and frequency in China, which increases risk to urban systems, human activities, health, properties, and the environment, extremely. Because of climate change, urban rainstorm floods have gradually been one of the most significant risks to urban activities and social development (V. Daksiya, Mandapaka, and Lo 2020; B. Li and Sivapalan 2020). Especially, urban rainstorm floods have already been one of the most severe natural disasters that restrict the healthy development of the economy and society in China (Wu et al. 2021). According to the Ministry of Water Resources of the People's Republic of China, more than 100 cities in China suffered from urban floods every year from 2008 to 2018, causing direct economic losses of 374.5, 267.5, 315.6, and 364.3 billion yuan in 2010, 2012, 2013, and 2016, respectively.

Velautham Daksiya, Mandapaka, and Lo (2021) found that climate change has a higher impact compared to urbanization on the flood protection decisions. Globally, scholars and researchers are trying to develop more precise and accurate models to project future extreme precipitation probabilities to a local level with local parameters. DeGaetano and Castellano (2017) developed a set of future extreme precipitation probabilities are developed for New York State based on different down-scaling approaches and climate model projections. The research results indicate that 100-year recurrence interval precipitation amounts exhibit a median increase of between 5 and 10% across the New York state in the 2010–2039 period regardless of greenhouse gas concentration. Cooper (2019) contributed plausible future precipitation scenarios for the Bangkok Metropolitan Region (BMR), which builds on the existing evidence base that projects increasing future precipitation. Their results indicate that in comparison to the past period (1980–2009), over the long-term (2070–2098) the total monthly heavy/very heavy precipitation is projected to increase by 100–120%. H. Zhu, Jiang, and Li (2021) presented projections of climate extremes over China under global warming of 1.5, 2, and 3°C above pre-industrial (1861–1900), based on the latest Coupled Model Intercomparison Project phase 6 (CMIP6) simulations. CMIP6 shows higher increases for both total precipitation and heavy precipitation by 5.3%, 8.6%, and 16.3%, respectively, in China.

Generally, urban floods are caused by extreme runoff in a developed area where drainage is insufficient (Barroca et al. 2006). While the exposure and sensitivity of urban system to storm floods risk is affected by the interaction of environmental and social forces. With the characteristics of a highly concentrated population and facilities, complex spatial structure, high-speed dynamic operations, and evolution, urban areas are complex and vast systems coupled with nature and humanity, which is distinct from any other natural system (X. Li and Willems 2020). The uncertainty lies in future changes of urban extent, land-use patterns and flood plain basin parameters, which impacts future flood risk significantly Velautham Daksiya, Mandapaka, and Lo (2021).

Reducing exposure and vulnerability can considerably reduce flood damage. Cities with higher potential impact do not necessarily lead to higher vulnerability for urban flooding because adaptive capacity can also mitigate the vulnerability of cities to extreme climate events (Chang and Huang 2015). In addition to rainfall and the underlying surface, urban planning and management have a significant impact on urban flooding (Zhou et al. 2017). L?We et al. (2017) proved that urban planning policies and spatial plans are an efficient means for urban flood reduction. Lee and Brody (2018) verified that a high-density development of compact designs decreases flood loss, even though urban built-up land with higher impervious surfaces may cause more flood damage. Improvement to stormwater infrastructure is usually costly. However, stormwater control measures, such as retention basin, bioswales, infiltration trench, porous pavement, rain barrels, detention pond, green roof, and rain garde, can be a cheaper solution to reduce the runoff (Hossain Anni, Cohen, and Praskievicz 2020). Cities in China are urged to adopt planning-oriented adaptation as a strategy of proactive risk planning in the context of rapid urbanization and global climate change (ZHENG et al. 2018).

According to Ketabchy et al. (2019) computer-based simulating can effectively reduce manpower, material resources and time investment for saving costs, and improve application and research efficiency. However, one of the major challenges in urban flood modelling and simulation is lack of data about the location and properties of stormwater infrastructure and land cover (Hossain Anni, Cohen, and Praskievicz 2020). In estimating risks from flooding scenarios, local governments usually play an important role as they have access to (spatial) data on the assets, such as buildings, infrastructure, and environmentally protected areas and socio-demographics of flood zones (Aerts et al. 2014). But data on stormwater management is still not readily available or attainable for most local urban environments, even in developed countries (Liptan and Santen 2017). There is an urgent need to develop open data solutions.

2. Literature review

Sustainable urban stormwater management using low impact development (LID) techniques, along with conventional urban stormwater management systems, can be implemented to mitigate climate-change-

induced flood impacts. LID practices have been mentioned as a promising strategy to control urban stormwater runoff and pollution in the urban ecosystem. However, this requires many experimental and modeling efforts to test LID characteristics and propose an adequate guideline for optimizing LID management. Baek et al. (2015) proposed a novel methodology to optimize the sizes of different types of LID by conducting intensive stormwater monitoring and numerical modeling in a commercial site in Korea. Ahiablame and Shakya (2016) conducted a case study based assessment of flood reduction capabilities of large-scale adoption of LID practices in an urban watershed in central Illinois using the Personal Computer Storm Water Management Model (PCSWMM).

Bahrami, Bozorg-Haddad, and Loáiciga (2019) proposed a simulation–optimization model that minimizes the costs of LID measures for mitigating impacts of future urban development on runoff. With a comparison of the results from two different scenarios of future development with the existing stormwater system’s performance shows the cost increase in redesigning the existing system to make it LID sensitive would equal 20% and 45%. Aerts et al. (2014) simulated 549 storm-surge simulations, varying from extremely low probability events to more frequent storms, using a coupled hurricane–hydrodynamic–inundation model to build up a flood risk probabilistic model for New York in the US. As stated by Xu et al. (2019), LIDs simulation is mainly integrated into the hydrological models in the form of functional components or plug-ins, such as MUSIC, MOUSE, P8-UCM, PURRS, SLMM, Storm Tac, SWMM, SUSTAIN, and L-THIA.

The newly applied “Sponge City” plan considers the concave green land as an effective tool in mitigating pluvial floods. Du et al. (2019) conducted a research by integrating urban flood simulation, scenario analysis, and mitigation assessment in central Shanghai, China. Their findings include CGL with a depth of 0.10–0.20m can mitigate direct runoffs by 23.63–98.35% and inundation extents by 26.09–82.41%. Pour et al. (2020) evaluated the effectiveness of LIDs in the mitigation of urban flood to identify their limitations. Their results revealed that LIDs can be an efficient method for mitigating urban flood impacts. However, most of the LID methods were found to be effective only for small flood peaks. Hossain Anni, Cohen, and Praskievicz (2020) investigated the sensitivity of urban flood simulations to inputs of stormwater infrastructure and soil characteristics. The results indicate that stormwater infrastructure decreases flooding volume of return period 10, 25, 50 and 100 by factors of 20, 14, 12, and 8, respectively.

Based on an empirical study of four mega-cities in China Wu et al. (2021) proposed a descriptive framework for cities and communities to identify sensitivity indicators of urban rainstorm flood disasters by using a random forest model. Their results indicate that that urban rainstorm flood disasters are the most sensitive to surface water resources, and are the least sensitive to relief degree of land surface. A multi-criteria decision analysis framework for optimal decision making is developed by Velautham Daksiya, Mandapaka, and Lo (2021) to adapt climate change and associated uncertainties of urban flood risk. Anni, Cohen, and Praskievicz (2020) analyzed the role of stormwater infrastructure and soil infiltration in urban floods. Mei et al. (2020) found that both rainfall intensity and rainfall patterns are the determining factors of urban flooding.

Urban and community resilience Schlör, Venghaus, and Hake (2018) is one of the most important concepts of urban flood risk management which is relative to risk exposure very closely. Definition of resilience was proposed by the United Nations as “Resilience is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner including through the preservation and restoration of its essential basic structures and functions” (Harrison and Williams 2016). By reviewing four decades of academic literature on urban resilience beginning in 1973, Meerow, Newell, and Stults (2016) defined: urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.

With the observed greater frequency of natural disasters worldwide, there has been an ever-increasing interest in urban resilience and its assessment (Rus, Kilar, and Koren 2018). Lu and Stead (2013) proposed

framework of six resilience attributes in relation to planning for climate disturbance and flood risk was implemented on the case study of the city of Rotterdam. Roggema (2014) proposed resilience as a framework for the successful integration of recovery planning and urban design. Simon et al. (2016) developed a qualitative framework for assessing resilience considering numerous characteristics of a safe and resilient community, divided into four main categories: external resources, assets, capacities and qualities. To identify major resilience characteristics, Sharifi and Yamagata (2016) proposed a matrix approach and introduced five major dimensions of urban resilience and an extensive list of criteria related to them. Serre and Heinzle (2018) assessed and mapped resilience levels to floods taking into account critical infrastructure networks as risk propagators at different spatial scales. ZHENG et al. (2018) conducted an exploratory factor analysis to justify an analytical framework and rank the urban resilience index for 16 districts in Beijing. Results indicate that urban resilience at the district level is distinguished by the characteristics of the district's functional zones, which implies that the development focus of each district influences the driving factors of urban resilience. Borsekova, Nijkamp, and Guevara (2018) explored urban resilience patterns after disasters and found that population size and density are critical parameters for the order of magnitude of damage.

Moura Rezende et al. (2019) proposed a multi-criteria index, the Urban Flood Resilience index-UFRI, to measure quantitatively urban resilience to floods, supported by a hydrodynamic mathematical model and socio-economic indicators, resulting in spatialized maps as a communicating tool. Brunetta and Salata (2019) made a first attempt to measure the vulnerability of the urban system for mapping urban resilience for spatial planning. The spatial interaction of these measures is useful to define the interventions essential to designing and building the adaptation of the built environment by planning governance.

McClymont et al. (2020) provided an understanding of how resilience is perceived in flood risk management along interdisciplinary spectrum of resilience and its operational concept for a full potential by a systematic review of 147 paper abstract and 67 full papers. The results reveal that few methods which integrate social and technical systems across different spatial scales, and a disconnect between bottom-up and top-down strategies in flood risk management. According to Campbell et al. (2019) the Zurich Flood Resilience Alliance developed an approach to test and validate a measure of community flood resilience, which measures a set of sources of community flood resilience when floods occur. Their study represents the first large scale analysis of systemic and replicable flood resilience baseline data from 118 communities across 9 countries. Kim and Song (2018) proposed a confirmatory factor analysis based method to measure urban resilience through 25 indicators to urban function and to classify 232 cities in Korea with regard to climate variability. Kontokosta and Malik (2018) focused on neighborhood resilience by developing a unified, multi-factor index, the Resilience to Emergencies and Disasters Index (REDI), of local and regional resilience capacity, which benefits the integration of measures of physical, natural, and social systems—operationalized through the collection and analysis of large-scale, heterogeneous, and high resolution urban data (over 12,000,000 records from New York City).

The China government has been devoting to the promotion of smart cities for many years. However, that is not clear whether smart city is more resilient to climate change or disasters. S. Zhu, Li, and Feng (2019) used a MCDM approach to assess and rank the resilience of 187 smart cities in China. Their results demonstrate that the overall resilience of smart cities is at a relatively low level. There is also a significant unbalance of resilience between smart cities due to different infrastructural, economic, social, institutional, and environmental conditions. Zhang et al. (2019) took 56 cities in China as the research object, by using the combination of weight method, exploratory spatial data analysis and spatial measurement model, and selects 29 indicators from urban infrastructure, economy, ecology and society to explore the spatial distribution of urban resilience and its influencing factors. Their results indicate that the values of the urban resilience show a significantly positive correlation in regard to their spatial distribution.

water points in the city, and about 50 flooding reports were received. On May 20, 2016, the average rainfall in Shenzhen was 109.5 mm. The heavy rainfall caused various levels of disasters and dangers in Shenzhen water conservancy projects and municipal facilities. During the torrential rain, more than 80 waterlogged occurred in Shenzhen, the depth of which was 0.3-0.5 meters, and the maximum exceeded 1 meter.

Figure 2. The annual daily rainfall and evaporation in Shenzhen

4. Methods

4.1 Water balance model

The goal of urban floods management is to reasonably organize and manage urban water resources to reduce the amount of surface runoff, or organize disordered surface runoff into orderly surface runoff, so as to weaken the impact and impact of rain and flood on urban system. Therefore, the accurate estimation of urban surface water during precipitation is the basis of planning and designing sponge city. The total surface water volume is balanced, which can be expressed as the balance of input water volume and output water volume, see Equation (2).

$$\begin{aligned}
 V &= V_i - V_o \\
 V_i &= V_{rain} + V_{in} \\
 V_o &= V_d + V_e + V_{runoff} + V_{per} \\
 V_{runoff} + V_{per} &= (V_{rain} + V_{in}) - (V_d + V_e) \quad (2)
 \end{aligned}$$

where, V_i is the input water volume, V_o is the output water volume, V_{rain} is the rainfall amount, V_{in} is the volume of inrush water from neighbor cells, V_d is the volume of drainage, V_e is evaporation, V_{runoff} is the surface runoff, and V_{per} is the ground permeation.

The input water volume is determined by precipitation and external water volume, including external runoff and inflow due to failure of drainage system. The output water volume is determined by the drainage volume, evaporation volume, runoff output and environmental absorption volume of the pipe network. Therefore, under the same rainfall conditions, the more water absorbed by the environment, the smaller the surface runoff. Accurately calculating the temporal and spatial distribution, velocity, flow and duration of rainwater and flood surface runoff is the premise to improve the rainwater and flood absorption capacity of the environment.

4.2 Surface infiltration rate model

The classical Horton infiltration model can be used to determine the theoretical infiltration rate of surface ponding caused by local rainfall, see Equation (3):

$$f_p(t) = f_c + (f_0 - f_c) \exp(-\alpha t) \quad (3)$$

where, $f_p(t)$ is the infiltration rate at time t , f_0 is the initial infiltration rate or maximum infiltration rate, f_c is the constant or equilibrium infiltration rate after the soil has been saturated or minimum infiltration rate, and α is the decay constant specific to the soil.

By consider the impact of local rainstorm intensity formula (1), practical infiltration rate is as Equation (4)

$$f(t) = \min(f_p(t), I(t)) \quad (4)$$

Finally, the integrated infiltration model is as Equation (5):

$$F(t_p) = \int_0^{t_p} f_p(t) dt = f_c t_p + \frac{f_0 - f_c}{\alpha} (1 - \exp(-\alpha t_p)) \quad (5)$$

4.3 Terrain surface reshape model

ASTER GDEM data sets are used as digital elevation model for terrain surface reshape modeling in this study. The spatial resolution of the ASTER GDEM is about 30m, which is not precis enough to model and simulate urban floods surface runoff in small areas. Kriging interpolation is employed in this study, which is an efficient method that use a limited set of sampled data points to estimate the value of a variable over a continuous spatial field. Kriging weights are calculated such that points nearby to the location of interest are given more weight than those far away. Clustering of points is also taken into account, so that clusters of points are weighted less heavily. This helps to reduce bias in the predictions. Kriging interpolation is a two-stage process: firstly, the spatial covariance structure of the sampled points is determined by fitting a variogram; secondly, weights derived from this covariance structure are used to interpolate values for unsampled points or blocks across the spatial field. Kriging interpolation is particular useful by preserving spatial variability when spatial autocorrelation exists.

The kriging predictor is an “optimal linear predictor” and an exact interpolator, meaning that each interpolated value is calculated to minimize the prediction error for that point. The value that is generated from the kriging process for any actually sampled location will be equal to the observed value at this point, and all the interpolated values will be the Best Linear Unbiased Predictors (BLUPs).

In matrix notation, terrain surface reshape model is as Equation (6):

$$\hat{z}(s_0) = q_0^T \hat{\beta}_{GLS} + \lambda_0^T (z - q \hat{\beta}_{GLS}) \quad (6)$$

where, $\hat{z}(s_0)$ is the predicted value at location s_0 , q_0 is the vector of $p + 1$ predictors and λ_0 is the vector of n kriging weights used to interpolate the residuals. The model is considered to be the best linear predictor of spatial data. It has a prediction variance that reflects the position of new locations in both geographical and feature space, see Equation (7):

$$\hat{\delta}^2(S_0) = (C_0 + C_1) - c_0^T C^{-1} c_0 + (q_0 - q^T C^{-1} c_0)^T (q^T C^{-1} q)^{-1} (q_0 - q^T C^{-1} c_0) \quad (7)$$

where, $C_0 + C_1$ is the still variation and c_0 is the vector of variances o residuals at the prediction location.

4.4 Surface water permeability and stagnation ratio

Values of the surface water permeability and stagnation ratio of the study area are determined by field investigation on the basis of China Construction Land Code (GB50137-2011) and the US Colorado Drainage Standard. The recommended reference values of surface water permeability and stagnation ratio of the study area are shown in Table 1 and table 2.

Table 1: The recommended reference values of surface water permeability

Land Use	surface water permeability(%)	Land Use	surface water permeability(%)
CBD	0	Public Land	15
Business Area	5	Along Railway	65
Flat Roofs	0	Roads	0
Slope Roofs	0	Side Way	5
Low Buildings	10	Green Belt	60
Multi-storey Building	5	Park	70
High Buildings	15	Grass Land	100
Light Industry	15	Forest	90
Heavy Industry	5	Sand	100
Stadium	20	Clay	95
Campus	20	Bare Land	10
Square	0	Unknow	30

Table 2: The recommended reference values of surface water stagnation ratio

Land Type		Reference Values	Recommended Values
Impermeable Surface	Pavement	0.05-0.15	0.1
	Flat Roofs	0.1 - 0.3	0.1
	Slope Roofs	0.05 - 0.1	0.05
Permeable Surface	Grass Land	0.2 -0.5	0.35
	Forest	0.2 -0.6	0.4
	Other Land	0.2 -0.6	0.4

5. Results

The raw data of ASTER GDEM (30m) were used to perform a city-level flood basin analysis and catchment analysis, the results are shown in Figure 3. A standard plot using a 10% sub-sample of the original ASTER GDEM 30m data set. The histogram shows that the values of the elevation data are

approximately normally distributed, with some clustering around low values. The clustered low values are floodplain, see Figure 4.

Figure 3. Elevation distribution and catchment analysis results from ASTER GDEM 30

Figure 4. Terrain surface reshaping from ASTER GDEM 30m to 10m

On the basis of understanding the spatial distribution of the raw data, the terrain surface reshape model parameters can be estimated by WLS (weighted least squares) by a simulation method: $\kappa = 0.5$, $\sigma^2 = 2459.1850$, and $\phi = 953.6299$; the practical range with $\text{cor}=0.05$ for asymptotic range at 2856.82 meters. The model results are shown in Figure 5. Figure 6 is a comparison of urban wetness distribution of spatial resolution calculated by the original 30m DEM and by a reshaped 10m DEM.

Figure 5 Terrain surface reshaping from ASTER GDEM 30m to 10m

Figure 6. Results comparison of urban wetness distribution of spatial resolution of 30m and 10m

6. Conclusions

Cities are typically complex mega-systems with a complex disaster interaction during urban floods. It is significantly important to improve urban and community resilience based on a profound understanding of the flood risk propagation in urban systems along with human activities. Scenario based simulation is an

effective approach to discover the spatial patterns of disaster risk exposure. It can be used to build up a basis for spatial planning strategies of disaster intervention and protection. Specifically, modeling and simulation results of urban floods are sensitive to the spatial resolution of DEM data. Open and Internet accessible data as alternatives to official data can be used as a reliable data source to be used for disaster risk reduction oriented modeling and simulation.

7. References

- Aerts, J. C. J. H. et al. (2014) 'Climate adaptation: Evaluating flood resilience strategies for coastal megacities', *Science*, 344(6183), pp. 473–475. doi: 10.1126/SCIENCE.1248222.
- Ahiablame, L. and Shakya, R. (2016) 'Modeling flood reduction effects of low impact development at a watershed scale', *Journal of Environmental Management*, 171, pp. 81–91. doi: 10.1016/J.JENVMAN.2016.01.036.
- Anni, A. H., Cohen, S. and Praskievicz, S. (2020) 'Sensitivity of Urban Flood Simulations to Stormwater Infrastructure and Soil Infiltration', *Journal of Hydrology*, 588, p. 125028.
- Baek, S. S. et al. (2015) 'Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: Experimental and modeling approach', *Water Research*, 86, pp. 122–131. doi: 10.1016/J.WATRES.2015.08.038.
- Bahrami, M., Bozorg-Haddad, O. and Loáiciga, H. A. (2019) 'Optimizing stormwater low-impact development strategies in an urban watershed considering sensitivity and uncertainty', *Environmental Monitoring and Assessment*, 191(6). doi: 10.1007/S10661-019-7488-Y
- Barroca, B. et al. (2006) 'Indicators for identification of urban flooding vulnerability', *Natural hazards and earth system sciences*, 6(4), pp. 553–561.
- Bermúdez, M. and Zischg, A. P. (2018) 'Sensitivity of flood loss estimates to building representation and flow depth attribution methods in micro-scale flood modelling', *Natural Hazards*.
- Borsekova, K., Nijkamp, P. and Guevara, P. (2018) 'Urban resilience patterns after an external shock: An exploratory study', *International Journal of Disaster Risk Reduction*, 31, pp. 381–392. doi: 10.1016/J.IJDRR.2018.05.012.
- Brunetta, G. and Salata, S. (2019) 'Mapping urban resilience for spatial planning-A first attempt to measure the vulnerability of the system', *Sustainability (Switzerland)*, 11(8). doi: 10.3390/SU11082331.
- Campbell, K. A. et al. (2019) 'First insights from the Flood Resilience Measurement Tool: A large-scale community flood resilience analysis', *International Journal of Disaster Risk Reduction*, 40. doi: 10.1016/J.IJDRR.2019.101257.
- Chang, L. F. and Huang, S. L. (2015) 'Assessing urban flooding vulnerability with an emergy approach', *Landscape and Urban Planning*, 143, pp. 11–24. doi: 10.1016/J.LANDURBPLAN.2015.06.004.
- Cooper, R. T. (2019) 'Projection of future precipitation extremes across the Bangkok Metropolitan Region', *Heliyon*, 5(5). doi: 10.1016/J.HELİYON.2019.E01678.
- Daksiya, V., Mandapaka, P. V. and Lo, E. (2020) 'Effect of climate change and urbanization on flood protection decision-making', *Journal of Flood Risk Management*.
- Daksiya, V., Mandapaka, P. V. and Lo, E. Y. M. (2021) 'Effect of climate change and urbanisation on flood protection decision-making', *Journal of Flood Risk Management*, 14(1). doi: 10.1111/JFR3.12681.
- DeGaetano, A. T. and Castellano, C. M. (2017) 'Future projections of extreme precipitation intensity-duration-frequency curves for climate adaptation planning in New York State', *Climate Services*, 5, pp. 23–35. doi: 10.1016/J.CLISER.2017.03.003.

- Du, S. et al. (2019) 'Mapping the capacity of concave green land in mitigating urban pluvial floods and its beneficiaries', *Sustainable Cities and Society*, 44, pp. 774–782. doi: 10.1016/J.SCS.2018.11.003.
- Harrison, C. G. and Williams, P. R. (2016) 'A systems approach to natural disaster resilience', *Simulation Modelling Practice & Theory*, pp. 11–31.
- Hossain Anni, A., Cohen, S. and Praskievicz, S. (2020) 'Sensitivity of urban flood simulations to stormwater infrastructure and soil infiltration', *Journal of Hydrology*, 588. doi: 10.1016/J.JHYDROL.2020.125028.
- Ketabchy, M. et al. (2019) 'Simulation of watershed-scale practices for mitigating stream thermal pollution due to urbanization', *Science of The Total Environment*, 671(JUN.25), pp. 215–231.
- Kim, D. and Song, S. K. (2018) 'Measuring changes in urban functional capacity for climate resilience: Perspectives from Korea', *Futures*, 102, pp. 89–103. doi: 10.1016/J.FUTURES.2018.05.001.
- Kontokosta, C. E. and Malik, A. (2018) 'The Resilience to Emergencies and Disasters Index: Applying big data to benchmark and validate neighborhood resilience capacity', *Sustainable Cities and Society*, 36, pp. 272–285. doi: 10.1016/J.SCS.2017.10.025.
- Lee, Y. and Brody, S. D. (2018) 'Examining the impact of land use on flood losses in Seoul, Korea', *Land Use Policy*, 70, pp. 500–509.
- Li, B. and Sivapalan, M. (2020) 'Long term Coevolution of an Urban Human Water System Under Climate Change: Critical Role of Human Adaptive Actions', *Water Resources Research*, 56(11).
- Li, X. and Willems, P. (2020) 'A Hybrid Model for Fast and Probabilistic Urban Pluvial Flood Prediction', *Water Resources Research*, 56(6).
- Liptan, T. and Santen, J. D. (2017) 'Sustainable Stormwater Management: A Landscape-Driven Approach to Planning and Design'.
- Lu, P. and Stead, D. (2013) 'Understanding the notion of resilience in spatial planning: A case study of Rotterdam, The Netherlands', *Cities*, 35(dec.), pp. 200–212.
- L?We, R. et al. (2017) 'Assessment of Urban Pluvial Flood Risk and Efficiency of Adaptation Options Through Simulations – A New Generation of Urban Planning Tools', *Journal of Hydrology*, p. S0022169417302962.
- McClymont, K. et al. (2020) 'Flood resilience: a systematic review', *Journal of Environmental Planning and Management*, 63(7), pp. 1151–1176. doi: 10.1080/09640568.2019.1641474.
- Meerow, S., Newell, J. P. and Stults, M. (2016) 'Defining urban resilience: A review', *Landscape and Urban Planning*, 147, pp. 38–49. doi: 10.1016/J.LANDURBPLAN.2015.11.011.
- Mei, C. et al. (2020) 'Urban flood inundation and damage assessment based on numerical simulations of design rainstorms with different characteristics'.
- Moura Rezende, O. et al. (2019) 'A framework to introduce urban flood resilience into the design of flood control alternatives', *Journal of Hydrology*, 576, pp. 478–493. doi: 10.1016/J.JHYDROL.2019.06.063.
- Pour, S. H. et al. (2020) 'Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges', *Sustainable Cities and Society*, 62, p. 102373. doi: 10.1016/J.SCS.2020.102373.
- Ribeiro, P. J. G. and Pena Jardim Gonçalves, L. A. (2019) 'Urban resilience: A conceptual framework', *Sustainable Cities and Society*, 50. doi: 10.1016/J.SCS.2019.101625.
- Roggema, R. (2014) 'Towards a Spatial Planning Framework for Climate Adaptation'.

- Rus, K., Kilar, V. and Koren, D. (2018) 'Resilience assessment of complex urban systems to natural disasters: A new literature review', *International Journal of Disaster Risk Reduction*, 31, pp. 311–330. doi: 10.1016/J.IJDRR.2018.05.015.
- Schlör, H., Venghaus, S. and Hake, J. F. (2018) 'The FEW-Nexus city index – Measuring urban resilience', *Applied Energy*, 210, pp. 382–392.
- Serre, D. and Heinzlef, C. (2018) 'Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks', *International Journal of Disaster Risk Reduction*, 30, pp. 235–243. doi: 10.1016/J.IJDRR.2018.02.018.
- Sharifi, A. and Yamagata, Y. (2016) 'Urban Resilience Assessment: Multiple Dimensions, Criteria, and Indicators', *Advanced Sciences and Technologies for Security Applications*, pp. 259–276. doi: 10.1007/978-3-319-39812-9_13.
- Simon et al. (2016) 'Towards measurable resilience: A novel framework tool for the assessment of resilience levels in slums', *International Journal of Disaster Risk Reduction*.
- Wu, M. et al. (2021) 'Identification of sensitivity indicators of urban rainstorm flood disasters: A case study in China', *Journal of Hydrology*, 599, p. 126393. doi: 10.1016/J.JHYDROL.2021.126393.
- Xu, T. et al. (2019) 'Optimal adaptation pathway for sustainable low impact development planning under deep uncertainty of climate change: A greedy strategy', *Journal of Environmental Management*, 248(Oct.15), pp. 109280.1–109280.10.
- Zhang, M. et al. (2019) 'Analysis of the spatial distribution characteristics of urban resilience and its influencing factors: A case study of 56 cities in China', *International Journal of Environmental Research and Public Health*, 16(22). doi: 10.3390/IJERPH16224442.
- ZHENG, Y. et al. (2018) 'Development as adaptation: Framing and measuring urban resilience in Beijing', *Advances in Climate Change Research*, 9(4), pp. 234–242. doi: 10.1016/J.ACCRE.2018.12.002.
- Zhou, Z. et al. (2017) 'The complexities of urban flood response: Flood frequency analyses for the Charlotte metropolitan region', *Water Resources Research*, 53(8), pp. 7401–7425.
- Zhu, H., Jiang, Z. and Li, L. (2021) 'Projection of climate extremes in China, an incremental exercise from CMIP5 to CMIP6', *Science Bulletin*. doi: 10.1016/J.SCIB.2021.07.026.
- Zhu, S., Li, D. and Feng, H. (2019) 'Is smart city resilient? Evidence from China', *Sustainable Cities and Society*, 50.