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COMMENTARY

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Key Points:

- Urban flood models (UFMs) are critical tools for flood risk assessment, emergency operations, and resilience planning in cities
- The ultimate goal of UFM development should be the capability for sustained, integrated simulation of urban watersheds
- A substantial effort will be needed to overcome existing barriers in urban flood modeling, which will be of great value for urban flood resilience

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The Value of Urban Flood Modeling

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Abstract Floods are important disturbances to urban socio-eco-technical systems and their meteorological drivers are projected to increase through the century due to global climate change. Urban flood models are numerical models that have the capability of representing the features of urban ecosystems and the mechanisms of flooding that impact them. They have the potential to play a critical role in flood risk assessment, operational response, and resilience planning, but existing models remain limited in their capability to represent integrated flooding processes in urban areas and provide the credible quantitative information needed to support risk assessment and resilience practice. Research to advance model development, facilitate intensive watershed monitoring for model parameterization and validation, and support collaboration between researchers and practitioners should be prioritized. This will represent a substantial, expensive effort, but will still be of great value as cities are faced with urgent challenges posed by climate change in coming decades.

Plain Language Summary Across the globe, floods in cities cause substantial loss of life, property damage, and other socioeconomic harms. As the global climate changes, meteorological events that cause flooding such as extreme rain, high tides, and coastal storms are projected to become more frequent and severe. Researchers and environmental managers use urban flood models (UFMs)—packages of mathematical equations that can simulate water flow and other flooding processes—to support risk assessment and emergency management and to develop strategies to mitigate future flooding. However, these models are currently limited in their potential to achieve these objectives, despite recent advances in computing and environmental monitoring. We recommend that the research community prioritizes development of improved UFMs, which will involve use of more sophisticated equations and approaches to solve them, intensive monitoring of flooding processes in cities, and development of institutions dedicated to supporting these efforts. Although these initiatives will be resource intensive, the value provided by UFMs and the urgency of urban flooding issues make such an effort worthwhile.

1. Introduction

As the human population and the impending magnitude of global climate change both continue to grow, there is an imperative to better understand the function of cities as ecosystems and their resilience to climate-driven disturbances. Floods are prominent disturbances to urban ecosystems (Grimm et al., 2017; Rentschler et al., 2019), and their meteorological drivers—including extreme precipitation, sea level rise, and coastal storms—are projected to increase in coming decades (Y. Chen et al., 2018). Numerical models are essential tools for understanding floods and their associated risks. But despite recent advances in computational resources, existing flood models remain limited in their capability to represent integrated flooding processes in urban areas and provide credible, quantitative information needed to support risk assessment and resilience practice. In this commentary, we discuss the potential value of urban flood modeling for urban resilience and limitations of existing modeling approaches. We then present a research agenda and vision for the future of urban flood modeling, realized through collaboration between researchers and practitioners.

We define urban flood models (UFMs) as numerical models that are capable of representing the features of urban ecosystems and the mechanisms of flooding that impact them. Cities are Social-Ecological-Technological

Systems (SETS; Markolf et al., 2018; McPhearson et al., 2016), and urban flooding results from the dynamics of their social institutions, natural ecosystems, and built infrastructure systems in response to meteorological drivers. UFMs must be able to represent all three SETS components and their contributions to flood response.

UFMs also must be capable of representing a variety of flooding mechanisms. The most widely studied of these is fluvial flooding, which occurs when rivers or streams rise out of their banks in response to precipitation (Kundzewicz et al., 2010). But the hydrology of highly urbanized environments is often dominated by sewer drainage and, as a result, precipitation-driven flooding frequently results from other mechanisms, or combinations of multiple flooding mechanisms within an event or season (A. S. Chen et al., 2010). These can include pluvial flooding, which occurs when intense precipitation exceeds the rate of natural and engineered drainage (Rosenzweig et al., 2018), and groundwater flooding, which occurs when the water table rises above the land surface (Macdonald et al., 2012). In coastal cities, flooding can also result from high tide conditions and storm surge, or combinations of these mechanisms with heavy or intense precipitation (Moftakhari et al., 2017; Zscheischler et al., 2018). While validated, high-skill models for coastal and fluvial flooding are available for research and practice (Georgas & Blumberg, 2010; Kauffeldt et al., 2016), models for pluvial and groundwater flooding remain in early stages of development.

Urban flooding already presents substantial socioeconomic risk. Between 1980 and 2018, direct economic losses due to floods have exceeded $1 trillion globally (US, 2018 values), with hundreds of thousands of lives lost (Munich, 2018; Winsemius et al., 2015). These socioeconomic losses tend to be concentrated in urbanized areas, where properties and assets are densely exposed (Peduzzi, 2017). In the absence of aggressive climate change mitigation, annual losses due to urban flooding are projected to increase more than tenfold by 2080 (Hallegatte et al., 2013; Winsemius et al., 2015).

UFMs can play a key role in flood risk assessment, facilitating the geospatial analysis of flood *hazard*, the probability that a flood of a given severity will occur at a site, with severity typically measured by hydraulic parameters such as flood depth or velocity (Arrighi & Campo, 2019; Crichton, 1999). Once flood hazard is delineated, UFM results can be utilized to evaluate populations and properties that would potentially be exposed to flooding, as well as to evaluate resulting damages and financial losses (Hammond et al., 2015; Tsakiris, 2014).

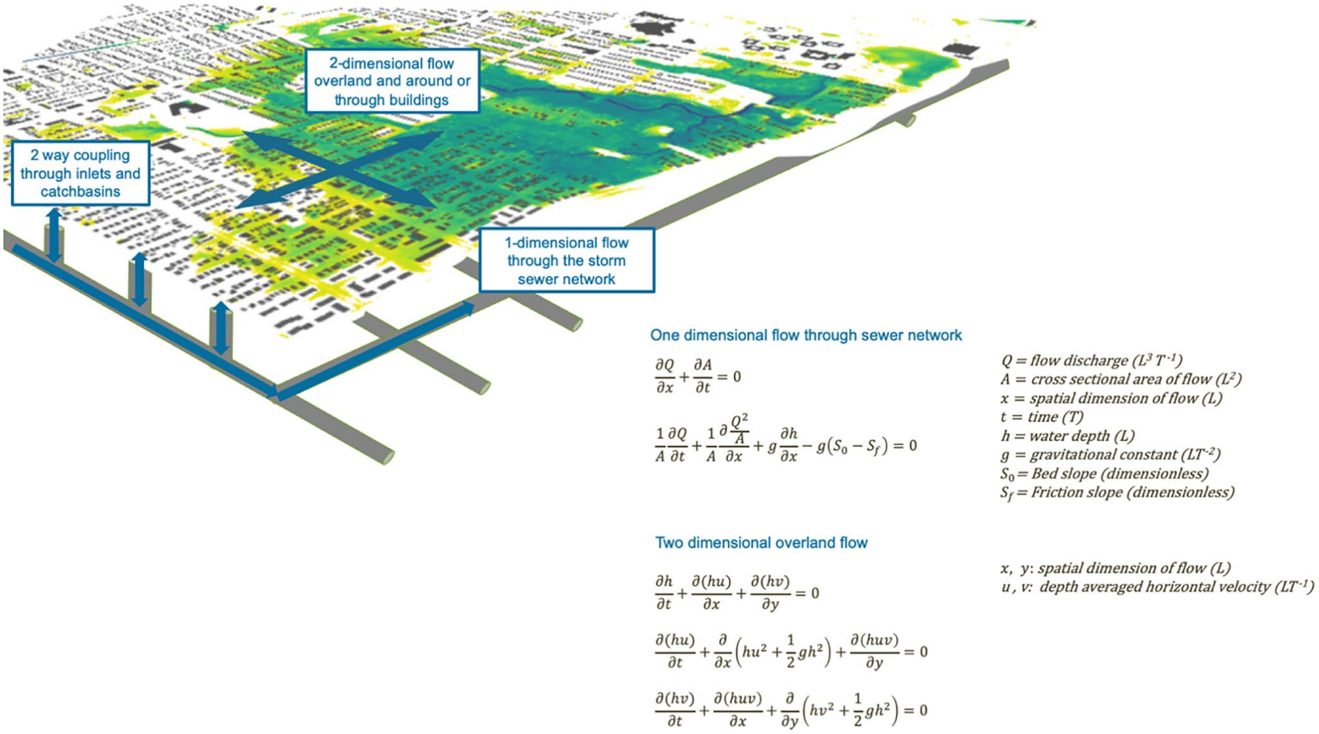
Along with flood risk assessment, operational UFMs can play an essential role in real-time urban flood warning and emergency response (Hapuarachchi et al., 2011). UFMs are incorporated into these systems in two ways: In the first, scenarios of meteorological conditions are run in advance, and used to identify thresholds that result in impactful flooding (Collier, 2007); In the second, meteorological forecasts are assimilated in real time, or near-real time, into UFMs and are used to provide warning for emergency responders and the general public (Hapuarachchi et al., 2011). The effectiveness of these systems is dependent on the type of model used, the availability and quality of input data, and the integration of the modeling results into city operations (Henonin et al., 2013).

UFMs also have the potential to play a critical role in development of urban flood resilience strategies. They can be used to evaluate scenarios of flood management strategy implementation under a variety of potential urbanization, weather and climate pathways. In combination with flood vulnerability assessment models (Hammond et al., 2015), results from UFMs can be used to evaluate the costs and benefits of flood resilience strategies (Lerer et al., 2017). However, use of UFMs to support resilience planning is heavily dependent on the capability of the model to represent both current conditions and the function of various management strategies, such as land use planning or the construction of gray and green infrastructure, under realistic operating conditions (Hemmati et al., 2020; Kaykhosravi, et al., 2018; Niazi et al., 2017). As cities plan multi-billion dollar flood resilience initiatives (Aerts, Botzen, Moel, & Bowman, 2013; City of Copenhagen, 2012; NYCDEP/Ramboll, 2017), development and use of robust UFMs present a great value to support the optimized design of these infrastructure and their operation.

2. Limitations of Existing Urban Flood Modeling Frameworks

2.1. Technical Limitations: Representation of Urban Flooding Processes

Existing UFMs vary in complexity, ranging from simple terrain-based routing models to hydrodynamic models that utilize physically based equations of fluid motion (Teng et al., 2017). Comprehensive reviews of



One dimensional flow through sewer network

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial \frac{Q^2}{A}}{\partial x} + g\frac{\partial h}{\partial x} - g(S_0 - S_f) = 0$$

Q = flow discharge ($L^3 T^{-1}$)
A = cross sectional area of flow (L^2)
x = spatial dimension of flow (L)
t = time (T)
h = water depth (L)
g = gravitational constant (LT^{-2})
S_0 = Bed slope (dimensionless)
S_f = Friction slope (dimensionless)

Two dimensional overland flow

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) + \frac{\partial (huv)}{\partial y} = 0$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2}gh^2\right) = 0$$

x, y: spatial dimension of flow (L)
u, v: depth averaged horizontal velocity (LT^{-1})

Figure 1. A graphic representation of coupling of two-dimensional overland flow and inundation with one-dimensional flow in the subterranean sewer network in a dual drainage model.

these models are provided by Bach et al. (2014), Salvadore et al. (2015), and WEF (2020). There are benefits and limitations associated with each approach: simpler models have fewer input data requirements and computational requirements, but are limited in their capability to accurately represent many urban flooding processes. More complex models are often limited by availability of input data for parameterization or in their capability to run rapidly enough to support real-time forecasting and warning (Costabile et al., 2020; Zanchetta & Coulibaly, 2020).

The recommended baseline UFM approach for flood risk assessment and resilience planning is a dual-drainage model that couples a one-dimensional hydrodynamic model of the stormwater drainage network with a two-dimensional hydrodynamic model of overland flow and inundation (Figure 1; Costabile et al., 2020; Vojinovic & Tutulic, 2009). Within each modeling component, water flow is represented by partial differential equations based on mass and momentum conservation principles and solved using numerical methods. Many dual-drainage modeling packages are commercially available; MIKE, Infoworks, and PCSWMM are examples of widely used models (Teng et al., 2017). However, licensing fees for these models can be prohibitively expensive for municipalities and researchers operating with limited budgets. These models can also require substantial computational resources, both in terms of capacity and computing time, particularly for studies of entire cities or when simulating longer duration events.

While dual-drainage models are primarily used to represent pluvial flooding processes, they can also be utilized to represent coastal and riverine flooding, with varying complexity. For example, flow in streams and small rivers can be directly represented as part of a 1D drainage network, with overbank flow propagated in 2D space. Alternatively, large rivers and coastal waterways can be represented as boundary conditions at outfalls or the shoreline (Apel et al., 2016; Tanim & Goharian, 2020). However, nearly all dual-drainage models used today remain limited in their capability to represent key flooding processes, particularly those related to groundwater or the built environment. For example, infiltration of groundwater into stormwater drainage sewers can significantly impact their capacity to convey stormwater; this condition also can exacerbate flooding during intense rain events (Cahoon & Hanke, 2017). Groundwater flooding can also result in direct inundation when the water table rises above the land surface, either due to tidal forcing or precipitation conditions (Sukop et al., 2018). Few existing dual-drainage models support coupling with a dynamic groundwater flow model, and those that do are limited in their representation of the interaction of groundwater and subterranean infrastructure (Saksena et al., 2020) and the performance of infiltration-based green infrastructure (Massoudieh et al., 2017; Zhang & Chui, 2018).

In addition, although buildings and other structures can make up a substantial fraction of the area of dense urban watersheds, representation of their role in rainfall-runoff, flow routing, and storage remains simplistic in existing dual-drainage models (Bruwier et al., 2020; Chang, Wang, & Chen, 2015; Leandro & Martins, 2016). Existing dual drainage models are also rarely capable of representing system operations and societal practices that can influence flooding processes. For example, behaviors such as littering or improper disposal of clogging substances in sewers can significantly increase flood risk (Alda-Vidal et al., 2020; Armitage, 2007), while infrastructure maintenance can play a key role in flood mitigation. Simulation of these processes using the parameterizations provided in existing UFMs remains challenging (Tscheikner-Gratl et al., 2019).

2.2. Technical Limitations: Data Availability

The predictive skill of any dual drainage model is dependent on the availability of high-quality data on the urban sewer network, along with robust digital terrain models (DTMs; Adeogun et al., 2015). But in practice, most cities do not have such datasets, and public safety and liability concerns may restrict their access (Blumensaat, Wolfram, & Krebs, 2012). In older cities, storm drains may be centuries old, and poorly represented in digitized maps. Even when digitized data of the full storm drain network are available, these datasets must be supplemented with information on sewer status in order to represent processes such as pipe clogging and deterioration that can significantly influence drainage capacity (Egger et al., 2013; Leitao et al., 2015). Also, while LiDAR-derived digital elevation models (DEMs) are becoming increasingly available for many cities, flood models are highly sensitive to representation of both the terrain and built environment, and thus significant errors remain even in high-resolution DEMs that explicitly represent built-environment features (Arrighi & Campo, 2019).

Meteorological data are also essential inputs to UFMs, but observational data are rarely available at finer spatial and temporal resolutions needed to accurately represent urban flooding processes. Urbanized watersheds are characterized by their rapid hydrologic responses to rainfall, and are particularly vulnerable to cloudburst events that can occur over small areas (Morin et al., 2009; Smith et al., 2013). Remotely sensed Quantitative Precipitation Estimates (QPEs) based on ground-based, dual-polarization radar observations offer great potential for enhanced representation of spatially variable rainfall. However, in practice, the use of these products in UFM remains limited. Many existing UFMs remain incapable of assimilating radar-based precipitation inputs and still require point data, or the assumption of uniform rainfall over modeled catchments. Radar coverage remains limited in many countries and, where it is available, data discovery and access can still present challenges for modelers (Seo et al., 2019; Skofronick-Jackson et al., 2017). In addition, while the recently available dual-polarization products generally offer improved QPEs compared to previous products, continued work is necessary to evaluate their associated uncertainty and develop improved algorithms for use in urban areas (Cunha et al., 2013; Thorndahl et al., 2016).

Development of robust UFMs also depends on availability of observational data to support model calibration and validation, but direct monitoring of flood inundation extent, depth, and velocity is rarely conducted in dense urban areas (Gallien, 2016). As an alternative, a variety of proxies are being increasingly utilized, including insurance claim data, social media, or municipal flooding reports (Re et al., 2019; Yu et al. 2016; Zischg et al., 2018). Physical modeling in a laboratory can also support evaluation of flow processes in highly urbanized environments (Mignot et al., 2019). But while both of these approaches are valuable for model evaluation, they are an inadequate substitute for hydrologic monitoring of field conditions.

2.3. Institutional Barriers

Institutional barriers present additional challenges for overcoming technical limitations. Urban flooding often does not fit into conventional domains or geographic boundaries of governance. For example, in the

United States, most resources for stormwater infrastructure modeling are focused on water quality legislation promulgated by the U.S. Environmental Protection Agency (Bahadur & Samuels, 2020). Most flood modeling is conducted to meet requirements of the Federal Emergency Management Agency and has typically focused only on fluvial or coastal flooding (Knowles & Kunreuther, 2014). As a result, in most U.S. cities, the role of the storm sewer system and other dominant SETS components are neglected in this modeling. UFM is primarily conduced on an as-needed basis at the city scale, in the absence of broad institutional support and regulatory mandates. Additionally, even within cities, governance is often fragmented with no single entity in charge of urban flooding (Casiano Flores et al., 2019). This fragmentation presents challenges for obtaining funding, accessing cross-jurisdictional data, and institutionalization of UFM results into flood mitigation practices (Rosenzweig et al., 2019).

3. A Research Agenda for Urban Flood Modeling

In light of these technical and institutional barriers, we propose the following research agenda to support development of UFMs and knowledge systems to facilitate their utilization.

3.1. Model Development

Most dual drainage models were developed through coupling code for an existing 1D sewer model with that of an existing 2D overland flow model using simplified approaches to represent flow through manholes and catch basin inlets (A. S. Chen et al., 2016). Recent studies have demonstrated that flood model results are sensitive to the approach used to represent these linkages (Chang et al., 2018; Martins et al., 2018). More robust and flexible options for linking model subdomains should be prioritized in future model development (A. S. Chen et al., 2016; Leandro & Martins, 2016).

In addition to improved representation of coupling between sewer and overland flow, UFMs should be developed to improve representation and linkages with other domains, such as aquifers, coastal waters, and built environment. Green infrastructure systems remain particularly limited in their representation in UFMs, even though they are increasingly incorporated in flood resilience planning. Improved representation of green roofs, rain gardens, and cloudburst roads and plazas should be prioritized in future model development. In cities, human behavior and societal operations can also play a significant role in urban flooding processes, which presents an opportunity for novel development to better represent social systems and practices in UFMs.

Any UFM development effort should have dual-priorities of optimizing model performance and increasing model accessibility. We recommend that the ultimate goal in this effort should be development of models that support sustained, integrated simulation of urban watersheds. Such models could be used to identify strategies that provide synergistic benefits for urban water supply and quality management, along with flood resilience.

3.2. Monitoring and Experimental Sewersheds

The foundations of much of modern hydrology were established through experimental watershed studies, where long-term, intensive monitoring is conducted on a focused study site (Hewlett et al., 1969). While experimental watershed studies have had a major influence on development of both conceptual and numerical hydrologic models (Tetzlaff et al., 2017), few of these studies have been conducted in urban settings, particularly those that were highly built-up and dominated by sewer drainage (Belt et al., 2014; Kaushal & Belt, 2012). Although resource-intensive, dedicated experimental sewershed studies are necessary to provide observational data for direct use in model calibration and validation and to advance our conceptual understanding of urban hydrologic processes to support UFM development.

The urban environment amplifies many well-known challenges associated with in situ hydrologic data collection (Burt & McDonnell, 2015). In cities, fieldwork must be conducted with minimal disruption to urban activities and with consideration of private property restrictions and public safety concerns. Recent advances in crowd-sourcing, citizen science, and in situ sensing provide many opportunities to collect needed data, while engaging the public in science (Paul et al., 2018). Some urban field sites may involve confined spaces, contaminants, and other conditions that are hazardous to researchers and instrumentation. However, development of high-skill UFM depends on conducting this work. Research to support development of instrumentation and best practices for urban field monitoring should be prioritized to address these challenges.

3.3. Facilitating Researcher/Practitioner Collaboration

Robust UFM development and monitoring research will depend on development of new approaches to facilitate collaboration between practitioners and academic researchers. For example, in the United States, academic researchers conducting advanced graduate or postdoctoral work may develop novel UFMs, but disconnects often exist between their obligation to publish studies in high-impact journals and the UFM development needs of practitioners, which typically require labor-intensive and expensive work that is not viewed as novel by many journals and research funders. As a result, there has been limited collobaration among academic reseachers and practitioners on developing UFMs for flood risk and resilience assessment that can be applicable in cities. Cities often rely on private sector consultants for both UFM development and monitoring to support UFM studies. While the private consulting works often respond to direct needs of cities in a timely manner, model advancements made during these works are usually exclusive, and not available for broader use or to researchers working on UFM improvements.

Some cities, including New York City and Copenhagen, have recently begun exploring "town-gown" partnerships involving municipal engineers, private sector consultants, and academic researchers (Matthews, 2013). While these collaborations have been valuable for studies using existing models and play an important role in the training of future professionals, they have not yet been utilized to support novel UFM development and full institutionalization of novel UFM into urban operations. We recommend building on these types of partnerships to establish dedicated UFM collaboration initiatives. Such initiatives would serve as hubs for novel UFM development and facilitate critical knowledge generation and sharing and the exchange of data, best practices, and experiences with UFM between cities and amongst stakeholders (Gan et al., 2020). Initial partnership UFM studies—even if limited by existing institutional barriers—can demonstrate the value of UFM and, ideally, the need for broader institutional support for this work.

4. Conclusions

Urban flood modeling has been recognized as a particularly challenging endeavor for nearly half a century (McPherson & Schneider, 1974). Despite substantial advances in computational hardware, environmental sensing, and information technology, UFMs remain limited in their capability to support flood resilience practice. Research to advance model development, facilitate intensive watershed monitoring for model parameterization and validation, and support collaboration between researchers and practitioners should be prioritized. These initiatives may present a substantial, expensive effort, but will still be of great value as society faces the dual challenges of rapid urbanization and climate change in coming decades.

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References

Adeogun, A. G., Daramola, M. O., & Pathirana, A. (2015). Coupled 1D-2D hydrodynamic inundation model for sewer overflow: Influence of modeling parameters. *Water Science*, *29*(2), 146–155.

Aerts, J. C., Botzen, W. J., Moel, H., & Bowman, M. (2013). Cost estimates for flood resilience and protection strategies in New York City. *Annals of the New York Academy of Sciences*, *1294*(1), 1–104.

Alda-Vidal, C., Browne, A. L., & Hoolohan, C. (2020). "Unflushables": Establishing a global agenda for action on everyday practices associated with sewer blockages, water quality, and plastic pollution. *Wiley Interdisciplinary Reviews: Water*, *7*, e1452. https://doi.org/10.1002/wat2.1452

Apel, H., Trepat, O. M., Hung, N. N., Chinh, D. T., Merz, B., & Dung, N. V. (2016). Combined fluvial and pluvial urban flood hazard analysis: Concept development and application to Can Tho city, Mekong Delta, Vietnam. *Natural Hazards and Earth System Sciences*, *16*(4), 941–961.

Armitage, N. (2007). The reduction of urban litter in the stormwater drains of South Africa. *Urban Water Journal*, *4*(3), 151–172.

Arrighi, C., & Campo, L. (2019). Effects of digital terrain model uncertainties on high-resolution urban flood damage assessment. *Journal of Flood Risk Management*, *12*(S2), e12530.

Bach, P. M., Rauch, W., Mikkelsen, P. S., Mccarthy, D. T., & Deletic, A. (2014). A critical review of integrated urban water modelling–Urban drainage and beyond. *Environmental Modelling & Software*, *54*, 88–107.

Bahadur, R., & Samuels, W. B. (2020). Role of federal funding for environmental model development. *Journal of Water Resources Planning and Management*, *146*(4), 02520001.

Belt, K. T., Stack, W. P., Pouyat, R. V., Burgess, K., Groffman, P. M., Frost, W. M., et al. (2014). Ultra-urban baseflow and stormflow concentrations and fluxes in a watershed undergoing restoration (WS263). *Proceedings of the Water Environment Federation, Stormwater*. *2012*(5), 262–276.

Blumensaat, F., Wolfram, M., & Krebs, P. (2012). Sewer model development under minimum data requirements. *Environmental Earth Sciences*, *65*(5), 1427–1437.

Bruwier, M., Maravat, C., Mustafa, A., Teller, J., Pirotton, M., Erpicum, S., et al. (2020). Influence of urban forms on surface flow in urban pluvial flooding. *Journal of Hydrology*, *582*, 124493.

Burt, T. P., & McDonnell, J. J. (2015). Whither field hydrology? The need for discovery science and outrageous hydrological hypotheses. *Water Resources Research*, *51*(8), 5919–5928.

Cahoon, L. B., & Hanke, M. H. (2017). Rainfall effects on inflow and infiltration in wastewater treatment systems in a coastal plain region. *Water Science and Technology*, *75*(8), 1909–1921. https://doi.org/10.2166/wst.2017.072

Casiano Flores, C., Crompvoets, J., Ibarraran Viniegra, M. E., & Farrelly, M. (2019). Governance Assessment of the Flood's Infrastructure Policy in San Pedro Cholula, Mexico: Potential for a Leapfrog to water sensitive. *Sustainability*, *11*(24), 7144.

Chang, T.-J., Wang, C.-H., & Chen, A. S. (2015). A novel approach to model dynamic flow interactions between storm sewer system and overland surface for different land covers in urban areas. *Journal of Hydrology*, *524*, 662–679.

Chang, T.-J., Wang, C.-H., Chen, A. S., & Djordjević, S. (2018). The effect of inclusion of inlets in dual drainage modelling. *Journal of Hydrology*, *559*, 541–555.

Chen, A. S., Djordjević, S., Leandro, J., & Savić, D. A. (2010). An analysis of the combined consequences of pluvial and fluvial flooding. *Water Science and Technology*, *62*(7), 1491–1498.

Chen, A. S., Leandro, J., & Djordjević, S. (2016). Modeling sewer discharge via displacement of manhole covers during flood events using 1D/2D SIPSON/P-DWave dual drainage simulations. *Urban Water Journal*, *13*(8), 830–840.

Chen, Y., Moufouma-Okia, W., Masson-Delmotte, V., Zhai, P., & Pirani, A. (2018). Recent progress and emerging topics on weather and climate extremes since the fifth assessment report of the intergovernmental panel on climate change. *Annual Review of Environment and Resources*, *43*, 35–59.

City of Copenhagen. (2012). *Cloudburst management plan*. Copenhagen, Denmark: Technical and Environmental Administration. Retrieved from http://en.klimatilpasning.dk/media/665626/cph_-_cloudburst_management_plan.pdf

Collier, C. G. (2007). Flash flood forecasting: What are the limits of predictability?. *Quarterly Journal of the Royal Meteorological Society: A Journal of the Atmospheric Sciences, Applied Meteorology and Physical Oceanography*, *133*(622), 3–23.

Costabile, P., Costanzo, C., De Lorenzo, G., & Macchione, F. (2020). Is local flood hazard assessment in urban areas significantly influenced by the physical complexity of the hydrodynamic inundation model? *Journal of Hydrology*, *580*, 124231.

Crichton, D. (1999). The risk triangle. *Natural Disaster Management*, *102*, 103.

Cunha, L. K., Smith, J. A., Baeck, M. L., & Krajewski, W. F. (2013). An early performance evaluation of the NEXRAD dual-polarization radar rainfall estimates for urban flood applications. *Weather and Forecasting*, *28*(6), 1478–1497.

Egger, C., Scheidegger, A., Reichert, P., & Maurer, M. (2013). Sewer deterioration modeling with condition data lacking historical records. *Water Research*, *47*(17), 6762–6779.

Gallien, T. W. (2016). Validated coastal flood modeling at Imperial Beach, California: Comparing total water level, empirical and numerical overtopping methodologies. *Coastal Engineering*, *111*, 95–104.

Gan, T., Tarboton, D. G., Horsburgh, J. S., Dash, P., Idaszak, R., & Yi, H. (2020). Collaborative sharing of multidimensional space-time data in a next generation hydrologic information system. *Environmental Modelling & Software*, *129*, 104706. https://doi.org/10.1016/j.envsoft.2020.104706

Georgas, N., & Blumberg, A. F. (2010). *Establishing confidence in marine forecast systems: The design and skill assessment of the New York Harbor Observation and Prediction System, version 3 (NYHOPS v3). In Estuarine and Coastal Modeling* (*2009*), pp. 660–685.

Grimm, N. B., Pickett, S. T., Hale, R. L., & Cadenasso, M. L. (2017). Does the ecological concept of disturbance have utility in urban social–ecological–technological systems? *Ecosystem Health and Sustainability*, *3*(1), e01255. https://doi.org/10.1002/ehs2.1255

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change*, *3*(9), 802–806. https://doi.org/10.1038/nclimate1979

Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, *12*(1), 14–29.

Hapuarachchi, H. A. P., Wang, Q. J., & Pagano, T. C. (2011). A review of advances in flash flood forecasting. *Hydrological Processes*, *25*(18), 2771–2784.

Hemmati, M., Ellingwood, B. R., & Mahmoud, H. N. (2020). The role of urban growth in resilience of communities under flood risk. *Earth's Future*, *8*(3) e2019EF001382.

Henonin, J., Russo, B., Mark, O., & Gourbesville, P. (2013). Real-time urban flood forecasting and modelling—A state of the art. *Journal of Hydroinformatics*, *15*(3), 717–736. https://doi.org/10.2166/hydro.2013.132

Hewlett, J. D., Lull, H. W., & Reinhart, K. G. (1969). In defense of experimental watersheds. *Water Resources Research*, *5*(1), 306–316.

Kauffeldt, A., Wetterhall, F., Pappenberger, F., Salamon, P., & Thielen, J. (2016). Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. *Environmental Modelling & Software*, *75*, 68–76.

Kaushal, S. S., & Belt, K. T. (2012). The urban watershed continuum: Evolving spatial and temporal dimensions. *Urban Ecosystems*, *15*(2), 409–435.

Kaykhosravi, S., Khan, U. T., & Jadidi, A. (2018). A comprehensive review of low impact development models for research, conceptual, preliminary and detailed design applications. *Water*, *10*(11), 1541.

Knowles, S. G., & Kunreuther, H. C. (2014). Troubled waters: The national flood insurance program in historical perspective. *Journal of Policy History*, *26*(3), 327–353.

Kundzewicz, Z. W., Lugeri, N., Dankers, R., Hirabayashi, Y., Döll, P., Pińskwar, I., et al. (2010). Assessing river flood risk and adaptation in Europe—Review of projections for the future. *Mitigation and Adaptation Strategies for Global Change*, *15*(7), 641–656.

Leandro, J., & Martins, R. (2016). A methodology for linking 2D overland flow models with the sewer network model SWMM 5.1 based on dynamic link libraries. *Water Science and Technology*, *73*(12), 3017–3026.

Leitao, J., Simoes, N., Pina, R. D., Ochoa-Rodriguez, S., Onof, C., & Sa Marques, A. (2015). Stochastic evaluation of sewer inlet capacity on urban pluvial flooding. In *10th International Urban Drainage Modelling Conference* (pp. 33–36). Mont-Sainte-Anne, Québec, Canada. https://spiral.imperial.ac.uk/bitstream/10044/1/29072/2/Leitao%20et%20al%20%202015%20-%20UDM.pdf

Lerer, S. M., Righetti, F., Rozario, T., & Mikkelsen, P. S. (2017). Integrated hydrological model-based assessment of stormwater management scenarios in Copenhagen's first climate resilient neighbourhood using the three point Approach. *Water*, *9*(11), 883. https://doi.org/10.3390/w9110883

Macdonald, D., Dixon, A., Newell, A., & Hallaways, A. (2012). Groundwater flooding within an urbanised flood plain. *Journal of Flood Risk Management*, *5*(1), 68–80.

Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., et al. (2018). Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. *Earth's Future*, *6*(12), 1638–1659. https://doi.org/10.1029/2018EF000926

Martins, R., Leandro, J., & Djordjević, S. (2018). Influence of sewer network models on urban flood damage assessment based on coupled 1D/2D models. *Journal of Flood Risk Management*, *11*, S717–S728.

Massoudieh, A., Maghrebi, M., Kamrani, B., Nietch, C., Tryby, M., Aflaki, S., & Panguluri, S. (2017). A flexible modeling framework for hydraulic and water quality performance assessment of stormwater green infrastructure. *Environmental Modelling & Software*, *92*, 57–73.

Matthews, T. (2013). Case study: New York City's Town+Gown Program. In C. A. Baker & P. E. Salkin (Eds.), *Town and Gown* (pp. 311–329). American Bar Association. Retrieved from https://www1.nyc.gov/assets/ddc/downloads/town-and-gown/articles/case-study-tg-program.pdf

McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., et al. (2016). Advancing urban ecology toward a science of cities. *BioScience*, *66*(3), 198–212. https://doi.org/10.1093/biosci/biw002

McPherson, M. B., & Schneider, W. J. (1974). Problems in modeling urban watersheds. *Water Resources Research*, *10*(3), 434–440.

Mignot, E., Li, X., & Dewals, B. (2019). Experimental modelling of urban flooding: A review. *Journal of Hydrology*, *568*, 334–342.

Moftakhari, H. R., Salvadori, G., AghaKouchak, A., Sanders, B. F., & Matthew, R. A. (2017). Compounding effects of sea level rise and fluvial flooding. *Proceedings of the National Academy of Sciences*, *114*(37), 9785–9790.

Morin, E., Jacoby, Y., Navon, S., & Bet-Halachmi, E. (2009). Towards flash-flood prediction in the dry Dead Sea region utilizing radar rainfall information. *Advances in Water Resources*, *32*(7), 1066–1076.

Munich, R. E. (2018). *NatCatSERVICE*. Retrieved from https://natcatservice.munichre.com/

Niazi, M., Nietch, C., Maghrebi, M., Jackson, N., Bennett, B. R., Tryby, M., & Massoudieh, A. (2017). Storm water management model: Performance review and gap analysis. *Journal of Sustainable Water in the Built Environment*, *3*(2), 04017002.

NYCDEP/Ramboll. (2017). *Cloudburst Resiliency Planning Study—Executive Summary*. New York City, NY: New York City Deparment of Environmental Protection. Retrieved from http://www.nyc.gov/html/dep/pdf/climate/nyc-cloudburst-study.pdf

Paul, J. D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J. A., Bhusal, J., Cieslik, K., et al. (2018). Citizen science for hydrological risk reduction and resilience building. *Wiley Interdisciplinary Reviews: Water*, *5*(1). https://doi.org/10.1002/wat2.1262

Peduzzi, P. (2017). Flooding: Prioritizing protection? *Nature Climate Change*, *7*(9), 625–626.

Re, M., Kazimierski, L. D., & Badano, N. D. (2019). High-resolution urban flood model for risk mitigation validated with records collected by the affected community. *Journal of Flood Risk Management*, *12*(S2), e12524.

Rentschler, J., Jones, N., Avner, P., & Braese, J. (2019). Three feet under: The impact of floods on urban jobs, connectivity, and infrastructure. In *Lifelines: The Resilient Infrastructure Opportunities* (Policy Research Working Paper No. 8898), Washington, DC: World Bank Group. Climate Change Group. Global Facility for Disaster Reduction and Recovery. Retrieved from http://repo.floodalliance.net/jspui/handle/44111/3156

Rosenzweig, B. R., McPhillips, L., Chang, H., Cheng, C., Welty, C., Matsler, M., et al. (2018). Pluvial flood risk and opportunities for resilience. *Wiley Interdisciplinary Reviews: Water*, *5*(6), e1302. https://doi.org/10.1002/wat2.1302

Rosenzweig, B. R., Ruddell, B. L., McPhillips, L., Hobbins, R., McPhearson, T., Cheng, Z., et al. (2019). Developing knowledge systems for urban resilience to cloudburst rain events. *Environmental Science & Policy*, *99*(150–159).

Saksena, S., Dey, S., Merwade, V., & Singhofen, P. J. (2020). A computationally efficient and physically based approach for urban flood modeling using a flexible spatiotemporal structure. *Water Resources Research*, *56*(1), e2019WR025769.

Salvadore, E., Bronders, J., & Batelaan, O. (2015). Hydrological modelling of urbanized catchments: A review and future directions. *Journal of Hydrology*, *529*(Part 1), 62–81. https://doi.org/10.1016/j.jhydrol.2015.06.028

Seo, B.-C., Keem, M., Hammond, R., Demir, I., & Krajewski, W. F. (2019). A pilot infrastructure for searching rainfall metadata and generating rainfall product using the big data of NEXRAD. *Environmental Modelling & Software*, *117*, 69–75.

Skofronick-Jackson, G., Petersen, W. A., Berg, W., Kidd, C., Stocker, E. F., Kirschbaum, D. B., et al. (2017). The Global Precipitation Measurement (GPM) mission for science and society. *Bulletin of the American Meteorological Society*, *98*(8), 1679–1695.

Smith, B. K., Smith, J. A., Baeck, M. L., Villarini, G., & Wright, D. B. (2013). Spectrum of storm event hydrologic response in urban watersheds. *Water Resources Research*, *49*(5), 2649–2663.

Sukop, M. C., Rogers, M., Guannel, G., Infanti, J. M., & Hagemann, K. (2018). High temporal resolution modeling of the impact of rain, tides, and sea level rise on water table flooding in the Arch Creek basin, Miami-Dade County Florida USA. *Science of the Total Environment*, *616*, 1668–1688.

Tanim, A. H., & Goharian, E. (2020). Hybrid modeling framework for simulating compound floods in a coastal city. In *World Environmental and Water Resources Congress 2020: Groundwater, Sustainability, Hydro-Climate/Climate Change, and Environmental Engineering*, (pp. 218–228). Reston, VA: American Society of Civil Engineers.

Teng, J., Jakemanb, A. J., Vazea, J., Crokeb, B. F. W., Duttaa, D., & Kima, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*. *90*(217), 201–216. https://doi.org/10.1016/j.envsoft.2017.01.006

Tetzlaff, D., Carey, S. K., McNamara, J. P., Laudon, H., & Soulsby, C. (2017). The essential value of long-term experimental data for hydrology and water management. *Water Resources Research*, *53*(4), 2598–2604.

Thorndahl, S., Balling, J. D., & Larsen, U. B. B. (2016). Analysis and integrated modelling of groundwater infiltration to sewer networks. *Hydrological Processes*, *30*(18), 3228–3238.

Tsakiris, G. (2014). Flood risk assessment: Concepts, modelling, applications. *Natural Hazards and Earth System Sciences*, *14*(5), 1361.

Tscheikner-Gratl, F., Caradot, N., Cherqui, F., Leitão, J. P., Ahmadi, M., Langeveld, J. G., et al. (2019). Sewer asset management–state of the art and research needs. *Urban Water Journal*, *16*(9), 662–675.

Vojinovic, Z., & Tutulic, D. (2009). On the use of 1D and coupled 1D-2D modelling approaches for assessment of flood damage in urban areas. *Urban Water Journal*, *6*(3), 183–199.

WEF. (2020). *Stormwater, watershed, and receiving water quality modeling*. Alexandria, VA: Water Environment Federation. Retrieved from https://www.wef.org/resources/publications/books/stormwater-modeling/

Winsemius, H. C., Aerts, J. C., van Beek, L. P., Bierkens, M. F., Bouwman, A., & Jongman, B., et al. (2015). Global drivers of future river flood risk. *Nature Climate Change*. Retrieved from https://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2893.html

Yu, D., Yin, J., & Liu, M. (2016). Validating city-scale surface water flood modelling using crowd-sourced data. *Environmental Research Letters*, *11*(12), 124011.

Zanchetta, A. D., & Coulibaly, P. (2020). Recent advances in real-time pluvial flash flood forecasting. *Water*, *12*(2), 570.

Zhang, K., & Chui, T. F. M. (2018). A comprehensive review of spatial allocation of LID-BMP-GI practices: Strategies and optimization tools. *The Science of the Total Environment*, *621*, 915–929.

Zischg, A. P., Mosimann, M., Bernet, D. B., & Röthlisberger, V. (2018). Validation of 2D flood models with insurance claims. *Journal of Hydrology*, *557*, 350–361.

Zscheischler, J., Westra, S., Van Den Hurk, B. J., Seneviratne, S. I., Ward, P. J., Pitman, A., et al. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477.