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Developing knowledge systems for urban resilience to cloudburst rain events

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ABSTRACT

Cities are particularly vulnerable to cloudbursts - short-duration, intense rainfall events – which are often inadequately addressed through conventional stormwater and flood management policy. Climate change is projected to increase the frequency and intensity of cloudbursts in many cities. As minor cloudburst events become more frequent and extreme events more severe, cities will need to rapidly transform their stormwater drainage and interdependent systems, and the knowledge systems that guide their infrastructure decisions and policy. In this paper, we discuss the evolution of knowledge systems to address these challenges, using three diverse cities (Phoenix, USA; Copenhagen, Denmark; and New York City, USA) as case studies. We found that partnerships between cities – even across national boundaries – can be a particularly important component of cloudburst knowledge systems. We also identified limitations in knowledge systems related to non-stationary climate, the vulnerability of private property and the representation of cloudburst infrastructure in integrated water management, which present opportunities for future research to support decision-making.

1. Introduction

The management of urban stormwater has evolved over millennia, transitioning from the conveyance of water through ditches, to the construction of underground sewer systems, to the recent adoption of stormwater 'best management practices' to regulate runoff and protect water quality (Burian and Edwards, 2002; Delleur, 2003). Contemporary cities rely on a complex mix of stormwater management approaches, integrating 'green' infrastructure to facilitate water retention with legacy 'gray' infrastructure, such as sewer systems that rapidly convey stormwater (Fletcher et al., 2015). However, while urban stormwater management has become increasingly sophisticated over the past century, most cities remain vulnerable to *cloudbursts*; short-duration, intense rainfall events that can cause flash flooding and the disruption of critical city systems.

The term 'cloudburst' has a long history in the meteorological literature (Harris and Lanfranco, 2017) and was formally defined by Woolley et al., 1946 as *"…a torrential downpour of rain which by its spottiness and relatively high intensity suggests the bursting and discharge of a whole cloud at once."* Although the term 'cloudburst' is increasingly used by the urban resilience community (Weisz, 2018), there is no consistent intensity threshold used to delineate cloudburst events. Alternative terms for intense, short-duration rain events such as 'downpour', 'water bomb', and 'torrential rain' are also commonly utilized (Harris and Lanfranco, 2017). Cloudbursts are already a chronic problem in many cities (Rosenzweig et al., 2018), and with projected increases in cloudburst frequency and magnitude with climate change (Donat et al., 2017; Fischer and Knutti, 2016; Loriaux et al., 2016), there is an urgent need for cities to adapt their policies and operations to enhance their resilience to these events (Fig.1).

There are also many definitions of resilience used in the literature and in practice. For this paper, we will use the definition provided for urban systems by Meerow et al., 2016:

"The ability of an urban system-and all its constituent socio-

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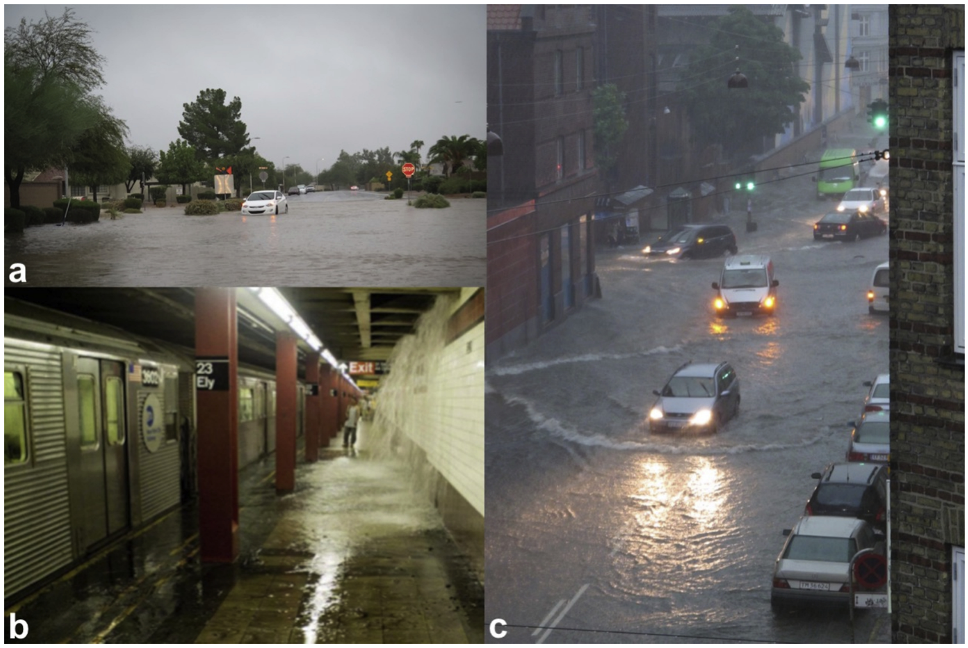

Fig. 1. a) Stormwater runoff begins to overtop the street curb during the 2014 monsoon in Phoenix (Devon Christopher Adams), b) Onset of flooding of a subterranean transit station in NYC during the 8 August 2007 cloudburst (Chris Johanssen), c) Street flooding during the 2011 Copenhagen cloudburst (Lisa Risager).

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."

A city that is resilient to cloudbursts would experience minimal disruptions when they occur and would be able to rapidly recover from any impacts they experience. They would also have systems in place to learn from their experiences with cloudbursts and to implement strategies to mitigate the potential impacts of future events. For most cities, this will require the development of new or modified *knowledge systems* – the institutionalized practices that generate, evaluate, utilize, and disseminate knowledge for decision making (Muñoz-Erickson et al., 2017). Practitioners at various levels of government and the private sector, along with stakeholders that live, visit or own property in cloudburst-impacted communities may all play a role in cloudburst knowledge systems.

While the form and character of knowledge systems may vary between cities, it is essential that they support three basic categories of knowledge to support cloudburst resilience:

1 **Knowledge of the contemporary weather and future climate conditions that determine cloudburst hazard:** From a management perspective, the cloudburst problem itself remains poorly defined (Engberg, 2018). The definitions of which events are cloudbursts are inconsistent and national-scale definitions may not represent local conditions (Harris and Lanfranco, 2017; Madsen et al., 2009). This issue is complicated by the relatively short temporal and small spatial scales over which cloudbursts occur, which makes them difficult to monitor (Barbero et al., 2017). Although there is increasing evidence that climate change will increase the frequency and intensity of cloudbursts, quantitative projections of these increases also remain unclear over decadal time scales (Westra et al., 2014).

2 **Knowledge of the vulnerability of urban social, ecological and infrastructure systems:** The particular vulnerability of cities to cloudbursts - relative to longer-duration heavy rain events - results both from their distinct hydrology and conventional patterns of urban development, which is associated with high impervious cover and major changes to surface water flowpaths (Kaushal and Belt, 2012). These features increase the sensitivity of urban areas to extreme rainfall rates and can result in amplified flash flooding in the absence of targeted mitigation efforts (Smith et al., 2005; Zellner et al., 2016). Nearly all contemporary cities rely on subterranean sewer systems to drain their dense core neighborhoods and prevent flooding. When operating as intended, storm sewers convey rates of stormwater associated with their design storm, usually moderately intense, i.e., 2-10-year return interval (Guo, 2006). However, when this rate threshold is exceeded, pluvial (overland) flooding can occur (Rosenzweig et al., 2018).

The dense development of cities also leads to high exposure of people and assets to flooding, even when it occurs over small areas. In many cities, these impacts remain poorly quantified since they can be transient (such as flash flooding and disruptions in transportation systems) and are often not represented using standard flood monitoring approaches and metrics of damages (Van Ootegem et al., 2015). For example, transportation disruptions can have substantial socio-economic impacts, even without permanent damage to property (Chang et al., 2010; Hammond et al., 2015; Kim et al., 2017). Also, in many cities, residences and critical infrastructure are located underground and can be inundated during cloudbursts even when surface flooding is limited. These more complex, transient impacts are frequently limited in their coverage by insurance and representation in conventional flood vulnerability assessment (Dixon et al., 2006; Hollenbeck, 2017).

3 **Knowledge of potential strategies for cloudburst management:** Even without climate change, the upgrade of conventional subterranean sewer systems to manage cloudburst rain events is usually financially infeasible (Lerer et al., 2017). Green infrastructure (GI), which is designed to 'infiltrate, evapotranspirate or reuse stormwater, with significant utilization of soils and vegetation rather than traditional hardscape collection, conveyance and storage structures' (USEPA, 2007), has the potential to play an important role in cloudburst management but, in practice, the flood mitigation effectiveness of existing green infrastructure is often rate-limited (Jia et al., 2017). GI that facilitates the subsurface infiltration of stormwater is limited by the maximum infiltration rates of their underlying sediments, which can be lower than the rainfall rates

associated with intense cloudbursts (Alizadehtazi et al., 2016; Zellner et al., 2016). Urban detention-based GI is typically designed for water quality improvement and the management of more frequent but less intense rainfall events and are thus unable to store the relatively large volumes of stormwater runoff generated by cloudbursts (Lerer et al., 2017). The implementation of both green and gray infrastructure for cloudburst management will require a transition from standard urban stormwater management to the use of novel technologies and strategies specifically designed to function during high-intensity events.

In this paper, we evaluate the evolution of knowledge systems to guide urban water management policies for cloudburst resilience in three cities (Phoenix, USA; Copenhagen, Denmark; and New York City, USA). These cities vary in climate, governance structure, and the maturity of their planning for cloudburst resilience, which will allow us to address the following research questions:

1 How important is experience with a locally occurring cloudburst event in the development of knowledge systems for cloudburst resilience?
2 How important are multilevel knowledge systems that extend from local communities across jurisdictions and levels of governance, considering the localized spatial extent of cloudburst events?
3 Are there identifiable limitations in the knowledge systems being utilized by cities that have begun cloudburst resilience planning?

2. Case study research methods

We first conducted a review of peer-reviewed journal articles related to urban cloudburst resilience in cities. Next, we selected three cities based on their initiation of cloudburst planning, diversity (in governance structure, climate, and the maturity of their plans), and accessibility of information (Fig.2). Two of the cities (NYC and Phoenix) are part of the Urban Resilience to Extremes Sustainability Research Network (UREXSRN.net), a partnership between researchers and practitioners in cities of the Americas.

For each city, we reviewed relevant academic literature and municipal reports and plans. In many cases, understanding the knowledge systems used to support these plans required us to directly engage practitioners actively involved in planning efforts, through in person meetings, phone calls, and email correspondence. These direct interactions are cited as personal communications throughout the text. Finally, the information obtained through our case study research was synthesized to support our discussion and conclusions. The sources of information used to support each case study are summarized in Supplemental Table 1.

3. Case studies

3.1. Phoenix, Arizona, united States of America

Phoenix is the capital city of the southwestern United States (U.S.) State of Arizona. The city is located in the Salt River Valley at the edge of the Sonoran Desert (Köppen: BWh). Phoenix' average annual rainfall of 204 mm is split between winter storms that bring long-duration rainfall and summer monsoon thunderstorms associated with intense, short-duration rainfall (FCDMC, 2017). With the high potential for runoff generation from the city's hydrophobic desert soils, flash flooding is a significant hazard, especially during the monsoon (McCollum et al., 1995).

Phoenix experienced rapid development during the second half of the 20th Century, with its population growing from 100,000 to 1.5 million people, accompanied by sprawling, low-density urban

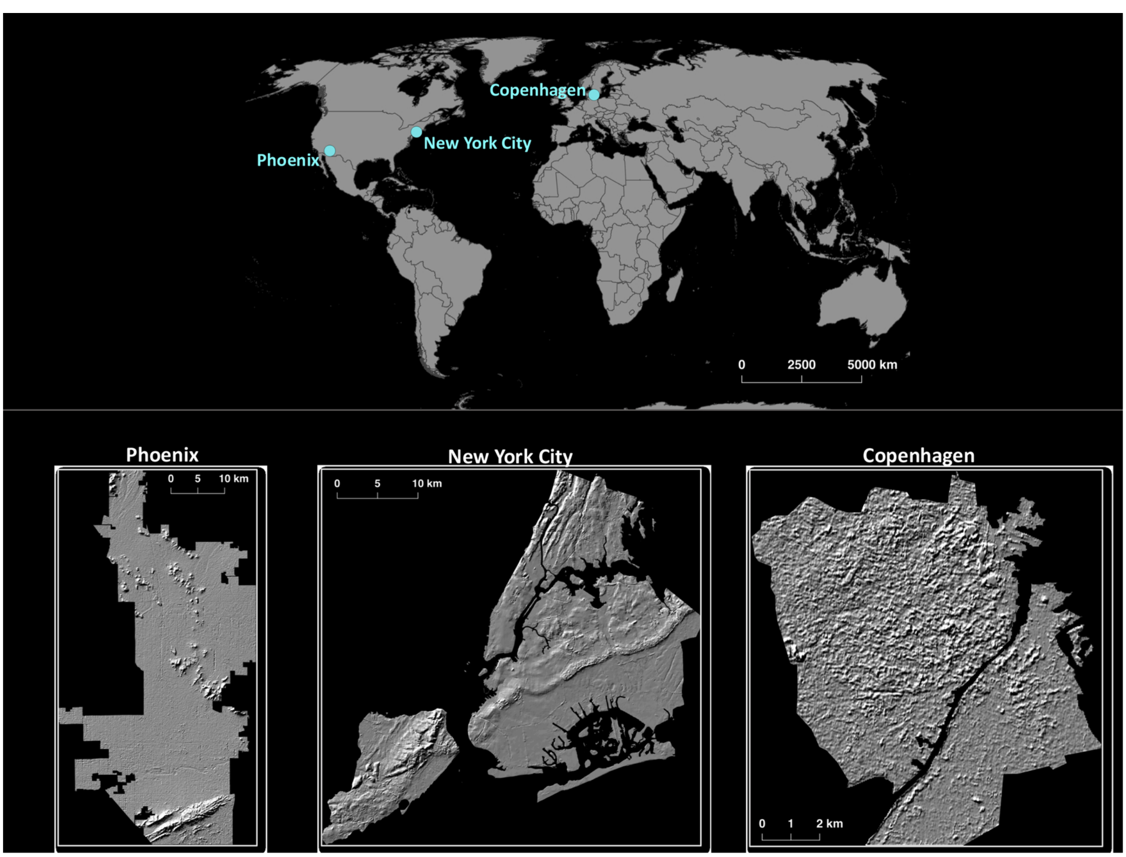

Fig. 2. Case study city locations and topographies. Note that the comparative topographic maps use different scales.
(Data: Copenhagen/Phoenix: NASA ASTGTM2 DEM, New York City: US National Elevation Dataset).

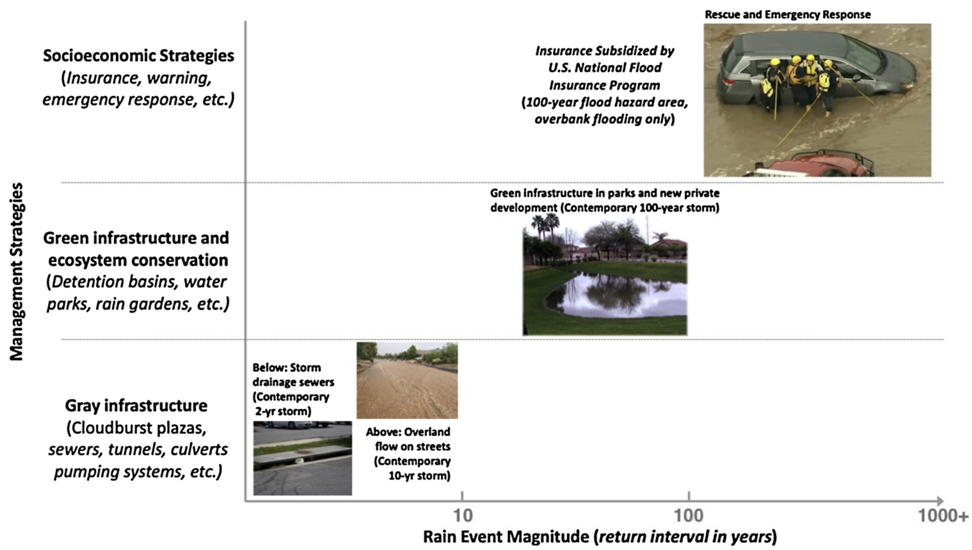

Fig. 3. Management strategies for different magnitudes of rain events in Phoenix.

development. Prior to this, natural drainage to the Salt River was dominated by desert washes (arroyos) that are dry for most of the year but facilitate overland flow during intense rainfalls. As the city urbanized, these washes were largely channelized or culverted to facilitate rapid drainage to the Salt River and a separated storm sewer system was constructed (Hale, 2016). Despite its relatively recent development, the storm sewer system in Phoenix was designed to convey only the runoff associated with the 2-year, 6 -h rainstorm (City of Phoenix, 2013).

The City of Phoenix does not have a dedicated plan for short-duration intense rainfall and does not use the term 'cloudburst' in its planning. Instead, planning for the management of these events is integrated into regional flood management planning and has evolved over the past five decades (Fig. 3). Flood management is administered by the Flood Control District of Maricopa County (FCDMC), a regional agency established in 1959. Although there is over a century-long record of floods causing substantial damage in the region, a flood on June 22, 1972 particularly catalyzed rethinking of regional stormwater management (FCDMC, Personal Communication, 7/18/2018). During this event, a thunderstorm generated up to 133 mm of precipitation in two hours, with the most severe impacts in the northeastern communities of the City of Phoenix (Hansen, 1975). The resulting flooding caused approximately $61 million in damages, accounting for inflation (Palmer, 2015).

Prior to the 1972 flooding event, stormwater management practices emphasized standard engineered channels and sewers for the conveyance of runoff (Hale, 2016). In the year following the 1972 flood, the City of Phoenix adopted a grading and draining ordinance that required onsite retention of stormwater from the 10-year return period event for new subdivisions (City of Phoenix, 2018). The city also released updated street design guidelines, which included the use of 'inverted crown' street profiles in flood-prone areas of the city (City of Phoenix, 1973). These street profiles are lowest at the centerline and elevated at the curbs to facilitate the overland conveyance of stormwater once subterranean sewers are at capacity.

Major flooding events occurring between 1978 and 1980 further motivated regional stormwater management policy. In 1987, FCDMC officially implemented its countywide 'Uniform Drainage Standards', which required on-site retention of the 2 h, 100-year storm event for most new development across the region (FCDMC, 1987; McPhillips and Matsler, 2018). In 1988, the City of Phoenix implemented this standard through the release of a Storm Drain Design Manual (SDDM) for engineers and architects (City of Phoenix, 1988). The SDDM also updated standards for stormwater conveyance over streets. Inverted crown streets were found to prohibitively increase maintenance costs and discontinued for public streets, although their use remains permitted on private roads within subdivisions. However, overland conveyance of excess stormwater over roads with standard grading remains an important component of Phoenix' stormwater management. Current standards require roads to convey runoff associated with the 10-year storm without overtopping of the street curb (15.2 cm) and prescribe street drainage discharge and velocity limits during the 100-year storm. Thus, roadways serve as a planned backup for conventional storm sewers, conveying runoff from moderate to extreme (> 2-100-year return interval) rainstorms to retention basins and washes, albeit at the cost of temporary roadway disruptions (FCDMC, Personal Communication, 9/13/2018). There is little underground development or transit in Phoenix, relatively few basements, and all new buildings' first floors are required to be graded above the street curb elevation. However, when cloudburst rainfall rates exceed the design standards for road conveyance, pluvial flooding still occurs. This type of flooding is not covered by the U.S. National Flood Insurance Program (NFIP, Burby, 2001).

To support emergency response when floods occur, the Central Arizona Water Conservation District, the regional water utility, provides specialized swift water rescue training for the City of Phoenix Fire and Police Departments (Vo, 2016). This training includes a variety of techniques for rescuing people stranded in floodwaters, including air and boat rescues. The FCDMC has also carried out periodic drainage master studies for subcatchments in Phoenix, which include detailed reassessment of flooding vulnerability and solicitation of input from community members on potential structural interventions (FCDMC, 2015). Community members also generate knowledge on flood vulnerability through the FCDCMC 'Report a Flood' program, an online service to report observations of flood impacts. Insight from the drainage master planning process and this reporting tool support ongoing identification of flood-vulnerable neighborhoods and potential management options.

3.2. Copenhagen, Denmark, European Union

Copenhagen, Denmark, is located along the Øresund Strait between the Baltic and North Seas. Copenhagen has a moderate, maritime climate (Köppen: Cfb), with rain distributed equally throughout the year. The city's topography has been substantially altered and most of its predevelopment streams were filled. It now relies on a combined sewer system constructed in the mid-19th Century for storm and wastewater management (City of Copenhagen, 2011).

Climate change mitigation and adaptation are priority issues for

Copenhagen. It is currently a steering committee member of the C40 Cities Climate Leadership Group, a network of cities developing strategies to reduce greenhouse gas emissions and climate risks. In August 2009, the city council unanimously approved the city's initial Climate Plan, which includes the ambitious goal of full carbon neutrality by 2025 and identified 'heavy downpours' as a primary climate hazard (Copenhagen City Council, 2009). In 2011 the City of Copenhagen released a complementary Climate Adaptation Plan (CCAP; City of Copenhagen, 2011), which assessed and proposed strategies for the management of cloudbursts and other extreme weather hazards. The CCAP relied on two sources of information on the intensity of extreme rain in the future: The first was a generalized 20–55% increase in the intensity of heavy downpours provided by the Danish Meteorological Institute (DMI), based on a scenario of ˜3 °C global temperature rise by 2099. The second source of information was more detailed projections of future rainfall intensity provided by the Danish Society of Engineers (WPC, 2008), using techniques developed by researchers at the Technical University of Denmark (Arnbjerg-Nielsen, 2008).

Using these more detailed projections, the Copenhagen Metropolitan Area utility (HOFOR) conducted an initial risk assessment that found that cloudbursts would present a high risk for the city's infrastructure through the 21st Century. The CCAP recommended a strategy that included the future separation of the sewer system, the use of GI to reduce the amount of stormwater entering the sewer system by 30%, installation of backwater valves in private residences, and the conveyance of excess stormwater overland to parks and other greenspaces, which was found to provide the most societal benefits at efficient cost. The CCAP prioritized knowledge sharing at multiple levels of governance – from municipal to international. It also focused on cooperation with the general public, who would be the users of GI during dry conditions and whose local knowledge was recognized as essential for successful planning.

On 2 July 2011, a few weeks before the planned adoption of the CCAP, the City of Copenhagen experienced the most intense rainfall in its observational record (1933–2016; Ziersen et al., 2017), with over 50 mm of rain falling in 30 min in some parts of the City. These intensities exceed those associated with a 2000-year return period for Copenhagen (Arnbjerg-Nielsen et al., 2015). This cloudburst caused severe flooding of roadways, basements and ground-level properties, resulting in total insurance claims that exceeded 800 million Euros (1.2 Billion U.S. Dollars; Lerer et al., 2017). Through this experience, it became clear that initial plans for intense rainfall management provided in the CCAP were inadequate (City of Copenhagen, 2012). For example, the parks and greenspaces that had been designated for stormwater infiltration and detention would hold only a small fraction of the runoff generated by the July 2011 storm. In response, a dedicated Cloudburst Management Plan (CCMP) for the City of Copenhagen and the Municipality of Frederiksberg was developed and released in 2012.

The CCMP went beyond the CCAP to identify a specific acceptable risk threshold for flooding frequency and depth. An acceptable roadway inundation level of 10 cm was identified based on an assessment by the municipal government, which determined that this water level would not allow for infiltration through most windows and would allow for some roadway transportation to be maintained. Using this inundation threshold, a cost-benefit analysis was performed for various scenarios and a return interval corresponding to the projected 100-year event was found to provide the most benefit relative to societal costs. The assessment used for this risk-dimensioning did not include the potential costs and benefits of infiltration-based GI or of private, property-scale flood defenses (City of Copenhagen, 2012).

In the CCMP, the 10-year return interval design standard for subterranean sewers remained unchanged. As an alternative, it prescribes the use of a combination of measures to mitigate pluvial flooding when the drainage capacity of subterranean sewers is exceeded. These include the direct conveyance of stormwater over roadways ('cloudburst boulevards') to the sea and detention of stormwater in paved spaces such as parking lots, integrated with new high-capacity subterranean drainage tunnels in the densely developed city core (Ziersen et al., 2017). Although GI was found to be inadequate to prevent pluvial flooding on its own and was not included in CCMP risk dimensioning calculations, the plan includes the full integration of cloudburst management projects with existing plans for GI. The CCMP does not include a specific deadline and instead suggests a *minimum* 20-year timeline for completion.

The CCMP also relies on an enhanced emergency response plan to mitigate the impacts of cloudburst events that occur in the decades before needed structural projects are completed or exceed the threshold 100-year cloudburst design storm. The emergency response plan consolidates municipal response units and increases collaboration with units from neighboring municipalities. Critical facilities such as hospitals at risk from pluvial flooding were identified and additional equipment was obtained to support floodwater pumping in response to an event.

The CCMP relies heavily on numerical hydraulic and hydrologic modeling conducted in-house by HOFOR, the municipal utility. In addition to conducting the risk dimensioning and cost-benefit analysis for the initial 2012 CCMP, HOFOR collaborated with private companies and university researchers to developed a portfolio of 350 specific cloudburst projects to be implemented throughout the city by 2035. HOFOR also evaluates all local development plans that involve changing land cover to ensure that their impacts on catchment-scale hydrology are considered (Ziersen et al., 2017).

Although the technically complex numerical modeling conducted by HOFOR is the primary knowledge source for developing cloudburst resilience strategies, HOFOR engages the general public in the aesthetic design and planning for recreation function of local strategies developed on public property. The public provides local knowledge on community needs and preferred amenities for projects on public space or social housing projects, and can also apply for funding to support cloudburst management projects on their properties. These public engagement efforts also allow HOFOR to share knowledge on the risks presented by cloudbursts and opportunities to apply for funding and support for projects on their property (Engberg, 2018).

The insurance industry has also played an important, dual role in the exchange of cloudburst knowledge. In 2013, the Danish Insurance Association entered a partnership agreement with the Danish Ministry of the Environment to provide insurance claim data free of charge to validate hydrologic modeling and support cloudburst resilience planning (Weiss Garne, 2013). This type of validation is a key function of knowledge systems (Miller and Munoz-Erickson, 2018). The Danish Insurance Association also entered a formal partnership with HOFOR and local landowners associations to disseminate information on flood mitigation responsibilities and opportunities on private property (Chng Wei Ping, 2016).

The flood vulnerable community of Skt. Kjelds was chosen as a demonstration neighborhood for the initial implementation of CCMP projects, including a mix of 'gray' and 'green' infrastructure projects, along with new regulation that required the installation of sewer backflow preventers on private property (City of Copenhagen/HOFOR, 2018). The design of these projects relied on the collaboration and shared knowledge of HOFOR, landscape architecture firms and residents. Construction of these projects began in 2013 and their efficacy is actively being assessed by the city utility and academic researchers (Fig. 4; Lerer et al., 2017).

Building on the existing C40 network, the City of Copenhagen proposed a partnership with NYC to exchange knowledge and export their emerging cloudburst resilience strategies. This partnership was formalized with a Memorandum of Cooperation in September 2015 (NYCDEP, *Personal Communication, 6/6/2018*). The lessons learned through evaluation of the Skt. Kjelds demonstration project, along with future pilot projects in New York and other C40 cities, will be utilized by city practitioners to inform the design and broad implementation of

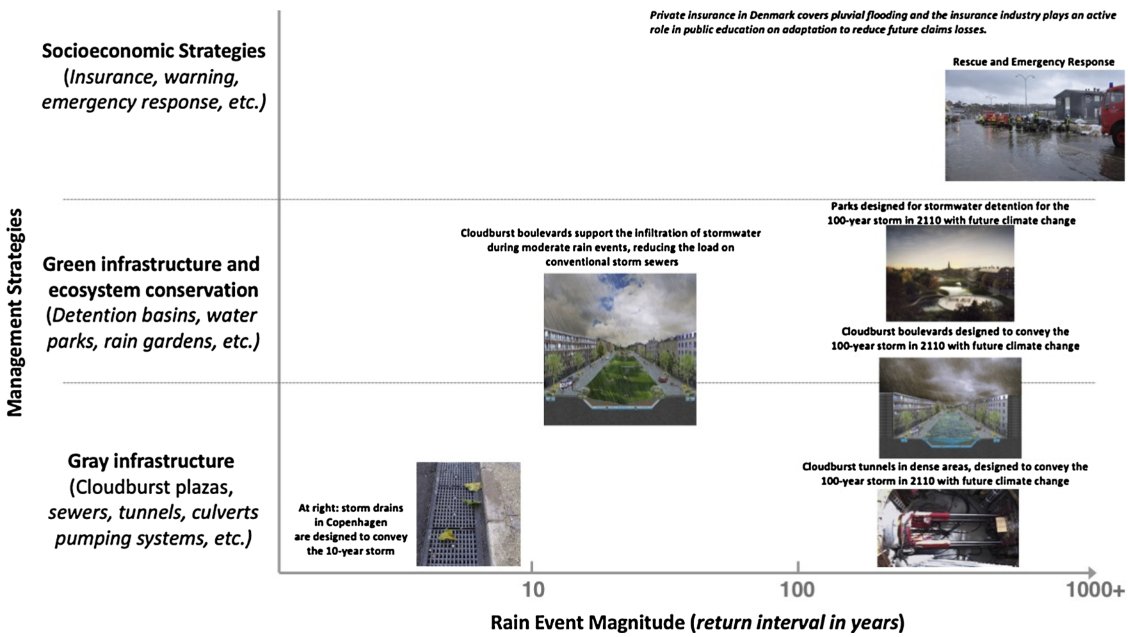

Fig. 4. Stormwater management strategies in Copenhagen for rain events of different magnitudes.

CCMP projects throughout Copenhagen.

3.3. New York City, New York, United States of America

New York City (NYC) is located at the mouth of the Hudson River Estuary, and has a humid, subtropical climate (Köppen: Cfa), with precipitation (annual average 1269 mm) distributed fairly evenly throughout the year. Although the city was historically drained by numerous tidal creeks, nearly all of these natural waterways were landfilled during the 20th Century and the city relies on a sewer system that includes combined and separate system areas (Walsh and LaFleur, 1995). Most of NYC's sewer system was constructed before 1960 and designed to convey runoff associated with rainfall rates of 38.1 mm/hr, which has a return interval of < 5 years (NYC, 2009).

As a coastal city, NYC is highly vulnerable to tidal flooding, but also experiences frequent pluvial flooding in response to intense rain events (NYC, 2009; Rosenzweig et al., 2018). In the late 20th Century, after most of the city's sewer system had already been constructed, the yards of many of the city's residential homes were paved over to provide space for parking and development. This increased impervious area resulted in the enhanced generation and overland transport of stormwater runoff. To meet demands for space, basements and underground tunnels are commonly used for both residential and commercial purposes, which are vulnerable to inundation by overland runoff. The city is also heavily reliant on its mass transit system, which includes an extensive network of flood-vulnerable subgrade subway lines. Although pluvial flooding is a frequent hazard in the city, this flooding mechanism is excluded by the U.S. National Flood Insurance Program and rain-driven flooding in NYC frequently occurs outside the Special Flood Hazard Areas covered by insurance requirements and subsidies (Burby, 2001; NYC, 2009).

On 8 August 2007, NYC experienced a widespread severe thunderstorm event, with observed rainfall ranging from 36 to 107 mm of rain in 2 h (MTA, 2007). This event did not meet the definition of a cloudburst provided by the American Meteorological Society (100 mm hr^{-1}; AMS, 2015) but was, nonetheless, an extremely intense rainfall event for NYC. For perspective, a storm generating 91 mm of rainfall in 2 h would have a 100-year return interval in NYC; (NOAA, 2015). Pluvial flooding from this event resulted in the complete shutdown of the city subway system on a weekday morning, stranding hundreds of thousands of commuters. This was exacerbated by flooding of many roads, which disrupted vehicle traffic and required the rescue of stranded motorists. A combination of pluvial flooding and sewer system backup also resulted in the flooding of residences and basements throughout the city.

The 2007 cloudburst spurred transitions in local transit and emergency response and planning. The New York State governor requested the formation of a task force to investigate the vulnerability of the city transit system to extreme rain. This task force, which included city agency representatives and local university researchers, provided recommendations for transit adaptation measures that included a general assessment of future climate change impacts. At the time of this assessment (2007–2008), robust techniques to project future sub-daily precipitation with climate change had not been developed and the recommendations of the report were based on projections of future annual precipitation.

In response to the 2007 cloudburst, the city Mayor's Office of Operations also convened a Flood Mitigation Task Force, comprised of several city agencies (NYC, 2009). This task force established a threshold rainfall rate of 25.4 mm/hr that, when forecasted by the National Weather Service, would trigger emergency preparations such as cleaning catch basins in recurring flood locations, monitoring flood-prone areas, preparing first-responders and establishing assistance centers (Loeser and Gallagher, 2008). The Task Force also developed an initial guide for residents with information on how to prepare for local flash floods (NYCOEM and NYCDEP, 2008). In 2011, the flash flood emergency protocols established by the Flood Mitigation Task Force were incorporated into local law, which also required annual reporting on the response to flash flood and other weather emergencies, to support ongoing adaptation and improvement to emergency response protocols and planning (NYCOEM, 2017).

However, beyond the transit system and emergency response, the city's experience in 2007 did not result in the development of new strategies for integrated cloudburst management. Although the city began transformative implementation of GI between 2007 and 2011, this infrastructure was designed primarily to meet regulated water quality objectives and provides limited flood mitigation benefit during cloudbursts (NYCDEP, 2016; Rosenzweig and Fekete, 2018). However, the observed impacts of the 2011 cloudburst event in Copenhagen played an important role in maintaining awareness of cloudburst hazard. In addition, NYC experienced several 'near misses': back-to-back tropical storms passed just west of NYC in 2011, causing severe flash flooding in the affected suburbs. Then, on 13 August 2014, suburbs east of the city were flooded by a cloudburst that produced more than 127 mm of rain in one hour (NYCDEP, *Personal Communication, 6/6/2018*).

Like Copenhagen, NYC has also prioritized climate mitigation and adaptation in its planning (NYC, 2015, 2013). NYC was one of the founding megacities of the C40 Cities Climate Leadership Group and remains a highly engaged member. In 2015, it also became the first city to join Copenhagen in a formal partnership to exchange knowledge on developing cloudburst resilience (NYCDEP, *Personal Communication, 6/6/2018*).

Using open, geolocated street flooding service request data provided through the city's 311 system (NYC Mayor's Office of Operations, *Personal Communication, 4/7/2017*), the NYCDEP identified the neighborhood of St. Albans as the cloudburst management pilot site. With Copenhagen and U.S. based engineering firms, the city completed a Cloudburst Resiliency Planning Study (CRPS) for St. Albans in 2017. This planning adopted the principles of the 3-Points Approach for water management (Fratini et al., 2012), merging dedicated cloudburst resiliency projects with existing stormwater best management practices to support cloudburst flood mitigation while providing socioecological amenities during normal conditions. These analyses were supported by design workshops with local stakeholders, including representatives from local environmental organizations, planners, architects and engineers. At these workshops, an acceptable risk threshold of the 100-year rainstorm was agreed upon by consensus. Workshop stakeholders also used a portfolio of structural cloudburst mitigation strategies from Copenhagen and other cities to guide the development of a final masterplan of 68 projects, including subterranean tunnels, cloudburst roads, and stormwater retention projects.

At the time of writing, two pilot cloudburst projects – a cloudburst road and onsite retention project - are currently being designed for future construction at sites in Southeast Queens (NYCDEP, 2018). These pilot sites are being designed to manage stormwater associated with the projected mid-century 10-year hourly rainfall (2.3 in. hr^{-1}), based on the 90th percentile of projections for RCP 8.5 developed by DeGaetano et al. (2015). Beyond the St. Albans Study Area, the CRPS provided recommendations to support citywide climate resiliency planning, which included citywide hydrodynamic modeling, risk dimensioning to determine the optimal design storm for structural cloudburst mitigation strategies, and citywide integrated planning across agencies.

NYC was further galvanized to take additional steps to understand its infrastructure and social risk to pluvial flooding after observing the extensive flood impacts of Hurricane Harvey in Houston, Texas in 2017 (NYCDEP, Personal Communication, 6/6/2017). As a result, the city initiated a collaborative project involving city agencies, university researchers, and a private sector consulting firm as a first step in implementing the CRPS recommendations. This ongoing project involves the development of citywide future scenarios of increased sea levels and cloudburst magnitude to delineate pluvial flood hazard areas and identify cost effective gray and green infrastructure strategies under multiple future scenarios.

Through a public-private learning collaborative involving private sector architects and engineers, local community organizations, city agencies, and representatives from the international resilience community, guidance on strategies for floodproofing multifamily residences was developed (Enterprise Community Partners, Inc., 2015). These strategies include the installation of backwater valves and sump pumps on private property to prevent inundation of residences during cloudburst rain events. NYC is also beginning to engage private sector partners in the implementation of these strategies (Partnership for NYC, *Personal Communication,*1/28/2018*)* (Fig. 5).

4. Discussion

4.1. Importance of local experience

All three case study cities directly experienced a cloudburst event with significant impacts for city systems, which were critical to the cities' recognition of cloudbursts as a distinct problem that would require the development of new knowledge systems. In the case of Phoenix and Copenhagen, the cloudburst flooding events they experienced in 1972 and 2011 were transformational, resulting in immediate and sustained changes in their stormwater management practices to minimize the impacts of future cloudbursts. In contrast, the 2007 cloudburst in NYC resulted in the development of sectoral adaptation strategies for mass transit and emergency response but did not lead to comprehensive transformations in citywide stormwater management practices to enhance cloudburst resilience.

The reasons for the delay in NYC's transition are unclear and should be considered in future research. One potential explanation is that NYC's 2007 cloudburst was moderate relative to the highly extreme events experienced by Phoenix and Copenhagen. This explanation is supported by the expressed importance of experiences of regional and international cities (particularly Copenhagen) as a motivator for the development of more comprehensive cloudburst management planning in NYC. However, it is also important to consider that the socio-economic impacts of the 2007 cloudburst resulted primarily from pluvial flooding and were poorly represented using conventional metrics, which may have played a role in the delay in policy development.

4.2. Importance of multi-level knowledge systems

The occurrence of cloudbursts tends to be highly localized and their resulting impacts are dependent on local-scale socioeconomic, hydrologic, and infrastructure features. As a result, local to regional actors dominate the knowledge systems of our case studies, with several key exceptions (Fig. 6). First, all three cities rely on data on historical climate observations provided by their national weather services. In addition, Copenhagen's national engineering society provides a projection of cloudburst intensity with climate change, based on recent academic research. Analogous projections are not available at the national-scale in the U.S. However, the U.S. government collaborated in the development of guidance for adapting multi-family residences for pluvial flooding, which are being utilized by NYC practitioners.

Another key exception is the formalized intercity partnership between NYC and Copenhagen. For NYC, Copenhagen provided both an example of the vulnerability of dense cities to extreme cloudbursts along with a source of knowledge on the development of site and catchment-scale cloudburst management plans. As NYC begins to implement their initial plans, there will be continued opportunities for co-learning and sharing of expertise between the two cities.

4.3. Identified limitations

We have identified three major knowledge system limitations in our case studies. The first involves the knowledge systems used to represent non-stationary climate. In Phoenix, potential changes in cloudburst frequency and magnitude are not considered in the design of cloudburst management infrastructure, despite the growing body of scientific research indicating that these increases will be significant even in dry regions (Westra et al., 2014). In the Copenhagen and St. Albans (NYC demonstration) cloudburst management plans, increased cloudburst intensity with climate change is considered, but only as a single scenario of potential climate change. Although this is a significant advance, climate adaptation research has found this 'predict-then-adapt' to be inadvisable, since it does not consider the deep uncertainty surrounding future global emissions trajectories and resulting increases in cloudburst intensity (Gersonius et al., 2012). As a more robust

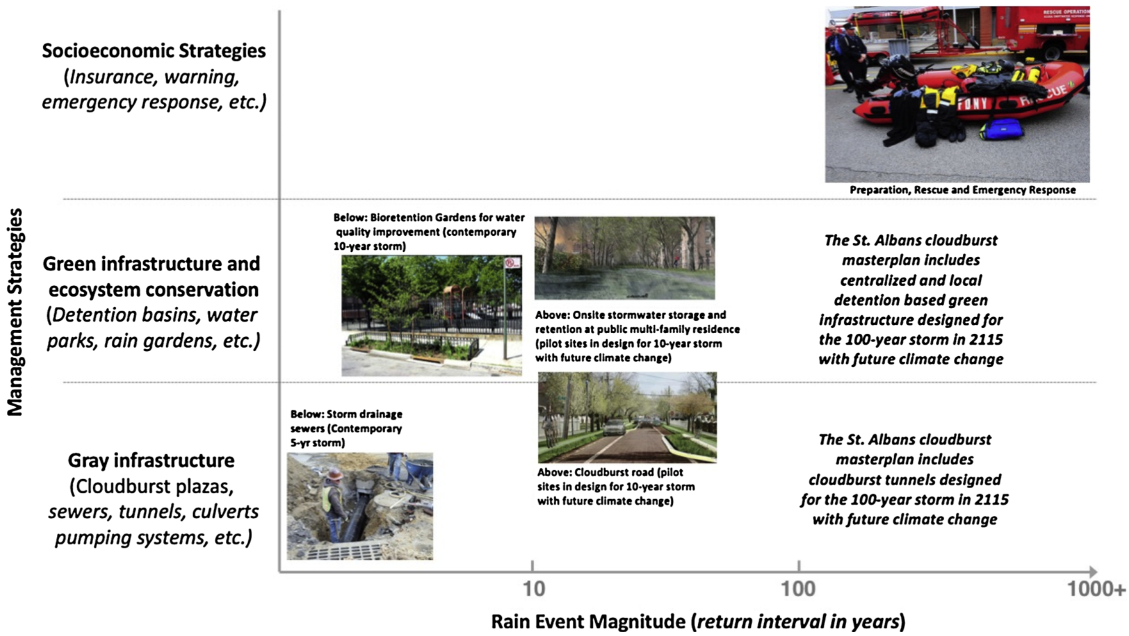

Fig. 5. Stormwater management strategies proposed for the St. Albans demonstration neighborhood in NYC for rain events of different magnitudes. Lessons learned from this project will be used to inform citywide cloudburst resilience planning.

alternative, NYC is now considering multiple scenarios of potential climate change in its risk dimensioning and the identification of cost-effective strategies, including integrating future precipitation scenarios into compound flood scenarios that include storm surge driven by sea level rise. This new NYC Citywide Stormwater Resiliency study is ongoing and the results are not yet available.

Second, the cloudburst plans for all three cities were developed by knowledge systems which failed to properly assess the vulnerability of private property to pluvial flooding. For example, in all three cities, it is the responsibility of private property owners to manage the impacts of pluvial flooding from events where rainfall intensity exceeds the design storm of cloudburst infrastructure, which range from the contemporary 10-year storm (local road conveyance in Phoenix) to the 100-year storm with climate change increases (cloudburst infrastructure in Copenhagen). However, the case study municipal cloudburst programs do not provide quantitative information on these potential expenses to property owners and tenants and do not consider them in the cost-benefit analyses to support risk dimensioning.

In Copenhagen, where pluvial flooding expenses are commonly covered by insurance, the insurance industry has begun playing an active role in providing data to support private property vulnerability assessment to city planners and communicating risk to the general public. In NYC and Phoenix, few residents and small business have insurance coverage for pluvial flooding since it is not mandated or subsidized. NYC has initiated outreach to property owners, but current awareness of this issue by the general public has not been studied. Survey based research conducted in Germany found that household-level awareness of the risk and responsibilities associated with pluvial

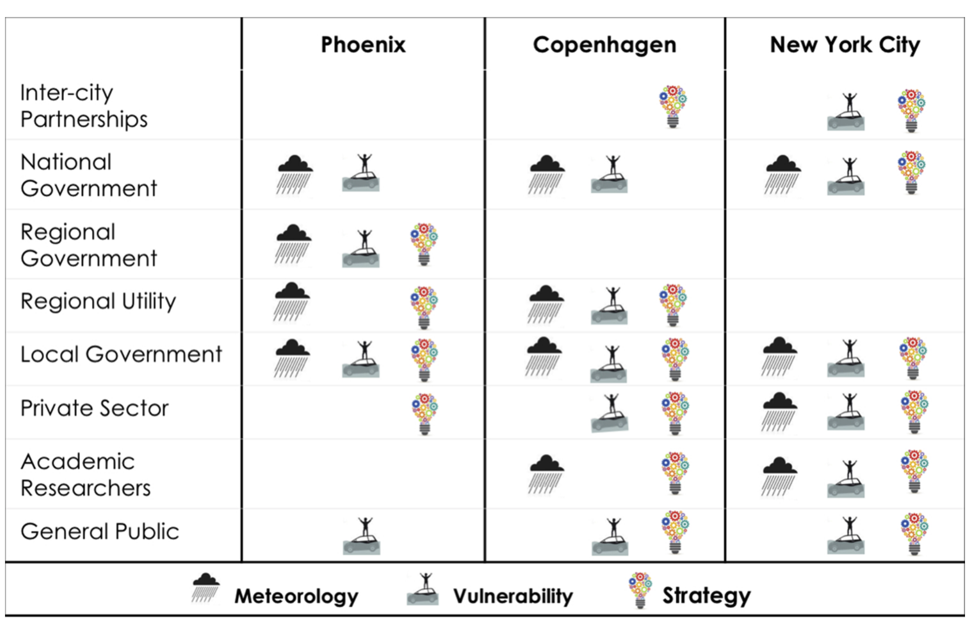

Fig. 6. Overview of knowledge systems in case study cities, comparing actors/institutions that generate, evaluate, utilize, and disseminate knowledge to others for decision making. See Supplemental Tables 2–4 for a detailed list of knowledge transfers.

flooding was low prior to direct experience with these events (Rözer et al., 2016). There is a need for empirical research on the perceived and actual vulnerability of private households and businesses in the case study cities to assess their resilience to cloudbursts that exceed their design storms and support the enhanced utilization of the local knowledge of the impacted general public in decision-making.

Finally, quantitative information to support the integration of cloudburst resilience planning with other elements of integrated water management, such as water quality protection, remains limited. For example, in NYC, GI planning for water quality improvement largely excluded cloudburst management for its first decade, although there have been recent efforts to begin to integrate this planning work (NYCDEP, 2018). In Copenhagen, HOFOR conducts numerical modeling to assess water quality co-benefits associated with cloudburst management projects. In addition, academic researchers have begun developing frameworks for the valuation of water quality and other co-benefits of cloudburst strategies in Copenhagen and New York (Lerer et al., 2017). In Phoenix, the integration of infrastructure for cloudburst flood mitigation into broader water management has not yet been quantitatively considered.

5. Conclusions

Although the cloudburst resilience planning efforts of Copenhagen, NYC, and Phoenix vary in their maturity and state of implementation, commonalities exist in the basic approach of all three cities. Urban stormwater management has been dominated by the use of sewers since the 20th Century, but none of the cities have adopted new drainage standards that would require their sewer systems to convey increased runoff. Instead, all rely primarily on a combined use of large-volume surface storage infrastructure (detention basins and plazas) along with the conveyance of excess stormwater along roadways during intense, short-duration rainfall events. These primary strategies are supplemented by the use of large-scale stormwater tunnels in older, densely developed areas of New York City and Copenhagen. This represents a new paradigm in stormwater management, prioritizing the design of large-scale multi-functional storage in dense, urban landscapes and a return to managed, surface conveyance of stormwater when feasible. While the overall strategy used by all cities is similar, the knowledge systems used to develop these strategies were very different, with implications for how the cities frame the cloudburst problem and identify solutions

As cloudburst management presents a distinct challenge for cities relative to less developed areas, partnerships between cities can be a particularly important component of cloudburst knowledge systems. There is an emerging literature on the potential for this type of transnational municipal partnership to advance resilience at the local level, but also a concern that local context and needs will be sacrificed for internationally standardized approaches (Bellinson, 2018; Fünfgeld, 2015). The partnership between NYC and Copenhagen provides an additional example of how such a partnership can work and also demonstrates how knowledge of best practices for locally-specific technical assessment and stakeholder engagement can be exchanged along with general strategies.

Through our case studies, we have also identified three key knowledge gaps that should be addressed in future research. First, there is a need for both improved projections of cloudburst intensity with climate change and the development of frameworks to support policy-makers in decision-making under the deep uncertainties associated with future climate. Second, there is a need for social science research to support improved quantification of the vulnerability of private properties to cloudburst flooding and the incorporation of this vulnerability into risk dimensioning. Local knowledge by the impacted public may play a particularly important role in these efforts. Finally, there is a need for additional quantitative information to support the improved incorporation of cloudburst resilient green and gray infrastructure into integrated water management.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2019.05.020.

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