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# Climate resilience strategies of Beijing and Copenhagen and their links to sustainability

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## Abstract

Like numerous other cities, Beijing and Copenhagen are experiencing more frequent urban flooding due to increased impervious cover and climate change. Consequently, huge investments are foreseen to maintain resilience. Analyses of planning documents and interviews with key stakeholders reveal that in their climate resilience strategies both cities do employ alternative approaches based on on-site retention-detention of stormwater runoff. However, when there is an emergency situation with heavy downpours, both cities rely heavily on conventional concepts involving deep tunnels for rapid discharge. The applied alternative solutions tend to be more engineering-based, like underground tanks in Beijing and detention-discharge plazas in Copenhagen. More nature-based solutions lag behind. Both cities are simultaneously targeting specific additional sustainability goals. Nevertheless, other potential goals seem to be neglected, like livability improvements in Beijing and biodiversity support and water footprint reduction in Copenhagen. The main barriers for implementing more nature-based solutions with greater sustainability potentials were a combination of time constraints caused by external political pressures for rapid problem solving, lack of routines for the innovation and documentation of solutions for dense urban areas, and insufficient multi-sectorial collaboration. These factors limit the propagation of alternative solutions and tip the balance of current investments towards a conventional approach.

*Keywords:* Alternative approach; Climate change; Detention; Engineering-based; Nature-based; Pluvial flooding; Retention; Sponge city; Sustainability

## Introduction

As the world urbanizes, the transition of cities towards sustainability is becoming crucial. Cities are required to respond to most of the great challenges the world is facing, whether by implementing changes in their physical structure or in their consumption of energy, water, food, and other goods.

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Transition patterns may differ depending on the severity of the challenges and the capacity of the city in terms of skills and resources to identify and implement adequate solutions. Adaptation to climate change is one major challenge that sets today's urban agenda. The urban drainage capacity needs to be enlarged and measures to control floods must be found. The associated investment is foreseen to be huge, opening a window for economically strong cities to combine forthcoming flood control actions with other sustainability issues.

According to the IPCC, many parts of the world have in recent years experienced climate change in the form of intensified rainfall, prolonged droughts, more frequent heat spells, and more hurricanes, with further severe weather expected to increase both in its intensity and frequency (IPCC, 2014). Cities are home to more than half of the current world population, forming hot spots in terms of greenhouse gas emissions. Additionally, cities are sensitive to climate extremes due to the accumulation of people (population density), infrastructure, economic activity, and cultural heritage, and consequently are both contributing to and victims of climate change (Grimm *et al*., 2008). Pluvial flooding of urban areas caused by intense rainfall exceeding the capacity of the drainage system is one of the most pronounced consequences of climate change, although the risks of the other two types of urban flooding (i.e., fluvial flooding by rivers and coastal flooding by storm surges) are also increasing with global warming (JRF, 2011).

The goal of existing cities is to maintain functioning in the economic, social, and cultural spheres; that is, to avoid the need to reorganize around a new set of structures and processes despite heavier rainfall (Alberti *et al*., 2003). The conventional approach to enhanced resilience towards pluvial flooding is to enlarge the dimensions of drainage systems, for instance, through the provision of bigger pipes, more detention basins, and stronger pumps for faster downstream discharge. An emerging alternative is to disconnect a fraction of the sealed surfaces from the conventional drainage system and, instead, manage the stormwater runoff right-of-way by engineering below-ground units or surface depressions within the urban landscape. In this way, water is retained (permanently held back) through infiltration and evaporation, or detained (temporarily held back) for later discharge at a reduced flow rate to other drainage elements. This alternative approach has been introduced in many cities over the past two decades and given names such as sustainable drainage systems (SuDS) (Fletcher *et al*., 2015), low impact development (LID) (Ahiablame *et al*., 2012), green (stormwater) infrastructures (GI/GSI) (Lennon *et al*., 2014; Philadelphia Water, 2016), landscape-based stormwater management (LSM) (Backhaus & Fryd, 2013), and sponge city (MOHURD, 2014). These systems have been used either as standalone solutions, typically in new urban developments, or in combination with conventional solutions, typically by retrofitting existing urban areas. The alternative approach often suggests applying natural features for on-site hydrologic control and is spurred by different motivations depending on the situations experienced by different regions, which may wish to re-establish the hydrograph that existed before urban runoff, reduce the temperature of the discharge water for marine ecosystem protection, or adapt to current and future climate change (Fletcher *et al*., 2015). In general, alternative approaches reflect a more eco-centric philosophy, as opposed to the more techno-centric philosophy of the conventional approach.

When a city decides to massively upgrade its drainage capacity, the mere size of the investment and high fraction of paved and built surfaces that are affected make it relevant to seek to improve the overall sustainability of the city. Obvious improvements that may be obtained jointly with increasing resilience towards pluvial flooding include: (1) separate stormwater runoff from wastewater to limit the number of combined sewer overflows and reduce the stormwater load at municipal treatment plants; (2) reduce the water footprint[1] of a city by linking stormwater management to water supply through stormwater harvesting or groundwater recharge; (3) increase livability and socioeconomic sustainability by introducing well-designed stormwater management features that improve esthetics, recreation, and social inclusiveness – this could include the creation of vegetated surfaces that improve air quality, reduce the urban heat island (UHI) and noise, provide areas for urban farming, and create new jobs for implementation and maintenance; (4) increase biodiversity and ecological performance, and conserve the regional ecosystem by designing stormwater management features that can compensate for the loss of nature and natural space caused by urbanization, minimizing the negative impact of urban drainage discharge into receptive water bodies (Grimm *et al*., 2008).

In many cities, the skills and organizational capacity required to combine climate resilience with further sustainability targets may not be available. Contrary to the mono-functional discharge target of conventional pipe-based stormwater management, the achievement of extra sustainability benefits relies on knowledge not only from technical disciplines but also from fields including the life sciences, humanities, and economics. Often, the above-ground design must be interwoven into the urban surface to obtain a pleasing esthetic design, which is ultimately negotiated among multiple stakeholders (van de Meene *et al*., 2011).

The objective of this paper is to present an overview of the recent flood control strategies of Beijing and Copenhagen, and to see whether the suggested measures are combined with the alternative approach introduced above. Furthermore, this paper reviews whether the two cities are working towards (or planning for) the attainment of other sustainability goals that go beyond the enhancement of climate resilience.

## Materials and methods

Beijing and Copenhagen were used as cases for this study due to two reasons. First, both cities have experienced pluvial flooding, hold a strong planning tradition, and are proactive with flood management. Being capital cities, they are their countries' front-runners in seeking solutions for climate resilience. Second, this research was partially funded by the Sino-Danish Center for Education and Research (SDC), and through this, the authors gained good channels for first-hand data in Beijing. Beijing Municipality (Beijing City Region) covers an area of 16,411 $km^2$ and has a population of 20.7 million (2012). Mountains occupy about 60% of the total land. Although most plans and strategies apply to the entire Beijing Municipality, the study focused on the Beijing Central City of 1,085 $km^2$, which corresponds roughly to the urbanized part, hereafter referred to as Beijing (Zhang, 2013). Copenhagen is the central part of the Capital Region of Denmark, which covers an area of 2,568 $km^2$ and has a population of 1.7 million (2014) (Wikipedia, 2014), while Copenhagen Municipality is located at the coast and is the focus of the study. Both cities' characteristics are shown in Table 1.

The study was conducted by analyzing plans and documents as well as interviewing key actors within the city administration of both Beijing and Copenhagen. Interviewees from Beijing and Copenhagen are designated *iB* and *iC*, respectively (Table 2).

[1] The water footprint of a city often includes water used directly (e.g., from a tap) in the city and virtual water used outside the city for the production of imported food and goods transported to and consumed by the city. Virtual water usually comprises most of the water footprint; however, this paper uses the term 'water footprint' to refer only to water used directly.

Table 1. Profiles of the city Beijing and the city Copenhagen.

| | Area (km$^2$) | Population (million) | Precipitation (mm) and distribution in a year | Potential evapo-transpiration (mm) | Climate | Sewer system; design standard |
|---|---|---|---|---|---|---|
| Beijing | 1,085 (2010) | Approx. 10 (2010) | 457[a], ¾ falls in June to August | Approx. 1,200 | Temperate, dry, monsoon-influenced humid continental climate | Combined sewer within the second-ring road, separated sewer in new areas (the second-ring road and outwards). Discharge to rivers and lakes. Most parts designed for 1–3-year rain events; 3–5-year in the future |
| Copenhagen | 86 (2015) | 0.56 (2015) | 691[b], Distributed all over the year, but highest in July to August | Approx. 600 | Temperate, humid, coastal climate | Most part (>90%) combined sewer. Discharge to a stream and the ocean. Designed for 10-year rain events |

Zhang (2013), Wikipedia (2014), Scharling & Cappelen (2016) and Statistics Denmark (2016).
[a]Average, 1999–2009.
[b]Average, 2006–2015.

Table 2. Actors within the municipality administrations for flood control and list of interviewees in Beijing (*iB*) and Copenhagen (*iC*).

| Actors within the municipality administrations | Major relevant responsibilities | Interviewees and role in administration |
|---|---|---|
| Beijing | | |
| Beijing Municipal Committee of Planning (BMCP) | Making plans; drafting local regulations and technical standards; organizing implementation; approval of land use and development projects | |
| Beijing Municipal Planning and Design Institute (BMPDI) (technical subsidiary body of BMCP) | | |
| Beijing Water Authorities (BWA) | Management of all water issues – water supply, drainage, surface water environment, flood management; planning of water infrastructure | |
| Beijing Institute for Water Science and Technology (BIWST) (technical subsidiary body of BWA, for research and technology development) | | $iB_1$, Water resources engineer; $iB_2$, Water resources engineer |
| Beijing Hydrology Planning and Design Institute (BHPDI) (*ibid*) | | $iB_3$, Hydraulic engineer |
| Beijing Government Flood Prevention & Flood Control and Drought Relief Headquarters | | |
| Beijing Municipal Bureau of Landscape and Forestry (BMBLF) | Public green space administration | |
| Beijing Institute of Landscape and Traditional Architectural Design and Research (Semi-public institution, as technical consultant for BMBLF) | | $iB_4$, Architect specializing in green space planning |
| Beijing Municipal Commission of Housing and Urban-rural Development (BMCHUD) | Construction administration | |
| Beijing Municipal Planning and Design Institute (BMPDI) (technical subsidiary body of BMCHUD) | | $iB_5$, Urban Planner specialized in municipal infrastructure |
| Beijing Drainage Group (State-owned company) | Executive institution of urban drainage, including stormwater | |
| Copenhagen | | |
| The Technical and Environmental Administration, City of Copenhagen (TMF) | In coordination with other teams and HOFOR, development and coordination of the overall plans for climate adaptation and cloudburst management; implementation of the cloudburst plan with approximately 350 projects | $iC_1$, Urban planner specializing in green space planning; $iC_2$, Hydraulic engineer; $iC_4$, Urban planner specializing in stakeholder involvement; $iC_5$, Civil engineer |

(*Continued.*)

Table 2. (*Continued.*)

| Actors within the municipality administrations | Major relevant responsibilities | Interviewees and role in administration |
|---|---|---|
| Climate Adaptation Team<br>Construction Project Development Team<br>Temporary Steering Committee and a Working Group for the city's top Climate Adaptation agenda | | |
| Finance Administration (ØKF), City of Copenhagen (part-owner of HOFOR) | Coordinating with HOFOR for financing plan implementation | |
| HOFOR (the utility company of greater Copenhagen) | Handling wastewater and rainwater; building and operating sewer pipes; co-financing of surface solutions through water taxes | $iC_3$, Water resources engineer |
| Regular directors' meetings and a Working Group between Climate Team (TMF) and ØKF; Working Group (Secretariat) and Partnership between TMF and HOFOR | Coordination within TMF and between the City of Copenhagen, HOFOR and surrounding cities and utility companies on solutions and financing issues | |

Based on pre-investigations.

In Beijing, the greatest water-related challenge is an ongoing water shortage. To supply water, the city has been reclaiming wastewater, importing water from the Yangzi River through the South-North Water Diversion project (Liu *et al*., 2014), and applying water-saving strategies during the last decade. Flood prevention has always been considered important due to Beijing's status as the capital of China. Beijing is subject to fluvial flooding from the mountainous surroundings as well as pluvial flooding, which is called 'waterlogging' in China, from runoff from urban sealed surfaces. An earlier draft Urban Flood Prevention Plan (UFPP) (1995–2010) led to intensified flood prevention installations, but heavy downpours still led to flooding, especially of low-lying roads under bridges ($iB_3$). On July 21, 2012, the whole Beijing Municipality experienced an extraordinary rainfall of 328 mm in 20 hours, costing 79 people's lives and at least 10 billion RMB (1.5 billion US dollars) in damage. Although the casualties of the event were primarily in suburban areas, Beijing's overall stormwater management strategy has inclined more towards control of floods since this emergency event, accelerating the development of a series of plans and guidelines.

With the relatively good quality of groundwater from the surrounding regions as water source, Copenhagen does not experience water shortages to any significant degree ($iC_2$; $iC_3$). The recent water issue is centered on climate adaptation, mainly in terms of pluvial flood management and (to a minor degree) protection against storm surges. The Copenhagen Climate Plan, the development of which was related to the international climate change event COP15 (the Copenhagen Climate Change Conference, held in 2009), with a goal of zero carbon emissions by 2025 was published, and an initiative to prepare the city for extreme weather was launched (City of Copenhagen, 2009). In 2011, the Copenhagen Climate Adaptation Plan was published; shortly thereafter, a cloudburst of approximately 150 mm in less than 3 hours inundated parts of the city on 2 July 2011 (Leonardsen, 2015), causing no casualties but damage of 6 billion Danish kroner (nearly 0.9 billion US dollars) due to flooding in basements and streets. This brought flood management to the top of the political agenda and the mayor announced that steps would immediately be taken to prevent the event from occurring again (Lilmoes, 2012; $iC_3$). Subsequently, the Copenhagen Cloudburst Management Plan was published in 2012. The details of this plan have been rolled out from 2012 to 2015, as further described in the Results section.

The methods employed in this study include semi-structured interviews on current practices and the progress of newly developed plans (Table 2), and analysis of planning documents (Tables 3 and 4). These interviews focused on those involved in the urban planning, green space, and water sectors. From May 2015 to April 2016, five semi-structured interviews were conducted in each city, followed by telephone and email communications for clarification and updates.

## Results

Recent plans and documents related to the enhancement of Beijing's and Copenhagen's respective drainage capacities are summarized in Tables 3 and 4, respectively. In this paper, the plans and relevant discourses are characterized city by city; full names and abbreviations for different institutions and documents are provided in Tables 2–4.

Regarding the plans drawn up by Beijing, the draft UFPP from 1995 suggested that sufficient storage should be developed in western urban areas; free drainage should be ensured in eastern urban areas; and flood diversion outside the second-ring road should be strengthened to prevent flooding. In line with this

Table 3. Beijing's major plans and standards for flood control.

| Plan/Standard | Goal[a] | Main strategies[b] (conventional discharge system refers to Table 1) | Implementation scope |
|---|---|---|---|
| Flood Prevention and Waterlogging Reduction Plan (FPWRP) for Beijing City Region, 2015 draft (focusing mainly on suburban area but also propose solutions for Beijing Central City), by BHPDI, BWA; prepared 2012–2015 | Plan to handle 200-year flood events (100-year events for flood coming from West Mountains), and waterlogging for 50-year rain events (100-year events for important areas), with floodwaters deeper than 0.15 m on urban road surface only allowed for $<30$ min. Two north-south flood prevention rivers for detention of up to 100-year flood events (200-year events for important areas); four west-east discharge rivers for up to 50-year rain events (100-year for important areas); stormwater pipes: 3–5-year rain events (10-year for important areas) | 'Retention at upstream, conveyance in mid-stream and discharge in downstream'; 'Seepage, retention, prevention, discharge, control, management', and 'to construct a sponge city with natural retention, natural infiltration, natural purification'; The central city: 'Two verticals and four horizontals (rivers), one (green) ring-belt and double networks (these measures referring to LFCP below), multi-points (pump stations) and two deep tunnels (the last two measures only in this plan)' | Short term: 2015–2020, (to coordinate with Beijing Master Plan 2004–2020). Long term: 2030 |
| Local Flooding Control Plan (LFCP) for Beijing Central Area, 2015 draft (roughly Beijing Central City), by BMPDI, BMCP; prepared 2011–2015 | Same as above | Construct 'two verticals and four horizontals (rivers), one (green) ring-belt and double networks': Two major north-south rivers for flood prevention; four west-east discharge rivers; a LID greenbelt for infiltration, retention-detention, harvesting (based on existing and planned green belts); stormwater pipe network and small river network for discharge. Source-process-receptor control: LID at the source; stormwater pipes, pump stations, discharge street and green/gray stormwater detention/retention areas; discharge rivers and waterlogging detention areas | Same as above |

(*Continued.*)

Table 3. (*Continued.*)

| Plan/Standard | Goal[a] | Main strategies[b] (conventional discharge system refers to Table 1) | Implementation scope |
|---|---|---|---|
| Beijing's Code for Design of Stormwater Management and Harvesting Engineering (CDSM) 2013 (Beijing Region City, especially for both the newly developed and the redeveloped building and residential areas), by Beijing Institute of Architectural Design (Group) Co. Ltd, Beijing General Municipal Engineering Design and Research Institute Co. Ltd and Beijing Institute for Water Science and Technology (issued by BMCP and Beijing Quality and Technology Supervision Bureau) | Runoff discharge after development no bigger than before development; Locally handled stormwater runoff no less than 85% of the annual runoff in new development areas; no less than 70% of the annual runoff in other areas | Project area bigger than 2000 $m^2$ must provide no less than 30 $m^3$ retention-detention volume per 1,000 $m^2$ sealed or impervious ground surface; projects required for green space ratio should have sunken green space no less than 50% of the total green area; public parking, pedestrian paths, walking streets, cycling paths, squares, etc. should have permeable paving no less than 70% of the total area | 2013 |

Beijing Institute of Architectural Design (Group) Co. Ltd, Beijing General Municipal Engineering Design and Research Institute Co. Ltd & Beijing Institute for Water Science and Technology (2013), Zhang (2014), BHPDI (2015); $iB_3$ and $iB_5$, 2015, 2016; $iB_1$ and $iB_2$, 2016.

[a]Beijing distinguishes between flooding (floods coming from outside of Beijing Central City) and waterlogging (water collecting/ponding occurring locally from within Beijing Central City); the two use different dimensional standards.

[b]FPWRP does incorporate some measures (though with a parallel planning process) of LFCP, which in the table are only explained in detail related with LFCP.

Table 4. Copenhagen's major plans and standards for stormwater and flood control.

| Plan/Standard | Goal | Main strategies (conventional discharge system refers to Table 1) | Implementation scope |
|---|---|---|---|
| Climate Adaptation Plan (CAP) 2011 by mainly City of Copenhagen | Maintain the current sewer system's service level of 10-year rain events, despite 30% increase in annual precipitation by 2100. Solutions contribute to livable city, UHI reduction and green growth | Disconnection of buildings and streets from sewers and local management of stormwater runoff, by diversion runoff into stormwater pipes or SuDS; conveyance of surplus stormwater to areas where it causes no harm; Enlargement of sewers to meet 10-year service level | 100 years |
| Cloudburst Management (CMP) Plan 2012 by City of Copenhagen, in collaboration with HOFOR | Prevent flooding in extreme rain events: the urban surface must not be ponded more than 0.1 m and more frequently than once in 100 years, except areas designated for flooding | Runoff from events exceeding 10-year discharged to the harbor through underground tunnels, or to a stream. 'Water breaks' divert above 10-year runoff away from combined sewers. Reprofiling selected streets for transporting diverted water. Further, some streets, plazas, and green areas modified to provide detention volume | At least 20 years |

City of Copenhagen (2011, 2012, 2015); $iC_4$ and $iC_5$, 2015.

approach, the recent FPWRP, drafted by BHPDI, relies mainly on conventional solutions, including the building of two deep tunnels and the upgrading of pumping stations (Table 3). The alternative solutions are presented as being supplementary and include managing a portion of the stormwater runoff at the source, developing more stormwater runoff retention zones, and developing green spaces along the rivers for increased retention-detention. Conversely, the LFCP drafted by BMPDI emphasizes the alternative approach for stormwater and flood control by proposing a LID greenbelt between the fourth-ring and fifth-ring roads for enhancing infiltration, retention-detention, and harvesting of stormwater while also relying on the conventional approach by enhancing stormwater pipes, pumping stations, and the rivers' discharge capacity. Although developed by different sectors and reported independently to the City Council, the two draft plans are supposed to be merged into a joint implementation action for the Beijing City Region; by the end of 2015, they were still drafted as two separate plans ($iB_1$; $iB_3$; $iB_5$). The local standard CDSM aims at prioritizing the alternative approach by prescribing low-lying terrain, sunken green space, pervious paving, below-ground retention-detention tanks, and other items for new and redeveloped areas, with an emphasis on on-site infiltration, retention-detention, and harvesting.

Since 2000, BWA has tested alternative solutions mainly for harvesting stormwater to conserve drinking water ($iB_2$), but also for stormwater runoff control. After the flood event in 2012, it became a shared understanding among various municipal sectors that flood control could no longer rely exclusively on conventional pipe systems, and alternative solutions also needed to be employed ($iB_4$). The emphasis on the infiltration of stormwater continues to increase ($iB_2$; $iB_4$; $iB_5$). Interviewees $iB_4$ and $iB_5$ expressed that the CDSM standard has resulted in a series of developments employing the recommended alternative approach to stormwater management.

The 2011 CAP for Copenhagen recommends alternative solutions to manage stormwater runoff locally wherever possible by disconnecting the stormwater runoff from the sewer system to SuDS or to new, separated stormwater pipes. Where this process is not possible, sewers should be enlarged to meet standards for managing ten-year rain events without causing harmful ponding on the terrain. To match the future (projected to occur by 2100) 30% increase in the intensity of ten-year rain events predicted by the Danish Meteorological Institute (City of Copenhagen, 2011), an additional goal is to disconnect 30% of the sealed surfaces that currently are discharging into the combined sewers. The construction estimates of CAP 2011 by alternative solutions is 5 billion Danish kroner (0.7 billion US dollars), compared with the estimate of 20 billion that conventional measures would cost. The 2012 CMP and associated 2015 Climate Adaptation and Investment Statement (later called Implementation Plan) confirms this ten-year event goal from CAP, and in addition sets up a new goal of preventing flood depths that exceed 10 cm on urban surface so they happen no more frequently than once every 100 years. Referring to CAP, the CMP reiterates that green recreational solutions should be preferred wherever possible. Beyond this recommendation, the new goal relies on detaining and discharging floodwaters that exceed the ten-year volume. Discharge is to be directed toward the ocean through new tunnels or to a local stream, using road surfaces and new below-ground pipes for transporting stormwater runoff to the tunnel inlets or the stream. The Implementation Plan details this operation by identifying 60 cloudburst branches[2] and four new cloudburst tunnels. Approximately 350 projects have been identified for the re-profiling of numerous roads and squares or new below-ground construction projects. Of these projects, about 290 are municipal tax-funded projects on urban surfaces co-funded by HOFOR, with the remainder being conventional engineering projects fully water-fee funded by HOFOR ($iC_3$). Many of these projects on urban surfaces aim mainly to discharge or detain floodwaters, which are categorized as cloudburst roads, detention roads, and detention areas. A high number of streets within the cloudburst branches are residential streets, some of which have been categorized as 'green streets'. On these streets, stormwater runoff for events of lesser severity than ten-year events is to be diverted from the sewers in order to contribute to the goal of 30% disconnection by 2100 ($iC_3$). Likewise, inner roofs and courtyards of housing areas adjacent to the cloudburst elements are also encouraged to disconnect stormwater runoffs from the sewer system and handle it within their courtyards wherever possible ($iC_3$), but such activities are not covered by the CMP budget. To what extent runoff from disconnected areas will be infiltrated locally or discharged through the cloudburst elements will depend on cost, contamination risks, and the secondary groundwater level ($iC_3$). The 350 projects will be implemented over the next 20–30 years, with a few different projects being started each year. Implementation will prioritize areas with highest risk, easiest implementation, and where it is possible to achieve good synergistic effects (e.g., livability) with urban development projects (City of Copenhagen, 2012). To make the system function, the downstream cloudburst tunnels have to be constructed first (*iC3*). In the Implementation Plan, the construction estimates for the implementation of Cloudburst Management Plan 2012 were updated to 11 billion

[2] A cloudburst branch is the smallest hydraulic unit that requires a coherent hydraulic solution. It includes a collection of cloudburst projects with several basic cloudburst elements – cloudburst roads, detention roads, detention areas, green streets, and cloudburst pipes.

Danish kroner (nearly 1.6 billion US dollars), including 5 billion for surface solutions financed by the municipality with HOFOR co-funding through raised water fees (the 290 projects on urban surfaces mentioned above); 2.6 billion for conventional solutions for the four cloudburst tunnels, cloudburst pipes, and canals with HOFOR's water fee; 2.4 billion from private landowners' investments; and 1 billion for disconnections and connections outside property boundaries with HOFOR's water fee.

Together with the publishing of the 2012 CMP, Sankt Kjelds Quarter (55°42′36.53″N, 12°34′4.60″E) was announced as Copenhagen's first 'climate-resilient neighborhood' for showcasing solutions related to cloudburst and to the enhancement of the quality of urban spaces (Climate-resilient Neighborhood, 2015). The neighborhood's first 'climate square', Taasinge Square, has been constructed as a retention-detention area by lowering a vegetated part of the square. Other cloudburst detention areas, such as Sankt Annae Square (55°40′54.19″N, 12°35′28.69″E) and Enghave Park (55°40′1.25″N, 12°32′32.18″E), are currently being created. Three 'Courtyard Gardens of the Future', in which disconnection with respect to stormwater runoff is one of the goals, are currently being designed. On top of these municipal-led projects, around 40 private streets and building associations in the outer parts of Copenhagen have voluntarily initiated the process of disconnection and retention of stormwater runoff within their local areas, with financial support from HOFOR ($iC_3$). HOFOR is also developing easy-to-build engineered infrastructures to secure the city against flooding. One example of this is the extra outlets with non-return valves that have been under construction since 2012 in the flood-prone areas along the harbor of the city. According to *iC3*, installation of the valves along the harbor of the central part of the city has helped prevent flooding in these previously vulnerable areas.

In Beijing, disagreement exists on how great a role the alternative approach to stormwater management can play for flood control. The FPWRP only regards alternative solutions as something that can potentially enhance the service level of the conventional infrastructure. According to hydraulic engineer $iB_3$, the conventional approach is prioritized because decentralized measures for stormwater management have been implemented at a slow pace in the past years, and as such, are considered a reasonable but unsecure solution. The LFCP aims to maximize the role of the alternative approach (represented by the LID greenbelt) while combining the approach with conventional solutions such as enlargement of sewers. It is assumed that alternative solutions can only manage three- to five-year rain events, and that bigger events (e.g., a 50-year rain event) require rivers and stormwater pipes as the primary solution, with alternative approaches playing a supportive role; flood control, then, should integrate both green and gray infrastructures under this construct ($iB_5$).

Although FPWRP's deep tunnel design was still in the research phase and LFCP had not reached a great level of detail with respect to beginning operations, both plans have been evaluated by expert committees and late in 2015 were submitted to the City Council for approval. The planners for LDCP disagreed on the necessity of deep tunnels and declined their inclusion in the submitted version of the plan ($iB_3$; $iB_5$).

The interviews revealed some further challenges related to the implementation of alternative solutions. The CDSM, which directly prescribes alternative solutions, has been criticized for resulting in underground tanks rather than integrated landscape solutions. Criticisms have included the following: 'Beijing's concentrated rain pattern is more suitable for infiltration measures wherever possible, which benefits the ecological environment and is cheaper to install compared to tanks' ($iB_4$); lack of feasibility of the required sunken spaces – 'The calculation method is unclear, and it conflicts with other landscape values such as visual effect and biodiversity' (also $iB_4$, referring to a need for specific vegetation in SuDS). Among other challenges, the lack of green spaces in the city center of Beijing is also a reason for the over-application of underground tanks (*$iB_2$*). *$iB_5$* indicated further that the effectiveness of the CDSM standard is questionable, as it only relates to the planning and design stages but the construction, inspection, and maintenance stages do not involve adequate control over the final output of the projects.

Beijing interviewees pointed to poor collaboration among different sectors as an additional challenge to any alternative approach. In the early practice of stormwater management, the Parks Administration (BMBLF) did not support the use of urban green spaces for stormwater management, seeing this use as a threat for maintaining a well-functioning green space (*$iB_4$*). Similarly, an individual engineer may, out of habit, use stormwater discharge pipes, even while conceptually agreeing with an alternative approach (*$iB_4$*). Issued as a semi-legally binding document, CDSM lacks power for many sectoral practices: 'Other sectors, like the roads department and parks department, need to revise their standards accordingly … there should be stronger enforcement for using CDSM' (*$iB_2$*). All sectors in Beijing after the 2012 flood have started to realize the importance of alternative approaches to flood control. The consensus is that infiltration, retention-detention, and re-use of stormwater should be prioritized over discharge. As a consequence of this conceptual change, the collaboration among sectors and adjustment of sector policies and technical standards are expected to be gradually intensified (*$iB_2$*; *$iB_4$*; *$iB_5$*).

In Copenhagen, the change in discourse from a disconnection focus with the alternative approach included in the CAP to a stronger detention-discharge focus of the CMP reflects a change in the two plans' goals. Such a change entails maintaining a ten-year service level despite climate change (in the CAP) to additionally controlling extreme events (in the CMP). It also reflects a rushed reaction to the extreme weather event that occurred in July 2011 (mentioned previously). The re-profiling of future cloudburst streets and reshaping of detention areas, be it a SuDS solution or not, are perceived as highly valuable 'alternative solutions' due to their potential synergies with urban space regeneration and their multiple beneficial effects on the city, in line with option (3) from the Introduction to this paper. For both HOFOR and TMF, no doubt exists that (in addition to the 'alternative solutions') big cloudburst tunnels are unavoidable to secure the city from 100-year rain events (*$iC_3$*; *$iC_4$*; *$iC_5$*). This is partly due to the lack of green spaces in the city center for alternative solutions and the physical barriers (for example, the railway) for discharging floodwaters to the ocean. In Copenhagen, alternative solutions are considered to prolong the lifetime of conventional solutions, which are implemented as the main countermeasure (*$iC_3$*).

Disagreement exists in Copenhagen concerning the use of existing public green areas and urban lakes for stormwater management (*$iC_3$*), with similar concerns expressed by the municipal green space administration on the impact of flood events on the subsequent recreational function of the park. Through joint inspection of the impact of earlier flood events on Copenhagen parks, HOFOR and the green space administration has gradually reached some agreement, but debates are ongoing concerning to what extent cloudburst runoff should be diverting to parks. Likewise, the freshwater administration is concerned about the stormwater runoff leading to water-quality deterioration in the lakes. Agreement on how to discharge runoff to the lakes had not been reached at the time of these interviews (per *$iC_3$*). Therefore, the CMP and the Implementation Plan are unlikely to be the final blueprints of Copenhagen's climate adaptation solution. Additional critical issues include identification of potential green-blue areas (e.g., the large park Kongens Have and lakes other than those mentioned in the Implementation Plan) for infiltration and retention, how to manage contaminant content of the less than ten-year stormwater runoff that is disconnected from sewer systems, documentation of the retention-detention capacity of surface elements (especially the green elements), and how to physically ensure separation of above ten-year stormwater runoff from below ($iC_3$).

Marked differences in the working objectives between the two closely cooperating institutions, the TMF and HOFOR, became evident from the interviews. The interviewee from TMF emphasized TMF's obligation to consider a broad range of issues and long-term goals for the city ($iC_3$), while HOFOR (according to the interviewee) focuses on fulfilling specific and well-defined goals relating strictly to water management. The interviewee from HOFOR expressed their duty to ensure implementation of hardcore engineering solutions, while the interviewee from TMF reflected a more holistic and somewhat visionary view. $iC_4$ commented on these marked differences: 'We have some challenges there, but now we are learning to cooperate in a more constructive way.'

## Discussion

While Beijing at the time of this study still lacked a final coherent plan for flood control operation, Copenhagen was in the implementation phase, with around 350 projects slated for completion over a two- to three-decade period. Copenhagen now operates by maintaining a ten-year service level of the sewer system with no harmful ponding and a 100-year service level for flood control with a maximal depth of 0.1 m ponding on public land, while Beijing plans to enhance its service level of the sewer system to three- to five-year (ten-year for important areas) and a 50–100-year service level for waterlogging control with a maximal depth of 0.15 m for no more than 30 minutes on public land. Disconnecting 30% of the runoff from sealed surfaces by 2100 to match the expected precipitation increase is a unique goal for Copenhagen. However, despite the fact that it is a major goal for CAP, CMP only mentions it very briefly without clarifying how this goal is adapted and how much cloudburst management elements can contribute to it. Thus, Copenhagen's plans are lacking coherence, which may be partially a result of the rushed reaction to the extreme cloudburst. Despite the lack of a specific goal, Beijing operates with a CDSM standard with requirements for LID measures in both newly developed and redeveloped areas. The absence of an integrated planning approach in Beijing may be due to the sectorial operation in the centralized planning system. Together with the 'command-and-control' culture, this results in fierce competition among government branches and the absence of coordination and multi-level governance, all aggravated by the number of services that need to be involved in the climate resilience agenda.

The interviews revealed that the conventional approach to climate resilience maintains its strong status in both cities, with discussion of two deep tunnels in Beijing and the decision on four cloudburst tunnels in Copenhagen pointing to the current foundation for flood control decisions being more techno-centric rather than eco-centric. This is true although both cities have for several years paid attention to the alternative approach, as expressed in Beijing's discussion on LID greenbelt and the CDSM standard, and Copenhagen's considerations of green-blue spaces for infiltration and retention-detention. In both cities, the emergency situations that have occurred following serious flood events have aligned the discourses in favor of tunnel solutions before a thorough analysis of alternatives is completed and innovative solutions can be developed. This can be seen in Copenhagen, where the change of goals and increase of investments from CAP to CMP after a heavy cloudburst clearly indicate a decision inversion in emergencies. Under time pressure, conventional solutions seem to be preferred, potentially due to the lack of experience with nature-based solutions and the paucity of suitable designs for dense urban areas that lack green spaces. Moreover, the key actors who were involved in developing the CMP may have individual interests and competences by choosing either conventional or alternative solutions, which may have an impact on this decision inversion in an emergency. A clarification of this potential impact requires detailed analyses on the planning process and finance of CAP and CMP, which are beyond the scope of this paper but of interest for further investigation.

The development in Beijing and Copenhagen points to the overall challenge of introducing new solutions and supports the statement by Brown *et al.* (2009) that the ability of innovative solutions (niche experiments) to truly impact and eventually redirect current practices of the responsible institutions towards sustainable transitions is critical. Documentation and development of alternative solutions are time-consuming and may occur at a rate too slow to match climate changes or the high political pressure for immediate solutions. This may lead to missing opportunities to improve the overall sustainability of these cities and all other cities that face similar challenges and external pressures.

Although the alternative approach typically suggests application of nature-based features for on-site hydrologic control, a closer look at the alternative solutions applied in the two cities indicates that some engineering-based solutions, such as Beijing's below-ground tanks and Copenhagen's detention streets (squares), are considered alternative approaches and take precedence over nature-based solutions. These solutions do play a role in mimicking pre-urban natural hydrological processes, which are more advanced than conventional solutions. However, the question is whether they are sufficient as an alternative approach for sustainability. More likely, nature-based solutions such as Beijing's sunken green spaces and Copenhagen's green streets, supposing they retain stormwater locally, have greater potential synergy with the various sustainability goals that were provided in the Introduction. Besides, according to HOFOR, below-ground solutions are about ten times costlier than surface measures ($iC_3$).

Table 5 shows an overview of the sustainability goals of Beijing and Copenhagen's climate-resilient strategies. In Beijing, linking flood control to stormwater harvesting and groundwater recharge, as expressed in the CDSM standard, reflects the proactive decision to combine urban drainage with urban water supply for reducing the water footprint. However, apart from this link and some other synergies related to improvements in scenery and recreation, no correlation has been found between stormwater management and further sustainability targets. Intentions to improve the quality of urban drainage water or link the urban drainage upgrading schemes with other sustainability goals have not been clearly identified during this study. In Copenhagen, the CAP contains goals to control the UHI effect, but these are not maintained in the CMP as potential co-benefits of cloudburst management measures. In fact, no synergy with improvement in the quality of urban drainage, groundwater recharge, stormwater harvesting, biodiversity, or ecological performance is expressed in the CMP. However, a strong synergy with livability is expressed, as many of the cloudburst projects on streets and in plazas attempt to improve the quality of urban spaces.

Table 5. Overview of the sustainability goals of Beijing and Copenhagen's climate resilience strategies.

| | Beijing | | Copenhagen | |
|---|---|---|---|---|
| Additional sustainability goals relevant to climate adaptation | LFCP/CDSM | FPWRP | CAP | CMP |
| 1. Separate stormwater from wastewater | + | + | + | − |
| 2. Reduce water footprint of the city | + | + (−) | − | − |
| 3. Increase urban livability | −(+) | − | + | + |
| 4. Support biodiversity and ecological performance | − | − | + | − |

## Conclusion

As economically strong cities, Beijing and Copenhagen apply both conventional and alternative approaches in their current flood control strategies for enhancing climate resilience. Conventional tunnel solutions and other engineering-based solutions seem to hold a stronger status, because of rushed reactions to heavy downpours. Under an emergency situation, the cities' existing technical solutions and inter-sectorial collaborations for more coherent and sustainable strategies seem to be insufficient. Development and documentation of alternative solutions, especially those that are more nature-based, may not be able to keep pace with climate change and the political pressure for quick solutions, possibly leading to missed opportunities with respect to taking large steps towards improving the overall sustainability of these cities. Both cities in their flood control strategies consider specific synergies with sustainability goals, such as linking flood control to water supply in Beijing and to improved livability in Copenhagen, but neglect others. The results of the study demonstrate, in general, the lack of a well-argued balance between conventional and alternative approaches, and a lack of perspective related to attaining broader sustainability goals beyond those of flood control. The study calls for more awareness of the importance of innovative solutions (niche experiments) embedded in the regime on new approaches, at a faster pace, and under close collaboration between key institutions.

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