

Article

Integrated Hydrological Model-Based Assessment of Stormwater Management Scenarios in Copenhagen's First Climate Resilient Neighbourhood Using the Three Point Approach

Sara Maria Lerer ^{1,*}, Francesco Righetti ^{1,2} , Thomas Rozario ^{1,3}  and Peter Steen Mikkelsen ¹ 

¹ Department of Environmental Engineering (DTU Environment), Technical University of Denmark, Bygningstorvet, Building 115, 2800 Kongens Lyngby, Denmark; psmi@env.dtu.dk

² COWI A/S, Karvesvingen 2, 0579 Oslo, Norway; frg@cowi.com

³ COWI A/S, Parallelsvej 2, 2800 Kongens Lyngby, Denmark; troz@cowi.com

* Correspondence: smrl@env.dtu.dk; Tel.: +45-5048-5947

Received: 14 September 2017; Accepted: 8 November 2017; Published: 12 November 2017

Abstract: The city of Copenhagen currently pursues a very ambitious plan to make the city ‘cloudburst proof’ within the next 30 years. The cloudburst management plan has the potential to support the city’s aim to become more green, liveable, and sustainable. In this study, we assessed stormwater system designs using the Three Point Approach (3PA) as a framework, where an indicator value for each domain was calculated using state-of-the-art modelling techniques. We demonstrated the methodology on scenarios representing sequential enhancements of the cloudburst management plan for a district that has been appointed to become the first climate resilient neighbourhood in Copenhagen. The results show that if the cloudburst system is exploited to discharge runoff from selected areas that are disconnected from the combined sewer system, then the plan leads to multiple benefits. These include improved flood protection under a 100-years storm (i.e., compliance with the new demands in domain C of the 3PA), reduced surcharge to terrain under a 10-years storm (i.e., compliance with the service goal in domain B of the 3PA) and an improved yearly water balance (i.e., better performance in domain A of the 3PA).

Keywords: climate adaptation; combined sewer; cloudburst; flooding; hydraulic modelling; Three Point Approach (3PA); urban drainage

1. Introduction

The municipality of Copenhagen passed its first Climate Change Adaptation Plan (CCAP) in 2011 [1]. In terms of stormwater management, the plan focused on how to maintain the current level of service, i.e., assuring that the combined sewer system does not surcharge more than once every 10 years, despite a predicted 30% increase in the intensity of a 10-year storm 100 years into the future [2]. The main solution recommended by the CCAP was a disconnection of 30% of the impermeable surfaces from the combined sewer system, redirecting these surfaces to local stormwater control measures (SCMs) (also known as local diversion of stormwater or LAR in Danish [3]). The planned SCMs were primarily based on detention and infiltration, as in rain gardens and swales, thus also contributing to a “greening” of the city, but many details related to implementation have yet to be clarified.

Soon after passing the CCAP, in July 2011, a very rare and intense rainfall event caused unprecedented widespread flooding in the city, with total insurance claims exceeding 800 million Euros [4]. This increased the city’s awareness of the importance of extreme events, and resulted in a new and complementary plan to the CCAP, the Cloudburst Management Plan (CMP) [5,6]. This plan

set a completely new goal for the municipality: to ensure that a 100-years storm, 100 years into the future, will not cause more than 10 cm of water on the street surface anywhere in the city. Another amendment was a shift of focus from the detention of extreme events, i.e., directing the stormwater to temporary storage areas, towards solutions that convey stormwater all the way out of the city, i.e., to the surrounding harbour. The plan advocates for establishing transport solutions on the surface wherever possible, yet allowing for underground tunnels where terrain and existing infrastructure prevents surface solutions.

The Three Point Approach (3PA, see Figure 1) is a systems thinking concept that has proven useful when organizing and communicating climate adaptation plans, particularly when involving multifunctional solutions [7,8]. Using the 3PA terminology, the CMP reflects an expansion of Copenhagen's perception of the challenge of managing stormwater: there is a shift from focusing only on domain B (the domain of traditional urban drainage engineering, targeted at technical optimisation and standard regulations) to the inclusion of domain C (the domain of extreme events, where traditional drainage systems are designed to fail and city planners together with rescue forces are charged with protecting assets and lives from flooding). Both the CMP and the CCAP also reflect the city's ambition to give the new stormwater management systems added values (mainly stemming from their "greening" potential), which can be regarded as an inclusion of domain A (the everyday domain, where the focus is on seeing rainwater as a resource that can be used to enhance sustainability, liveability, etc.).

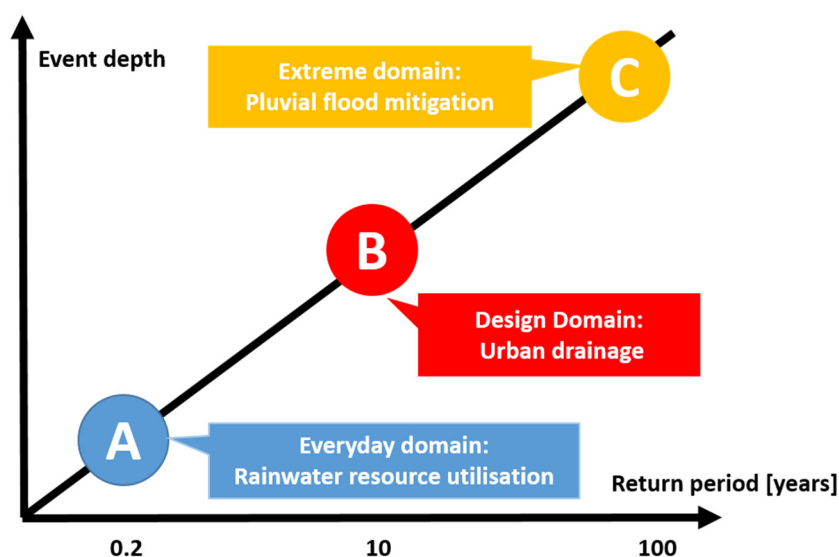


Figure 1. The Three Point Approach. Figure adapted from [8].

Copenhagen's climate adaptation plans are unique in their ambitiousness, as expressed by the many international prizes won, including i.a. the INDEX:Award in 2013 [9] and the C40 Cities Award in 2016 [10]. Our study aimed to assess the impact of the plans in a suitably ambitious manner, evaluating their performance in all three domains of the 3PA. To this end, we used advanced modelling techniques to calculate an indicator for each domain. Furthermore, we wished to investigate how modifications to the official CMP could improve the overall system performance. To this end, we developed four scenarios with gradually increasing investments. We demonstrate the methodology by application to a section of Copenhagen where some of the first climate adaptation projects have been built, and where combinations of aboveground green elements and underground tunnel systems are planned.

2. Materials and Methods

2.1. Case Study—The Ydre Østerbro Cloudburst Branch, Copenhagen

Copenhagen is the capital city of Denmark, overlooking the strait of Øresund, which connects the North Sea and the Baltic Sea. At 55 degrees north, the climate is oceanic, with an annual precipitation of about 600 mm rather evenly distributed throughout the year. The topography varies between 0 and 50 m above sea level, and has been substantially affected by human activity such as land reclamation and military defence construction. Hence, the urban hydrology is highly disturbed compared to natural conditions, and the original surface watercourses are no longer visible.

The CMP divides the city into seven overall surface runoff catchments, each containing multiple sub-catchments termed “cloudburst branches”. These branches delineate the future planned flow paths of rainfall-runoff on the city surface in case of flooding due to cloudburst. The city is also served by an old combined sewer system that controls the underground flow of stormwater runoff and wastewater (the catchments formed by this system differ to varying degrees from the respective cloudburst branch delineations). The latest version of the CMP [11] uses a typology of five different measures to control the storage and flow of stormwater under cloudburst conditions. These include two measures based on conveyance (cloudburst roads/boulevards and cloudburst pipes/tunnels) and three measures based on different combinations of detention (i.e., temporary storage) and retention (i.e., hydrological losses in the form of evapotranspiration or infiltration). This CMP is still rather rough, indicating only the expected overall structure of the cloudburst management system and not detailing how each measure will be implemented.

The cloudburst branch “Ydre Østerbro”, located in the north-eastern part of Copenhagen, was in 2011 declared “the first climate resilient neighbourhood” in the City of Copenhagen [12]. The ambition was to combine a pilot implementation of the CCAP with an ongoing regeneration project of the Sankt Kjelds district, which focussed on improving social well-being through improvements in housing and outdoor recreation options [13]. Some public space projects conceived in this phase have already been constructed, e.g., the Taasinge Square [14]. The latest version of the CMP for this branch is shown in Figure 2. It features a substantial number of cloudburst pipes, culminating in a large cloudburst tunnel that under extreme weather conditions conveys stormwater runoff directly to the harbour. There are also several cloudburst roads and retention roads, as well as a single retention space.

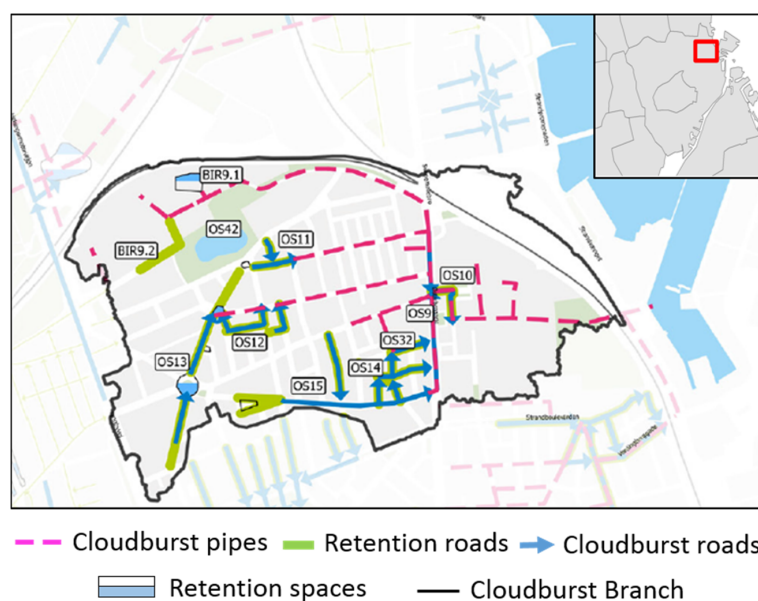


Figure 2. The cloudburst management solution for the cloudburst branch “Ydre Østerbro”, adapted from Reference [11].

The cloudburst branch of Ydre Østerbro consists of approximately 118 ha of primarily residential areas, of which about 73 ha are impermeable (~62%). The branch slopes from west to east (towards the harbour), with the highest point at 12.5 m above sea level and the lowest point at 1 m above sea level. The combined sewage (i.e., stormwater runoff and wastewater) from the case study area and surrounding areas to the north and west is pumped to Lynetten wastewater treatment plant (WWTP) via a pumping station near the harbour. There are no overflow structures from the combined sewer system within the Ydre Østerbro branch, but several downstream from the outlet point of the branch.

2.2. Modelling Approach

A comprehensive 1D semi-distributed urban drainage network model representing the drainage system of the entire catchment of Lynetten WWTP, created using MIKE URBAN software (MU, from DHI, Hørsholm, Denmark [15]), served as a point of departure. It contained a total of 7454 catchments, 5618 nodes, and 5935 links for a total network length of 492 km. From this model we extracted a sub-model containing only the combined sewer system within the study area, i.e., the Ydre Østerbro cloudburst branch. The land use description in the extracted model had a high level of detail, containing 2942 catchments with a mean area of 436 m². The catchments were classified as roads, sidewalks, roofs facing inner yards, roofs facing the roads, green areas, railways, or “diverse paved”. The final sewer network model included 413 manholes and a total pipe length of 24 km. We applied upstream boundary conditions to account for water discharged into the network from areas upstream from the study area, and downstream boundary conditions to account for flow limitations in the outlet points from the study area. We obtained the boundary conditions by running the entire original model and extracting time series of flow and water level at the points of interest.

Historical rainfall data from the rain gauge network of the Water Pollution Committee of The Society of Danish Engineers (SVK, in Danish) [16] were used as input for long-term continuous simulations. For single event analysis, we used synthetic rainfalls of 4-h duration modelled as symmetrical design storms based on the “Chicago Design Storm” (CDS) concept [17], derived from Danish regional intensity-duration-frequency curves [18] using a spreadsheet provided by the Water Pollution Committee of the Society of Danish Engineers [19]. This spreadsheet allows incorporating two types of safety factors in the CDS: a factor accounting for model uncertainty (due to e.g., lack of model calibration), which was set to 1.2, and a factor accounting for future climatic changes (climate factor), which was set to 1.3, in accordance with national guidelines [20]. The resulting storms had 10-min peak intensities of 32.58 µm/s and 55.41 µm/s for return periods of 10 years and 100 years, respectively.

For analysing flooding extent, we further developed the MU model of the study area into a MIKE FLOOD (MF) model by coupling the one-dimensional (1D) network model with a two-dimensional (2D) surface model [21]. We used the Danish national digital terrain model of 2015, which we modified to include buildings by lifting the surfaces falling within building polygons (using the national building registry). We also reduced the spatial resolution of the resulting raster from 1.6 m × 1.6 m to 3.2 m × 3.2 m in order to speed up computation time.

Table 1 describes each of the five types of cloudburst management elements in the CMP and how they were represented in our MU/MF model.

2.3. Scenario Development

Figure 3 provides an overview of the scenarios. In addition to the baseline scenario (BL) which represents the current sewer system, we developed four new scenarios (S1–S4), representing different enhancements of the cloudburst management system described in the latest CMP for the Ydre Østerbro branch. The main concept was to increase the fraction of surfaces disconnected from the combined sewer system and reconnected to the planned cloudburst system in a stepwise manner, thereby exploiting the latter also in non-extreme events. The modifications made in each scenario are explained below.

Table 1. Typology of measures used in the cloudburst management plan (CMP) [11] and how they were modelled in this study.

Solution Typology	Description	Modelling Approach
Cloudburst road	Main road that is re-profiled by making changes to terrain or raising the kerb in order to allow conveying stormwater on the surface during cloudburst events. Also referred to as cloudburst boulevard.	In the MIKE FLOOD model this was represented in the one-dimensional (1D) model by adding an open channel with the same dimensions as the road; water surcharging from the combined sewer system was directed to this channel, and if the channel reached its limit, the water was directed to the two-dimensional (2D) model.
Retention road	Road that retains and stores stormwater using elements such as bioretention units.	The sub-catchments representing these road surfaces were modified from 100% impermeable to include permeable stretches 1 m wide with an initial loss of 20 cm.
Retention space	Public or private space that is re-designed to provide some volume that can retain and store stormwater.	Same as retention roads.
Green road	Smaller road where there is space to retain all stormwater locally.	Not part of the CMP for Ydre Østerbro.
Cloudburst pipe	Underground solution for conveying and discharging stormwater mainly during cloudbursts, usually of larger dimension than a typical drainage pipe (thus also referred to as cloudburst tunnel), and applied only where existing city topography and infrastructure does not allow for conveying the necessary flows on the surface.	Normal MIKE URBAN (MU) pipe link element.

In scenario 1 (Figure 3-S1), we added a cloudburst management system to the existing combined sewer system, based on the latest CMP. Furthermore, we redirected runoff from the most obvious surfaces to the nearest cloudburst pipes, thus effectively disconnecting these areas from the combined sewer system. By most obvious surfaces, we mean the road surfaces designated as cloudburst roads or retention roads, and the road surfaces that are directly above a cloudburst pipe (the latter only if the road is classified as a low intensity traffic road, i.e., having an annual average daily traffic load of less than 5000 cars).

In this part of Copenhagen, runoff from the roofs that face the street is most often led through small gutters across the sidewalk directly to the street gutters. Therefore, the sub-catchments classified as “roof facing road” next to the abovementioned roads were redirected to the cloudburst system together with the roads. Ideally, this mixed roof and road runoff would first be treated in e.g., bioretention units before being discharged through the cloudburst pipes to the harbour. However, current guidelines in Copenhagen do not allow infiltration of road runoff to groundwater due to the risk of contamination of the groundwater with de-icing salts. Hence, bioretention units for road runoff would need to be sealed at the bottom, and their application would not affect the overall water balance (runoff would only be temporarily detained in them). Furthermore, current guidelines in Copenhagen allow for discharging runoff from low intensity traffic roads to flow into the harbour without treatment. Therefore, this scenario does not include any SCMs. The sum of areas redirected to the cloudburst system in this scenario is equivalent to 18% of the total impervious area in the cloudburst branch.

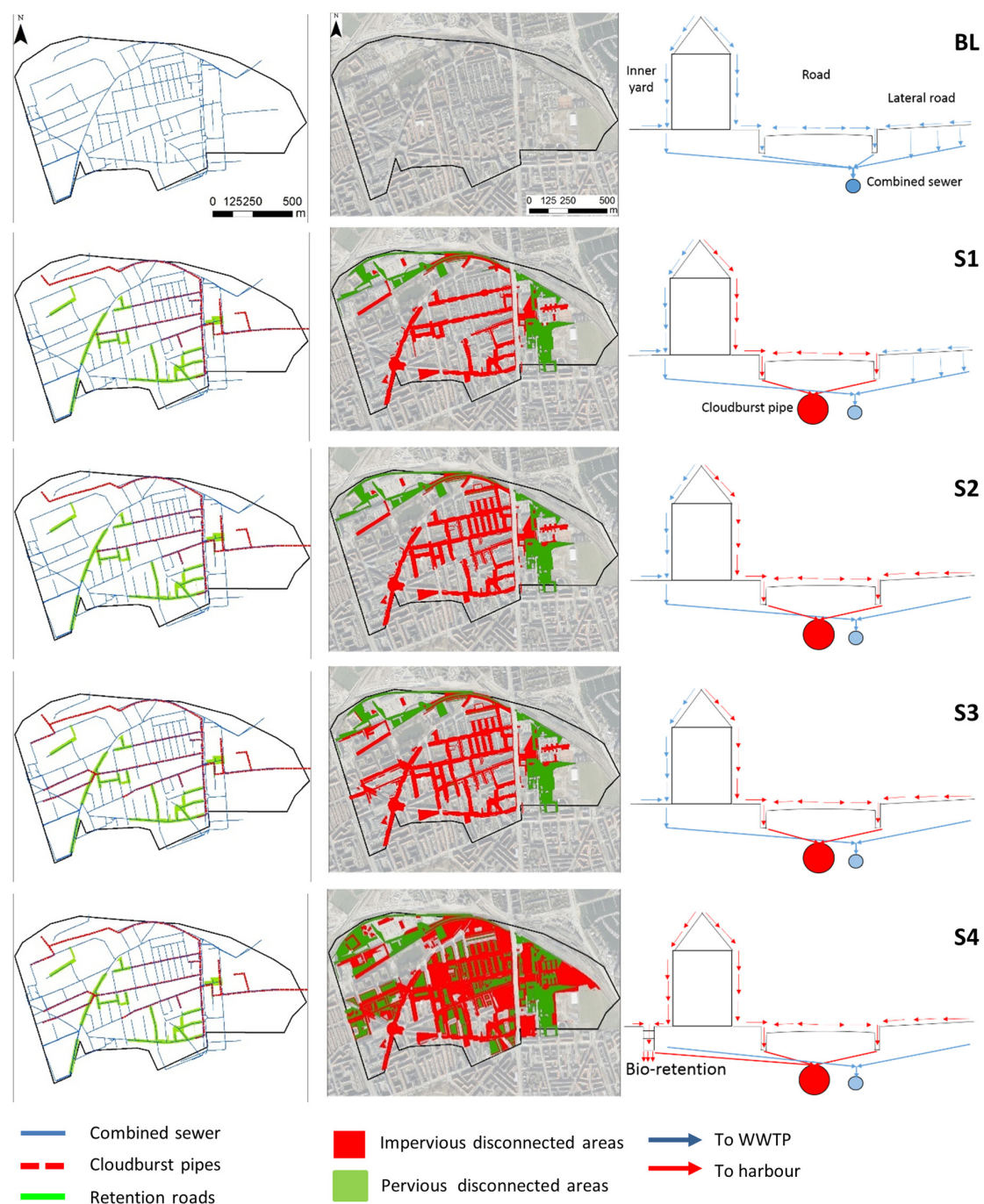


Figure 3. Overview of the different scenarios: (**left panel**) conveyance measures implemented in each scenario; (**centre panel**) areas disconnected from the combined sewer system in each scenario; (**right panel**) a typical street profile illustrating which surfaces are directed to the combined sewer system and to the cloudburst system, respectively.

Scenario 2 (Figure 3-S2) extends the fraction of surfaces redirected to the cloudburst system by adding all low intensity traffic lateral roads that slope towards any of the roads redirected in scenario 1 (including the roofs facing the street along these roads). Our rationale for adding this as an obvious next step is that this can be implemented using simple surface solutions (e.g., swales or gutters) at relatively low costs, especially if done in connection with ordinary road maintenance works (accepting

a long implementation horizon). The sum of areas redirected to the cloudburst system in this scenario is equivalent to 25% of the total impervious area in the cloudburst branch.

In scenario 3 (Figure 3-S3), we extended the system of cloudburst pipes in order to address sewer surcharge problems that persisted in some parts of the cloudburst branch (according to results from scenario 2). These parts were too far away from the cloudburst pipes in the CMP. The extension of cloudburst pipes (and accompanying redirection of road- and roof-surfaces) was done gradually until a satisfactory solution was reached at an extension level corresponding to 15% of the originally planned length of pipes. The sum of areas redirected to the cloudburst system in this scenario is equivalent to 30% of the total impervious area in the cloudburst branch.

In scenario 4 (Figure 3-S4), we significantly increased the fraction of surfaces disconnected from the combined sewer system and redirected to the cloudburst system by adding all the inner yards, and roofs facing inner yards, in the buildings that are next to roads that were redirected in the previous scenarios. Runoff from the inner-yard-roofs was led through bioretention units with infiltration to groundwater, designed to manage 90% of the annual runoff volume, and modelled using the new Low Impact Development Screening module in MU [22]. The sum of areas redirected to the cloudburst system in this scenario is equivalent to 49% of the total impervious area in the cloudburst branch.

2.4. Scenario Assessment

To evaluate the performance of the different system designs with respect to domain A of the 3PA (the everyday domain), we wanted to examine the fate of all rainwater flowing through the systems. As shown earlier [8], domain A is mainly composed of rain events smaller than the typical design storm. Therefore, we ran the model in a continuous simulation mode throughout a whole year and summarised how much rainwater ended up at the pumping station (which primarily sends it onwards to the WWTP), how much was directed to the harbour via the cloudburst conveyance system, and how much evaporated or infiltrated to groundwater. We chose the year 2003 from a 37-year-long rain gauge series (1979–2015, SVK station number 5740) after ensuring this year had similar statistical properties to the entire series (in terms of mean annual precipitation and occurrence of extreme events).

To evaluate the performance of the different system designs with respect to domain B of the 3PA (the design domain) we wanted to examine how well the systems complied with the explicit service goal of limiting surcharge from the combined sewers to terrain to once every 10 years. Therefore, we ran the model with a 10-years CDS and calculated the number of manholes that surcharged during the simulation.

The baseline situation (BL) and the final system design (S4) were evaluated with respect to domain C of the 3PA, the extreme domain, by examining the extent of surface flooding. For this purpose, we ran the MF model with a 100-years CDS.

3. Results

3.1. System Performance in Domain A

Figure 4 and Table 2 illustrate the total water balance for each of the five scenarios during the selected year (year 2003). In the baseline scenario, approximately half of the yearly rainfall volume is evapotranspired or infiltrated to the groundwater, while the other half ends up at the WWTP. In reality, a small fraction of the latter overflows to the harbour before reaching the WWTP, but our model setup focusing entirely on the Ydre Østerbro cloudburst branch could not distinguish this fraction because all overflow structures are located outside the study area. This half-half division on a yearly basis is as expected, given that about 62% of the area is impermeable and the model includes initial losses (i.e., depression storage and evapotranspiration/infiltration) from the impermeable surfaces.

For each of the suggested system designs (S1–S4), an increasing fraction of the yearly rainfall ends up as direct outflow to the harbour via the cloudburst system, coupled with reduced flow to the WWTP. This is an expected result of the progressive disconnection of surface areas from the combined

sewer system and their reconnection to the cloudburst system. In the most comprehensive redesign, S4, the discharge to the WWTP is reduced from 50% to 29% of the annual rainfall over the model area, i.e., a relative reduction of 42%. Such a reduction, if achieved throughout the entire catchment of the WWTP, is expected to have significant environmental and economic benefits at the WWTP due to reduced bypass, reduced pumping costs, etc. The slight increase in evapotranspiration and infiltration in scenario 4 is attributable to the implementation of bioretention units in back yards.

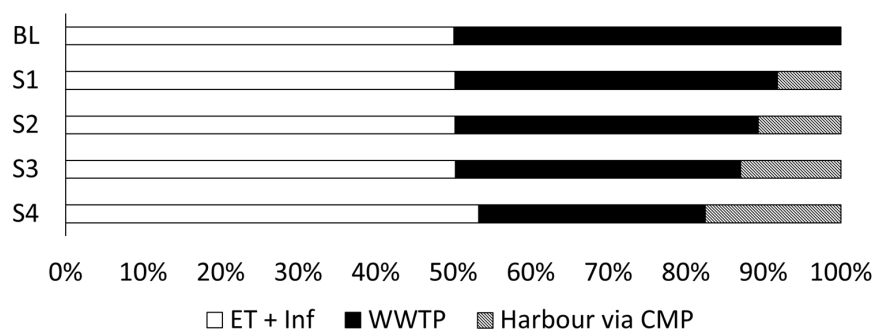


Figure 4. Total water balance for the different scenarios for one year of continuous simulation (2003); ET stands for evapotranspiration, Inf for infiltration, WWTP for wastewater treatment plant, and CMP for cloudburst management plan.

Table 2. System performance summarised for each scenario and each domain of the Three Point Approach (3PA).

	A Everyday Domain			B Design Domain			C Extreme Domain	
	ET and Inf * (%)	Harbour via CMP (%)	WWTP (%)	No. of Manholes within the Project Area	No. of Surcharging Manholes	Surcharging Manholes (%)	Water on Surface (1000 m ³)	Flooding Extent (m ²)
BL	50	0	50	413	190	46	43.1	143,349
S1	50	8	42	456	84	18		
S2	50	11	39	456	39	9		
S3	50	13	37	478	20	4		
S4	53	17	29	478	3	1	7.4	15,322

Note: * ET for evapotranspiration and Inf for infiltration.

3.2. System Performance in Domain B

In the baseline model, when forced with a 10-years CDS without climate factor, 58 of the manholes in the study area surcharge (approx. 15%, result not included in Table 2). This indicates that already today the system may not comply with the municipality's service goal. When forced with the required factors to account for model uncertainty (1.2) and future climate (1.3), 190 of the manholes (46%) surcharge (as shown in Table 2), distributed around the entire study area, with a high density along the north-south arterial road in the eastern part of the area, see Figure 5 (top, left panel). This indicates, as expected, that the capacity of the entire system is insufficient to deal with the expected increase in rainfall intensities.

The first suggested system redesign, S1 (involving the reconnection of surfaces directly affected by the construction of the officially proposed cloudburst system cf. Figure 3), achieves a significant reduction of surcharged manholes to around 18%. Further redesign reduces the proportion of surcharged manholes to 9%, 4%, and 1% for scenarios S2, S3, and S4, respectively. The few manholes that surcharge in S4, see Figure 5, S4 (top, right panel), are located in two different upstream locations in the network where the adjacent surfaces cannot easily be reconnected to the cloudburst system, indicating a need for local solutions outside the scope of this study.

Note that the upstream boundary conditions were the same for all scenarios. In reality, we also expect some retrofitting in the combined sewer system that is upstream of this area, causing a reduced flow into the study area in scenarios 1–4 compared with BL. This implies that some of the manholes might stop surcharging at a lower degree of surface reconnection than indicated by our results. Note also that the impermeable area disconnected from the combined sewer system in S3 corresponds to 30% of the impermeable area, the same degree of disconnection that was advised in the CCAP. In our simulations, this level still leaves 4% of the manholes surcharging, which is why we also included a fourth, more radical scenario (disconnecting 49% of the impermeable area). However, considering the expected effect of changing upstream boundary conditions and the need for some local solutions outside the scope of this study, our results support the recommendation of 30% disconnection level to mitigate climate change impacts.

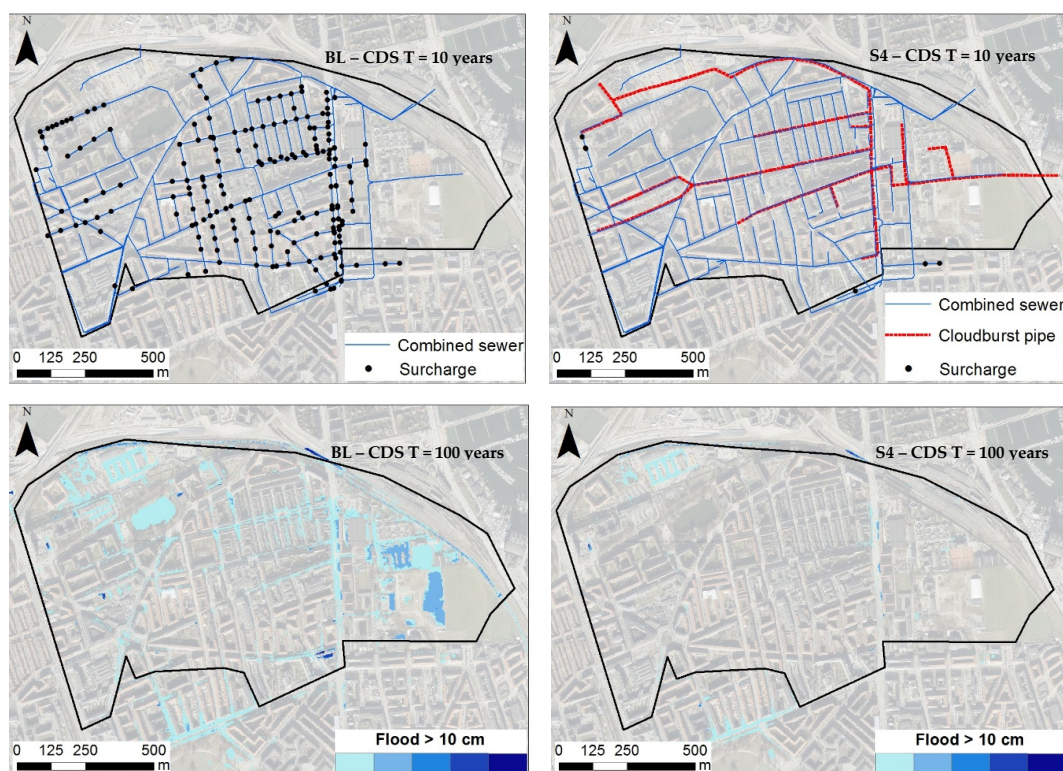


Figure 5. Extent of manhole surcharge under a 10-years Chicago Design Storm (CDS) (**upper panels**) and maximum flood levels above 10 cm under a 100-years CDS (**lower panels**) for the baseline scenario (BL, **left side**) and for the last design scenario (S4, **right side**).

3.3. System Performance in Domain C

The flooding simulation results for the baseline model (BL, current system configuration in future climate) and for the final system redesign (S4) are illustrated in Figure 5 (bottom panels) in terms of maximum depth of water on terrain in each model cell during a future 100-years CDS (showing only water depths above 10 cm). Vast inundations appear all over the study area and especially in the low-lying eastern part of the area with the given system design (BL), where more than 140,000 m² are covered by more than 10 cm of water (~12% of the area). In the final system design (S4), the inundated area is limited mainly to a few stretches along the north-south arterial road in the east and a bus terminal area in the north-west, totalling approx. 15,000 m² (~1% of the area). The persistent inundation on the arterial road reflects two main limitations of the approach taken in constructing the scenarios. First, as discussed for the domain B results, with better boundary conditions the surcharging under a 10-years storm can probably be mitigated at a reconnection level of around 30% (as in scenario S3).

At this level of reconnection, the cloudburst system is not expected to overflow. Secondly, if some reconnection of back yards still turns out to be necessary, it would be preferable (and more realistic) to make it stepwise rather than all-or-none, as was done here. The all-or-none approach serves to demonstrate the impact of an extreme scenario rather than pointing at an optimum.

4. Discussion of Modelling Approach

The modelling approaches used in this study are not new in themselves; it is the combination of several modelling approaches in a single study and how we chose to present the results, inspired by the 3PA, that is new. We find that the 3PA is a useful thinking system when dealing with the adaptation of stormwater systems to climate change, as proposed initially by Fratini et al. [7] and later used as a quantitative analytical frame by Sørup et al. [8] for simple hydrologic cases without the use of sophisticated modelling, as well as by Brudler et al. [23] for the lifecycle assessment of alternative SCMs. The 3PA inspired us to make a comprehensive assessment of the CMP that addresses all three domains, showing very few results for each domain. Thus, the 3PA helped to structure and present a very complex hydrologic and hydraulic analysis in a rather simple way, which does not reduce the complexity of the problem but supports effective communication about the solutions.

An important issue not covered by this approach is water quality, e.g., the impact of discharging untreated runoff from roofs and roads to the harbour. At first this impact may seem as a purely negative consequence, yet it must be weighed against the positive impact of reduced flow to the WWTP, which is expected to reduce combined sewer overflows and by-passes. A way to better address water quality within the framework could be to further refine the water balance in domain A, e.g., use a model that allows dividing the flow to the WWTP into how much overflows en route to the WWTP, how much is by-passed at the WWTP, and how much is effectively treated. These results could then be coupled with quantitative knowledge about the environmental impact of each fraction.

Due to the extensive modelling done in this study and the limited space in a journal paper, it was not possible to elaborate on all modelling choices we had to make. The most important choice in terms of how much uncertainty it adds to the results is probably the use of constant boundary conditions. The Ydre Østerbro branch is a separate catchment with regard to planned conveyance of cloudburst water, but the combined sewer system within the branch interacts with the combined sewer system outside the branch both upstream and downstream. Thus, climate adaptation measures implemented outside the branch will have an effect on the performance of both the combined sewer network and the cloudburst system within the branch, as discussed earlier.

Also, the compromise we chose for modelling retention roads and retention spaces may have some impact on the results. We planned to use the swale option in the new Low Impact Development (LID) module of MU 2016 for this purpose, but unfortunately this was not yet functioning. Turning a stretch of road into a pervious channel as we did misses the effect that a swale has on the runoff from the rest of the road. Thus, if an alternative modelling approach was used, it may have predicted less runoff from the retention roads ending up in the cloudburst system, and thus the desired performance in domains B and C may have been attained earlier (i.e., with less modifications to the original CMP).

Using a CDS of only 4-h duration is debatable in our models, especially for the 100-years CDS. However, given that the cloudburst system in the study area is mainly based on conveyance and not on detention or retention, the impact of larger rainfall volumes (entailed by longer duration CDS) is not considered significant.

5. Conclusions

In this study, we developed and applied an innovative and comprehensive modelling approach to assess the performance of increasingly ambitious urban stormwater system retrofits with respect to all three domains of the Three Point Approach (3PA), and we chose simple indicators to illustrate the results.

- Using a one-year long continuous simulation, we calculated the water balance and used this to indicate the system performance in domain A (the everyday domain).
- Using a simulation with a 10-years CDS, we calculated the percentage of surcharging manholes and used this to indicate the system performance in domain B (the design domain).
- Using a coupled 1D-2D simulation with a 100-years CDS, we calculated the extent of flooding and used this to indicate the system performance in domain C (the extreme domain).

Our study evaluates realistic combinations of “green” and “grey” SCMs that are partly visible on the surface and partly hidden underground, and which in combination lead to multiple benefits according to the 3PA. It furthermore shows how the 3PA, which was essentially developed for communicating and negotiating complex issues related to climate adaptation, can be combined with comprehensive state-of-the-art quantitative hydrologic engineering assessments.

The officially suggested cloudburst system for the case study area (Ydre Østerbro, Copenhagen) was, in scenario S1, enhanced by reconnecting obvious surfaces from the combined sewer system to the cloudburst system. This improved the system performance with respect to domain A (reducing the percentage of yearly rainfall on the case study area that is lead to the WWTP from 50% to 42%) and with respect to domain B (reducing the percentage of surcharging manholes from 46% to 18%). A reduction of the percentage of surcharging manholes to 1% (considered an acceptable compliance with demands in domain B) was predicted in scenario S4, which extended the cloudburst pipes with approximately 15% of the original pipe length and reconnected 49% of the study area to the cloudburst system. This final scenario also achieved a reduction of flow to the WWTP to 29% of the yearly rainfall (thus making a significant improvement in domain A), and a mere 1% of the area inundated in a 100-years storm (considered an acceptable compliance with demands in domain C). This scenario is substantially more ambitious than the current plan for the case study area, but if reconnections are implemented concurrently with other maintenance works over the next decades, it may not need to be substantially more expensive.

The extensive modelling approach suggested in this study allows for evaluating the different system designs in a structured, comprehensive manner that supports clear communication among stakeholders and decision-makers. The modelling results could be improved by including in the models the upstream areas that drain through the study area, implementing CMP-induced retrofits in the upstream areas at the same rate as in the study area. Nevertheless, however comprehensive the model, it is still limited to the hydrologic and hydraulic aspects of the system; the decision of which system design to choose will in reality be affected also by other aspects such as economics, aesthetics, biodiversity, demands for co-creation, politics, etc.

Acknowledgments: The authors would like to thank Greater Copenhagen Utility (HOFOR) for delivering data to the project. Special thanks go to Francisco Laurito Torres from DHI for his invaluable technical support. The rainfall dataset used is a product of The Water Pollution Committee of The Society of Danish Engineers made freely available for this research.

Author Contributions: Sara Maria Lerer designed the concept and methodology developed in this article and selected the case study, together with the other co-authors. Francesco Righetti and Thomas Rozario adapted the model boundaries to the defined purpose, elaborated the scenarios in detail and implemented them in the model, and ran the simulations and analysed and interpreted the results, under supervision of Sara Maria Lerer and Peter Steen Mikkelsen. Thomas Rozario and Francisco Righetti prepared the initial draft manuscript, Sara Maria Lerer wrote the final draft, with final illustrations made by Francisco Righetti and final editing by Peter Steen Mikkelsen. All authors read and approved the manuscript prior to submission.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. City of Copenhagen. *Copenhagen Climate Adaptation Plan*; The Technical and Environmental Administration: Copenhagen, Denmark, 2011.

2. Gregersen, I.B.; Sunyer, M.; Madsen, H.; Funder, S.; Luchner, J.; Rosbjerg, D.; Arnbjerg-Nielsen, K. *Past, Present and Future Variations of Extreme Precipitation in Denmark: Technical Report*; DTU Environment: Kgs. Lyngby, Denmark, 2014.
3. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.-L.; et al. SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **2015**, *12*, 525–542. [[CrossRef](#)]
4. Arnbjerg-Nielsen, K.; Leonardsen, L.; Madsen, H. Evaluating adaptation options for urban flooding based on new high-end emission scenario regional climate model simulations. *Clim. Res.* **2015**, *64*, 73–84. [[CrossRef](#)]
5. City of Copenhagen. *Cloudburst Management Plan*; The Technical and Environmental Administration: Copenhagen, Denmark, 2012.
6. Ziersen, J.; Clauson-Kaas, J.; Rasmussen, J. The role of Greater Copenhagen Utility in implementing the city's Cloudburst Management Plan. *Water Pract. Technol.* **2017**, *12*, 338–343. [[CrossRef](#)]
7. Fratini, C.F.; Geldof, G.D.; Kluck, J.; Mikkelsen, P.S. Three Points Approach (3PA) for urban flood risk management: A tool to support climate change adaptation through transdisciplinarity and multifunctionality. *Urban Water J.* **2012**, *9*, 317–331. [[CrossRef](#)]
8. Sørup, H.J.D.; Lerer, S.M.; Arnbjerg-Nielsen, K.; Mikkelsen, P.S.; Rygaard, M. Efficiency of stormwater control measures for combined sewer retrofitting under varying rain conditions: Quantifying the Three Points Approach (3PA). *Environ. Sci. Policy* **2016**, *63*, 19–26. [[CrossRef](#)]
9. Index Danish Capital Adapts Successfully to Changing Climate. Available online: <https://designtoimprovelife.dk/danish-capital-adapts-succesfully-to-changing-climate/> (accessed on 16 June 2017).
10. C40 Cities Awards 2016. Available online: <http://www.c40.org/awards/2016-awards/profiles> (accessed on 16 June 2017).
11. City of Copenhagen. *Climate Change Adaptation and Investment Statement*; The Technical and Environmental Administration: Copenhagen, Denmark, 2015.
12. Ydre Østerbro i København Får Klimatilpasset Kvarter. Available online: <http://www.klimatilpasning.dk/aktuelt/nyheder/2012/juni2012/ydreosterbro.aspx> (accessed on 16 June 2017). (In Danish)
13. City of Copenhagen. *Områdefornyelse i Sankt Kjelds Kvarter—Et Kvarter i Bevægelse*; Områdefornyelsen Skt. Kjelds Kvarter: Copenhagen, Denmark, 2011. (In Danish)
14. City of Copenhagen. *Tåsinge Plads*; The Technical and Environmental Administration: Copenhagen, Denmark, 2015.
15. DHI. *Mike 1D—DHI Simulation Engine for 1D River and Urban Modelling—Reference Manual*; DHI: Hørsholm, Denmark, 2016.
16. Jørgensen, H.K.; Rosenørn, S.; Madsen, H.; Mikkelsen, P.S. Quality control of rain data used for urban runoff systems. *Water Sci. Technol.* **1998**, *37*, 113–120.
17. Keifer, C.J.; Chu, H.H. Synthetic storm pattern for drainage design. *J. Hydraul. Div. ASCE* **1957**, *83*, 1–25.
18. Madsen, H.; Gregersen, I.B.; Rosbjerg, D.; Arnbjerg-Nielsen, K. Regional frequency analysis of short duration rainfall extremes using gridded daily rainfall data as co-variate. *Water Sci. Technol.* **2017**, *75*, 1971–1981. [[CrossRef](#)] [[PubMed](#)]
19. Arnbjerg-Nielsen, K.; Harremoës, P.; Mikkelsen, P.S. Dissemination of regional rainfall analysis in design and analysis of urban drainage at un-gauged locations. *Water Sci. Technol.* **2002**, *45*, 69–74. [[PubMed](#)]
20. Bülow, I.G.; Madsen, H.; Linde, J.J.; Arnbjerg-Nielsen, K. *Skrift 30—Opdaterede Klimafaktorer og Dimensionsgivende Regnintensiteter*; Water Pollution Committee of the Society of Danish Engineers: Copenhagen, Denmark, 2014. (In Danish)
21. DHI. *MIKE FLOOD—1D-2D Modelling—User Manual*; DHI: Hørsholm, Denmark, 2016.
22. DHI. *MIKE URBAN Collection System*; DHI: Hørsholm, Denmark, 2016.
23. Brudler, S.; Arnbjerg-Nielsen, K.; Hauschild, M.Z.; Rygaard, M. Life cycle assessment of stormwater management in the context of climate change adaptation. *Water Res.* **2016**, *106*, 394–404. [[CrossRef](#)] [[PubMed](#)]

