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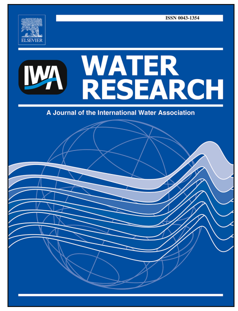

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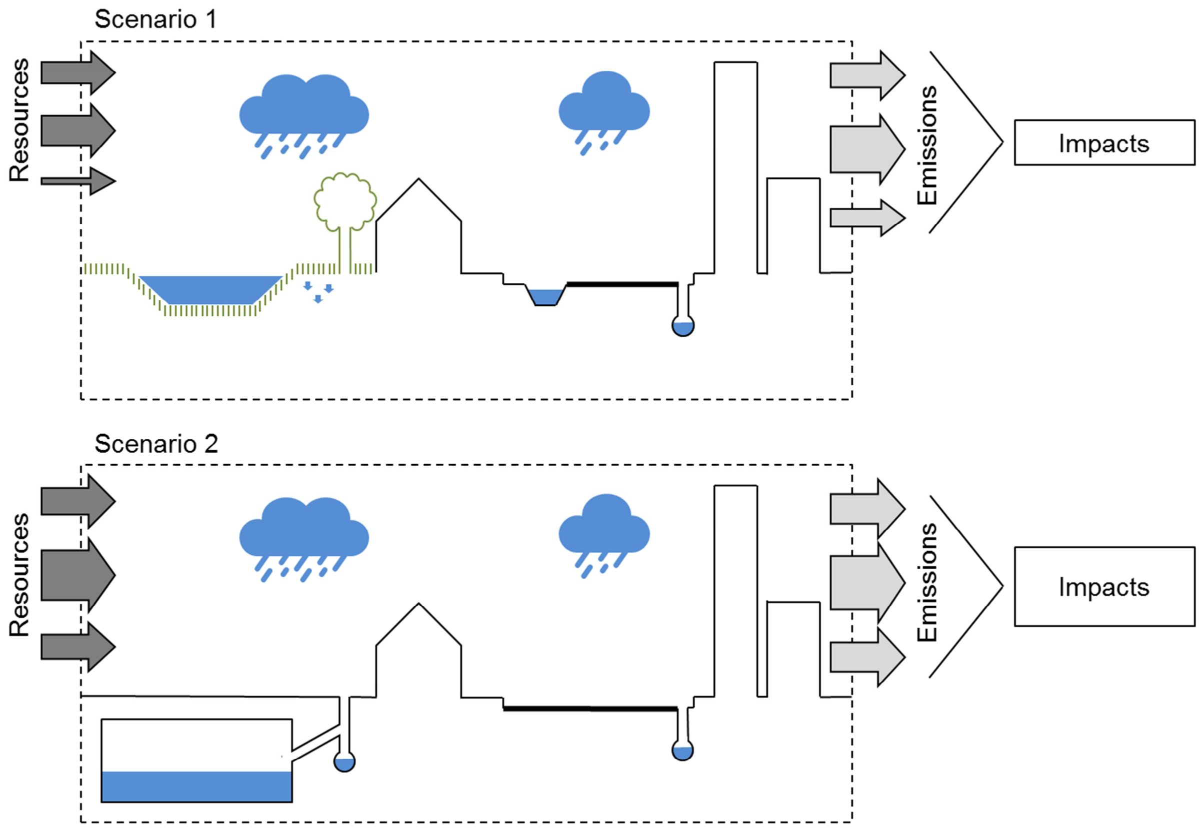
Scenario 1
Resources
Emissions
Impacts
Scenario 2
Resources
Emissions
Impacts

Life cycle assessment of stormwater management in the context of climate change adaptation

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Keywords: allocation, environmental impact, flood protection, functional unit, LCA, Three Points Approach

Abstract

Expected increases in pluvial flooding, due to climatic changes, require large investments in the retrofitting of cities to keep damage at an acceptable level. Many cities have investigated the possibility of implementing stormwater management (SWM) systems which are multi-functional and consist of different elements interacting to achieve desired safety levels. Typically, an economic assessment is carried out in the planning phase, while environmental sustainability is given little or no attention. In this paper, life cycle assessment is used to quantify environmental impacts of climate change adaptation strategies. The approach is tested using a climate change adaptation strategy for a catchment in Copenhagen, Denmark. A stormwater management system, using green infrastructure and local retention measures in combination with planned routing of stormwater on the surfaces to manage runoff, is compared to a traditional, sub-surface approach. Flood safety levels based on the Three Points Approach are defined as the functional unit to ensure comparability between systems. The adaptation plan has significantly lower impacts (3 – 18 person equivalents/year) than the traditional alternative (14 – 103 person equivalents/year) in all analysed impact categories. The main impacts are caused by managing rain events with return periods between 0.2 and 10 years. The impacts of handling smaller events with a return period of up to 0.2 years and extreme events with a return period of up to 100 years are lower in both alternatives. The uncertainty analysis shows the advantages of conducting an environmental assessment in the early stages of the planning process, when the design can still be optimised, but it also highlights the importance of detailed and site-specific data.

1. Introduction

Climate change (CC) is expected to change the volume and pattern of precipitation in the future (IPCC, 2014). In particular, precipitation extremes are expected to increase worldwide (IPCC, 2012). To protect people, properties and infrastructure from damage caused by pluvial flooding, adaptation measures are necessary, especially in urban areas. New ways of managing runoff are increasingly utilised, many focusing on local infiltration and the retention and discharge of water on the surface, which additionally introduces green and blue elements in cities (Wong and Brown, 2009). This approach differs significantly from traditional underground solutions that mainly utilise pipes and sub-surface retention basins. Material demands and construction, operation and disposal processes vary between the two approaches, which leads to different environmental impacts throughout their life cycle. Given the foreseeable extent of CC adaptation measures in the future, their environmental impact is an important parameter. While economic evaluations are frequently carried out, quantitative environmental assessments, including all life cycle stages, are usually not included in the planning process of urban drainage systems. Using life cycle assessment (LCA), the environmental impacts of different adaptation strategies can be quantified. LCA is a standardised approach to evaluating the environmental performance of products and systems (ISO, 2006a), and it is increasingly used in the assessment of water technologies and systems (Loubet et al., 2015). LCA methods are also starting to gain attention in the sub-domain of stormwater management (SWM). A review of existing literature in LCAs of SWM shows a limited number of publications, and the scope is rather inconsistent across studies (Table 1). Urban water systems are complex and serve various purposes. SWM has to meet multiple targets regarding environmental quality, flood safety and liveability. The clear definition and separation of the elementary (primary) function, and additional (secondary) functions, is crucial in comparative LCA. All alternatives have to provide the same primary function, as defined and quantified in the functional unit, to allow a comparison of environmental impacts. Various approaches employed to define the functional unit have been chosen in previous research. Some researchers define only a specific area, and not the actual service provided, as the functional unit (Flynn and Traver, 2013; Spatari et al., 2011). De Sousa et al. (2012) define a drainage area as the functional unit and implicitly state the function, which in this case is the reduction of annual combined sewer overflow volume. Other researchers define the management of a water volume as the functional unit. This volume is often defined as the runoff from a specific area during a design event (Andrew and Vesely, 2008; Wang et al., 2013) or as a standard volume, for example one cubic meter (Petit-Boix et al., 2015). Secondary functions, for example recreational benefits, are not explicitly stated in any of the reviewed studies. Water quality parameters are considered by various researchers (Clauson-Kaas et al., 2012; Kosareo and Ries, 2007; Taylor and Barrett, 2008), for example by including information regarding treatment efficiencies in the study, without directly relating it to LCA results. Water quality and removal efficiency requirements are included in the functional unit only by Andrew and Vesely (2008) and O'Sullivan et al. (2015).

Differences in the functional unit, leading to problems when comparing alternatives, have been dealt with differently in previous research. Spatari et al. (2011) , for instance, account for differences in runoff reduction by crediting the system with savings due to a reduced wastewater treatment (WWT) demand, while Taylor and Barrett (2008) normalise pollutant removal efficiency of each alternative in incorporating differences in water quality. Wang et al. (2013) compare systems which are dimensioned for different design events, by crediting the positive impacts of reduced system capacity requirements. A territorial approach to handling different functionalities is introduced by Loiseau et al. (2013) and adapted to urban water systems by Loubet et al. (2015): An area is defined as the reference flow, which is equal for all the studied alternatives, from which individual functions are derived for different land use scenarios. Results are provided both in the form of environmental impacts and land use functions, which are only partly assessed qualitatively. This allows one to assess alternatives that do not have the same function, which is otherwise not possible in LCA (ISO, 2006b). However, it only permits qualitative and no consistent quantitative comparison.

Apart from differences in the methodological approach, previous research also covers a diverse range of alternatives. Most researchers include a comparison between multi-functional, green infrastructure approaches and traditional SWM. Some focus on single technologies or installations, e.g. green roofs (Chenani et al., 2015; Kosareo and Ries, 2007), rain gardens or sand filters (Andrew and Vesely, 2008). A more comprehensive approach is chosen by De Sousa et al. (2012), who assess the environmental impacts of a combination of different elements to reduce combined sewer overflows, and Spatari et al. (2011), who evaluate the SWM system of a neighbourhood block. From an urban hydrologic viewpoint, it can be problematic to narrow the scope to single installations, because catchments are interconnected. An inflow in one area depends on the characteristics of upstream areas, such as imperviousness and detention and retention capacity. Previous studies have not assessed a CC adaptation strategy that is designed to protect people and assets from more severe rainfall events, and environmental impacts of single elements are only a fraction of the impacts that arise when flood protection targets have to be met. Only with a comprehensive solution, combining various elements over whole catchments, can this goal be achieved. In the following, we present a novel method to analyse and evaluate the environmental performance of CC adaptation strategies for urban areas.

TABLE 1

The reality of rainfall with large variations in intensity, duration and event frequency is not taken into account in any of the reviewed papers. It is neither included in the functional unit definition nor incorporated in the analysis of the results. Different rainfall events, ranging from small to extreme, require different solutions and elements; for example, retention basins are usually designed for a 10-year event in Denmark, and they will not be fully utilised in the case of smaller events or provide sufficient capacities to store runoff from larger events. This consequently leads to different environmental impacts that arise from managing different fractions of rainfall. By analysing this coherency, LCA can actively support decision-making during the design phase and help to communicate different stakeholder perspectives and priorities.

The aim of this paper is to address the limitations identified in previous research by answering the following questions:

- How can the functions of CC adaptation strategies be defined to take into account all relevant elements and thus ensure comparability between alternatives?
- What are sources of uncertainty, and how do they influence the life cycle impacts of CC strategies?
- How do different flood protection goals and system capacities contribute to total environmental impacts?
- In terms of environmental impacts, how do strategies managing stormwater locally and above surface perform compared to traditional solutions?

2. Methods and data

2.1 Climate change adaptation in Nørrebro, Copenhagen

The approach developed to meet the stated objectives was tested using the Nørrebro catchment in Copenhagen, Denmark (Fig. 1). In adapting to climatic change, cloudburst management plans (CMP) have been developed for the whole city of Copenhagen (The City of Copenhagen, 2015a). These plans, which are specified for seven sub-catchments, utilise green infrastructure and local retention as key elements in the management of stormwater, which are implemented by redesigning parks and roads. They are complemented by routing on the surface as well as underground pipes to meet flood safety requirements. In addition, large areas in parks are lowered and used, e.g. for sports, during dry periods, but they can retain water during extreme events. The system is designed to handle all additional runoff, which is expected due to CC until 2110, while the current runoff is managed in the existing combined sewer system. To benchmark the CMP for Nørrebro (HOFOR et al., 2013), an alternative, where green and blue elements are replaced by underground pipes and basins, is assessed. In this sub-surface alternative (SSA), it is assumed that the water is routed via a combined sewer system and treated in an existing wastewater treatment plant (WWTP), before being discharged into the harbour. In extreme events, the runoff is not or only partially cleaned before discharge.

FIGURE 1

2.2 Assessment methodology

The suggested methodology is in accordance with the four steps defined in ISO (2006a), namely goal and scope definition, inventory analysis, impact assessment and results interpretation. The impact assessment is performed using EASETECH, which focuses on material flow modelling and allows a simple set-up of different scenarios (Clavreul et al., 2014). The processes are modelled using the widely used ecoinvent database (Weidema et al., 2013). The International Reference Life Cycle Data System (ILCD) recommended method is used for the impact assessment, and combines methods to assess 16 different impact categories (European Commission, 2010a). Thirteen of these are implemented in EASETECH. The results are presented at midpoint level and are normalised using factors developed in the PROSUITE project (European Commission, 2010b). Furthermore, characterised impacts, which are impact indicator scores with individual units, are aggregated and expressed in person equivalents (PE). This normalisation relates the impact to the average impact per person per year in Europe. The actual effects on endpoint level to humans and ecosystems, such as a decrease in biodiversity or an increase in diseases, are specified in the ILCD handbook (European Commission, 2011).

2.3 Goal and scope definition

The functional unit, which is equal for both alternatives, is the management of all additional runoff expected due to CC in a catchment area of $2.6km^2$, while meeting well-defined flood safety requirements, for the next 100 years. The amount of water handled in both alternatives is the expected additional runoff due to climatic change, which is calculated using delta changes proposed for Denmark by Arnbjerg-Nielsen (2012). The safety levels are directly linked to the Three Points Approach (3PA) introduced by Fratini et al. (2012). The 3PA divides all rainfall events into three different domains based on their return period (RP): A) the everyday domain with an RP up to 0.2 years; (B) the design domain with an RP up to 10 years and (C) the extreme domain with an RP up to 100 years (Sørup et al., 2016). The corresponding flood safety levels are specified in Table 2, as well as the different strategies utilised in the CMP and the SSA to meet these targets. The combination of all elements constitutes the reference flow for the LCA, which differs between the two alternatives.

TABLE 2

Runoff from different rain events flows through the system along different paths (Fig. 2). Runoff from domain A events is not retained but infiltrated (CMP) or discharged to the WWTP (SSA). Based on the planning documents, it is assumed that all domain A runoff can be handled in a $7330m^2$ green area implemented in areas currently used as roads.

This is done by reducing the number of lanes or by narrowing existing streets and sidewalks. Plants potentially have beneficial local effects, e.g. air pollutant removal and carbon storage. However, as newly implemented green areas cover less than 1% of the total catchment area, these potential benefits from plants are not expected to affect the environmental impacts significantly. Domain B runoff is discharged into pipes and channels and retained in retention volumes in parks and roads in the CMP. Assumptions are necessary regarding the ratio of water that will be discharged via pipes or channels and then retained or discharged directly. In the SSA, it is assumed that all domain B runoff is temporarily stored in retention basins and partly treated at the WWTP (25%) or discharged directly (75%) via pipes. During domain C events, water will be on the surface in both alternatives, before discharge into a lake (CMP) or a harbour (SSA). The runoff is not treated in the SSA, while it is still partly purified by filtration in drainage layers in the CMP.

FIGURE 2

Different approaches to including water quality in an assessment can be found in literature, but no standard approach exists at the moment. Water quality parameters are not considered herein, and it is assumed that the same requirements are met in both alternatives, in that runoff is sufficiently cleaned by either infiltration (CMP) or treatment in a traditional WWTP (SSA). Additional functions not directly related to SWM could be defined, e.g. adding recreational value by increasing green areas. If these functions are included as primary functions, they have to be provided by all alternatives, which would have to be ensured through system expansion (European Commission, 2010a). In this example, this would mean that the same amount of additional green areas would have to be constructed in the SSA, as in the CMP. Since that option is not considered in the planning phase (and indeed is not feasible), the analysis is carried out by assuming that recreational value is a secondary function. It is only provided by the CMP, and is therefore not assessed to ensure comparability with the SSA.

All life cycle stages in the two systems are considered: material production and manufacturing, transport to site, construction and operation. Decommissioning and disposal are included to ensure comparability between the alternatives, even though a partial reuse or transformation is more likely than a complete decommissioning. Some processes occur identically in both alternatives, and thus they can be excluded from the comparison; for instance, the maintenance requirements of redesigned park areas (CMP) and park areas in current state (SSA)s are assumed to be equal, and no new park areas are implemented in either alternative. The operation and maintenance of parks is therefore not part of the assessment. Other processes are not included because only a minor fraction would be allocated to the assessed system. Runoff from Nørrebro is treated in the Lynetten WWTP in the SSA which has a catchment area of $76km^2$, i.e. 30 times the size of the Nørrebro catchment (Lynettefællesskabet, 2015); consequently, the construction and end of life of this WWTP are not included. All processes included in the modelling of the two systems are listed in Table 3. The temporal scope of the LCA covers the planning period of 100 years.

TABLE 3

2.4 Uncertainty

Following Huijbregts (1998), uncertainties in LCA are divided into three categories: parameter uncertainty, uncertainty from model choices and model uncertainty.

2.4.1 Parameter uncertainty

Parameter uncertainty describes uncertainty in data input into the life cycle inventory of the assessment, resulting, for example, from a lack of data or limited representability. The uncertainty of central parameters is tested for their sensitivity by varying the following inputs (Table 4):

- Pipe construction: a great deal of variety can be found in the literature regarding the construction demands for laying pipes. In the baseline scenario, only excavation work is included in the inventory, as done by several researchers (Andrew and Vesely, 2008; Flynn and Traver, 2013; O'Sullivan et al., 2015). To test this simplification, an estimate of 75L diesel per metre of pipe is used in the model. This is based on measured data from a construction site in Denmark with comparable characteristics. It includes fuel consumption for all required machinery, e.g. soil compressors, and the transportation of soil to treatment facilities.

- End-of-life pipes: pipes are usually not excavated when no longer needed, in order to avoid disruptions due to large construction sites. To prevent collapse, they are filled with thermo beton, which is a lot less dense than normal concrete. This technology is assessed in the baseline scenario, and only small polyethylene pipes are excavated and recycled. Since the decommissioning would take place in 100 years' time and the actual processes can only be guessed, an alternative approach is tested in which concrete pipes are also excavated and treated.
- Reuse of stones (only CMP): some paved areas in parks, e.g. paths, have to be decommissioned during reconstruction, whereby areas are lowered and drainage layers are installed. It is assumed in the baseline scenario that all paved areas can be reinstalled using decommissioned material, and no additional stones have to be produced and transported to the area. In the uncertainty assessment, a reduced reuse rate of 50% is tested.
- Maintenance of green areas (only CMP): in the baseline scenario, only mowing and the disposal of grass cuttings are considered in the operation phase. The frequency is assumed to be 26 times per year,

which is an average of higher demands in summer and lower demands in winter. The alternative scenario includes a transport demand of 5 tons/km for every mowing.

- Road materials (only SSA): where there are channels in the CMP, it is assumed that conventional roads are maintained in the SSA. A possible reduction in road material demand by 20% is assessed, which could be achieved with a change in road design.

Another type of uncertainty important in the case study is caused by "structural" uncertainty and arises from the choice of boundary conditions for the assessment:

- The CC adaptation plan for Nørrebro is in the relatively early planning stage. The system design is currently not specified in detail, and numerous options to implement the different elements are possible. For example, the channels can be implemented using either concrete walls or planted surfaces. This choice is tested with a simplified "green" channel approach, assuming only grass and no other plants on the surface, to benchmark against the baseline scenario with concrete surfaces.
- The SSA is designed to economically benchmark the CMP. It could be optimised if surrounding catchments and other possible discharge paths were taken into account. For example, the SSA suggests 14 sub-surface basins, ranging in size between 227m^3 and 60,000m^3, which would not realistically be constructed in a densely populated area like

Nørrebro. A simple option to improve the system by introducing only one basin is therefore tested.

TABLE 4

Additional parameter uncertainty stems from lack of knowledge in particular about the future operation of the system:

- The assessment has a temporal scope of 100 years, which makes assumptions regarding future operation and disposal processes necessary. In the assessment, it is assumed that currently available processes will still be used in the year 2110. Also, the construction phase of all elements is expected to take place in the coming decades, which is not taken into account in the assessment. The inventory is based on the simplified notion that the plans are fully implemented at the beginning of the planning period.
- "Green" SWM is relatively new in Denmark, and only limited measured data are available for the maintenance and renewal processes. Assumptions are made based on expert interviews and handbooks developed by the Copenhagen Municipality (e.g., Københavns Kommune, 2011). Measured data could decrease uncertainty, but they are currently not available.

Not only is the operation of the system in the future uncertain, but also its performance under changing conditions. Water systems are vulnerable towards climate and socio-economic changes, which cannot be predicted with certainty (Lempert, 2013). However, the optimisation of the assessed alternatives regarding possible future scenarios does not lie within the scope of this paper and the future performance is therefore not assessed.

2.4.2 Uncertainty from model choices and model uncertainty

Uncertainty from model choices generally describes potential inaccuracies resulting from choices made throughout the whole assessment process, from the definition of the functional unit to the choice of modelled processes. Huijbregts (1998) proposes standardising approaches and methods as one possible option to reduce this type of uncertainty, which is done here by following international standards (ISO, 2006a, 2006b). Model uncertainty describes uncertainty inherent in the model due to, for example, spatial and temporal aggregation or characterisation factors used to transfer emissions to impacts. Limitations due to model uncertainty lead to choices, which is why uncertainty from model choices and model uncertainty are described conjointly in this section.

There are known shortcomings and limitations in the impact assessment phase of LCA. Laurent and Hauschild (2015), for instance, identify problems in normalisation references arising from the inventory, characterisation factors and incomplete coverage of environmental flows. This uncertainty is especially high for toxicity categories. Therefore, results in the toxicity categories (carcinogenic and non-carcinogenic human toxicity and ecotoxicity) are not presented in this paper, as it is assumed they do not reflect the actual impacts. Resource depletion relative to global reserves is not included, as impacts resulting from the depletion of metals are likely to be overestimated, while impacts from the use of mineral resources are underestimated (Rørbech et al., 2014). The stratospheric ozone depletion impacts are not discussed, as they most likely reflect inaccuracies in the applied process data, since all important ozone-depleting gases were abandoned in 1996. Consequently, six categories are left out, as uncertainties are identified as unacceptably high. This leaves eight impact categories within the ILCD recommended impact assessment method that are included in the discussion.

All impacts are calculated solely from the processes illustrated in Table 3. Processes arising from the discharge of polluted runoff in the system, such as accumulation of substances in the soil or discharge into freshwater bodies, are not considered. Further research is necessary to include these local impacts in the assessment.

2.5 Allocation of impacts

To meet the different defined flood safety levels, specific elements are utilised. The overall impacts of the system can therefore be allocated to different safety levels. This can be useful when communicating with different stakeholders, or for optimisation during the design phase. Two allocation schemes are tested, one volume-based and one importance-based (Table 5).

Volume-based allocation builds on the flow of runoff from the different domains throughout the system (Fig. 2). Domain A events contribute 75% to the total annual runoff, 25% stem from domain B and 1% from domain C events (Sørup et al., 2016). The quantities of water that pass through the single elements are analysed and based on these, the impacts are allocated to the different domains. If an element, for example, only handles domain A runoff, all impacts arising over the life cycle of this element are allocated to domain A. If several domains are managed in an element, the impacts are allocated based on the fraction of the total water volume handled in the element that is contributed by each domain. For instance, 93% of the water treated at the WWTP stems from domain A events, and only 7% from domain B events, which directly translates to allocation factors.

The other tested allocation scheme is based on a rating of the importance of single flood safety targets, i.e. handling single domains. Stakeholders might value the targets differently: while planners often focus on the design domain (B), people living in flood-prone areas will value protection against extreme events (C) higher, and utilities will try to reduce the flow of lightly polluted everyday runoff (A) through the WWTP. Herein, it is assumed that all flood protection targets are equally important, which means if an element handles runoff from different domains, the impacts will be allocated equally to all domains. If an element handles only runoff from one domain, all impacts will be allocated to that domain (Table 5).

TABLE 5

Some impacts cannot be allocated in both allocation schemes, since they do not arise from processes directly contributing to flood safety. They are caused by necessary by-processes, e.g. for decommissioning of park inventory before lowering. Other impacts cannot be allocated due to the comparative nature of the assessment; for instance, where channels are implemented in the CMP, conventional roads have to be maintained in the SSA.

The choice of allocation scheme depends on the context. While flow-based allocation can advocate designing the system and defining flood safety levels, the importance and cost-based schemes are useful support for communication between stakeholders and the analysis of trade-offs.

3. Results and discussion

3.1 Life Cycle Inventory

Data for the inventory were collected from plans and expert interviews and complemented with information from databases. Since the planning is in the rather early stage, numerous assumptions based on existing literature and expert opinions have been made, upon which the life cycle inventory is built. Some important choices are:

- Elements have different lifetimes and partly have to be renewed during the assessed time period of 100 years. The resulting material, transport, construction and disposal demands are included in the inventory. Several elements consist of different materials which have varying lifetimes, e.g. roads, where the asphalt, bitumen and gravel layers have different renewal demands (Fachverband Infra, 2016).
- To model WWT, only electricity consumption at the plant is considered, as proposed by Godskesen et al. (2013), who develop data specific for Copenhagen.
- No detailed plans for vegetation in the newly implemented green areas have been developed yet. As a simplification, it is assumed that the areas are covered with grass, and trees are planted at a density of $1/40m^2$. They are assumed to be common lime (Tilia x europaea) (Sæbø et al., 2003), which influences the disposal processes: based on the average height and diameter of the species, the volume of wood for composting at the end of life is calculated.

Extensive data collection is carried out for processes in all life cycle stages (Table 3). The inventory specifies energy, fuel, transport and material demands. Table 6 lists the central material demands, and a comprehensive inventory including assumptions is provided in the supporting information.

TABLE 6

3.2 Impacts of climate change adaptation

The impacts of the CMP vary between 3 and 18 PE/year. The impacts of the SSA are consistently higher in all impact categories, ranging between 14 and 103 PE/year (Fig. 3). The magnitude of the results seems reasonable considering that 79,000 people live in the administrative area Nørrebro (The City of Copenhagen, 2015b), which is to a large extent covered by the catchment. The impacts of the passive SWM systems only contribute a small fraction of the total impacts that arise in the catchment, which take into account all goods and services, such as transport and energy. For climate change impacts, this translates to approximately 0.02% of the average total impacts per person, which is less than Clauson-Kaas et al. (2012) estimate as a contribution of stormwater treatment alone (0.15% – 0.5%). It is difficult to compare the calculated impacts to the results found in the literature, since different methodology and system definitions are used. De Sousa et al. (2012) compare two different SWM alternatives for a catchment area of 784 ha, which is three times the size of the Nørrebro catchment. Assessing the impacts arising from green infrastructure elements, or a retention basin alternative, they found that the implementation of the green infrastructure caused emissions of 20,000 t CO_2 eq., that 100,000 t CO_2 eq. are caused by the basin. Overall emissions for the CMP are 11,500 t CO_2 eq., and 31,200 t

CO_2 eq. for the SSA. In both cases, the impacts of the green infrastructure-based system are significantly lower, and a major share of the impacts in all alternatives stems from material production.

For both the CMP and the SSA, the category with the highest impacts is depletion of fossil resources (18 PE/year for the CMP, and 103 PE/year for the SSA), mainly caused by the production of concrete, steel and road materials, and the consumption of fuels for construction. For the CMP, the second-highest impacts are caused by a group of categories (climate change and marine and terrestrial eutrophication) with impacts at around 14 PE/year, which mainly stem from fuel combustion in the production of materials like concrete. For the SSA, the second-highest impacts are for climate change (52 PE/year). Across the categories, impacts from the SSA are three to 12 times higher than the impacts from the CMP. The largest difference is observed for freshwater eutrophication. Eutrophication impacts in freshwater are caused by discharges of phosphorus and phosphates, and only emissions from life cycle processes and the WWTP are taken into account. As water quality is defined as a secondary function, no direct discharges from runoff are taken into account. This could possibly increase the eutrophication impacts of the CMP, and so further research is necessary to quantify this indication.

FIGURE 3

Analysing the contribution of the single life cycle stages to the total impacts shows that material production contributes most to the total impacts in both alternatives (42 – 75% for the CMP, and 62 – 96% in the SSA) (Fig. 4). This is in accordance with (Flynn and Traver, 2013), who assess the impacts of rain gardens. They find that 80% stem from material production, and only 20% from construction processes, while other life cycle stages have minor or even positive impacts. In the CMP, concrete production for channels and pipes causes between 75 and up to 99% of the material production impacts. The channels are implemented on road areas which explains the high contribution of roads in the CMP to the overall impacts (55 – 67%). Parks are the elements with the second-highest impacts (10 – 41%), with the transport of material for the drainage layers for runoff treatment being the most significant process (36 – 74% of the park impacts). More than 7,000t of gravel and 1,500t of clay are assumed to be necessary to construct the drainage layers, and these extend over an area of almost 5,000m^2. It is also assumed that the gravel layer has to be renewed every 25 years, due to the accumulation of pollutants. Positive environmental impacts are caused by recycling pipes made from polyethylene, which reduces the overall impacts by between 12 and 21%.

Steel used in basins causes most of the impacts to the SSA at the material production stage (26 – 79%), with concrete being the second most causal material (6 – 28%). Also, asphalt and bitumen required for road renewal in the SSA cause relatively high impacts (14 – 69% of the material production impacts). This leads to high contributions to the total impacts by both roads (16 – 65%) and basins (28 – 80%) (Fig. 4). Emissions of carbon dioxide, NOx, sulphur dioxide and phosphate cause high impacts in the different impact categories. They are mainly due to high energy demands for the production process of steel, and in the model it is assumed that this energy is provided by burning coal, gas and oil. The Danish government is aiming to replace these completely with renewable energy sources by 2050 (The Danish Government, 2011). This change would lead to reductions in impacts, e.g. for fossil resource depletion due to electricity consumption for WWT.

Operation contributes insignificantly in both alternatives and across impact categories. This is due to the fact that even though the systems have to be maintained over 100 years, the attributed resource and energy demands are small compared to the initial implementation stage, where large amounts of materials and intensive construction works are necessary. Decommissioning and disposal only take place once, and since a lot of the waste can be composted (grass and tree clippings) or landfilled (gravel and soil), these processes also only contribute marginally.

FIGURE 4

3.3 Uncertainty

3.3.1 Sensitivity analysis

Parameters that are characterised by high uncertainty are tested for their influence on the results in a sensitivity analysis. Impacts from alternative scenarios with significant influence are illustrated in Fig. 5. The parameter showing the largest effect in both scenarios is the pipe construction process: taking into account not only excavation, but also other machinery use based on an expert estimate, increases total impacts across the categories by 1% to 68% for the CMP and by <1 to 18% for the SSA (Fig. 5). The terrestrial eutrophication impacts are most affected, with NOx emissions from fuel combustion causing the largest share of the impacts. The high sensitivity shows the importance of taking into account supporting processes and using case-specific data. Depending on the size and depth of the pipe, as well as the characteristics of the area (existing structures and restrictions), the required machinery and processes for laying pipes vary widely. These data can only be collected with certainty during the implementation phase of the project.

Opposed to the construction phase, the end-of-life of pipes does not contribute significantly. The overall impacts only vary by up to 3% for the CMP, and less than 1% for the SSA, if the concrete pipes are excavated and treated instead of being filled with thermo beton. Also, the alternative maintenance scenario, which includes transport of equipment to the site, does not lead to significant increases in CMP impacts (<1% for all impact categories). Assuming a reduced reuse rate of 50% for stones for paved areas in the CMP increases the overall impacts by 13 to 30%. A reduction in used road materials by 20% in the SSA lowers the impacts by 3 to 13% (Fig. 5). The reuse rate of materials and the demand for road materials are parameters that can be optimised, and they should therefore be taken into consideration throughout the planning of a CC adaptation strategy. However, all tested alternative SSA scenarios have higher impacts than the CMP scenarios. Taking parameter uncertainty into account, therefore, does not change the overall conclusion that the CMP is the environmentally preferable alternative.

FIGURE 5

3.3.2 Structural uncertainty

Two different system designs are tested to assess structural uncertainty. For the CMP, a change in design from concrete to “green” channels reduces the impacts by 9 to 27% (Fig. 6). The assessment of the “green” channel design is simplified, and the impacts could therefore likely be higher, albeit still below the baseline scenario, as the use of concrete causes significant impacts in all life cycle stages: It is energy-intensive to produce, heavy to transport and poses a significant burden at the end of its life. The large differences between alternative channel layouts highlights the possibility of influencing environmental impacts during the system design and is a strong argument for conducting an LCA to reveal optimisation possibilities and potential trade-offs already in an early stage of the planning, when substantial design choices are yet to be made. Changes in design that reduce the demand for resource- and energy-intensive materials, i.e. “green” elements that fulfil the same function, will lower the environmental impacts of SWM solutions. This conclusion is in accordance with O’Sullivan et al. (2015), who find that stormwater treatment systems using a lot of concrete have the largest environmental impacts.

For the SSA, an improved design alternative incorporating only one basin, instead of 14, is tested. This leads to a reduction in impacts between 9 and 15% (Fig. 6). Additionally, for a decreased number of basins, a reduction in retention volume would be environmentally beneficial. It might also be economically favourable to compensate the greater damage that would arise from flooding instead. This option could be considered in the decision-making process. However, the CMP remains the environmentally preferable option, regardless of structural changes in the systems.

FIGURE 6

3.4 Allocation of impacts to rain domains

Using the volume-based allocation scheme, the management of domain B events with return periods between 0.2 and 10 years causes the major share of impacts in both alternatives (90 – 95% for the CMP, and 30 – 81% for the SSA) (Fig. 7). This seems like a logical consequence of the fact that events with a return period of 10 years are usually used to design SWM systems. Domain A runoff has a much larger total annual volume, but it can be handled in smaller systems, i.e. designed to infiltrate instead of discharge, which causes fewer environmental impacts. As it is assumed that all domain A runoff can be handled in the new green areas, the share of impacts of this domain is very small in the CMP (1 – 6%). Other elements, like channels and pipes, are possibly used during domain A events, which would lead to a higher share of impacts allocated to domain A. Only a detailed flow analysis during a later planning stage can reduce the uncertainty of the results based on the volume based allocation.

The handling of domain C runoff, which stems from extreme events with a return period greater than 10 years, does not contribute significantly to the overall results (4 – 5% of the CMP, and ≤ 1% of the SSA) (Fig. 7), due to the primary function of the system, which allows 10cm of water on the surface during domain C events. This creates a retention space without actually implementing SWM elements. Also, it is assumed that structures designed for domain B events are used during domain C events, until their capacity is reached and the water “overflows”, either into lakes (in the CMP) or a harbour (in the SSA).

However, using the importance-based allocation scheme, domain C contributes much more significantly to the impacts of the CMP (48 – 49%), which is equal to the contribution of domain B. It is assumed that all discharge and retention elements of the CMP are both used in cases of domain B and C events. If both domains are valued equally, the impacts have to be distributed uniformly, regardless of the frequency and depth of the events.

In the SSA, the share of domain C is still small compared to domain B (1 – 3%, and 39 – 81% respectively). The increased capacity of the sewer system, by introducing pipes, is assumed to ensure a maximum water level of 10cm on the surface during domain C events, and no additional structures like basins are used, which limits the environmental impacts.

The share of unallocated impacts not directly linked to the functional unit is quite large for the SSA (16 – 65%) (Fig. 7). These impacts mainly result from renewed roads, in that where there are channels implemented in the CMP, it is assumed that the traditional road surface has to be maintained in the SSA, which causes renewal, operation and disposal demands. The roads do not handle runoff, though, and their impacts can therefore not be allocated to any of the three domains. These implicitly required elements causing “hidden” impacts have to be included to ensure comparability between systems. Unallocated impacts arise also in the CMP, due to necessary preparation works, for example in connection with reconstructing parks. They constitute a much smaller fraction of the total impacts than in the SSA (≤ 1%).

The volume-based allocation shows that even though the plans aim to prevent damage from extreme events, environmental impacts mainly arise from handling smaller events. In the planning processes, especially when defining flood safety targets, this is valuable information. By adjusting both acceptable water levels and the frequency of allowed flooding, environmental impacts can be reduced, but greater damage will occur. By allocating the impacts to rain domains, this trade-off can be quantified and therefore supports a transparent decision-making process. Importance weighting can add more information, if flood safety levels are valued differently. While some plans, as in this case, aim to handle over 99% of all rain events, others focus on frequent, small rain events to reduce the load going into the sewer system. Importance based-allocation reflects this prioritisation; for example, if domain A events are the focus of an adaptation plan, it seems acceptable that they will also contribute the main share of the impacts. If, on the other hand, secondary interests cause significant environmental impacts, there is potential for optimisation in the planning phase. The difference in results between the allocation schemes shows a discrepancy between anticipated system design and actual system function: The main goal is protection against extreme events, which is mirrored in the weighting-based allocation. However, implemented elements are mainly used in the case of events with a return period of up to 10 years, and not during more severe events.

FIGURE 7

4. Conclusion

LCA of CC adaptation strategies provides quantitative information regarding the environmental impacts of different adaptation options. By defining the primary function as providing flood safety targets, the comparability of the alternatives is ensured. However, defining a water volume or catchment area as the functional unit does not allow the same conclusions. This novel approach to defining the system and scope allows conclusions on a system level, in contrast to previous research focused on single installations or only parts of SWM systems, instead of comprehensive strategies. The focus of previous research is often on CO_2 emissions and energy demands, but analysing eight impact categories gives a broader picture of occurring environmental impacts. Using the Three Points Approach to differentiate between rainfall domains allows a clear definition of the functional unit. As such, we found that:

- Allocating environmental impacts to different flood safety levels provides valuable information during the planning process. It allows for analysing the contribution to the overall impacts of managing the different domains, which can be used to optimise systems and define design criteria. It also facilitates communication between stakeholders with different priorities and allows one to quantify trade-offs between environmental sustainability and flood safety.

- In order to optimise the environmental performance of SWM systems, LCAs are ideally conducted at different stages of the planning process, in order to influence the design process already in an early stage. Uncertainty has to be assessed systematically, in order to be able to draw conclusions. Parameter and structural uncertainty is high in early planning stages, and a sensitivity analysis allows one to identify environmentally preferable design alternatives while taking uncertainties into account.
- The case study shows that the Cloudburst Management Plan, which mainly uses green infrastructure elements, has 71 to 92% fewer environmental impacts than a sub-surface alternative (3 to 18 PE/year for the CMP, and 14 to 103 PE/year for the SSA). Material production processes cause the largest share of overall impacts, with concrete, steel and road materials contributing most in this regard. Handling of events with a return period between 0.2 and 10 years contributes most to the impacts. Small events (return period up to 0.2 years) contribute the least, regardless of the allocation scheme. Analysing uncertainty highlights the importance of using site-specific data.

Appendix A. Supporting information

Acknowledgements

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Table 1. Study scope of the existing literature on life cycle assessment in stormwater management. Life cycle stage abbreviations: material production (M), construction (C), operation (O), decommissioning and disposal (D), transport (T). *Study does not explicitly define a functional unit.

Reference	Region	Functional unit	Temporal scope	No. of alternatives	No. of impact categories	Life cycle stages[1]
(Kosareo and Ries, 2007)	Pittsburgh, US	Roof area*	50 years	3	15	O, D, T
(De Sousa et al., 2012)	Bronx, US	Area	50 years	3	1	M, O, T
(Spatari et al., 2011)	New York City, US	Area	(not specified)	2	2	M, O, T
(Taylor and Barrett, 2008)	California, US	Area*	20 years	7	1	C, O
(Wang et al., 2013)	Northeast US	Water volume*	(not specified)	3	2	M, C, O, T
(Andrew and Vesely, 2008)	North Shore City, NZ	Water volume	50 years	3	2	M, C, O, D
(Flynn and Traver, 2013)	Villanova, US	Area	30 years	1	8	M, C, O, D, T
(Clauson-Kaas et al., 2012)	Copenhagen, DK	Water volume	1 year	4	13	M, O, D
(Petit-Boix et al., 2015)	Sao Carlos, BR	Water volume	10 years	3	10	M, C, D, T
(O'Sullivan et al., 2015)	NZ	Water volume	30 years	3	18	M, C, O, T

Table 2. Flood safety levels and reference flows for the different alternatives. The return periods refer to anticipated precipitation amounts for Copenhagen in 2110.

Flood safety level (for the year 2110)	Reference flow	
	Cloudburst Management Plan	Sub-surface alternative
Domain A: No water on the surface for events with a return period up to 0.2 years	Green road elements	Pipes, WWTP
Domain B: Water above the surface only in designated areas for events with a return period up to 10 years	Pipes, channels, retention volumes in parks, drainage layers	Pipes, underground retention basins, wastewater treatment plant
Domain C: A maximum of 10cm of water on the surface for events with a return period up to 100 years	Pipes, channels, retention volumes in parks, drainage layers	Pipes

Table 3. Considered processes and lifetimes for the different elements in all life cycle stages of the two alternatives. The detailed inventory is provided in the supporting information. * Components of the elements have varying lifetimes, e.g. grass areas will be completely renewed every 2 years, while trees only have to be planted once. ** Complete reuse of existing pavement material, and no additional material demands are assumed.

Element		Alternative	Materials	Transport	Preparation & construction	Operation & maintenance	Decommiss. & disposal	Life time
Roads	Channels	CMP	Concrete	Truck	Excavation, soil disposal	Cleaning	Excavation, treatment	25 years
	Green areas	CMP	Grass seeds, tree seedlings	Truck	Sowing, planting	Cutting, composting	Excavation, composting	2 – 100 years*
	Renewed road	SSA	Asphalt, bitumen, gravel	Truck	Excavation, soil disposal	Cleaning	Exc., treatment, landfilling	25 years
Parks	Lowered areas	CMP	-	-	Excavation, soil disposal	-	-	-
	Drainage layers	CMP	Clay & gravel	Truck	Excavation	-	Excavation, landfilling	25 – 50 years*
	Paved areas	CMP	-**	-	Excavation, soil disposal	-	-	30 – 95 years*
Pipes	Concrete pipes	CMP, SSA	Concrete	Truck	Excavation, soil disposal	Cleaning, inspection	Filling with thermo beton	100 years
	Polyethylene pipes	CMP, SSA	Polyethylene	Truck	Excavation, soil disposal	Cleaning, inspection	Excavation, recycling	100 years
Basins	Underground retention basins	SSA	Reinforced concrete	Truck	Excavation, soil disposal	-	Excavation, treatment	100 years
WWTP	Wastewater treatment	SSA	-	-	-	Electricity consumption	-	-

Table 4. Approach for testing the importance of parameter uncertainty.

Parameter	Baseline approach	Alternative approach
Pipe construction	Only excavation works	Excavation, transport and other processes
End-of-life concrete pipes	Filling of pipes with thermo beton	Excavation and treatment
Reuse of stones	100% reuse	50% reuse
Maintenance of green areas	Only mowing and disposal of clippings	Mowing, disposal of clippings and transport
Road materials	10cm asphalt, 10cm bitumen, 55cm gravel	Total material reduction by 20%
Channel design	Concrete surface	Grass surface
Number of basins	14 (99,942m^3)	1 (100,000m^3)

Table 5. Volume of runoff from the different domains managed by single elements, and the resulting allocation factors.

	Element		Allocation factors: volume-based			Allocation factors: importance-based		
			Domain A	Domain B	Domain C	Domain A	Domain B	Domain C
CMP	Roads	Channels	0%	96%	4%	0%	50%	50%
		Green areas	100%	0%	0%	100%	0%	0%
	Parks	Lowered areas	0%	98%	2%	0%	50%	50%
		Drainage layers	0%	98%	2%	0%	50%	50%
	Pipes	Concrete & PE pipes	0%	96%	4%	0%	50%	50%
SSA	Basins	Sub-surface basins	0%	100%	0%	0%	100%	0%
	Pipes	Concrete pipes	75%	24%	1%	33%	33%	33%
	WWTP	Wastewater treatment	93%	7%	0%	50%	50%	0%

Table 6. Quantities of the most important materials in both alternatives. The complete inventory is provided in the supporting information.

Material	Concrete [t]	Steel [t]	Asphalt [t]	Bitumen [t]	Gravel [t]	Clay [t]	Grass seeds [t]	Total transport [tons.km]
Cloudburst Management Plan	40,905	-	-	-	29,102	3,392	12	9,761,526
Sub-surface alternative	46,355	4,497	17,586	3,920	16,408	-	-	19,013,544

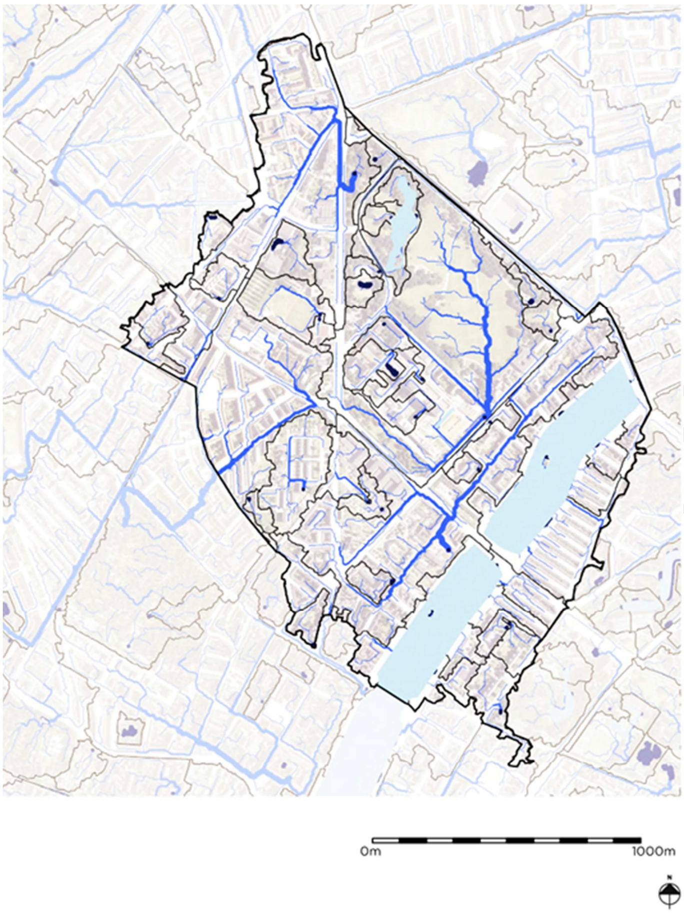
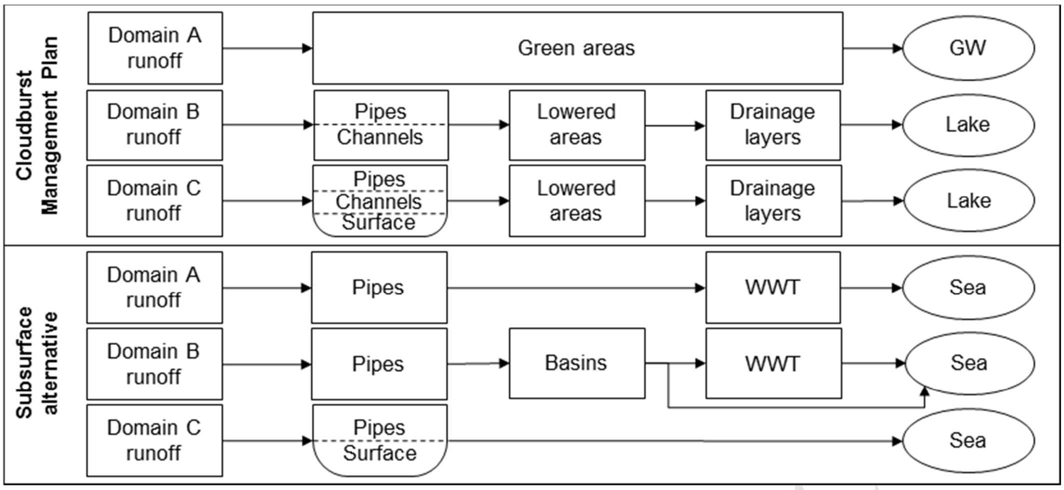


Fig. 1. Water flow in the Nørrebro catchment (courtesy of Rambøll & Atelier Dreiseitl).

904 

905 Fig. 2. Runoff flow from different rain domains through the system, for the
906 Cloudburst Management Plan and the sub-surface alternative.

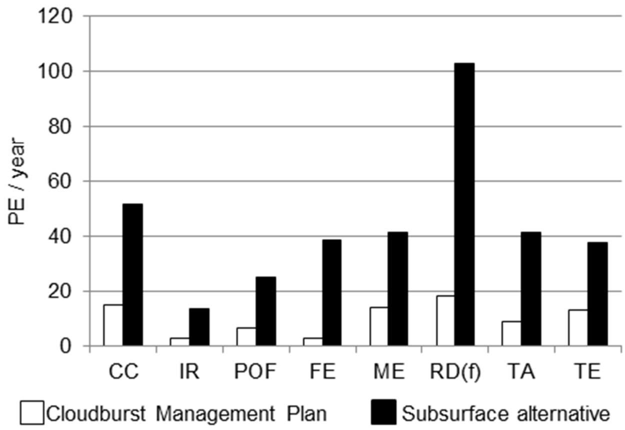


Fig. 3. Normalised environmental impacts for the Cloudburst Management Plan (CMP) and the sub-surface alternative (SSA) per year. Impact category abbreviations: climate change (CC), ionising radiation (IR), photochemical oxidant formation (POF), freshwater eutrophication (FE), marine eutrophication (ME), resource depletion (fossil) (RD(f)), terrestrial acidification (TA), terrestrial eutrophication (TE).

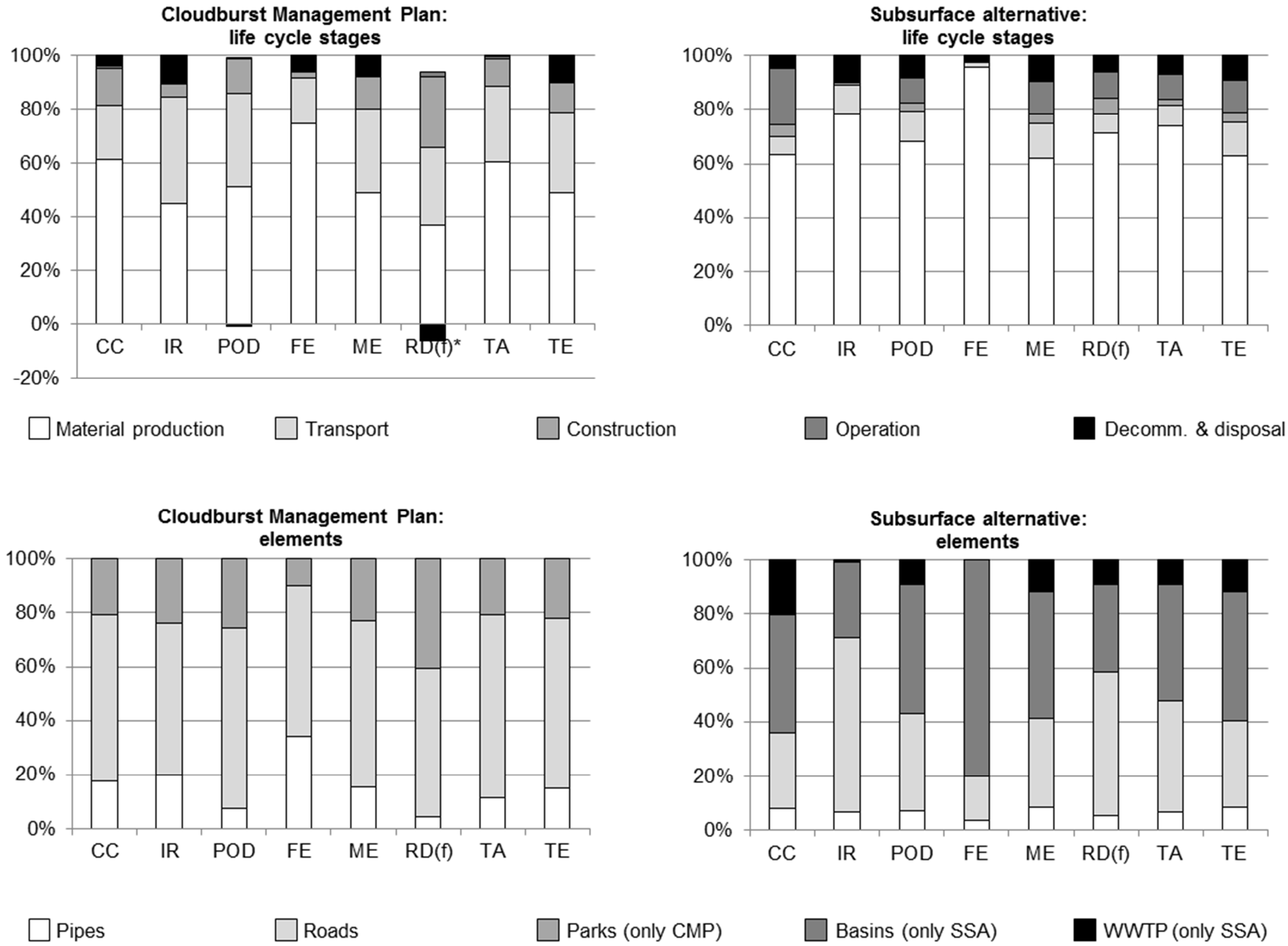


Fig. 4. Contribution of the single life cycle stages and system elements to the total environmental impacts of the Cloudburst Management Plan and sub-surface alternative. *Negative impacts result from reduced resource consumption, due to the recycling of polyethylene. Refer to Fig. 2 for abbreviations.

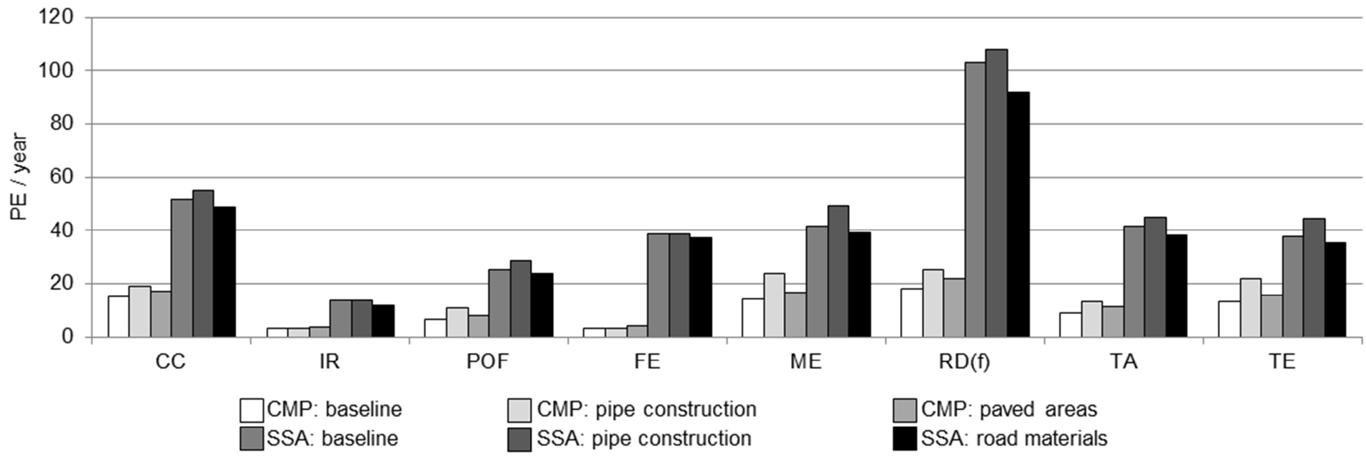
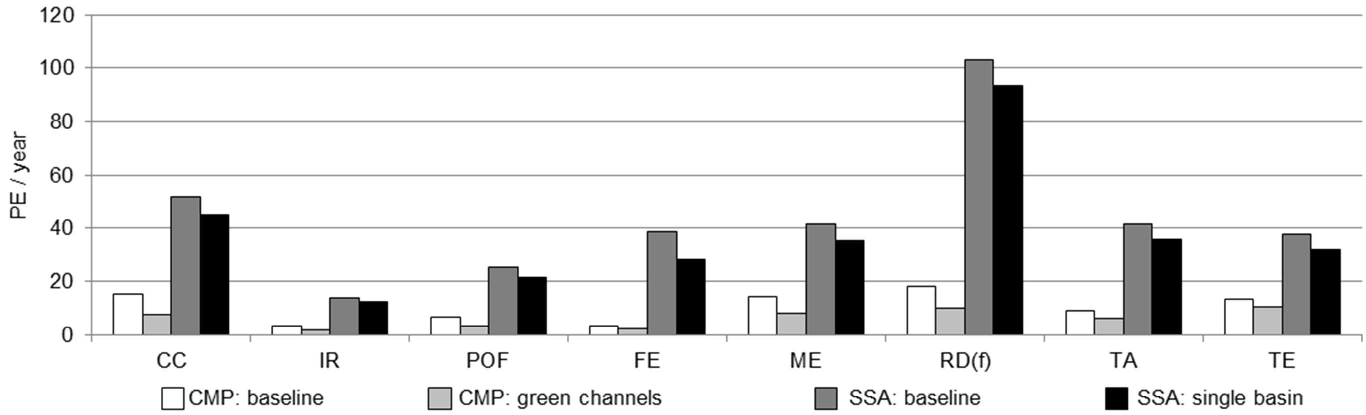
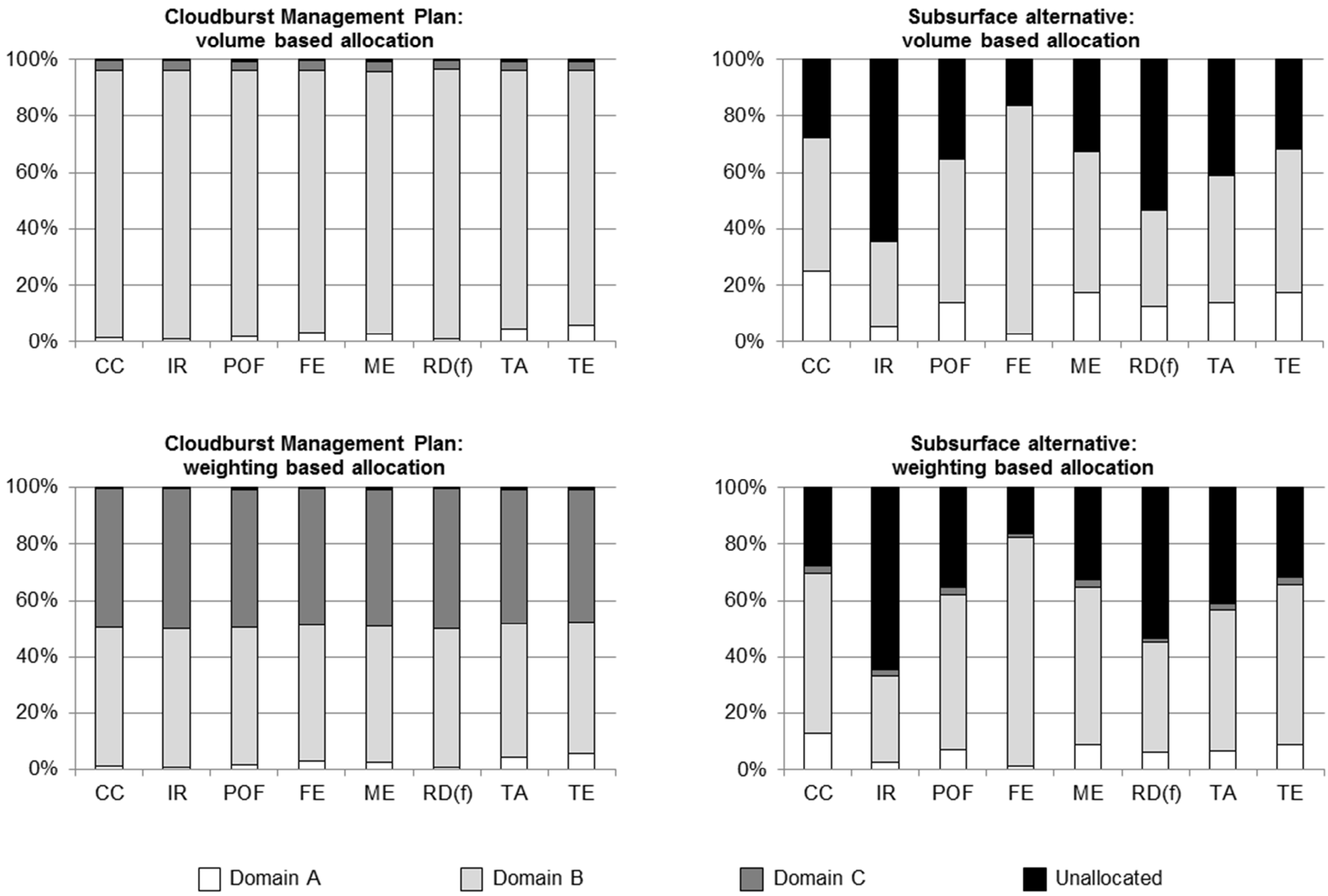


Fig. 5. Normalised environmental impacts of the Cloudburst Management Plan (CMP) and sub-surface alternative (SSA) baseline scenario and four alternatives with varying input parameters. Refer to Fig. 2 for abbreviations.



926 Fig. 6. Normalised environmental impacts of the Cloudburst Management
927 Plan (CMP) and the sub-surface alternative (SSA) baseline scenarios and
928 two structurally different scenarios. Refer to Fig. 2 for abbreviations.



930 Fig. 7. Environmental impacts of the Cloudburst Management Plan and a
931 sub-surface alternative, allocated to different rain domains based on water
932 volume and the weighting of flood safety targets. Refer to Fig. 2 for
933 abbreviations.

Life cycle assessment of stormwater management in the context of climate change adaptation

Sarah Brudler, Karsten Arnbjerg-Nielsen, Michael Zwicky Hauschild, Martin Rygaard

Highlights

- Environmental impacts of climate change adaptation strategies are assessed
- A life cycle assessment is conducted on a large -scale strategy for the first time
- Comparability is ensured through equal flood safety level definitions
- Impacts are allocated to different flood safety levels