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Life cycle assessment of point source emissions and infrastructure impacts of four types of urban stormwater systems

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11

12 Key words: urban water systems, green infrastructure, stormwater discharges,
13 environmental impacts, ecosystem damage, resource availability

14 Graphical abstract

16 Abstract

17 The implementation, operation and decommissioning of stormwater management systems
 18 causes environmental damage, while at the same time reducing pollutant loads in
 19 receiving waters by treating stormwater. The focus in research has been either on
 20 assessing impacts caused by stormwater infrastructure, or risks associated with
 21 stormwater discharges, but rarely have these two sources of environmental impacts been
 22 combined to allow a comprehensive environmental evaluation of stormwater management.
 23 We assess the environmental sustainability of four different generic stormwater
 24 management systems for a catchment of 260ha by a) modelling the flow of pollutants in
 25 stormwater, and resulting point source emissions to freshwater, and b) quantifying
 26 emissions and resources for all relevant processes associated with the life cycle of the
 27 infrastructure. Using life cycle impact assessment, we quantify the resulting environmental
 28 impacts and consequent damage to two areas of protection – ecosystems (expressed in
 29 time-integrated species loss) and natural resource availability (expressed in extra costs for
 30 future resource extraction). Our assessment shows that combined stormwater

management causes the highest damage to both ecosystems ($1.4\text{E-}03$ species.yr/yr) and resource availability ($8.8\text{E}+03$ USD/yr). Separate systems using only green infrastructure were found to avoid damage to resource availability (-3.7 to -5.2 USD/yr) and cause lower ecosystem damage (1.1 to $1.3\text{E-}03$ species.yr/yr). Stormwater discharges contribute significantly to the total ecosystem damage of the different systems (36 to 88%), and the sustainability of separate systems can be further improved by optimizing the removal efficiency of low-tech elements like surface basins and filter soil. The systems are designed according to engineering standards. Choosing different criteria, e.g. identical flood safety levels, would result in substantial changes of the relative performance of the systems. The findings highlight the importance of including point source emissions into the assessment to allow comparative conclusions and minimisation of environmental damage of stormwater management.

1. Introduction

Stormwater management (SWM) aims to prevent damage to humans, property and the environment by limiting exposure to polluted stormwater and preventing flooding. At the same time, the implementation, operation, and decommissioning of these systems cause environmental damage, e.g. through emissions of greenhouse gases associated with the energy and transport that is involved. In this paper, we use life cycle assessment (LCA) to quantify the caused environmental damage (ISO, 2006a, 2006b). The whole life cycle from implementation (material generation, transport and construction), through operation and maintenance, to end of life (decommissioning and disposal or recycling) is considered. As a novelty, we include damage from discharges of polluted stormwater in the assessment.

LCA is increasingly used to analyse multifunctional systems, such as urban water systems (UWS) (Loubet et al., 2014). Numerous studies assessed the impacts of single installations and some also considered complete SWM systems (Brudler et al., 2016). However, most publications focused on environmental impacts caused by the systems, and did not include impacts from discharges of stormwater itself. This limitation in scope consequently hinders the comparability as these discharges are specific for each SWM system and neglecting differences in their impacts might lead to wrong conclusions. Taylor and Barrett (2008) took pollutant discharges to the environment into account indirectly by relating life cycle impacts of different alternatives to their removal efficiency. Spatari et al. (2011) assessed the changes in electricity consumption at the wastewater treatment plant (WWTP) caused by alternate discharge paths, but neglected impacts by direct discharges. Clauson-Kaas et al. (2001) included eutrophication and toxicity impacts of selected pollutants, but only assessed combined sewer overflow treatment and not a comprehensive strategy including a number of elements to manage stormwater. Byrne et al. (2017) used a similar approach for roadway drainage systems. Wang et al. (2013) included eutrophication impacts of stormwater discharges in the LCA of catchment-wide SWM strategies, but neglected ecotoxicity impacts.

Many compounds are present in stormwater, including nutrients and toxic substances such as metals (Brudler et al., 2019; Ingvertsen et al., 2011). Assessing their impacts using LCA is challenging, as stormwater discharges are characterized by large temporal and spatial variations, which are difficult to represent in LCA which quantifies total emissions but not the resulting environmental concentrations or location specific impacts (Pfister and Hellweg, 2009). Existing publications on pollutants in stormwater have a strong focus on peak concentrations and associated risks (Göbel et al., 2007; Gosset et

77 al., 2017; Wicke et al., 2015). In contrast, LCA quantifies long-term, accumulative effects,
78 for which average concentrations are needed. Only recently has life cycle impact
79 assessment been used to quantify impacts of stormwater discharges. Brudler et al. (2019)
80 calculated generic impacts of stormwater discharges, and Risch et al. (2018) assessed the
81 impacts of wet and dry weather discharges. The relative importance of stormwater
82 discharges for the ecotoxicity and eutrophication impacts of SWM systems has never been
83 quantified at catchment scale. Excluding stormwater discharges does not only influence
84 the magnitude of the total impacts, but could also lead to incorrect decisions when
85 comparing different SWM systems with different treatment efficiencies.

86 To distinguish impacts resulting from stormwater discharges from the impacts
87 associated with the life cycle of the SWM infrastructure, we denote them as point source
88 emission impacts (United States Federal Law, 2002). All other impacts resulting from
89 implementation, operation, and decommissioning of SWM systems are denoted as
90 infrastructure impacts. The two impact sources should be analysed in combination when
91 assessing the environmental sustainability of SWM systems. For example, a reduction of
92 point source emission impacts may be accompanied by increased infrastructure impacts if
93 it is achieved through more extensive treatment. This trade-off has been highlighted also in
94 other areas, e.g. remediation of contaminated sites (Lemming et al., 2010). As a novelty,
95 we quantify all relevant infrastructure and point source emission impacts of four complete
96 SWM systems in a generic case study. We then combine the two to calculate the total
97 environmental damage to assess the environmental performance for the different SWM
98 systems (Figure 1). This allows us to compare the environmental performance of different
99 archetypal SWM systems and to evaluate the relative importance of point source

emissions and infrastructure life cycle. Furthermore, we analyse the uncertainties accompanying the calculated environmental damage.

Figure 1. Sources of environmental impacts in stormwater management: infrastructure and point source emission impacts, causing damage.

2. Methods and data

When comparing different systems, it has to be ensured that all alternatives fulfil the same essential, primary function, which is expressed in a functional unit (ISO, 2006b). In our case, we defined the functional unit as stormwater management according to existing Danish flood safety standards (IDA Spildevandskomiteen, 2005) in a catchment area of 260 ha (100ha impervious area) over 25 years. The standards dictate that separate systems are to be dimensioned to prevent flooding for events with a return period of five years, while combined systems are to be dimensioned for ten year return periods. This is within the typically accepted range of standards for sewer systems in Europe. The difference in protection level is due to the higher human health risk during flooding with combined sewage. Hence this functional unit is preferred over one of identical flood safety. The standards do not define water quality targets for discharge of stormwater. The catchment characteristics, and infrastructure elements and pollution management in the different systems are further explained in section 2.3.

2.1 Inventory

The processes required within each of the systems to provide the defined functional unit were described using documentation of existing and planned SWM systems, literature, and expert interviews (SI). Their exchanges with the environment were modelled in EASETECH V2.4.5 (Clavreul et al., 2014) using standard unit process data from the Ecoinvent database (Weidema et al., 2013), and compiled in the life cycle inventory (ISO, 2006b).

We considered point source emissions of pollutants in stormwater during the operation stage separately. We first assessed the flow path of stormwater through the different systems, and then quantified the pollutant loads using generic concentration data per litre of stormwater, derived from Brudler et al. (2019). Besides phosphorous (3.2mg/l), only copper (59µg/l) and zinc (490µg/l) emissions were included in the point source emission inventory, as they have been shown to cause over 90% of the ecotoxicity impacts of stormwater discharges across a wide variety of stormwater compositions (Brudler et al., 2019). Removal efficiencies were calculated based on values found in literature and databases for the single SWM elements, and the flow of pollutants was modelled accordingly. Leaching of metals from agricultural soil was modelled using fate factors from the USEtox® model (Rosenbaum et al., 2011). For phosphorous, a conservative leaching rate of 50% was assumed based on runoff and infiltration factors for different soil types published by Kirkeby et al. (2013).

2.2 Impact assessment

In the life cycle impact assessment (LCIA), the life cycle inventory was translated to environmental impacts (ISO, 2006b). Midpoint impacts I in 13 different categories i were

142 calculated as the sum the single substance emissions or resource consumption E ,
 143 multiplied with a midpoint characterisation factor ($CF_{m,i}$) that for each flow represents its
 144 ability to contribute to the modelled impact:

$$145 \quad I_i = \sum(E * CF_{m,i}) \quad (1)$$

146 We used the characterisation factors from ReCiPe 2016 for 10 impact categories
 147 (Huijbregts et al., 2016). Point source emissions of phosphorous were translated to
 148 freshwater eutrophication impacts employing the methodology described by Brudler et al.
 149 (2019). To assess toxicity impacts of infrastructure and point source emissions, we used
 150 characterisation factors from the USEtox® model (Rosenbaum et al., 2008). USEtox is not
 151 part of the ReCiPe 2016 method, but it has the same scope as the method applied in
 152 ReCiPe (USES-LCA 2.0), and the substitution leads to no overlapping or double counting
 153 with the other impact categories covered by ReCiPe 2016. As impacts on groundwater are
 154 not represented in standard LCIA (Lemming et al., 2010), we used characterisation factors
 155 for freshwater discharges for leachate reaching groundwater to represent its ecotoxicity
 156 impacts. Assuming that all pollutants in the aquifer eventually seep into surface freshwater
 157 is a worst case assumption.

158 Annual point source emissions were calculated directly based on the discharge of
 159 pollutants over one year. Infrastructure impacts were first calculated for the whole
 160 assessment period of 25 years, and then normalized in relation to the lifetime of the single
 161 elements. Annual operation impacts were found as the average annual impacts over the
 162 assessment period of 25 years. Total annual impacts $I_{infrastructure,annual,i,k}$ of system k in the
 163 impact category i were then calculated by adding up impacts from all elements:

$$I_{infrastructure,annual,i,k} = \sum_j \left(\frac{I_{material,i,j} + I_{transport,i,j} + I_{construction,i,j} + I_{disposal,i,j}}{lifetime_j} + \frac{I_{operation,i,j}}{assessment\ period} \right) (2)$$

Where $I_{i,j}$ are the total impacts over the assessment period of 25 years, and $lifetime_j$ is the expected life span of the element j .

Impacts at midpoint level allow to compare systems within specific categories, e.g. to evaluate which scenario has the lowest global warming impacts. To assess the relative performance of the systems at midpoint level, an internal normalisation was performed relating the impacts to the systems with the highest and lowest impact in each impact category by assigning each impact a value between 1 (highest impact) and 0 (lowest impact):

$$I_{annual,normalised,i,k} = \frac{I_{annual,i,k} - \min(I_{annual,i,1}, \dots, I_{annual,i,n})}{\max(I_{annual,i,1}, \dots, I_{annual,i,n}) - \min(I_{annual,i,1}, \dots, I_{annual,i,n})} (3)$$

Where $I_{annual,normalised,i,k}$ is the annual normalised impact of system k in the impact category i , $I_{annual,i,k}$ is the annual impact of system k in the impact category i , and n is the number of compared systems.

At midpoint level, point source emission impacts were assessed separately from the infrastructure impacts to keep track of where environmental impacts arise and analyse how this varies between the compared systems. The separate assessment at midpoint level also allows decision makers to assign different importance to them reflecting their different nature in that the point source impacts occur locally during rain events while the infrastructure impacts are spread over its life cycle and occur at multiple locations.

The scores for the midpoint impact categories are expressed in category specific units, which means that the systems cannot be compared across impact categories. To

allow such a comparison, the resulting environmental damage was calculated for the midpoint scores, reflecting the ability of the midpoint indicators to contribute to damaging different areas of protection that represent components of the environment of direct value to human society (UNEP/SETAC, 2005). In ReCiPe, the areas of protection are defined as ecosystems, resource availability, and human health (Goedkoop et al., 2013). Damage from different impact categories to the same area of protection are expressed in the same unit, which means that the systems' performance can be compared across midpoint impact categories within each area of protection. A midpoint impact category contributes to damage to one or more areas of protection, for example climate change causes damage to ecosystems and human health, but does not affect resource scarcity in the ReCiPe methodology (Huijbregts et al., 2016). We multiplied midpoint impacts with endpoint characterisation factors CF_e from ReCiPe 2016 and the USEtox® model, and then added infrastructure and point source emission damage up to calculate total annual damage $D_{total,annual}$ to each area of protection p :

$$D_{total,annual,p,k} = \sum_i (I_{infrastructure,annual,i,k} * CF_e) + \sum_i (I_{point\ source,annual,i,k} * CF_e) \quad (4)$$

Where $I_{annual,i,k}$ is the annual impact of system k in the impact category i .

2.3 Case description and systems

The Skibhus catchment in Odense, Denmark was used as the basis for a generic case study (Zhou et al., 2012). It has an extent of 260ha, of which 100ha are impermeable, and approximately 3,400 buildings and 6,000 inhabitants. The catchment characteristics are typical in a European context: The area is mainly residential, with little industry. It consists of low density housing and green areas, which are used as gardens, parks and allotment gardens. These area characteristics were used to develop four different SWM systems,

each dimensioned based on full hydrodynamic modelling (MIKE URBAN, DHI) or simplified modelling (WEST, DHI) of such systems. All elements were designed according to existing guidelines and recommendations (CIRIA, 2015; The City of Copenhagen, 2011) (Figure 2).

Figure 2. Schematic sketches of the elements in the four different stormwater management systems. The water level during an event with a return period of 5 (10) years is illustrated in light (dark) blue. The water level rises above surface level for events with a return period of 10 years in the systems 2-4.

S1: Combined subsurface system

Stormwater and wastewater are handled in one pipe system with pipe diameters ranging between 200mm and 3000mm. The system was dimensioned to prevent surcharging for events with a return period of up to 10 years. A subsurface retention basin for mixed sewage was designed to limit combined sewer overflows to the recipient to five

times per year (Nature Agency DK, 2011), which results in a basin volume of 7000m³. Except for overflows, all combined sewage is treated in a central WWTP. No separate WW system has to be implemented, which was factored in as avoided material demands for WW pipes.

S2: *Separate subsurface system*

Stormwater is handled separately from wastewater, in pipes dimensioned to prevent surcharging for events with a 5 year return period ($\varnothing = 200\text{-}2000\text{mm}$). A surface retention basin was dimensioned according to an existing design criterion (200m³ per reduced ha), which results in a basin volume of 20,000m³. This criterion is based on water quality considerations, allowing sedimentation and subsequent pollutant removal before discharge (Vollertsen et al., 2012).

S3: *Separate system with soakaways*

Stormwater is managed completely in soakaways (also called dry wells) dimensioned for a 5-year-event, which results in a total soakaway volume of 26,700m³. The system is decentralized, i.e. the soakaways are implemented on private properties and existing roads, and not connected. Sand traps for roof runoff and green strips for road runoff partly remove sediments and pollutants. All stormwater is infiltrated from the soakaways. Avoided impacts were quantified for existing road areas that were transformed to green areas, consequently reducing asphalt demands.

S4: *Separate system with dry swales*

Stormwater is handled in dry swales with a total volume of 20,600m³, which is provided mainly above the surface. The swales are implemented on existing road areas,

and avoided impacts from avoided asphalt demands were accounted for. The surface area is vegetated for additional pollutant removal. Stormwater percolates through filter soil and gravel before entering a perforated pipe ($\varnothing = 80\text{mm}$). Infiltration is prevented by a geotextile liner.

2.4 Assumptions and uncertainties

To make the case study as generic as possible, four simplifications were made:

- The existing SWM system was neglected, and it was assumed that a system would be built from scratch;
- Stormwater is managed in only one type of SWM element (soakaways or swales) in the green infrastructure systems, instead of a more realistic combination of different elements typically employed in retrofitting;
- It was assumed that elements on existing roads would be implemented when road renewals are required, or would only move renewals up in time, i.e. that renewal demands do not differ between the systems;
- We assumed that stormwater and WWTP effluent are both discharged to freshwater, which made a worst-case scenario. In reality, the Skibhus catchment is atypical and discharges its stormwater to the harbour, and WWTP effluent to freshwater.

The freshwater bodies that the stormwater is discharged to are assumed not to be used for drinking water. If receiving water bodies are used for recreational activities, dilution and the short exposure span is expected to limit harmful effects. Consequently, the exposure of humans to pollutants is considered to be negligible and point source emission damage to human health are therefore not considered. Additionally, human health damage

from stormwater is expected to mainly be caused by pathogens, which is not included in existing LCIA methods.

Electricity consumption has been found to cause the major share of environmental impacts of wastewater treatment (Godskesen et al., 2013), and we therefore did not include other processes at the WWTP. The electricity demand differs depending on the quantity and quality of the influent. Since we were only interested in the incremental change caused by the treatment of stormwater, we analysed electricity consumption at the existing wastewater treatment plant in the catchment for the year 2016 and estimated an average extra electricity consumption of 0.07 kWh per m³ of stormwater (SI).

Impacts from sanitary wastewater management were only considered when they differed between the systems. We assumed that wastewater is treated in a central WWTP in both combined and separate systems, and therefore did not consider point source emissions of treated wastewater. This is a simplification, as the treatment efficiency and consequently the effluent pollutant concentration depends on the influent concentration. Mixing wastewater with stormwater will lead to lower removal efficiencies, which results in different impacts from treated stormwater in combined and separate system. We did not have sufficient data to quantify this effect. However, we included point source emission impacts caused by discharges of untreated wastewater in the combined system (S1). Using data from the year 2016, we calculated an annual combined sewer overflow volume of 4414m³, of which 3% is wastewater.

Nitrogen present in stormwater may cause marine eutrophication impacts when discharged to marine water. ReCiPe 2016 does not define characterisation factors for marine eutrophication at mid- or endpoint level (Huijbregts et al., 2016), and these impacts

are therefore not included. However, long-term damage is not expected from nitrogen discharges due to mixing and dilution effects in the sea.

2.4.1 Uncertainty analysis

To evaluate the uncertainty of infrastructure and point source emission damage, we identified processes contributing significantly to total damage, and varied the input parameters (SI). Uncertainties in infrastructure processes were classified according to Huijbregts (1998) into parameter uncertainty, which includes the filter strip areas for soakaways and the lifetime of green infrastructure elements (soakaways, filter strips, swales), and uncertainty due to choices including the electricity demand and production mix for WWT and for pumping, and the disposal process for plastic. We did not assess model uncertainty, i.e. the uncertainty connected to characterisation factors and impact pathways defined in the underlying LCIA methods. Since we use the same methodology for all systems, we can assume that relative conclusions are valid since the same uncertainty is attached to all results. However, we note that the characterisation at endpoint damage level requires modelling of the full impact pathway and hence has a higher model and parameter uncertainty than the characterisation at midpoint level, particularly for climate change impacts.

The point source emissions are determined by the removal efficiency of the single elements in the systems. While pollutant removal in WWTPs is well documented and regulated (Danish Nature Agency, 2014), large variations in the efficiency of low-tech elements like retention ponds and filter soil are documented in literature (Center for Watershed Protection, 2007). Additionally to calculating median removal efficiencies, maximum and minimum removal efficiencies were used to calculate the impacts from all

311 separate systems (S2-4) in analysis of the sensitivity of the results to this parameter.
312 Some studies reported negative removal, i.e. addition of pollutants. This is caused by initial
313 wash out of pollutants from soil, which will fade during operation (Clary and Jones, 2016).
314 Negative removal efficiencies were therefore not considered in the calculation of median
315 removal efficiencies, but included in the uncertainty analysis.

316 We assumed that the top 20cm of soil in green strips and swales has to be
317 renewed, and that sediment in the surface basin has to be removed every ten years due to
318 accumulation of pollutants (SI). However, the fate of polluted soil and sediment is unclear
319 as no treatment requirements are defined. Extensive treatment, such as thermal treatment
320 or washing, is only required for heavily polluted soils, for example stemming from industrial
321 or waste handling sites. We assumed landfilling or use in construction instead, which is a
322 practice commonly used for soil with limited metal contamination (McAdams and Shanight,
323 2014; Mulligan et al., 2001), and from which leaching was considered to be negligible. We
324 tested the sensitivity of this assumption by analysing a worst case scenario, where
325 removed soil and sediment is applied to natural soil, leaching to surface water by erosion.
326 The resulting ecotoxicity impacts were modelled using USEtox® characterisation factors
327 (Dong et al., 2014) for emissions of metals to natural soil. For nutrients, a conservative
328 leaching rate of 50% was used based on factors for agricultural soil published by Kirkeby
329 et al. (2013).

3. Results and discussion

3.1 Pollutant flow and discharges

The fate of metals and nutrients depends on the flow path of stormwater and the removal efficiencies of the single elements in each system (Figure 3). WWTPs (S1) remove both metals (70-90%) and nutrients (84%) efficiently (Table 1), largely through accumulation in the sludge (Yoshida et al., 2015). 50% of sludge is applied to agricultural soil for fertilization in Denmark (Kirkeby et al., 2013). The remaining sludge is incinerated, landfilled or mineralized and it is assumed that pollutants will not be released into the environment during any of these processes.

None of the other elements is as efficient as the WWTP in removing pollutants. Sedimentation in surface basins (S2) removes around half of the pollutants (Table 1). Green strips implemented before soakaways and swales do not remove phosphorous, but bind metals (35-57% in green strips, and 46-65% in swales). Sand traps only show a very limited potential to remove pollutants (0-22%). Large fractions of metals (25-83%) and phosphorous (42%) remain in the soil during infiltration both in soakaways (S3) and swales (S4) (Table 1). All separate systems (S2-4) are designed for events with a five year return period, and stormwater stemming from more severe events passes through the system without removal and is discharged directly. This accounts for 3% of the total annual rain volume (Sørup et al., 2016).

349 Table 1. Median removal efficiencies of copper, zinc, and phosphorous by different stormwater infrastructure
 350 elements. Minimum and maximum efficiencies are given in brackets. * If the calculated median removal
 351 efficiency was negative, no removal was assumed.

Element	Median removal efficiency (minimum – maximum)			References
	Copper	Zinc	Phosphorous	
WWTP	90%	70%	84%	(Danish Nature Agency, 2014)
Surface basin	46% (1% - 95%)	65% (1% - 96%)	52% (12% - 91%)	(Center for Watershed Protection, 2007; CIRIA, 2015; Clary and Jones, 2016)
Sand trap	22%	0%* (-23% - 0%)	0%* (-6% - 0%)	(Caltrans, 2003)
Green strip	35% (-6% - 52%)	57% (52% - 62%)	0%* (-100% - 0%)	(Cederkvist et al., 2016; CIRIA, 2015; Clary and Jones, 2016)
Swales	46% (1% - 95%)	65% (1% - 96%)	0%* (-100% - 99%)	(Center for Watershed Protection, 2007; Clary and Jones, 2016)
Infiltration (soakaways / swales)	25% (2% - 90%)	83% (33% - 100%)	42% (-233% - 88%)	(Cederkvist et al., 2015; Center for Watershed Protection, 2007; Clary and Jones, 2016; Langeveld et al., 2012; Rembout et al., 2007)

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1 Combined

2 Separate

3 Soakaways

4 Swales

— Phosphorous
— Copper
— Zinc

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Figure 3. Pollutant flow in the four different systems, starting with 100% of the pollutant load in runoff (P: 3.2mg/l, Cu: 59µg/l, Zn: 490µg/l (Brudler et al., 2019)). The grey boxes mark pollutant “sinks”, i.e. compartments in which it is assumed the pollutants are bound and disposed without leaching.

3.2 Infrastructure and point source emission impacts

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358 The conclusions regarding the most (and least) sustainable systems differ when evaluating
359 infrastructure and point source emission impacts. The combined system (S1) has the
360 highest infrastructure impacts in all impact categories, with up to two times the impacts of
361 the separate system (S2). Concurrently, it has the lowest point source emission impacts.
362 Both green infrastructure systems have low infrastructure impacts, with swales (S4) having
363 the lowest infrastructure impacts in nine, and soakaways (S3) in four out of 13
364 infrastructure midpoint impact categories. However, with 54% higher impacts than the
365 combined system, the green infrastructure systems have the highest freshwater
366 eutrophication impacts caused by point source emissions. The separate system (S2) has
367 the highest point source ecotoxicity impacts (4-50% higher than the other systems).
368 Detailed values are listed in SI, and the maximum impact across all systems in each
369 category is shown in Figure 4.

370

371 This highlights that infrastructure and point source emission impacts have to be
372 evaluated in combination to assess the sustainability of SWM. If only infrastructure impacts
373 are included, the combined system (S1) is clearly the least sustainable option at midpoint
374 level. In contrast, only analysing point source emissions would lead to the conclusion that
it is the most sustainable system.

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Figure 4. Annual infrastructure and point source emission impacts of the four different systems, normalized with reference to the highest (1) and lowest (0) impact in the single impact categories (GW = global warming, SOD = stratospheric ozone depletion, IR = ionizing radiation, HOF = human damage ozone formation, PM = particulate matter formation, EOF = ecosystem damage ozone formation, TA = terrestrial acidification, FE = freshwater eutrophication, MR = mineral resource availability, FR = fossil resource availability, WC = water consumption, ETOX = ecotoxicity, HTOX = human toxicity (c = cancer, nc = non-cancer)). Toxicity impacts are expressed in comparative toxic units (CTU).

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3.3 Environmental damage

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To compare the systems across impact categories and analyse point source emission and infrastructure impacts in combination, we calculated the resulting endpoint damage to three areas of protection: resource availability, ecosystems, and human health (Goedkoop et al., 2013). The damage to each area of protection is within the same order of magnitude across systems. The combined system (S1) causes most damage to resource availability and ecosystems, and second most to human health. In contrast to subsurface systems, GI systems prevent damage to resource availability. Soakaways (S3) cause least damage to ecosystems and swales (S4) least damage to human health (Table 2).

Table 2. Annual infrastructure and point source emission (in *italic*) damage to three areas of protection (resource availability, ecosystems, human health) caused by four different systems for managing stormwater according to Danish flood safety standards in a catchment area of 260ha, over 25 years. Damage to human health and ecosystems caused by short-time exposure e.g. caused by flooding or overflows is not considered.

	1 Combined		2 Separate		3 Soakaways		4 Swales	
	Infra-structure	<i>Point source emission</i>	Infra-structure	<i>Point source emission</i>	Infra-structure	<i>Point source emission</i>	Infra-structure	<i>Point source emission</i>
Resource availability [USD/yr]								
Mineral resource availability	1.2E+02		7.1E+01		-8.7E+00		-9.0E+00	
Fossil resource availability	8.7E+03		4.0E+03		-3.7E+03		-5.2E+03	
SUM	8.8E+03		4.1E+03		-3.7E+03		-5.2E+03	
Ecosystems [species.yr/yr]								
Freshwater ecosystems								
Global warming	2.1E-08		1.0E-08		6.5E-09		3.7E-09	
Eutrophication	1.4E-05	<i>3.3E-04</i>	7.7E-06	<i>4.2E-04</i>	-7.4E-07	<i>5.1E-04</i>	-1.7E-06	<i>8.5E-04</i>
Ecotoxicity	6.0E-08	<i>1.8E-04</i>	3.9E-08	<i>2.7E-04</i>	2.2E-08	<i>2.6E-04</i>	-6.0E-09	<i>3.0E-04</i>
Water consumption	9.5E-10		6.5E-10		4.8E-11		5.8E-10	
Terrestrial ecosystems								
Global warming	7.6E-04		3.7E-04		2.4E-04		1.4E-04	
Photochem. ozone form.	4.3E-05		2.5E-05		1.8E-05		9.1E-06	
Acidification	6.1E-05		3.5E-05		-8.5E-06		-3.9E-06	
Water consumption	2.1E-05		1.5E-05		1.1E-06		1.3E-05	
SUM	9.0E-04	<i>5.1E-04</i>	4.5E-04	<i>6.9E-04</i>	2.5E-04	<i>7.6E-04</i>	1.5E-04	<i>1.2E-03</i>
Human Health [DALY/yr]								
	3.6E-01		1.9E-01		8.1E-02		5.9E-02	

Total ecosystem damage ranges between 1.0E-03 (S3) and 1.4E-03 species.yr/yr (S1). Freshwater and terrestrial ecosystem damage contribute within the same order of magnitude to total ecosystem damage. Point source emissions cause the majority of ecosystem damage in the separate systems (60-88%) and 38% of the damage of the combined system (Table 2). Across systems, point source emissions of nutrients causing eutrophication impacts contribute almost twice as much to ecosystem damage as point source emissions of metals causing ecotoxicity impacts.

If all stormwater would be discharged directly without treatment, 1.3E-03 species.yr/yr would be expected lost by ecosystem damage (SI). For all separate systems,

the total ecosystem damage caused is lower than this value, which implies that they are effective in reducing ecosystem damage. This is in line with Clauson-Kaas et al. (2001) and Byrne et al. (2017), who concluded that the avoided environmental impacts outweigh the impacts of implementing and operating single SWM elements. However, this does not apply to the combined system, which causes higher ecosystem damage than caused by discharging stormwater without any SWM present.

Soakaways cause the lowest ecosystem damage, with point source emissions contributing 75%. This damage is calculated using characterisation factors for freshwater, assuming that all pollutants in stormwater infiltrated to groundwater eventually reach surface water. This is a worst case assumption as some pollutants would be retained in the soil, i.e. removed by sorption and sequestration. Consequently, the ecosystem damage of soakaways is probably even lower than the calculated results. However, impacts on groundwater or the fate of pollutants discharged to groundwater are not incorporated in existing LCIA methods, and would require the development of a new impact pathway, which is outside of the scope of this paper.

Damage to resource availability, expressed as surplus cost, ranges between 4.1E+03 (S2) and 8.8E+03 USD/yr (S1) for the systems utilizing pipes. The difference in damage can be partly explained by the difference in flood safety level, i.e. larger pipes, and consequently more resources, are necessary for the combined system (S1) than for the separate system (S2). The green infrastructure systems save resource costs, with prevented damage ranging from -3.7E+03 (S3) to -5.2E+03 USD/yr (S4). Damage to fossil resource availability is 2-3 orders of magnitude higher than damage to mineral resource availability across all systems (Table 2).

According to the functional unit definition, the combined system is designed to prevent flooding during events with a return period of ten years due to the increased risk to humans from flooding with combined sewage. This results in higher resource demands for larger pipes and basins than in separate systems, which are designed for events with a return period of five years and consequently allow flooding from stormwater more often. Flooding of infrastructure and buildings causes significant environmental damage due to disposal and renovation processes (Hennequin et al., 2018; Petit-Boix et al., 2017). The higher the flood safety level of the SWM system, the more economic and environmental damage is prevented. Based on Hennequin et al. (2018), we calculated the environmental damage to resource availability caused by the recovery from a 15cm flooding of a single house to 516 USD. A rain event with a return period of 10 years would be managed without flooding in the combined system (S1) but would create flooding in the separate systems (S2-4) and cause incremental environmental damage. If only nine (S2) to 27 (S4) houses are flooded during such an event, the differences in resource availability damage to the combined system (S1) are offset, effectively making the combined system the most sustainable system for this area of protection. Detailed modelling of this damage is beyond the scope of this paper, and would be too case dependent to be of generic interest. It points, however, towards the fact that accounting for differences in flood safety levels by including flood damage could substantially affect the conclusions of the comparative assessment. This is aligned well with studies using economic assessments of cost of infrastructure versus reduction of economic damage from flooding (Olsen et al., 2015; Zhou et al., 2012).

The damage to human health ranges between $5.9\text{E-}02$ (S4) and $3.6\text{E-}01$ DALY/yr (S1) (Table 2). The sustainability of the systems relative to each other and the contribution

and uncertainty analysis of human health damage showed very similar patterns to resource availability damage (SI). We therefore only discuss damage to resource availability in the following. The systems are furthermore designed to prevent flooding and subsequent human contact with contaminated water, i.e. minimize human health damage from contact with contaminated water. The WHO estimated that 3.7% of global DALYs are attributable to water, sanitation, and hygiene (Prüss-Üstün et al., 2002), and the caused damage is assumed to be negligible in comparison to the prevented damage.

Figure 5. Damage to a) resource availability, b) ecosystems, caused by four different systems managing stormwater according to Danish flood safety standards in a catchment area of 260ha, over 25 years. Negative values indicate prevented damage. Error bars illustrate the damage for a worst and best case for each system of all tested scenarios varying both infrastructure processes and point source emissions.

3.3.1 Sensitivity of ecosystem damage

The four systems show small differences in ecosystem damage that are hardly significant, considering the uncertainties that accompany the underlying modelling. The nominal ecosystem damage score is highest for the combined system ($1.4\text{E-}03$ species.yr/yr), and is mainly attributed to the operation stage with its discharges of polluted stormwater (36%) and electricity consumption for WWT and pumping (19%). The production of concrete, steel, plastic and gravel for pipes and basins causes significant damage (23%), followed by filling and recycling of pipes at the end of life (18%) (Figure 6).

Overall, infrastructure processes contribute more (64%) than point source emissions (36%) to total ecosystem damage, with discharges of untreated wastewater from overflows contributing less than 1%. The results are most sensitive to changes in the electricity production: If electricity for WWT and pumping is produced only using wind power instead of a Danish production mix, the damage is reduced by 18% (Figure 5). An increased demand of electricity (+25%) using a Danish production mix only leads to an increase in total damage of 2%.

481

482 Figure 6. Relative contribution of life cycle stages (materials, transport, construction, operation with
483 stormwater discharges, decommissioning) to a) the total resource availability damage, b) the total ecosystem
484 damage.

Removal of pollutants at the WWTP in the combined system (S1) is well documented and regulated (Danish Nature Agency, 2014), but data differentiating between wet and dry days is limited. The treatment efficiency depends on the quantity and quality of the influent, which differs between the combined and separate systems. We could not quantify these changes as no data was available. However, we tested the sensitivity of changes in the assumption regarding the fate of the sludge. We assume that 50% of the sludge is applied to agricultural soil, from where pollutants leach to freshwater, which

causes 23% of the ecosystem damage of the combined system. However, this is a worst case scenario, as Danish regulation specifies maximum concentrations of metals in sludge that can be applied to agricultural soil (Ministry of Environment and Food DK, 2006). It is difficult to evaluate how this affects the total mass of metals that ends up on agricultural soil, as pre-treatment of sludge and metal content depend strongly on the treatment facility. For treatment facilities in larger cities, sludge is not applied to soil at all, since the transport to agricultural areas makes this economically unattractive. Consequently, the damage from wastewater treatment could potentially be lower than in the base case. For the separate systems, point source emissions account for the majority of ecosystem damage (60-88%) (Figure 6). Consequently, changes in the assumptions regarding the fate of pollutants in stormwater affect the damage most. The removal efficiencies of basins, filter soil and vegetation are highly uncertain, and measured values reported in literature vary significantly (Table 1). Assuming maximum removal efficiencies decreases the damage by 48 to 82%, making separate systems less sustainable than the combined system regarding ecosystem damage. In contrast, assuming minimum efficiencies increases the damage between 53 and 105% (Figure 5). Damage caused by swales is most sensitive to these changes, making it either the most or least sustainable option compared to all other systems.

Assuming 50% leaching from disposed soil and sediment, the damage is increased only within the same order of magnitude and the conclusions regarding the systems with highest and lowest damage do not change (SI). Consequently, ecosystem damage is less sensitive to changes in leaching rates, than to changes in removal efficiency.

Pollutant removal in swales and soakaways is based on sorption of pollutants to soil. Flushing effects, e.g. of nutrients that are transformed from organic, sediment-bound

form can lead to addition of pollutants (Winer, 2000). On the other hand, metals generally sorb strongly to soils and a large fraction remains in the top layers of the soil (Johnson and Hunt, 2016; Lemming et al., 2010; Turer et al., 2001). In surface basins, removal takes place through sedimentation, which is significantly influenced by the basin design. For example, implementing a forebay can remove up to 80% of particles and subsequently a large fraction of metals (CIRIA, 2015). Similarly, elements like green strips can be optimized to maximize removal before stormwater enters soakaways. Swales give the opportunity to use designed filter media to maximize metal removal. This highlights the possibility to significantly increase the sustainability of SWM systems: Low-tech elements can be very efficient in removing pollutants and cause significantly less ecosystem damage than combined systems, when designed accordingly. Additionally, regular maintenance of all green infrastructure is necessary to ensure efficient removal over time (CIRIA, 2015).

As an alternative to designing the systems to increase the removal efficiency of pollutants, damage can also be limited at the source: Rain is only lightly polluted, and takes up toxic compounds and nutrients from roofs and roads. If the sources of pollutants in runoff are regulated, e.g. by restricting the use of metals in buildings and car parts, the sustainability of SWM systems can be increased further (Ledin et al., 2004).

3.3.2 Sensitivity of resource availability damage

Damage to resource availability is only caused by infrastructure processes, and within these mainly by material generation and decommissioning processes. The contribution of transport and construction are minor in all systems. Operation consists of removal of polluted sediment and soil and maintenance of green areas in separate

539 systems, which contributes insignificantly to the total impacts (Figure 6). Only in the
540 combined system (S1), continuous electricity consumption for WWT and pumping during
541 the operation stage causes a major share of the damage (29%) (Figure 6). The energy
542 consumption at the WWTP strongly depends on the treatment design, and the quantity
543 and quality of the influent. If electricity would be provided only by wind power, the total
544 damage to resource availability could be decreased by 27% (S1) (SI).

545 The resource availability damage associated with pipes are higher in the combined
 546 system (S1: 5.8E+03 USD/yr) than in the separate system (S2: 4.0E+03 USD/yr) (SI).
 547 Larger pipes are needed in the combined system, and the avoided damage of not
 548 implementing a separate WW system (S1: -1.5E+02 USD/yr) does not offset this damage.
 549 However, the relative importance of pipes is significantly higher in the separate system
 550 (S2), where they account for 99% of the damage (S1: 66%). This is because the separate
 551 system doesn't require any continuous operation processes, and has very limited material
 552 demands for the surface basin.

553 Plastic is used in significant amounts in all systems, for pipes with a diameter up to
 554 400mm (S1-2), soakaways (S3) and geotextiles (S4). Soakaways and the connected
 555 infrastructure of pipes and sand traps require most plastic (1,265t). Recycling of 1kg of
 556 plastic prevents resource availability damage of 0.39 USD, which is more than half of the
 557 damage caused by the production of 1kg of polypropylene and polyethylene (0.64 USD),
 558 and equal to the damage caused by the production of 1kg polyvinylchloride. These values
 559 are characterized by some uncertainty, since the type of plastic could not be specified in
 560 the recycling process used to model the impacts, and the resulting avoided impacts could
 561 potentially be lower due to losses in the recycling process. Additionally, the disposal
 562 process itself is uncertain, as technologies and legislation cannot be foreseen with
 563 certainty. If we assume plastic is incinerated instead of recycled, resource availability
 564 damage changes significantly in all separate scenarios (+12% in S1 to +432% in S3),
 565 making soakaways the least sustainable system (SI). Subsurface infrastructure has an
 566 even longer expected life span (75 to 100 years), which makes the decommissioning
 567 processes more unpredictable. We assume that excavation and recycling of concrete is
 568 not economically feasible, especially for large structures like retention basins. If materials

of subsurface solutions could be reused in the future, i.e. damage from material production could be partly compensated for, the total damage from other life cycle phases would still make subsurface systems less sustainable than GI.

Where green infrastructure is implemented on existing road areas, it leads to avoided material demands for road renewal, and avoided damage consequently. This avoided damage negates the caused damage during other life cycle stages of swales (S4), and in combination with benefits from plastic recycling also negates caused damage of soakaways (S3). The size of the green strips implemented before soakaways consequently has a large influence on the damage and assessing minimum and maximum area requirements affects the damage significantly (-77% to +37%) (SI).

Grey infrastructure, i.e. pipes and retention basins, was assumed to have a longer life time than green infrastructure. Halving the life time of green infrastructure elements from 30 to 15 years reduces the avoided damage for swales by 45% (S4), and even leads to induced, instead of avoided damage, for soakaways (SI). The lifetime is characterized by a high uncertainty, since experience with green infrastructure is still limited. Continuous maintenance, which is included in our assessment, can prolong the lifetime, and should therefore be a priority when planning green infrastructure.

3.4 Differentiation from risk assessment

An impact assessment of point source emissions cannot replace a risk assessment (RA), as is traditionally carried out when applying for discharge permits. A RA assesses worst case scenarios, i.e. analyses maximum peak discharges, and takes into account local recipient characteristics. However, our assessment allows to compare the solutions between each other, and to assess the long-term, accumulative effects. In the planning of

592 stormwater systems, a life cycle impact assessment would realistically be supplemented
593 by a RA, and further assessments, e.g. regarding economic, recreational, and aesthetic
594 value of different systems.

595 **4. Conclusion**

596 Our study showed that the conclusions regarding the most, and least, sustainable system
597 for managing stormwater differ for infrastructure and point source emission impacts. A
598 combined sewer system causes the highest infrastructure impacts, and the lowest point
599 source emission impacts. Green infrastructure has significantly lower infrastructure
600 impacts due to limited material and operation demands, but current solutions remove less
601 stormwater pollutants and consequently cause higher point source emission impacts. Point
602 source emission impacts are significantly higher than infrastructure impacts at midpoint
603 level (ecotoxicity: four orders of magnitude, eutrophication: up to one order of magnitude).

604 The resulting endpoint damage to resource availability is highest for the combined system.
605 This is mainly caused by the production of materials like concrete and steel,
606 decommissioning processes of the pipe systems and continuous electricity consumption
607 for wastewater treatment and pumping. Higher flood safety levels are required for
608 combined than for separate systems due to higher health risks associated with flooding
609 with combined sewage. This requires more extensive infrastructure for combined system,
610 which partly explains the higher damage to resource availability. Green infrastructure
611 systems prevent damage to resource availability if roads are transformed to green areas,
612 and materials are recycled.

Point source emissions contribute significantly to the total ecosystem damage of the different systems (36 to 88%), which highlights the importance of including stormwater discharges in the assessment of SWM systems. The removal efficiency of low-tech treatment elements like filter soil or surface basins is characterized by high uncertainty and a potential increase in pollutant removal would make green infrastructure systems significantly more sustainable than the combined system. The sustainability of green infrastructure can further be optimized, e.g. through maximizing the life time with targeted and continuous maintenance and recycling of materials.

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Life cycle assessment of point source emissions and infrastructure impacts of four types of urban stormwater systems

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Highlights

- Life cycle assessment of stormwater management at catchment scale
- Environmental impacts of four different stormwater systems are quantified
- All relevant impacts from point source emission and infrastructure are included
- Stormwater discharges cause significant impacts relative to the infrastructure
- Strategies to increase the sustainability of stormwater management are highlighted