Carbon footprint and life cycle assessment of centralised and decentralised handling of wastewater during rain
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ABSTRACT
The most widely used approaches for handling of combined sewer overflows (CSOs) are: (1) storage in smaller retention basins and local decentralised treatment; and (2) storage in larger retention basins and treatment at a central wastewater treatment plant. This paper compares the environmental impact including carbon footprint for these two approaches using the life cycle assessment (LCA) method, and provides a holistic view of how CSO is to be treated considering technical, economic and environmental issues. The analysis is based on the results of the EU-financed LotWater project and 9 years of operational data from wastewater treatment in Copenhagen. All technologies are analysed for handling of 1 m³ of CSO. However, costs are compared based on cost per reduced area. The study showed that decentralised treatment of CSO is the cheapest method and the power consumption for the decentralised treatment is five times less than that for central treatment of CSO. However, central treatment of CSO appeared to be most efficient in reducing discharge of nutrients and environmental toxics. The LCA showed that the largest environmental impacts from handling CSOs are eutrophication and aquatic ecotoxicity. This study concludes that focusing on global warming alone in the form of reduced energy consumption could result in negative impacts on recipient waters.

Key words | carbon footprint, combined sewer overflow (CSO), life cycle assessment, wastewater treatment

INTRODUCTION
The implementation of the EU’s Water Framework Directive on regulations for water quality in local water recipients and the increase in rain and rainfall intensity due to climate change will in future result in handling of increasing amounts of combined sewer overflows (CSOs). As an example, the maximum number of overflows allowed per year is now reduced to two; however, many existing retention basins are sized for a maximum of 10, 20 or more overflow events per year.

One way of solving the problem could be source control methods such as disconnecting rainfall run-off from roofs, squares and streets. These methods are widely pursued all over the world. However the implementation of these methods is time-consuming and many municipalities do not have sufficient time to wait for these methods to be implemented. Another method could be constructing larger retention basins and transporting the retained water to a centralised wastewater treatment plant (WWTP) for treatment. This method of
expanding retention basins results in huge investment costs for local authorities. A third method can be increasing the treatment capacity of the centralised WWTP and thereby reducing the size of the retention basins. A fourth method could be treating the overflow locally before discharging and thereby achieving the required reduction in annual pollution load.

Since 2001, we have tested the above-mentioned methods for handling of CSO under different projects, except the method of source control, and the results show that the choice of method depends on many factors and if the decision is solely based on a single factor such as global warming potential, there is a risk of overseeing other important factors. The three factors considered in this paper are economy, global warming potential and recipient quality. There is no doubt that centralised wastewater treatment leads to higher energy consumption due to transportation and treatment of the CSOs, compared with many decentralised treatment methods. However, the overall treatment efficiency of centralised wastewater treatment is higher than the decentralised treatment plants.

Therefore the aim of this paper is to provide a methodology for comparing decentralised treatment of CSO with centralised treatment. The assessment includes both the carbon footprint and life cycle assessment (LCA) and also includes a rough cost comparison between these two principal alternatives.

The data for the centralised wastewater treatment are based on 9 years of operational data from the WWTPs serving Copenhagen (Lynettefællesskabet and Avedøre WWTP) with a total load of 2 million p.e. (www.lyn-is.dk). The data for the decentralised method are based on the operational data from the EU-financed LotWater project. The two decentralised methods tested during this project are: screening and microfiltration followed by UV-treatment and chemical dosing (iron salts) and sedimentation enhanced by lamella separators (www.spildevandscenter.dk; www.cowiprojects.dk/lotwater/). Copenhagen alone currently has 70 CSOs.

### METHODS

#### System description

The functional unit is treatment of 1 m³ of overflow water. Table 1 shows the quality of the overflow water from CSOs and the quality of wastewater arriving at the centralised wastewater treatment plant during rain (causing overflow before entering the plant). The quality of CSO is calculated based on samples taken from three overflows in major cities (Copenhagen, Odense and Aarhus) in Denmark and the quality of wastewater after rainfall is calculated based on the samples taken from the inlet to Avedøre WWTP. The dilution factor is 2.5 compared with dry weather flow (DWF). The number of measurements for the different parameters varies between 15 and 23 with an average of 19 measurements per parameter. The table shows that the concentrations are usually lower in the CSOs compared with the inlet to the WWTP. In a large catchment area there will not be heavy rainfall everywhere and the quality of the wastewater arriving at the WWTP will be influenced by areas receiving rain and areas with dry weather. Therefore concentrations in the incoming wastewater are higher compared with the CSO discharged locally.

The following decentralised treatment methods were considered:

- Screening and micro-filtration followed by UV-treatment.
- Chemical dosing (iron salts) and sedimentation enhanced by lamella separators.

The following centralised wastewater treatment methods were considered:

- Activated sludge treatment using advanced online control to meet EU Urban Wastewater Directive effluent criteria with overflow after mechanical treatment at about two times dry weather flow.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Local CSO</th>
<th>Inlet to WWTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>g/m³</td>
<td>140</td>
<td>300</td>
</tr>
<tr>
<td>TotN</td>
<td>g/m³</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>TotP</td>
<td>g/m³</td>
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<td>5</td>
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<tr>
<td>Suspended solids</td>
<td>g/m³</td>
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<tr>
<td>Cd</td>
<td>mg/m³</td>
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<td>Ni</td>
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<tr>
<td>PAH</td>
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</tr>
<tr>
<td>E. coli</td>
<td>CFU/100 ml</td>
<td>1,600,000</td>
<td>15,000,000</td>
</tr>
</tbody>
</table>

Table 1: Quality of CSO water and wet weather inflow to centralised wastewater treatment plant.
As above, with additional treatment of the overflow water in an ActiFlo treatment unit (enhanced mechanical-chemical precipitation).

Figure 1 shows an overview of the wastewater system and as shown in the figure the bypass at a wastewater treatment plant occurs after the mechanical treatment to avoid hydraulic overloading of the biological treatment.

Life cycle assessment

Life cycle assessments have been applied in the water sector for more than 10 years, for example as a decision support tool in wastewater treatment operation and maintenance (Clauson-Kaas et al. 2001), comparing economic and environmental optimisation of wastewater management (Clauson-Kaas et al. 2007), selecting tertiary treatment technologies (Hoibye et al. 2004), water system planning (Lundie et al. 2007) and when comparing water supply based on different resources (Lyons et al. 2009; Godskesen et al. 2009).

The life cycle assessment applied here is based on the EDIP LCA methodology (Wenzel et al. 1997, 2008; Hauschild et al. 1998). The model shown in Figure 2 is used.

The data on consumption of materials, energy and treatment chemicals are recorded for each of the methods along with their treatment efficiencies and emissions where relevant. All consumptions and disposals are accounted for per m³ wastewater treated and converted to potential environmental impacts. Each consumption or discharge is expressed in units related to the environmental impact (classification and characterisation): for example, all greenhouse gases are converted to CO₂-equivalents and contribution to ecotoxicity is expressed based on ‘predicted no effect concentration’ or ‘lowest observed effect concentration’. For each type of impact, the contributions are summed up and compared with an average person’s total contribution to the impact (normalisation).

The potential environmental impacts considered relevant for the wastewater sector are: global warming, eutrophication, ecotoxicity, human toxicity and disposal of slag and ash.

Normalisation relates the released mass of a substance to the actual average release of a substance for one person per year in Denmark (also known as person equivalent). The weighting is determined by the supply horizon or by political reduction goals. The weighting factor is determined as the actual emission divided by the target emission in for example 10 years into the future. For example, a reduction in CO₂ of 12% in 10 years would result in a weighting factor of 1.12 (in this case it is 12% higher now than the target in 10 years). The factor used in this study is related to the EDIP 2003 method. The method is illustrated in Table 2, where induced effects per m³ effluent discharged from the WWTP included in this study are shown.
The normalisation and weighting factors will vary from country to country although emissions per person will be of similar size in the industrialised countries. A target emission for a 20% reduction of greenhouse gas emissions by 2020 referring to a 1990 baseline corresponds to a target emission of approximately 6,000 kg CO\textsubscript{2}-eq./person/year (IPCC 2007). The total greenhouse gas emission in 2004 was, according to the Intergovernmental Panel on Climate Change (IPCC), around 49 Gt/year, and the world population according to the United Nations was around 6.45 billion (United Nations 2011). This corresponds to an emission of approximately 7,600 kg CO\textsubscript{2} equivalent/person/year. Using the emission level of 2004 as a reference and a target of 6,000 kg CO\textsubscript{2}-eq./person/year after 10 years (2014) will correspond to a weighting factor of 1.27, i.e. 10% higher than that used in Table 2. The weighting factor will depend on international (e.g. the Kyoto Protocol), regional (e.g. at EU level) or national agreed reduction goals and this is an aspect which needs to be considered when assessing the conclusion of this study.

All avoided impacts are generally considered equally good for the environment and the induced impacts are considered equally bad. The normalisation and weighting factors make it possible to assess the importance of the parameters in relation to each other. If a WWTP is treating the wastewater to lower concentrations than required in the discharge limits, this is not considered an important parameter in this study.

If discharge to a sensitive recipient is incorporated in weighting factors, for example for eutrophication and ecotoxicity, this will increase the environmental gains from more efficient treatment.
Carbon footprint calculation

The carbon footprint calculation draws on the same data as used for the life cycle assessment. This is in accordance with the Greenhouse Gas Protocol (2010), where all greenhouse gases emitted from ‘cradle to grave’ are accounted for. Besides power and fuel consumption, this also includes the other greenhouse gas emissions from, for example, burning of biogas and sludge, and emissions from processes.

A range of products, consumptions and activities contribute to emission of greenhouse gases. The production of heat and power at the WWTP will reduce the overall emission of greenhouse gas.

Contributing to emissions of greenhouse gases are: consumption of power for pumping and the treatment process, consumption of chemicals and fuels for trucks, and sludge incineration.

Greenhouse gas emissions from aeration tanks and incineration of the organic content in the sludge are considered neutral as the biological conversion of organic compounds are similar in the environment and therefore do not contribute significantly to a change in the CO2 balance.

The total emission of CO2-equivalents per person per year is compared with the total annual discharge from one person, which in Denmark is about 9 t.

RESULTS AND DISCUSSION

Individual assessment

Carbon footprint

Figure 3 shows the additional direct power consumption for treatment of CSO, for the two decentralised and two central methods compared with the do-nothing situation, i.e. no extra power consumption. Figure 4 shows the carbon footprint covering all power consumptions, also indirect power consumption for production of materials and chemicals and greenhouse gas emissions for the same methods as in Figure 3. Figure 3 clearly shows that the power consumption for the centralised methods is five times higher than for the decentralised methods. When applying enhanced precipitation, the results for carbon footprint show that treatment of the overflow using chemicals (iron salts) results in an extra discharge of greenhouse gases from the production and to a very small extent the transportation of these chemicals.

For the WWTPs included in this study, the import of energy (power) accounts for about 85% of the greenhouse gases. When treating the overflow with enhanced precipitation using a large amount of chemicals, the contribution to greenhouse gases from production (and later incineration with the sludge) of the chemicals can constitute about one-third of the total emissions from treating the CSO.

Assuming that the annual overflow per person is about 100 m³/year, then, based on Figure 4, the annual discharge of CO2-equ. is between 15 and 50 kg. Assuming an average annual total discharge of 9 t CO2-equ. per person, it can be seen that the extra contribution to global warming (the carbon footprint) is about 0.15–0.5% of a person’s average annual carbon footprint.
The WWTPs in Copenhagen are operating in the range of 0.2–0.4 kg CO₂-eq./m³ (excluding CO₂-neutral emissions such as biogas) compared with the average emission in the UK of 0.69 kg CO₂-eq./m³ (Water UK 2009). Larger WWTPs in Denmark have digesters with combined heat and power generation, which considerably reduce greenhouse gas emissions from external energy.

Treatment efficiencies

Figure 5 shows the treatment efficiency for removal of total phosphorus and it can be seen that the centralised treatment is more efficient than decentralised treatment and depends on chemical addition. The addition of chemicals will not have a significant impact on the removal of nitrogen.

The treatment efficiencies for heavy metals (represented by Cu) and PAH are shown in Figures 6 and 7, respectively. The figures show that centralised treatment is the most efficient.

Cost

The investment and O&M (operation and maintenance) costs for each of the four methods have been calculated and converted into a net present value (NPV) for each. They are expressed in cost per reduced ha. The reason for using this unit is that investments are based on the size of the impermeable area (expressed as ‘reduced ha’) and not the amount of rainwater expected to fall over the lifetime of the investment (this is not predictable). The decentralised CSO is assumed to have a catchment area of 25 ha, whereas the central WWTP used in this study has a catchment area of 585 ha.

Figure 8 shows that the advanced decentralised method with filters and UV is the most expensive, whereas the decentralised method with chemical dosing and lamella enhanced separation has the lowest cost. However, at CSOs located in city areas with high land prices, the cost of constructing retention basins can be so excessive (if possible at all) that the advanced decentralised method becomes feasible.

Overall evaluation using life cycle assessment

The results of the life cycle assessments are shown in Figures 9–12. These include the avoided environmental impacts and the induced environmental effects compared
Figure 9 | LCA results for decentralised treatment in filters and with UV: (a) avoided environmental impacts; (b) induced environmental impacts per m³ wastewater.

Figure 10 | LCA of decentralised treatment with chemical dosing and lamella separation: (a) avoided environmental impacts; (b) induced environmental impacts.
with the do-nothing situation. The unit on the axis, PET (person equivalent target), refers to normalised and weighted data. Please note that the dark grey legend corresponds to the change in phosphorus concentration, when looking at aquatic eutrophication (P), the change in nitrogen concentration when looking at aquatic eutrophication (N), amount of specific type of waste when looking at the waste categories and level of greenhouse gases when looking at global warming.

Decentralised treatment based on filter and UV

Figure 9(a) shows avoided environmental impacts and Figure 9(b) shows induced environmental effects compared with the reference (do-nothing) situation for decentralised treatment based on filter and UV-treatment. The results show that treatment using filter and UV results in the avoided discharge of ecotoxic compounds and phosphorus, while especially ecotoxic and human toxic compounds are induced from the materials used for this solution.

Decentralised treatment based on chemical dosing and lamella separation

Figure 10(a) shows avoided environmental impacts and Figure 10(b) shows induced environmental effects compared with the reference (do-nothing) situation for decentralised treatment based on chemical dosing and lamella separation. The results show this solution is more efficient in removal of ecotoxics and phosphorus without inducing much impact compared with the decentralised solution with filter and UV.

Centralised treatment at a wastewater treatment plant

Figure 11(a) shows avoided environmental impacts and Figure 11(b) shows induced environmental effects compared with the reference (do-nothing) situation for centralised treatment at a wastewater treatment plant. The results show that the avoided impacts are much larger than for decentralised treatment solutions without inducing more impacts.
Centralised treatment at a wastewater treatment plant with ActiFlo

Figure 12(a) shows avoided environmental impacts and Figure 12(b) shows induced environmental effects compared with the reference (do-nothing) situation for centralised treatment at a wastewater treatment plant with ActiFlo and the results show that introducing ActiFlo treatment at the central wastewater treatment plant led to a larger avoidance of eutrophication at the cost of greater induced impact on human toxicity.

CONCLUSIONS

Overall, the LCA results from the four methods show that handling of overflow water from CSOs has very little induced impact on global warming compared with ecotoxicity, human toxicity and eutrophication.

The LCA also shows that the environmental gain from reducing the discharge of harmful compounds is much higher than the induced environmental impacts from extra facilities for treatment and their operation. It also shows that using the central WWTPs for handling the overflow water provides the largest gain for the environment.

This study shows that the energy consumption for central treatment is about five times higher than decentralised treatment of overflow water. The overall carbon footprint for the decentralised treatment methods is therefore considerably lower than keeping the stormwater-diluted wastewater in retention basins and pumping it for central wastewater treatment. However, the carbon footprint of wastewater handling per person is a small fraction (here 0.15–0.5%) of the total average annual emissions of greenhouse gases per person, from all society’s activities.

The overall life cycle assessment of the potential environmental impact from treatment of overflow water shows that the dominating impacts come from discharge of phosphorus and ecotoxic compounds. This assessment
also shows that solely focusing on global warming will result in other environmental impacts being overlooked. Lassaux et al. (2005) arrived at the same conclusion using a different LCA tool (Eco-indicator 99). For example, the weighting and normalisation factors for CO₂ need to be at least 10 times larger before affecting the significance of the carbon footprint in relation to the other factors investigated in this study. This would correspond to a political reduction goal of 90% in 10 years.

This study also shows that central treatment is much more efficient in removing nutrients and ecotoxic compounds compared with the technologies applied for decentralised treatment in this project, which were low technology and an advanced method (highly mechanical). A number of other advanced methods are now being developed and could be tested in the same manner. However, the range of decentralised methods assessed makes the overall conclusions more generally applicable. The centralised treatment methods assessed are the dominant types of WWTP in Denmark, which all comply with the EU Urban Wastewater Directive. Since compliance with this Directive and the Water Framework Directive applies to the whole of Europe, the conclusions are relevant where these and similar demands on the quality of the water environment prevail.

Finally, the ranking of the methods according to the life cycle assessment should be combined with a parallel life cycle cost assessment. Many decentralised treatment facilities will increase operating costs compared with a centralised method and if demands on discharge of nutrients, toxic compounds and *Escherichia coli* are strict, the centralised methods become the most feasible.

**ACKNOWLEDGEMENT**

The study was conducted by COWI, University of Southern Denmark-SDU and Avedøre Wastewater Services and financed by a joint grant from the Danish Water and Wastewater Association (DANVA) and the development association between Copenhagen Energy, Lynettefaellesskabet and Avedøre Wastewater Services. Special thanks are extended to Bo Neergaard Jacobsen for initiating the study.

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