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Life cycle assessment of three water systems in Copenhagen–a management tool of the future

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ABSTRACT

Environmental life-cycle assessment (LCA) was applied to evaluate three different water systems of the water sector in Copenhagen, Denmark, including technologies within water supply, facilities recycling water and treatment of sewer overflow. In these three water systems LCA was used to evaluate the environmental impacts of each of the processes involved. The overall conclusion was that LCA is suitable as a decision support tool in the water sector as it provides a holistic evaluation platform of the considered alternatives categorised in environmental impact categories. The use of LCA in the water sector of this region has limitations since it does not yet consider impact categories assessing freshwater scarcity and ecological sustainability.

Key words | decision support, life-cycle assessment, sewer overflow, technology comparison, water reuse, water supply

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INTRODUCTION

Copenhagen Energy (KE) supplies 52 million m^3 water per year to one million citizens in Copenhagen and 18 surrounding municipalities. KE also transports sewage to the wastewater treatment plants, and thus KE is a major player in the urban water cycle in this region. Such major water companies continuously have to adapt to changes such as growing awareness of environmental impacts, greenhouse effects and energy consumption.

The drinking water production in KE is currently exclusively based on groundwater abstraction. However, alternative

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technologies and resources are considered to solve the reduced availability of raw water in the cross field of the consequences of implementing the EU-water framework directive, which are restricting freshwater (surface and groundwater) abstraction and increasing groundwater contamination. In this context it is important to assess the environmental impacts of the technologies (e.g. desalination, membrane treatment of fresh surface waters) and sources such as recycling water for toilet flushing. Other parts of the urban water cycle are also considered, e.g. responses to the increasing number of intensified rain events (Arnbjerg-Nielsen 2006) and the increasing requirements to reduce pollution during sewer overflow.

The principles of environmental life-cycle assessment (LCA) are evaluation of all impact categories and resource consumptions in a product's or service's full life span – from cradle to grave. The results of an LCA are tailored to the product manufacturer or service supplier to build environmental considerations into new products or services (Wenzel *et al.* 1997). Thus LCA provides decision makers with an overview of potential environmental consequences of new initiatives and technologies in their water systems.

Applying LCA methodology to different water systems allows for evaluating its usefulness as a tool in the decision-making processes for assessing overall environmental consequences of different processes and technologies in the water business. The novel use of LCA in this sector (Lundie *et al.* 2004; Muñoz & Fernández-Alba 2008) calls for more and broader studies to evaluate LCA's applicability to water systems.

The objectives of the study were: a) to demonstrate the use of environmental life-cycle assessment of three water systems, comparing impact categories such as greenhouse effect, toxicity, nutrient enrichment and acidification, and b) to evaluate LCA as decision-support tool when planning the introduction of new processes or technologies in the water sector. The long-term goal is to develop a holistic tool to support "the right decisions" from both commercial and environmental points of view.

METHODS

Water systems

LCA was applied to three water systems in Copenhagen (Table 1).

In Water System I seven water treatment technologies were considered for future water supply. Besides treatment, all seven technologies included water abstraction and transport to the city's distribution network (COWI A/S 2009*b*).

Water System II included four scenarios recycling water for toilet flushing. The greywater scenario included an increase in capacity, and the lifetime of all facilities was set to 50 years (Force Technology 2009).

Water System III included two categories of scenarios for treating sewer overflow: *Local treatment* (storage in basins and local treatment) and *Central treatment* (storage in basins and transport to a central wastewater treatment plant). Each scenario was based on a catchment area of 25 hectares and maximum of 10 overflow events per year. The base scenario was today's situation without any collection in basins or treatment of sewer overflow (COWI A/S 2009*a*).

The complete water systems were modelled from cradle to grave for all systems, which included data for all stages of their life-cycle: from extraction of raw materials, during operation phase, to disposal of materials. The assessments included several scenarios or technologies for three systems and therefore the volume of input data was relatively large and diverse. However, the three water systems had energy consumption in the use phase in common as input data, e.g. 0.25 kWh/m^3 for groundwater abstraction and 1.83 kWh/m^3 for desalination (Water System I) (COWI A/S 2009*b*); 0.80 kWh/m^3 for rainwater harvesting and 2.33 kWh/m^3 for greywater recycling (85 flats) (Water System II) (Force Technology 2009); and 0.25 kWh/m^3 for central treatment and 0.05 kWh/m^3 for local treatment of sewer overflow (Water System III) (COWI A/S 2009*a*).

LCA methodology

The technologies were assessed using the commercially available life-cycle PC tool GaBi4 (Water Systems I and II) or SimaPro (Water System III) obtaining data from the databases PE International or Ecoinvent v.2.0. The assessments were comparing technologies (Water System I) or treatment (Water System III) to the existing scenario. In Water System II the functional unit of the results is m^3 of supply water substituted with recycled (non-potable) water for toilet flush. Thereby, the outcome does not evaluate whether it is advantageous to establish recycling water facilities, but compare the environmental impacts among the four scenarios.

All LCA results are expressed in personal equivalence (PE) using the potential impacts which society imposes on the environment in the European region as normalisation reference which is in accordance with the EDIP method (Environmental Design of Industrial Products) (Wenzel *et al.* 1997). The impact categories were not weighted, but

Table 1 | An overview of the evaluated technologies in Water Systems I–III of the water cycle of Copenhagen

Technology	Specifications of technology
Water System I – LCA of alternative technologies to the existing water supply	
Groundwater abstraction	Establishment of wells, abstraction of groundwater, transport to waterworks, simple aeration and filtration.
Artificial recharge of groundwater	Pumping of water from lake Arresø, recharging lake-water through layers of unsaturated soil, abstraction of artificial groundwater, transport to waterworks, simple aeration and filtration.
New wells	Identical to Groundwater abstraction, but with a longer transport distance (+25 km) compared to groundwater abstraction.
Granular activated carbon filtration	Abstraction of groundwater, transport to waterworks, and treatment with granular activated carbon filters. Filters were reactivated in Belgium.
Freshwater treatment	Extraction of water from lake Haraldsted, transport to waterworks, chlorination, addition of Al_2SO_4 and H_2SO_4, ultra filtration, nanofiltration and ultraviolet disinfection.
Desalination	Extraction of brackish seawater from Køge bugt (south of Copenhagen), treatment using ultra filtration followed by 2-pass reverse osmosis filtration and UV treatment.
Softening	Addition of NaOH and sand in a pellet reactor. Waste matter containing lime scale and sand was considered deposited in lakes.
Water System II – LCA of facilities recycling water for toilet flush	
Greywater 85 flats	Reuse of water from shower and washbasin from 85 flats. Before reuse the water passed a settling tank, multi-stage biological filters, secondary settling and UV-disinfection before reaching service water tank. From here water was pumped to the flats. Supplemented by water supply to secure constant supply. If not collected for reuse, the water would have been led directly to wastewater treatment plant.
Greywater 295 flats	Equivalent facility to "Greywater 85 flats", with an increase in capacity to cover 295 flats.
Wellwater 295 flats	Establishment of local well pumping water from subsurface and led to the building, passing through sand filters, aeration, and kept in tank from which it was pumped to the flats.
Rainwater 85 flats	Rainwater harvesting from roof (existing reed) filtered to sort away leaves and other matters. Water was kept in tanks until pumped to the flats. Supplemented by water supply to secure constant supply. Collected rainwater would have been led directly to wastewater treatment plant (in areas with combined sewers).
Water System III – LCA of treatment of sewer overflow	
Base	No collection or treatment of sewer overflow, which is discharged directly to recipient.
Local treatment 1, L1	Sewer overflow passing through a grid (3 mm), two drum filters and disinfection by UV treatment.
Local treatment 2, L2	Sewer overflow passing through a screen (3 mm) and two drum filters.
Local treatment 3, L3	Addition of $FeCl_3$ (coagulant) enhancing precipitation, settlement of flocs in large basins by countercurrent lamella clarification.
Local treatment 4, L4	Sewer overflow passing through a screen, scum board retaining floating matter, settlement with lamella clarification.

Table 1 | *(Continued)*

Technology	Specifications of technology
Central treatm. 1, C1	Transport to wastewater plant, mixing with regular wastewater and mechanical treatment.
Central treatm. 2, C2	Transport to wastewater plant, addition of $FeCl_3$ (coagulant) enhancing precipitation combined with lamella settling (ActiFlo method).
Central treatm. 3, C3	Transport to the wastewater plant, enhanced hydraulic control of process tank and secondary sedimentation tank increasing the hydraulic capacity of the biological treatment by 50%.

the normalised results were compared. For all water systems uncertainty analysis showed that the results were relatively robust.

RESULTS AND DISCUSSION

Water system I – LCA of technologies alternative to the existing water supply

In the life-cycle assessment of water supply technologies the greenhouse effect was the strongest environmental impact (measured in PE/m^3 water supply) compared to acidification, photochemical oxidant formation and nutrient enrichment (Figure 1). The observation of energy being key data in the water sector is in accordance with Raluy *et al.* (2006), who stated that the greenhouse effect had a high impact score in LCA in the water sector, and was mainly affected by energy consumption in the operation phase.

Transforming the impacts to a relative scale, by dividing the value of each scenario within an impact category by the value of the existing scenario (here Groundwater), it becomes clear that groundwater abstraction had the lowest impact in all impact categories (Figure 2). Desalination, artificial groundwater infiltration and softening had a high impact potential.

If the groundwater abstraction has to be supplemented, the conducted LCA indicated that treatment of slightly contaminated groundwater by granular activated carbon filtration, establishing new wells or membrane treatment of fresh surface water had the lowest impact from an environmental viewpoint.

If Copenhagen completely shifted water supply sources from groundwater to desalination of brackish sea water (the

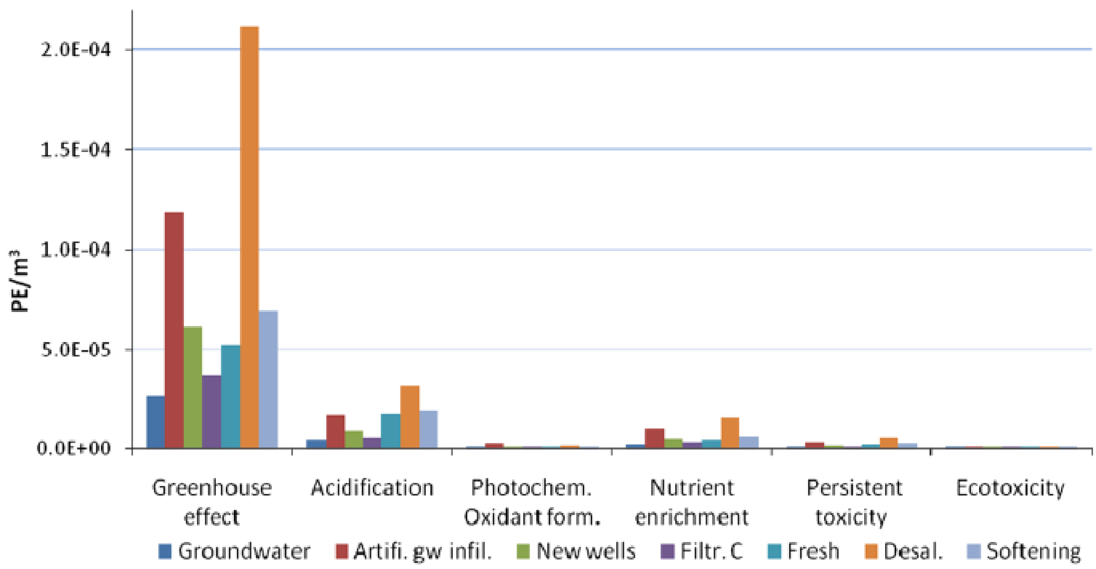

Figure 1 | Contribution to environmental life-cycle impacts of seven water supply technologies considered as alternatives to existing groundwater abstraction (Water System I).

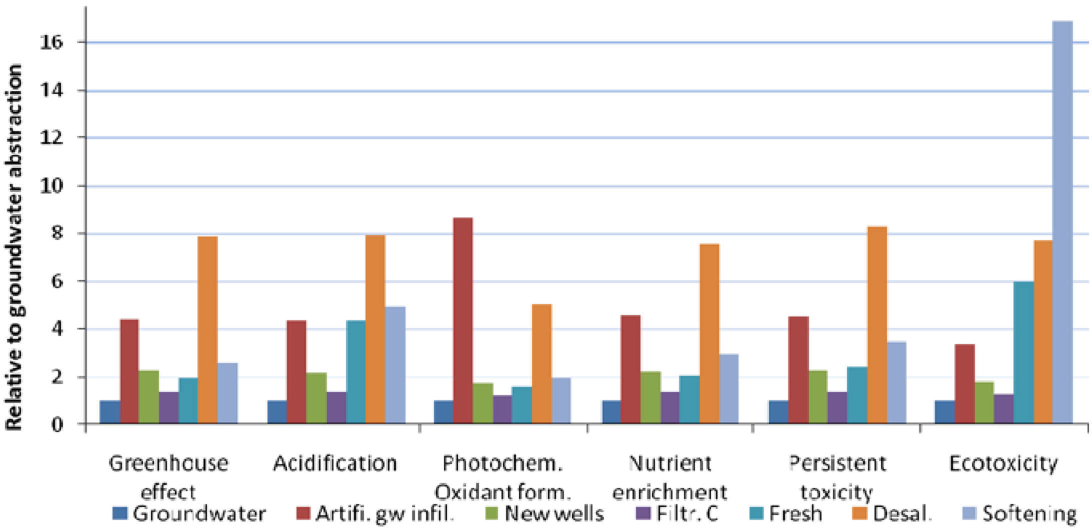

Figure 2 | Relative contribution to environmental life-cycle impacts of seven water supply technologies scaled relative to groundwater abstraction, set as 1 for each impact category (Water System I).

salinity of the Baltic Sea is approx 10‰ (Rygaard *et al.* 2009)), the greenhouse effect would increase by 9,600 PE per year. Today the greenhouse effect is 1,400 PE per year. A similar high impact of desalination compared to e.g. conventional groundwater abstraction was also observed by others (Einav *et al.* 2003; Stokes & Horvath 2006; Vince *et al.* 2008). To decrease the greenhouse effect from the water supply renewable energy sources such as wind turbines and solar cells has been suggested to provide energy for treatment and pumping (Kalogirou 2005; Fernández-López *et al.* 2009).

Despite the heavy greenhouse effect, desalination was the only technology considered here that can reduce the pressure on the freshwater resources from the groundwater abstraction around Copenhagen. Including impact on the freshwater resources and consequent ecological sustainability in the LCA assessment would strongly improve the application of the LCA, especially when applied to water systems (Alcamo *et al.* 2003; Koehler 2008; Pfister *et al.* 2009). Assessing freshwater scarcity is also relevant to ensure the different technologies fulfil the EU water framework directive.

Water system II – LCA of facilities recycling water for toilet flush

Rainwater harvesting facilities prevented rain from going directly to the combined sewer and the facilities used gravity controlled collection of rainwater which resulted in the net benefit for establishment and operation. The toxicity impacts were not assessed since they were anticipated to be relatively minor for Water System II. The results from the LCA (Figure 3) showed that the greenhouse effect was the most significant environmental impact of all four facilities recycling water. Rainwater had the best environmental profile among the four scenarios, but it is important to remember that the potential volume of rainwater harvesting is limited by the roof area available as well as the climate.

The greywater facility for 85 flats had the largest environmental impact, and up-scaling the facility to supply 295 flats was beneficial, since energy consumption per m^3 of water was high for operating the facility. Similar decreases in impact per household with increased scale were found in another greywater study in California (Memon *et al.* 2007).

Water system III – LCA of treatment of sewer overflow

For Water System III the impact on greenhouse effect was the lowest of the investigated environmental parameters for handling sewer overflow (Figure 4). This is remarkable, since the greenhouse effect was the category with the highest impact in the two other water systems (Figures 1 and 3). However, this high impact is caused by the intense waste water treatment processes only relevant for Water System III. The impact categories acidification and photochemical oxidant formation are not presented (Figure 4) since their contributions were assessed and found relatively minor.

Central sewage treatment had the lowest impact regarding nutrient enrichment, ecotoxicity and persistent toxicity. On the contrary, local sewage treatment had a lower impact on greenhouse effect compared to central treatment (Figure 5), which required more energy for the higher

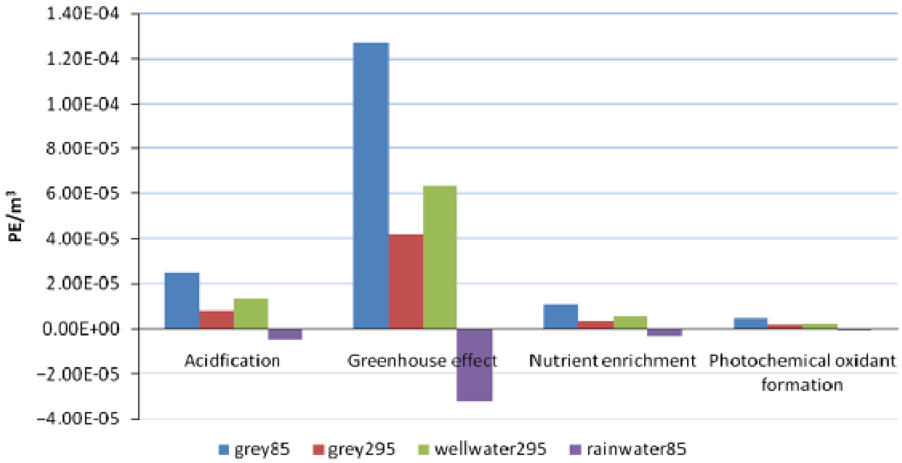

Figure 3 | Contribution to environmental life-cycle impacts of the four facilities per m³ substituted supply water by recycling water – Water System II.

level of treatment. A Belgian study revealed a similar negative correlation between greenhouse effect and nutrient enrichment (Lassaux *et al.* 2007).

If the study of this water system had focused exclusively on greenhouse effect – which is the case in carbon footprint studies – local treatment would have given the lowest impact on the environment. However, since the LCA assessed several other environmental impacts than just greenhouse effect, the central treatment had the lowest overall environmental impact. This stresses the importance of including all impact categories before presenting LCA results to decision makers. This approach is essential within the LCA framework (ISO 2006), and such considerations are needed for a holistic and sound decision.

It must be noticed that the base scenario had no measurable impact in the greenhouse effect category, since this scenario did not include any treatment or other processes with CO_2 emission. For greenhouse effect the other scenarios were transformed into a relative scale by dividing the value by C1 instead of base scenario.

CONCLUSIONS

The technologies for water supply of Water System I were ranked in the same way for all four relevant impact categories. The present groundwater abstraction approach had the lowest impact in all environmental categories, whereas desalination had the highest impacts. However, LCA did not consider impacts on the freshwater resources, which is of great concern and could change the outcome of the interpretation dramatically.

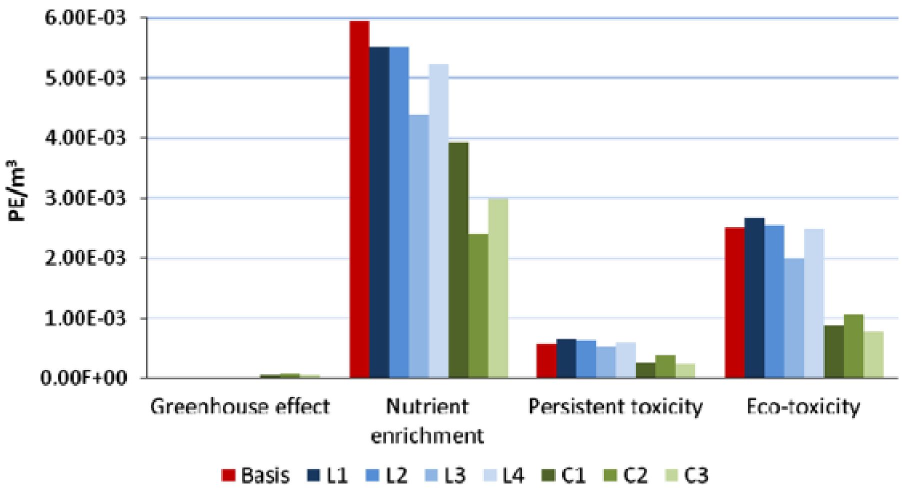

Figure 4 | Contribution to environmental life-cycle impacts of the base scenario and the seven suggested solutions. The scenarios L1–L4 are local treatments and the scenarios C1–C3 are central treatments of sewer overflow – Water System III. For details see Table 1.

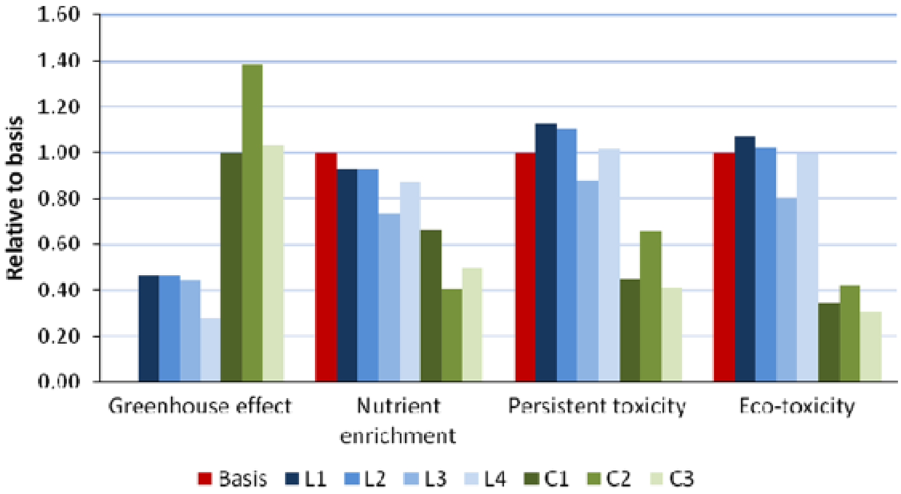

Figure 5 | Relative contribution to environmental life-cycle impacts of the seven suggested treatments of sewer overflow (Water System III) scaled relative to the base scenario. This is set as 1 for each impact category except for greenhouse effect, which is scaled relative to C1 since no contribution to greenhouse effect was found in the base scenario.

In the water recycling facilities (Water System II), establishment and operation of the rainwater facility ended up in a net environmental benefit when it came to all four impacts – especially for greenhouse effect. The capacity of the facility is important, since the environmental impact of recycling greywater was lower per person for 295 than for 85 persons.

In the handling of sewer overflow (Water System III) LCA showed that it was important to consider all impact categories and not just a certain category prevailing at the time being. If only greenhouse effect had been assessed in this water system then local treatment of sewer overflow would have been given an overall better environmental score. However, when all the impacts were considered by the LCA tool, central treatment had the lowest environmental impact.

Assessing all three investigated water systems by environmental life-cycle (LCA) approach demonstrated that the obtained results presented a solid platform for supporting decisions regarding water supply technology, water recycling facility or treatment of sewer overflow, and LCA was a useful tool to evaluate environmental impacts of technologies in the water sector. Even though evaluation of a new technology with respect to greenhouse effect is very important and often is in focus, all environmental impacts must be included when supporting decision-making. With a standardised LCA framework in environmental assessment of water systems, it also becomes extremely important to consider if any significant impacts occur outside the typical LCA range of impact categories. A major challenge for the water sector is to include the impact of groundwater abstraction on the freshwater resource and the subsequent impact on the ecosystems.

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