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Life-cycle and freshwater withdrawal impact assessment of water supply technologies

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Abstract

Four alternative cases for water supply were environmentally evaluated and compared based on the standard environmental impact categories from the life-cycle assessment (LCA) methodology extended with a freshwater withdrawal category (FWI). The cases were designed for Copenhagen, a part of Denmark with high population density and relatively low available water resources. FWI was applied at local groundwater catchments based on data from the national implementation of the EU Water Framework Directive. The base case of the study was the current practice of groundwater abstraction from well fields situated near Copenhagen. The 4 cases studied were: Rain & stormwater harvesting from several blocks in the city; Today's groundwater abstraction with compensating actions applied in the affected freshwater environments to ensure sufficient water flow in water courses; Establishment of well fields further away from the city; And seawater desalination. The standard LCA showed that the Rain & stormwater harvesting case had the lowest overall environmental impact (81.9 μPET/m^3*)* followed by the cases relying on groundwater abstraction (123.5-137.8 μPET/m^3), and that desalination had a relatively small but still important increase in environmental impact (204.8 μPET/m^3). Rain & stormwater harvesting and desalination had a markedly lower environmental impact compared to the base case, due to the reduced water hardness leading to e.g. a decrease in electricity consumption in households. For a relevant comparison, it is therefore essential to include the effects of water hardness when comparing the environmental impacts of water systems of different hardness. This study also emphasizes the necessity of including freshwater withdrawal respecting the relevant affected geographical scale, i.e. by focusing the assessment on the local groundwater catchments rather than on the regional catchments. Our work shows that freshwater withdrawal methods previously used on a regional level can also be applied to local groundwater catchments and integrated into the standard LCA as an impact category. When standard LCA is extended to include impacts of freshwater withdrawal, rain & stormwater and seawater (0.09-0.18 compared to 11.45-17.16 mPET/m^3) were the resources resulting in least overall environmental impact.

Keywords

Life-cycle assessment; Freshwater withdrawal impact; Groundwater abstraction; Rain & stormwater harvesting; Desalination; Water hardness

1 Introduction

Conflicts over water have been occurring since the beginning of time. Even though the Danish capitol Copenhagen is usually not considered as being in water shortage, water use is currently sowing the seeds of dispute. Industry, agriculture and urban water supply are the main activities responsible for withdrawing water from the natural environment. The purity of groundwater is acknowledged in the region and most water consuming activities are based on this resource.

The European Water framework directive (EU-WFD) is being implemented in the EU-Member States by the River Basin Management Plans which among other parameters regulate the water flow requirements for water flows and the utilizable amount of water in each freshwater (ground and surface water) compartment (European Union, 2000). The implementation has revealed that groundwater is not an abundant resource as often believed (European Environment Agency, 2007), and the water utility HOFOR has been forced to seek new water resources or new approaches to sustain the water withdrawal permissions in order to supply the City with sufficient water for urban purposes. This has led to the identification of 4 relevant cases for water supply which fulfill the EU-WFD and which either alone or as a mix can constitute the future water supply.

In this study we performed an environmental evaluation of the 4 cases for water supply since environmental performance is a well established criterion and should per se be included in any evaluation of future supply options and in our search for the optimal water supply option. One way to evaluate the environmental performance is to use life-cycle assessment (LCA) which has proven its strengths for evaluating water systems environmentally by using a “cradle-to-grave” approach (Lundie *et al.*, 2004; Lyons *et al.*, 2009; Godskesen *et al.*, 2011; Schulz *et al.*, 2012). LCA can also include effects of reduced water hardness in the households which are relevant when evaluating water systems of different water hardness (Godskesen *et al.*, 2012). However, the impacts of a product or system on freshwater resources are not included in the current typical LCA practice. Many have previously expressed the volume of freshwater withdrawn for water supply (Sharma *et al.*, 2009; Lundie *et al.*, 2004) e.g. by water foot-printing (Hoekstra *et al.*, 2011) where water is considered a resource for man rather than an environmental media with environmental impacts when withdrawn. Recently methods have been suggested to integrate freshwater use into the LCA methodology by treating freshwater withdrawal as an environmental impact category with an impact on the freshwater environment (Muñoz *et al.*, 2010; Milà-i-Canals *et al.*, 2009; Lévová & Hauschild, 2011; Zelm *et al.*, 2010; Pfister *et al.*, 2009; Kounina *et al.*, 2012).

In our study we adopted the method of Lévová & Hauschild (2011) for integrating freshwater withdrawal into the standard LCA and further developed it by applying the method to the local level of groundwater compartments via regulations and data in the national implementation of the EU-WFD. We chose the method because it has modest data requirements that can be fulfilled both at regional and local scale. It calculates the characterization factor (CF) which is a part of the freshwater withdrawal impact (FWI) based on water resource measures (Milà-i-Canals *et al.*, 2010; Muñoz *et al.*, 2010; Pfister *et al.*, 2009) as opposed to native species occurrence (Zelm *et al.*, 2010). We also applied normalization and weighting according to the local level and in accordance with the LCA methodology converting freshwater withdrawal impact to the same metric as the standard environmental LCA categories. Our method only considers freshwater withdrawal as an impact since saline water is not in shortage. Most of the Earth's water is present in the oceans as saline water and only 2.5% is freshwater. Icecaps and glaciers make up 69% of Earth's freshwater leaving 31% as directly available ground and surface water (Gleick, 2000). It is our hope that in future environmental evaluations of water consuming products or systems, freshwater withdrawal will be given the attention it deserves, and this is our suggestion of how to address it.

The aim of this study is to compare the environmental impact of 4 cases for water supply and include the impacts of freshwater withdrawal.

2 Material and methods

2.1 Life-cycle assessment

A standard LCA (ISO, 2006) generally consists of 4 phases: 1. Goal and scope definition, 2. Inventory analysis, 3. Impact assessment and 4. Interpretation. Prior to the LCA we went through each phase in relationship to our study.

2.1.1 Goal and scope definition

The defined goal was to assess the environmental impacts of 4 cases for water supply all tailored to fulfill the requirements of the EU-WFD. Thereby the goal allowed for ranking the cases according to their environmental performance. The functional unit was production of water which fulfilled the EU-WFD's water flow requirements for water courses where freshwater was withdrawn and replacing 1 m^3 of potable drinking water as produced today. The produced water could be potable or non-potable depending on the use of the drinking water that it replaces.

The system boundaries were the same for all cases (**Figure** 1): 1) Intake, withdrawal or harvest of water from a source which was groundwater, rain & stormwater or seawater; 2) Treatment facilities such as waterworks, desalination plant and rainwater basins, pumps, electricity consumption and auxilliary chemical consumption during water treatment were included; 3) Distribution to consumers' taps via piped distribution system including the effects in the households caused by an altered water quality e.g. reduced water hardness for the 2 cases with lower concentration of calcium and magnesium; 4) Transport of wastewater to the wastewater treatment plant (WWTP) for treatment via the City's combined sewer system before discharging to the sea (Øresund). Only electricity consumption at the WWTP was included since other impacts from this activity are of minor importance (Lundie *et al.*, 2004;

Danva, 2010) and since the discharged water was assumed to contain the same pollutants for all cases and hence would not affect the comparison of the cases. An average grid mix was developed for electricity consumption based on electricity production data from 2010 in Denmark consisting of 56% hard coal, 23% wind power, 20% natural gas and 1% heavy fuel oils. In the sensitivity analysis it was investigated how an alternative energy mix according to Danish governmental predictions on future scenarios for electricity mix would affect the results. **Table** 1 and section 2.3 contain details of each case.

2.1.2 Inventory

On the input side, the life-cycle inventory consisted of materials, chemicals and energy input primarily based on data from the water utility in Copenhagen (HOFOR) and otherwise most accurate data estimations from literature. All material and energy inputs were determined based on the functional unit. The PE database as offered by PE Consulting group was used and when pre-developed processes were not found of sufficient accuracy processes were developed according to local data estimations, e.g. electricity mix for Denmark.

2.1.3 Impact assessment

The LCA was performed with the GaBi 4.4 software developed by PE International according to the ISO 14044 standard procedure (ISO, 2006) with the exception that a weighting step was performed. Impacts were assessed with the EDIP 1997 method which is a standardized LCA method initially developed for the Environmental Design of Industrial Products (Wenzel *et al.*, 1997) but also found applicable for services such as drinking water supply (Godskesen *et al.*, 2011). The impact assessment covered the steps classification and characterization, normalization and weighting. Classification meant sorting all substance flows in the LCA according to their impacts on the environment. In the characterization step the intensity of the impacts was determined by multiplying the quantities of a substance flow by its characterization factor (CF), which expresses the potential impact of the flow on a per unit level. Normalization brought all impact scores on a common scale by dividing each of them by the corresponding normalization reference representing an average European citizen's annual contribution within each impact category. Hereby all the impacts were expressed in person equivalents, representing the impact of consuming 1 m^3 water relative to a person's total annual impact on the environment. The result of the LCA is presented in impact categories within the EDIP method which is a midpoint method (Hauschild & Potting, 2005). Finally, the normalized impact scores were weighted using weighting factors that for the environmental impacts are based on the distance from current levels of impact to the European or Global politically set targets within each impact category (Stranddorf *et al.*, 2005). For resource impacts the weighting is based on the scarcity of the resource. After weighting, all environmental impacts can be summed and so can all resource impacts. The weighting expresses the environmental impacts in targeted person equivalents (PET) - the annual impact that can be caused by an average citizen in accordance with the current political targets. The resource impacts are expressed as person reserves (PR) - the amount of the resource available in the currently known extractable reserves per person in the world today. We based the comparison of the 4 cases on 4 environmental impact categories: *Global warming*, *Acidification*, *Nutrient enrichment* and *Photochemical ozone formation*. Likewise, 3 chemical related toxicity categories were included: *Chronic ecotoxicity in water*, *Human toxicity via soil* and *Human toxicity via water*. Resource consumption was also evaluated for the relevant resources.

2.2 Freshwater withdrawal impact

The environmental impacts of withdrawing freshwater are not represented by any of the impact categories, and in order to support inclusion of these potentially important impacts we modified the water use impact method developed for industry by Lévová & Hauschild (2011) by applying it to local groundwater catchments. The method was further integrated into the LCA by adding both a normalization and weighting step in accordance with the EDIP methodology. This allowed for comparison with the already established LCA impact categories since we considered freshwater withdrawal an environmental impact in accordance with e.g. global warming.

The Freshwater withdrawal impact was reflected in the impact score FWI calculated by multiplying the volume of water withdrawn by each case (Q, m^3) by the characterization factor for the freshwater withdrawal impact on the ecosystem (CF) representing the sensitivity of freshwater ecosystems towards freshwater withdrawal on a local level. Within the 4 phases of a standardized LCA the FWI method involved 3 special considerations since the FWI is not yet standardized: 1) Quantification from a life-cycle perspective of groundwater volume withdrawn to produce the functional unit; 2) Determination of characterization factors; and 3) Normalization and weighting.

2.2.1 Quantification of freshwater withdrawn

The withdrawal of freshwater (Q) was quantified in the inventory of the LCA. Since this case is about water production both water withdrawn for water supply and water used throughout the life-cycle was included. In the city combined sewers lead rain & stormwater to the wastewater treatment plants where it after treatment is discharged into the Sea. Since the precipitation does not infiltrate and increase the groundwater recharge the volumes withdrawn for production were not included for cases based on rain & stormwater as well as seawater.

We assumed that the water used throughout the life-cycle originated from local groundwater. Water leaving the production or returned to the same local water catchment after treatment was deducted.

2.2.2 Characterization factor

In the characterization step the freshwater use impact was converted into its potential impact on the freshwater environment. The Characterization factor (CF) was calculated as follows:

$$CF = \left(\frac{WU}{WR-EWR}\right)^{(WR/(2xEWR))} \qquad \text{(Lévová \& Hauschild, 2011)} \qquad (1)$$

The water use (WU), water resource (WR) and environmental water requirements (EWR), [km^3/y], were extracted from the local EU-WFD plan for areas where HOFOR had well fields and only groundwater was considered for the CF. A general EWR was stated by the Danish EPA as 65% of WR for the whole country without consideration of the specific site. This is considered a precautionary decision and primarily applicable for comparison of exploitation among groundwater catchments (Danish Nature Agency, 2011). This relatively high EWR has been estimated lower (35%) for the surface and groundwater catchments in the region (Smakhtin *et al.*, 2004). We applied 65% of WR for EWR as the default and tested the application of a lower EWR in our sensitivity analysis. CFs were calculated for all local water catchments identified in the EU-WFD plans and a weighted average representing the total abstraction of HOFOR was calculated according to the volume withdrawn in each region. Hereby CFs were based on local measures of sensitivity of freshwater withdrawal and FWI was characterized to express the contribution to the standard environmental impacts from water withdrawal.

2.2.3 Normalization and weighting

The results for FWI were normalized by dividing with the normalization reference for the local area as water use impacts are generally considered depending on the local conditions (Lévová & Hauschild, 2011). Development of a regional normalization reference was done by multiplying the total water withdrawal originating from groundwater with the regional CF and dividing by the region's population (Statistics Denmark, 2012) thereby obtaining a reference for an average citizen in this area. The total groundwater withdrawal in the region is reported each year to a national water database (Danish Geological Survey, 2012) gathering withdrawals from water supplies, industries, agriculture, etc. The normalization step converted FWI into the common metric PE (person equivalent) as the other environmental impact categories within the LCA. The last step was weighting where the seriousness of the impact category is multiplied by a weighting factor. Since there is no weighting factor in the EDIP-method for freshwater withdrawal yet, the minimum importance 1 (representing no political reduction targets for the impact) was assumed for FWI. For comparison the weighting for the global warming impact category is 1.3. The low weight of FWI opens for investigation of the importance of FWI. A lower weighting can only occur if another approach other than distance to target is applied. The weighting allows for aggregation of FWI with the other weighted environmental impact categories of the LCA.

2.3 Description of the cases

We identified 4 hypothetical cases for water supply of relevance for Copenhagen in the search for the optimal water supply technology which fulfills the EU-WFD's water flow requirements and replaces 1 m^3 of potable drinking water as of today. The 4 cases were: A1 rain & stormwater harvesting, A2 compensating actions, A3 new well fields and A4 desalination. The existing system was also included, A0 base case. A0 enabled us to compare the environmental impacts and FWI of the 4 cases with today's water production. See *Supplementary material I* for inventory of LCA and FWI of the 4 cases.

2.3.1 A0 Base case

In 2009 the City of Copenhagen (population of 0.52 million) used a total volume of 29.8 million m^3 drinking water. The water is abstracted from groundwater sources located outside the city and requires only simple treatment at the waterworks in terms of aeration and sand filtration before distribution. During aeration CH_4 and H_2S were emitted and these are included in the LCA. The water abstraction, treatment and distribution consume only 0.27 kWh per m^3 drinking water. Since the groundwater originates from chalk aquifers the hardness is 362 mg/L as $CaCO_3$ and categorized as very hard drinking water (US Geological Survey, 2012). Actual data on materials and consumptions for water supply were used in the assessments. After use drinking water is considered as wastewater and is transported via combined sewers to the WWTPs where it was treated before discharged to the Sea (Øresund). Electricity consumption for wastewater transportation was based on average consumption in the period 2007-09 and processes at WWTP on consumptions from 2005-09 (Danva, 2010).

2.3.2 A1 Rain & stormwater harvesting

In the A1 case rain and stormwater is considered harvested from an urban area of 68,500 m^2 (roof area 20,200 m^2; main road area 8,500 m^2) populated by 1,000 residents and 200 employees. Rainwater is collected from the roofs and led to an underground basin (750 m^3). Stormwater from the main road is collected in large pipes (Ø1,000 mm) and led to a basin established in connection with a clarifier and pumping station controlling the flow. The clarifier separated oils from the water before it passes through a dual porosity filter. In dual filtration stormwater floats by gravity on a solid phase consisting of layers of $CaCO_3$ particles resulting in suspended solids, heavy metals and PAHs in the stormwater being adsorbed and thereby removed (Jensen, 2009). Afterwards the treated stormwater is mixed with rainwater and stored in a basin. Prior to distribution to the same residential and office buildings as where collected the water is UV-treated. The water is of non-potable quality and is used for flushing toilets and washing clothes. The area is as most parts of Copenhagen drained by combined sewers and the decoupling of the rain and stormwater is a significant environmental advantage of A1 as electricity consumption for transport and treatment of wastewater is reduced. Rainwater is soft but since it passed through a filter of $CaCO_3$ particles the resulting hardness of the non-potable water was 145 mg/L as $CaCO_3$ (Jensen, 2009). This hardness is lower than in the drinking water in the base case (A0). Effects of changed hardness levels in the households were included in the LCA, i.e. decreased consumption of laundry detergent and electricity and prolonged service life of washing machine and toilets (Godskesen *et al.*, 2012).

2.3.3 A2 Compensating actions

Compensating actions (case A2) cover various initiatives implemented to fulfill the requirements for water flows in watercourses to maintain the current abstraction volume as described by the implementation of EU-WFD. In this study compensating actions included abstraction of groundwater, transfer of water from lakes to watercourses and reestablishment of wetlands from forest land (**Table 1**). Besides the various compensating actions A2 included all processes in the base case (A0). Regarding calculation of the characterization factor (CF) it was assumed that HOFOR obtained permissions for groundwater withdrawal equivalent to the permissions before EU-WFD resulting in a CF at approximately 1.

2.3.4 A3 New well fields

The new well site case (A3) is also equivalent to the base case with addition of a 20 km longer pipeline from well fields to the waterworks. In A0 water is transported 5 km from well fields to waterworks. The longer distance means increased energy consumption. Regarding FWI we assumed we could find well fields with a surplus of available groundwater according to the EU-WFD within this distance. Therefore, CF was estimated to 1.

2.3.5 A4 Desalination

Copenhagen is situated at the entrance to the Baltic Sea (Øresund) and desalination of seawater is an option. The treatment plant is considered to be located 5 km south of the city. First, water is filtrated mechanically (150µm) to remove large particles, a coagulant is added and pH adjusted and the water is ultra filtrated where 10% of the water is lost and returned to Øresund after extraction of dry material. An anti scaling agent is added before the water passes through a 2 step reverse osmosis membrane and hydrochloric acid and sodium hydroxide are dosed regularly to clean membranes from fouling. Finally calcium hydroxide is added and the water UV treated (Rygaard, 2010). The water has a hardness of 108 mg/L as CaCO3 when distributed as drinking water and the positive effects in the households due to the lower hardness were included in the LCA as for Case A1. The effects for A4 are besides the ones mentioned for A1 decreased electricity consumption when heating water (washing machine, coffee maker and kettle), decreased consumption of soap for personal hygiene, etc. (Godskesen *et al.*, 2012), see **Table** 1 for all included effects.

2.4 Sensitivity Analysis

Selected parameters were changed to check the robustness of the results for standard LCA impact categories and FWI and are described in **Table** 2.

3 Results and Discussion

3.1 Standard LCA

Selected inventory data for the 4 cases (A1-A4) and base case (A0) show relatively similar electricity consumptions during use stage (**Table** 3) for A0, A2 and A3 (3.73 – 4.44 MJ/m^3) whereas it was lower for A1 (0.92 MJ/m^3) due to avoidance of discharge to the combined sewers in the area and the following treatment at the WWTP. In contrast, electricity consumption (7.49 MJ/m^3) was higher with desalination which is in accordance with the findings of others (Vince *et al.*, 2008; Lyons *et al.*, 2009). A1 (rain & stormwater harvesting) had the highest material requirement per functional unit involving infrastructure elements such as concrete, cast iron and plastics due to the construction of the storage basins and pipes. The freshwater withdrawn to deliver the functional unit (-0.0014 – 1.0201 m^3 groundwater) included only groundwater and not rain, storm- or seawater, leaving freshwater consumption for A1 and A4 relatively small. In our case study harvested rain & stormwater would have been included as freshwater withdrawal if it had been infiltrated into the ground (thus being part of the surface- and groundwater recharge), rather than being led into combined sewers as is the current practice.

The results of the cases differ markedly for the impact scores for the EDIP impact categories (**Table** 4) and show that the rain & stormwater harvesting case (A1) has the lowest total aggregated environmental impact (81.9 μPET/m3). The cases relying on groundwater abstraction (A0, A2 and A3) had an environmental impact of 123.5 – 137.8 μPET/m3. A1 had a low environmental impact mainly due to the role of combined sewers and the positive effects of lower water hardness in the households. Desalination has the highest total environmental impact score (204.8 μPET/m3), primarily due to the use of electricity.

The environmental impact category with the highest importance for the 4 cases is global warming potential (67-80% of the total environmental impacts; **Table** 4) and this impact over the life cycle of the water production originates from different parts when dividing them into infrastructure and electricity (**Fig. 2)**. The contribution from water treatment is relatively higher for A1 compared to the others. The cases relying on groundwater abstraction (A0, A2 - A3) show very similar patterns with little contribution from water production and more than 50% from wastewater transport and treatment. If wastewater treatment had not been included, these 3 cases would have had the lowest impact, but then the cases would not have been comparable, since the rain & stormwater harvesting reduced the amount of wastewater to be treated. This emphasizes the importance of a thorough assessment of proper system boundaries, functional unit, etc. in the preparation of an LCA (ISO, 2006).

3.1.1 Effects of water hardness

This study shows that a difference in water hardness of 215 mg/L as $CaCO_3$ or higher between the systems is important to the results of the LCA (**Fig**. 2, negative values of A1 and A4) which is in accordance with findings of a previous study (Godskesen *et al.,* 2012). Lower water hardness reduces global warming impact of the desalination case A4 from 224.7 to 151.4µPET and the total environmental impact from 336.7 to 204.8µPET (**Table** 4) equivalent to approximately 40% reduction. In comparison an increase of environmental impacts of approximately 500% was found by Lyons et al. (2009) when comparing import of freshwater over a distance of 280 km with desalination. In spite of the energy requirements of the desalination process, we found an increase of only 60% in total environmental impacts when comparing desalination with our base case. This relatively small increase is mainly due to the positive effects of reduced water hardness.

Toxicity impacts of A1 and A4 are relatively low (125.7 and 180.6µPET) primarily due to reduced consumption of laundry detergent and prolonged service life of household appliances compared to the base case (**Table** 4). Also consumption of chromium and copper is reduced due to prolonged service life of domestic appliances and hence lower consumption of chromium for alloying of steel. These effects of reduced water hardness are also the reason for the net benefit in freshwater withdrawal of A4 (**Table** 3) since it is assumed that the water extraction for manufacture of the household appliances occurs in the catchment areas. Thus the systems delivering water with reduced water hardness have relatively lower impacts regarding toxicity and resource consumptions even though included infrastructure materials or electricity consumption are higher.

3.2 Freshwater withdrawal impact (FWI)

Characterization factor (CF) for the FWI of groundwater withdrawal of the base case was 1.51. When either compensating the environment by water transfer to the water scarce watercourses or moving well fields out where more water is available CF was reduced to 1.38 or 1.00, respectively (**Table** 5). The FWIs were higher for the groundwater-based cases (A0, A2 and A3) due to higher freshwater withdrawal (Q, **Table** 3). FWI was negative for A4 meaning the case provides a net benefit in freshwater availability. For comparison the withdrawal-to-availability indicator (WTA) (Milà-i-Canals *et al.*, 2009) was applied. **Table** 6 shows that the WTAs of our region's groundwater resources (0.48-0.61) are similar to WTA for freshwater resources in Spain (0.33) suggesting that our withdrawal of groundwater is as severe as withdrawal of freshwater in Spain.

3.2.1 Water stress index

The base of the CF is also called the water stress index (WSI) which is also another way of determining environmental water balance:

$$WSI = \frac{WU}{WR-EWR} \qquad \text{(Smakhtin } et\ al.\text{, 2004)} \quad (2)$$

WSI is categorized as presented in **Table** 7 (Smakhtin *et al.*, 2004). Applying this definition to HOFOR's groundwater catchments (1.73) shows that the withdrawal is categorized as environmental water scarce (**Table** 5- 7). A WSI of 1 as for A3 implies that on average the actual water use is equivalent to the utilizable freshwater volume however it still indicates environmental water stress for low flow water courses in the water catchments. Aggregating catchments for a larger area (Sjælland - Copenhagen and nearby rural area bounded by the Sea) still results in water stress (WSI 1.37). Upscaling to national level or moving to rural areas results in low CFs and WSIs (0.05 – 0.28) indicating withdrawals which are environmentally safe (**Table** 6). CF has previously been considered lower (0.04) for the country when focusing on the entire freshwater resources (ground and surface water) (Lévová & Hauschild, 2011). We here show the necessity of downscaling since this is where we find the magnitude of the impact on the local water bodies. We also see the importance of distinguishing groundwater from surface water when calculating impacts of freshwater withdrawal. Surface water and groundwater are two different resources which do not present the same scarcity and may not even serve the same users or purposes, as also discussed by Boulay *et al.*, (2011). Calculations of CF, WTA and WSI are shown in *Supplementary material II*.

3.3 LCA and Freshwater withdrawal impact (FWI)

The contribution from FWI to the total environmental impact is substantial (-0.02 – 17.04 mPET) (**Fig.** 3) compared to the standard impact categories (0.08 - 0.20 mPET). This is a logical consequence of water production being the activity which requires the highest withdrawal of groundwater whereas many other processes in our daily life such as transportation and heating of houses contribute markedly more to other impact categories e.g. global warming. The average drinking water consumption is 38 m^3/p/y and the annual groundwater withdrawal of the region is 70 m^3/p/y since groundwater is also used for industrial and agricultural purposes. The high impact of FWI underlines the importance of incorporating impacts on freshwater in the decision making process within the water sector and is in accordance with the global trend of considering water consumption a matter of high priority (Gleick, 2009; European Environment Agency, 2012).

We also show that the methods previously used on national levels can be applied to local water catchments and can be integrated into the standard LCA method as an impact category (**Fig**. 3) focusing on the relevant local source. Including the FWI in the LCA (**Fig**. 3) changed the ranking of the cases compared to the ranking by the standard LCA. The rain & stormwater case (A1) continues to have lowest impact and the desalinated seawater (A4) goes from being the highest environmental burden to the second lowest when including FWI. The cases relying on groundwater (A0, A2 and A3) obtain a higher impact due to the heavy withdrawal of groundwater which after delivery and use in the urban area is treated at the WWTP and discharged into the Sea. If reclaimed wastewater is returned to restore natural flows it would have changed the impact of the cases.

Sensitivity analysis

The results from the standard LCA and FWI are relatively robust as they do not change much when altering most of the selected parameters in the sensitivity analysis (**Fig**. 4). However future predictions of changes in electricity mix significantly decreased the environmental impacts of a standard LCA when the renewable share of the energy mix was increased. The sensitivity analysis clearly states that with an energy mix in 2050 consisting of 100% renewables the A4 desalination of seawater has the lowest impact compared to groundwater based technologies with high water hardness and no central softening applied. However, this change in water production will lead to an overall increased energy consumption which is unfavorable in terms of environmental impacts unless it is based on surplus electricity from the grid. We also see that in 2050 rain & stormwater harvesting is less favorable due to the electricity needed to build large concrete basins for storage since our model contains basins constructed with electricity mix of today. We find that changing the EWR from 65 to 35% halves the impact of the FWI. EWR is in our study somewhat arbitrary since it has been predetermined by authorities without considerations of local conditions. However, it does not change the fact that whether EWR is low or high the FWI category is significantly higher than the standard LCA categories and therefore is essential to include in our LCA (**Fig**. 4).

4 Conclusion

This study extended the standard LCA method with the impact of freshwater withdrawal by further developing an existing method which was originally developed for assessing industrial freshwater use at a regional scale. We applied the method to the water supply system of Copenhagen where the EU-WFD puts restrictions on the available local groundwater resources. The main findings of this work include:

- We developed and implemented a method to integrate freshwater withdrawal impact (FWI) into the standard LCA by applying a method previously used on national levels to the relevant local water catchments. The integration emphasizes the high importance of FWI, even when choosing the weakest weighting according to the distance-to-political-target method, compared to standard LCA categories especially within the water production sector.
- Integrating freshwater withdrawal impact assessment into the standard LCA categories resulted in the cases rain & stormwater harvesting (A1) and desalination of seawater (A4) (0.09 and 0.18 mPET/m^3) had the lowest impact compared to the cases based on groundwater resources (11.45-17.16 mPET/m^3) and this is due to a scarcity of groundwater considering the amount of available groundwater and water withdrawal in this region.
- The standard LCA showed that the rain & stormwater harvesting case (A1) has the lowest environmental impact (81.9 μPET/m^3) followed by the cases relying on groundwater abstraction (123.5-137.8 μPET/m^3), and that A4 desalination (204.8 μPET/m^3) has a noteworthy increase in environmental impact. If the rain & stormwater is not harvested it is led to combined sewers where e.g. energy is consumed to transport and treat the wastewater. Therefore, it is environmentally beneficial mainly due to energy savings to prevent precipitation from discharging into the sewers e.g. by harvesting and recycling for non-potable purposes.
- It is also essential to include the beneficial effects of reduced water hardness in households when comparing the environmental impacts of water supply cases leading to water of different

hardness. Especially for desalination of seawater the reduced water hardness reduces the environmental impacts of our standard LCA by approximately 40%.

- The sensitivity analysis indicated that if we have to rethink the water supply in the year 2050 with an electricity mix of 100% renewable sources desalination of seawater (A4) has the lowest environmental impact when it comes to the standard LCA and FWI, provided that renewable electricity sources will be able to meet the increased electricity use that would result from a major shift towards desalination in the drinking water supply.

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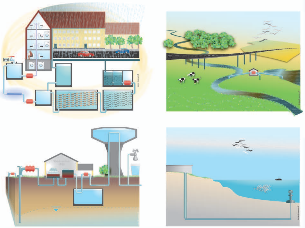
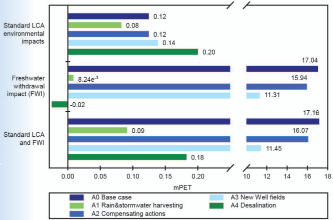
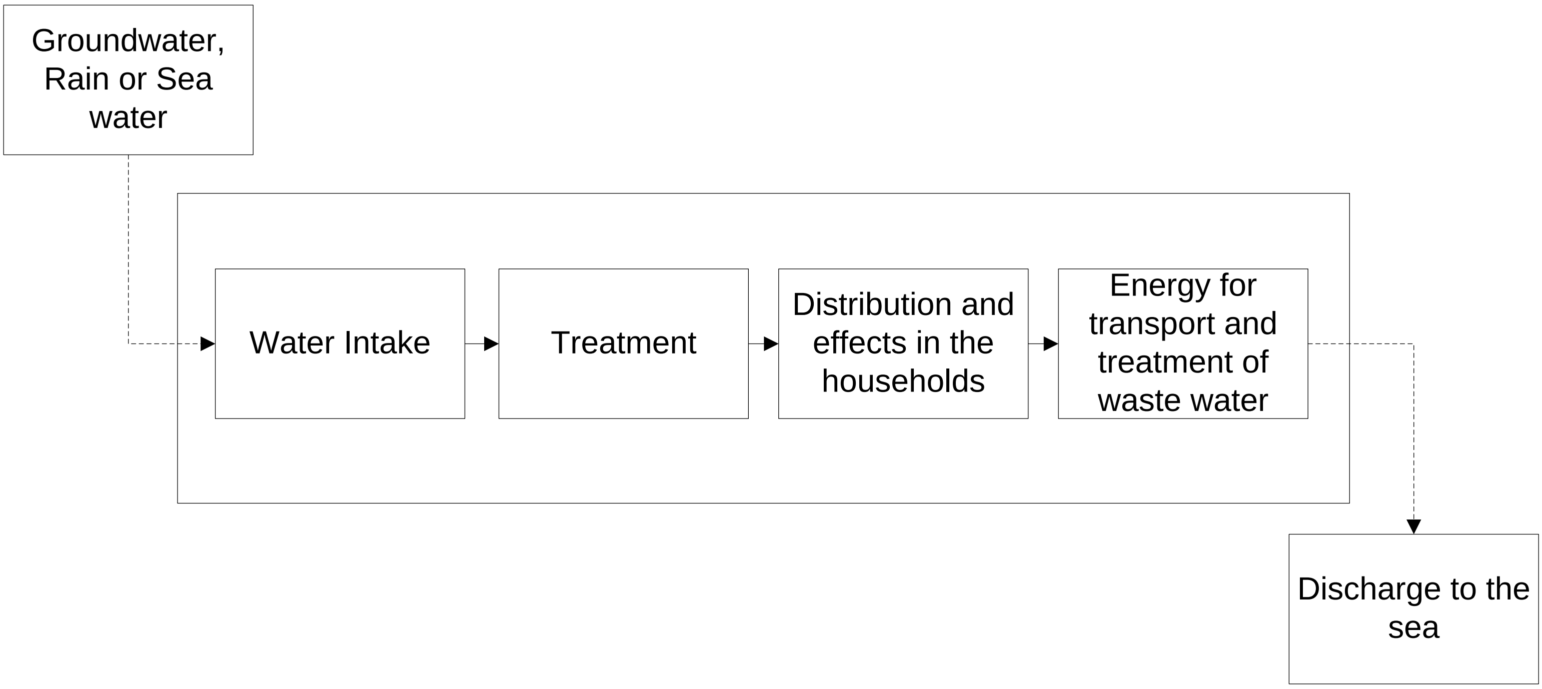
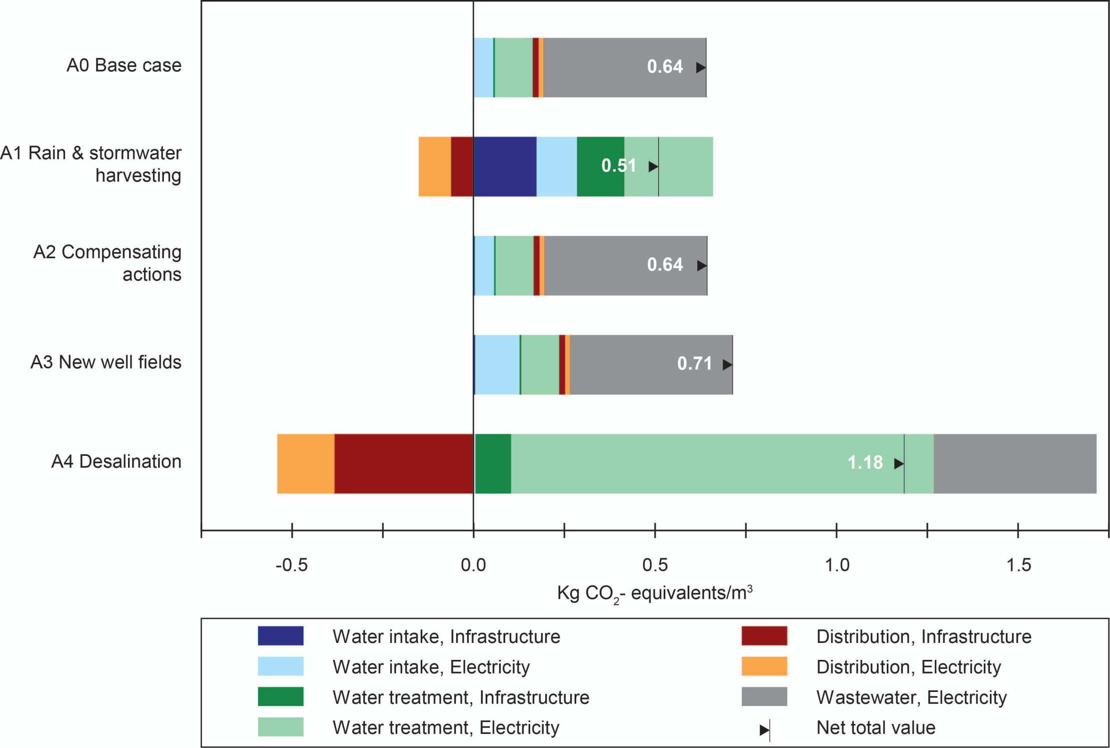
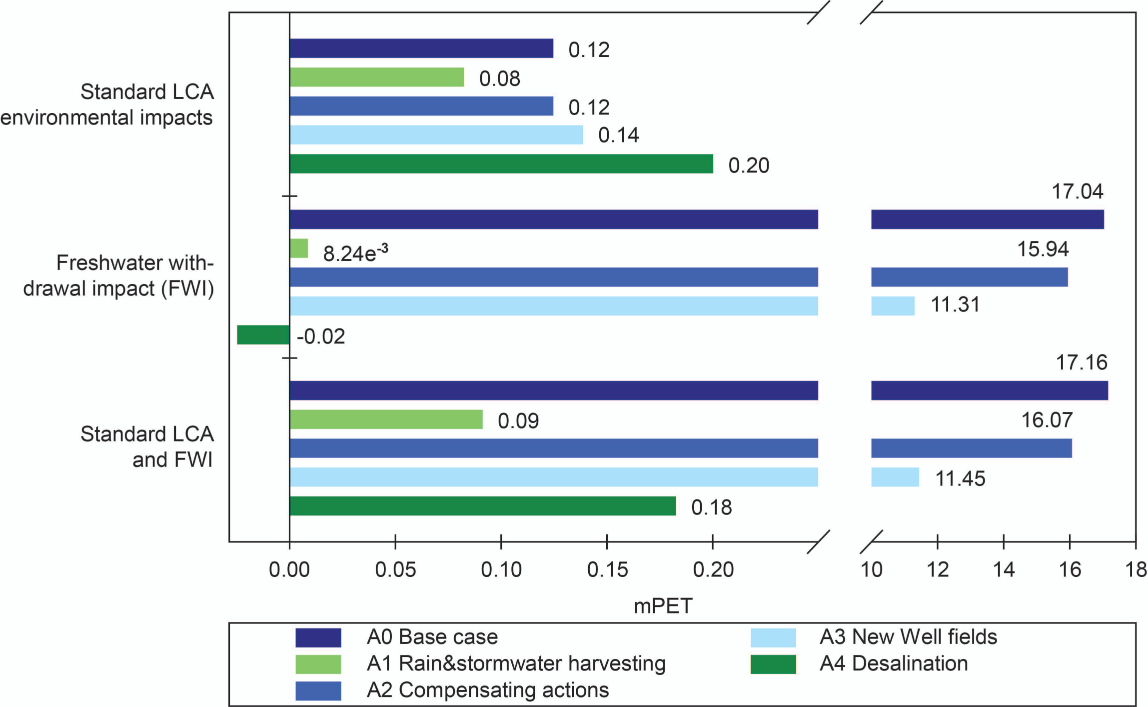


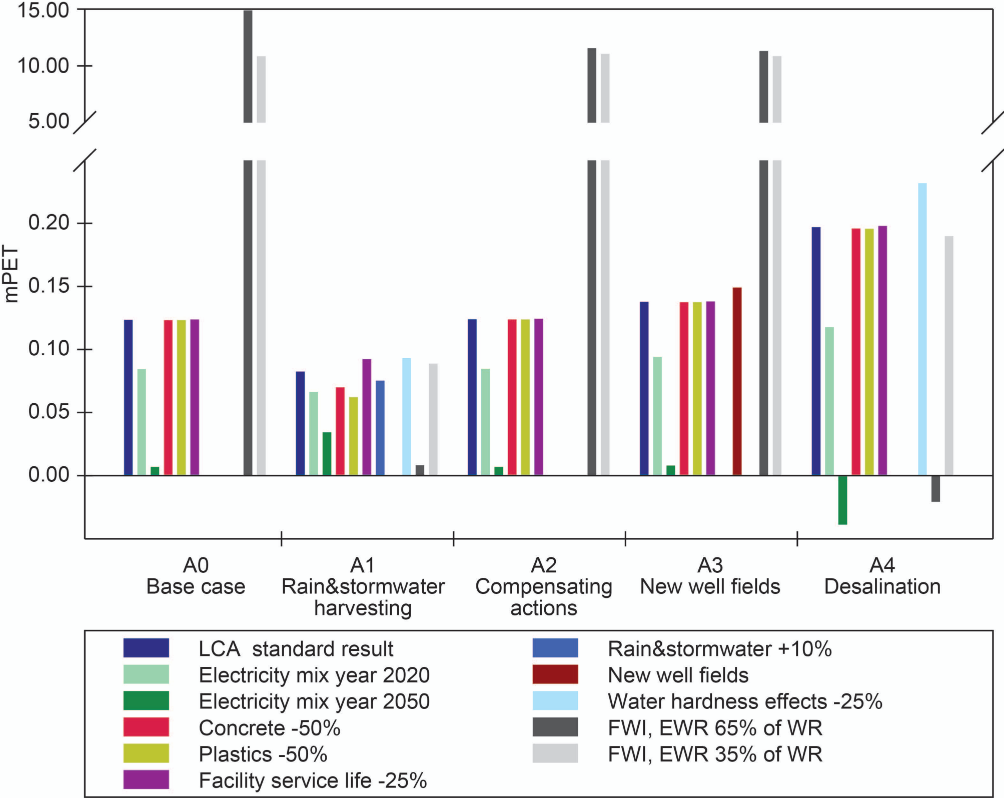
Life-cycle & freshwater withdrawal assessment




Groundwater, Rain or Sea water
Water Intake
Treatment
Distribution and effects in the households
Energy for transport and treatment of waste water
Discharge to the sea


A0 Base case
0.64
A1 Rain & stormwater harvesting
0.51
A2 Compensating actions
0.64
A3 New well fields
0.71
A4 Desalination
1.18
-0.5
0.0
0.5
1.0
1.5
Kg CO$_2$- equivalents/m^3
Water intake, Infrastructure
Water intake, Electricity
Water treatment, Infrastructure
Water treatment, Electricity
Distribution, Infrastructure
Distribution, Electricity
Wastewater, Electricity
Net total value


Standard LCA environmental impacts
Freshwater withdrawal impact (FWI)
Standard LCA and FWI
0.12
0.08
0.12
0.14
0.20
17.04
8.24e-3
15.94
11.31
-0.02
17.16
0.09
16.07
11.45
0.18
0.00
0.05
0.10
0.15
0.20
10
12
14
16
18
mPET
A0 Base case
A1 Rain&stormwater harvesting
A2 Compensating actions
A3 New Well fields
A4 Desalination


mPET
15.00
10.00
5.00
0.20
0.15
0.10
0.05
0.00
A0
Base case
A1
Rain&stormwater harvesting
A2
Compensating actions
A3
New well fields
A4
Desalination
LCA standard result
Electricity mix year 2020
Electricity mix year 2050
Concrete -50%
Plastics -50%
Facility service life -25%
Rain&stormwater +10%
New well fields
Water hardness effects -25%
FWI, EWR 65% of WR
FWI, EWR 35% of WR

List of Abbreviations	
CE	Copenhagen Energy (water utility)
CF	Characterization factor
EU-WFD	European Union Water Framework Directive
EWR	Environmental water requirements
FWI	Freshwater withdrawal impact
LCA	Life-cycle assessment
WR	Renewable water resource
WSI	Water stress index
WTA	Withdrawal to availability ratio
WU	Water use
WWTP	Wastewater treatment plant

Table 1. Processes included in the LCA modeling of the cases: A0 Base case; A1 Rain- & stormwater harvesting; A2 Compensating actions; A3 Building well fields 20 km further away; A4 Desalination of seawater. Processes are structured into the categories *Water intake method, Treatment, Distribution and effects in the households and Transport and treatment of wastewater*. See supplementary material for specific data.

Processes or descriptor of the cases A0-A4	
Water intake method	
A0	Abstraction of groundwater including establishment of well sites; Electricity for abstraction and transport to waterworks (5 km)
A1	Harvesting of rainwater (pipes to storage basin) and stormwater (transported and stored in large pipe lines)
A2	As described for A0; Establishment of wells and pumps pumping ground- and surface water into watercourses 3-6 months a year; Re-establishment of wetlands
A3	As described for A0; 25 km pipeline for transport of raw water to waterworks
A4	Intake of brackish seawater from Øresund
Water treatment	
A0	Establishment of waterworks; Aeration and sand filtration at waterworks
A1	Rainwater: Storage basin (700 m^3); UV treatment. Stormwater: Dual porosity filtration; UV-treatment
A2	As described for A0
A3	As described for A0
A4	Establishment of desalination plant; Coagulation and acid treatment; Ultra filtration; Reverse Osmosis; Remineralization; UV treatment
Distribution of water and effects in the households	
A0	Establishment of the existing piped distribution system from waterworks to tap; Water hardness 362 mg/L as $CaCO_3$ - effects in households are considered zero-effect
A1	Piped distribution system from basin to tap; Water hardness of 145 mg/L as $CaCO_3$ - effects in households leading to decreased consumption of laundry detergent, prolonged service life of washing machine and toilets
A2	As described for A0
A3	As described for A0
A4	Establishment of the existing piped distribution system from plant to tap; Water hardness of 108 mg/L as $CaCO_3$ - effects in households leading to decreased consumption of: Soap for personal hygiene; Laundry detergent; Electricity consumption (washing machine, coffee maker and kettle); Soap for doing dishes by hand and Salt for regeneration of ion exchanger fitted on dishwasher; Prolonged service life: Washing machine; Dishwasher; Coffee maker; Kettle and Toilets; More energy efficient district heating
Transport and treatment of wastewater and rain	
A0, A2, A3 & A4	Pumped via combined sewer system to the wastewater treatment plant before discharged to the Sea (Øresund). Energy consumption is included for wastewater processes.
A1	Rain- & stormwater is harvested and prevented from entering combined sewer system

Table 2. Parameters included in the sensitivity analysis.

Parameters changed in the sensitivity analysis	Description of the change of parameter
Electricity mix according to future political plans	In the year 2020 50% of the electricity comes from renewable sources
	In the year 2050 100% of the electricity comes from renewable sources *(Energinet.dk, 2010; Danish Ministry of Climate, Energy and Building, 2012)*
Use of concrete for infrastructure material	Materials reduced by 50%
Use of plastic for infrastructure material	Materials reduced by 50%
Service life of facilities	Reduced by 25% as assets might be changed before necessary
Harvested volumes of rain- and stormwater	Increased by 10% in accordance with predictions for rainfall (case A1)
Efficiency of water transport	65% less energy efficient in accordance with estimations of CE for aged well fields (case A3)
Effects of reduced water hardness	Effects in the households reduced by 25%
Environmental water requirements (EWR)	Reduced from the national figure of 65% (Danish Nature Agency, 2011) to 35% of WR in accordance with other findings of international water catchments *(Smakhtin et al., 2004; Pfister et al., 2009)*

Table 3. Inventory data for selected materials and electricity use for the cases in this study: A0 Base case; A1 Rain- & stormwater harvesting; A2 Compensating actions; A3 Building well fields 20km further away; A4 Desalination of seawater All parameters are given per functional unit, deliverance of 1 m^3 of water.

	A0 Base case	A1 Rain & stormwater	A2 Compensating actions	A3 New well fields	A4 Desalination
Direct Electricity consumption, *MJ (use stage)*					
	3.7248	0.9180	3.7559	4.4410	7.4921
Concrete, *kg*					
	0.0080	0.4833	0.0080	0.0080	0.0458
Cast iron & steel, *kg*					
	0.0143	0.0001	0.0143	0.0143	0.0175
Plastics, *kg*					
	0.0009	0.1010	0.0009	0.0009	0.0012
Freshwater withdrawal, Q *(ground and surface water),* m^3					
	1.0010	0.0006	1.0201	1.0011	-0.0014

Table 4. Normalized and weighted impact scores per 1 m^3 water delivered by the 4 cases, grouped after Environmental impacts, Toxicity impacts and Resource consumption.

	A0 Base case	A1 Rain&storm -water	A2 Compensating Actions	A3 New well fields	A4 Desalination
Environmental impacts, µPET (Person Equivalent Targeted, weighted result)					
Total environmental imp.	*123.5*	*81.9*	*123.9*	*137.8*	*204.8*
Global Warming	82.5	65.5	82.8	91.9	151.4
Acidification	24.6	10.3	24.7	27.5	36.3
Nutrient enrichment	14.5	7.6	14.5	16.2	23.6
Photochem. ozone form.	1.9	-1.5	1.9	2.2	-6.5
Toxicity impacts, µPET (Person Equivalent Targeted, weighted result)					
Total toxicity imp.	*176.0*	*125.7*	*180.3*	*193.7*	*180.6*
Ecotoxicity water chronic	63.7	24.9	64.8	70.1	85.7
Human toxicity soil	69.9	69.8	70.3	78.7	58.8
Human toxicity water	42.4	31.0	45.2	44.9	36.1
Resource consumption, µPR (Person Reserve)					
Chromium	17.3	-34.1	17.4	17.3	-38.3
Copper	5.6E-02	-3.0	5.7E-02	6.3E-02	-5.3
Hard coal	2.6	1.2	2.6	2.9	5.1
Natural gas	1.7	1.1	1.7	1.9	2.4

Table 5. Freshwater withdrawal impact (FWI) results. The characterization factors (CF) are calculated for the groundwater catchments where water is withdrawn. Water stress index (WSI) according to Smakhtin *et al*. (2004). For A4 FWI is -0.026. *WSI is calculated for water used to establish case A1 and A4.

	Characterization factor (CF)	**Freshwater withdrawal impact (FWI) [mPET]**	**Water stress index (WSI)**
Alternatives for water supply			
A0, Base case	1.51	17.04	1.73
A1, Rain-&stormwater harvesting	1.51	0.01	*1.73
A2, Compensating actions	1.38	15.94	1.55
A3, New well fields	1.00	11.31	1.00
A4, Desalination	1.51	<0.00	*1.73

Table 6. Calculation of Characterization Factors (CF) (Lévová & Hauschild, 2011) and Withdrawal to availability ratio (WTA) (Milà-i-Canals *et al.*, 2009) for water withdrawal scaled according to regional groundwater catchments or international regions for freshwater (ground- and surface water).

	Characterization factor (CF)	**Withdrawal to availability (WTA)**	**Water stress index (WSI)**
Local groundwater catchments, Urban area			
Copenhagen (CE's area) (*app.* 3,000 km^2)	1.51	0.61	1.73
Århus[1] (772 km^2)	1.36	0.52	1.49
Local groundwater catchments, Rural area			
Vidå-Kruså	0.38	0.10	0.28
Bornholm	0.11	0.02	0.05
Larger scale groundwater catchments			
Sjælland (7,450 km^2 incl. Copenhagen)	1.27	0.48	1.37
Denmark (43,000 km^2)	0.34	0.09	0.25
International regions based on freshwater (Lévová & Hauschild, 2011)			
Denmark	0.04	0.04	0.07
Spain	0.42	0.33	0.52
Egypt	1.10	0.79	1.05

[1] Århus is the 2nd largest city in Denmark after Copenhagen.

Table 7. Categorization of water stress index (WSI) determining the condition of the freshwater system (modified according to Smakhtin *et al.*, 2004).

WSI	**Categorization**
> 1.0	Environmental water scarce
0.6 - 1.0	Environmentally water stressed
0.3 - 0.6	Moderately exploited
< 0.3	Environmentally safe

Figure 1. System boundaries for all 4 cases illustrating the stages included in the LCA. The study included the urban water cycle from water intake and treatment over distribution and effects of water hardness to wastewater transport and treatment.

Figure 2. Distribution over the life cycle of processes contributing to Global warming potential for the 4 cases for water supply.

Figure 3. Weighted impact results for standard LCA environmental impacts and FWI for the base case and 4 alternative cases for water supply. The lower bars are the result from a standard LCA, followed in the middle by FWI and at the top the sum of the LCA and FWI.

Figure 4. Results of the sensitivity analysis on Total environmental impact of the 4 cases for selected parameters. The parameters “More rain, +10%”; “New well sites, 65% Energy for transportation” and “Effects of soft water reduced 25%” were only calculated for A1, A3 and A1 and A4 respectively as the parameters only had an effect for these specific cases.