Technical University of Denmark

Sustainability evaluation of water supply technologies

By using life-cycle and freshwater withdrawal impact assessment & multi-criteria decision analysis

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PhD Thesis
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The thesis will be available as a pdf-file for downloading from the homepage of the department: www.env.dtu.dk

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Preface

The work presented in this thesis, entitled ”Environmental and sustainability assessment of water supply technologies” is the outcome of an industrial PhD project carried out in cooperation between Department of Environmental Engineering, Technical University of Denmark and Copenhagen Energy, Department of Water supply and Sewage. The project was supervised by Professor Hans-Jørgen Albrechtsen, Professor Michael Hauschild (Department of Management Engineering), Assistant Professor Martin Rygaard and Section Manager Kim Zambrano.

The thesis is based on 4 scientific journal papers:

I. Godskesen B., Zambrano K. C., Trautner A., Johansen N. B., Thiesson L., Andersen L., Clauson-Kaas J., Neidel T. L., Rygaard M., Kløverpris N. H. and Albrechtsen H. (2011). Life cycle assessment of three water systems in Copenhagen - a management tool of the future. *Water Science and Technology*. **63**, issue 3, 565-572.

II. Godskesen B., Hauschild M., Rygaard M., Zambrano K. and Albrechtsen H.-J. (2012). Life cycle assessment of central softening of very hard drinking water. *Journal of Environmental Management*. **105**, 83-89.

III. Godskesen B., Hauschild M., Rygaard M., Zambrano K. and Albrechtsen H.-J. Life-cycle and freshwater withdrawal impact assessment of water supply technologies. *Submitted manuscript.*

IV. Godskesen B., Hauschild M., Rygaard M., Zambrano K. and Albrechtsen H.-J. A method for Multi-criteria evaluation of water supply technologies to identify the most sustainable case for Copenhagen. *Manuscript.*

In the thesis these scientific papers are cited as e.g. *Godskesen et al. (IV)*.

During my PhD I have presented results at International and Danish conferences, which have resulted in contributions to the following conference proceedings:

Godskesen B., Rygaard M., Hauschild M., Zambrano K. and Albrechtsen H.-J. (2012). Sustainability assessment of water supply in Copenhagen – what is the impact of freshwater withdrawal. *Proceedings* 4th NorLCA Symposium, November 26-28, Copenhagen, p.59 (oral presentation).

Godskesen B, Zambrano K. C. and Albrechtsen H.-J. (2012). Life-cycle assessment of 3 alternatives for stormwater management in Nordhavn. *Proceedings* 6th annual meeting of the Danish Water Research Platform, January 26-27, Copenhagen, p.14 (oral presentation).

Godskesen B., Hauschild M. Z., Zambrano K. C., Rygaard M. and Albrechtsen H.-J. (2011). Assessing the most sustainable alternative for production of drinking water - ASTA a decision support system. *Proceedings* 7th IWA specialist conference on assessment and control of micropollutants/hazardous substances in water – Micropol & Ecohazard, July 11-13, Sydney, Australia (oral presentation).

Godskesen B., Hauschild M. Z., Zambrano K. C., Rygaard M. and Albrechtsen H.-J. (2011). Assessing the most sustainable alternative for production of drinking water - ASTA a decision support system. *Proceedings* 5th annual meeting of the Danish Water Research Platform, January 27-28, Copenhagen, p.14-15 (oral presentation).

Godskesen B., Zambrano K. C. and Albrechtsen H.-J. (2010). Life Cycle Management - Life cycle assessment of central softening and Concept for sustainable production of drinking water. *Proceedings* Water & Energy 2010, IWA, November 10-12, Amsterdam, The Netherlands, ID 271152 (oral presentation).

Godskesen B., Zambrano K. C. and Albrechtsen H.-J. (2010). Life Cycle Assessment and evaluation of environmental benefits of softening water. *Proceedings* World Water Congress and Exhibition, September 19-24, Montreal, Canada, p. IWA-3306 (poster presentation).

Godskesen B., Zambrano K. C. and Albrechtsen H.-J. (2010). Life Cycle Assessment of Central Softening of drinking water in Copenhagen. *Proceedings* 7th Nordic Drinkingwater Conference, DANVA, June 7-9, Copenhagen, Denmark (poster presentation).

In addition, the PhD project resulted in the report A6 “Alternative management of the water cycle” which is a summary of inspirations and learning from a technical visit to Berlin, October 27-28th 2010.

During June – August 2011 I had the pleasure of an external stay in Australia at a water utility in Melbourne (Yarra Valley Water, Research and Innovation) and a University in Sydney (University of New South Wales, Water Research Center).

November 2012
Berit Godskesen

In the thesis the scientific papers are cited as e.g. *Godskesen et al. (IV)*.
The papers are not included in this web-version, but can be obtained from the library at DTU Environment.

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I wish to deeply thank my 4 supervisors - first of all, for sharing their enormous knowledge and experiences within this research area and for always allowing me to follow through on ideas. In particular, I would like to thank Hans-Jørgen Albrechtsen for having faith in me when I began the research and for guiding me safely through the entire process of the PhD study; Michael Hauschild for introducing me to the world of LCA and giving essential feedback on the LCA part along with other aspects of the PhD work; Martin Rygaard for bringing attention to this great research area before and while I did the PhD and for being extremely inspiring; and Kim Zambrano for great and continuously support throughout the project and for showing the immediate relevance of this research from a utility's point of view.

It has been a pleasure having 2 work stations throughout the PhD and I really enjoyed combining the different worlds of a university and a water utility. A warm and special thank you to all the colleagues from both worlds – Copenhagen Energy and DTU Environment - for providing an inspiring and excellent atmosphere to carry out a PhD in.

A special thank to Francis Pamminger and colleagues at Yarra Valley Water, Melbourne who invited me to spend time at a water utility where sustainability and alternative resources for water supply are high on the agenda. Also thanks to colleagues at the Water Research Center at University of New South Wales, Sydney for exchanging experiences and thoughts with me.

Last but never the least, my deepest thanks are to my family because without their immediate support and encouragement I would never have begun this PhD or completed this work. Special warm thanks to my husband for fully supporting me when I was doubtful about whether to apply for the PhD position. Also thanks for, together with our 2 very special kids, bringing continuously joy and happiness and for bearing with me when I was an absent-minded wife and mother. Also, thanks to my sister for reminding me about the great adventures of my PhD when I was feeling worn out; and to my parents for being supportive when beginning another new chapter in my life.

Summary

Sustainability evaluation of water supply systems is important to include in the decision making process when planning new technologies or resources for water supply. In Denmark the motivations may be many and different for changing technology, but since water supply is based on groundwater the main driver is the limitations of the available resource from the groundwater bodies.

The environmental impact of products and systems can be evaluated by life-cycle assessment (LCA) which is a comprehensive and dominant decision support tool capable of evaluating a water system from the cradle to the grave. The first aim of this PhD thesis was to assess the environmental impacts of water supply technologies. For this LCA was used to compare the impacts of Copenhagen's water supply technology of today with relevant cases considered for implementation in future water supply. The importance of placing the system boundaries right so the cases are comparable was emphasized due to the nature of the included cases. LCA was also found suitable to evaluate the effects of water quality parameters such as water hardness. The second aim was to evaluate the sustainability of the technologies and for this a multi-criteria decision analysis method was used to develop a decision support system and applied to the study.

In this thesis a standard LCA of the drinking water supply technology of today (base case) and 4 alternative cases for water supply technologies is conducted. The standard LCA points at the case rain- & stormwater harvesting as the most environmentally friendly technology followed by the cases relying on groundwater abstraction. The least favorable case is desalination of seawater. Rain- & stormwater harvesting and desalination have markedly lower environmental impacts in the use stage compared to the base case, due to the reduced water hardness leading to e.g. a decrease in electricity consumption in households. To make relevant comparisons, it is therefore essential to include the effects of water hardness when the environmental impacts of water systems of different hardness are compared.

However, a shortcoming of the standard LCA is that it does not cover the impacts of freshwater withdrawal. Therefore we further developed an existing method to evaluate the impacts of water use on a regional scale and it was applied to the local groundwater bodies from where water is abstracted for Copenhagen. Local

data was extracted from the national implementation of the EU water framework directive. When incorporating the impacts of freshwater withdrawal in addition to the standard LCA the rank order is partly reversed since rain- & stormwater harvesting and desalination are significantly more preferable compared to the groundwater based cases. This shows the importance of integrating impacts of freshwater withdrawal in the environmental evaluation.

A decision support system is needed which takes all identified criteria of relevance into account when choosing between several technologies for drinking water supply. During this PhD a decision support system called ASTA *(acronym for: Assess the most SusTainable Alternative)* was developed based on the multicriteria decision analysis methods rank ordering distribution weights and analytic hierarchy process. The ASTA decision support system incorporates the criteria of the 3 sustainability dimensions – environment, economy and society – referred to as categories in ASTA. After having assessed the 4 water supply technologies for Copenhagen with the developed system (ASTA), the results point at one preferable water supply technology. However, the results also showed that the result depends upon the weighting of the sustainability categories.

This study shows that when the highest weight is assigned to environment then the case of rain- & stormwater harvesting is the most sustainable followed by desalination of seawater. When the highest weight was assigned to economy or society then the most sustainable alternative is the case of compensating actions followed by either rain- & stormwater harvesting or desalination. For all 3 sets of weighting the case new well fields has the lowest sustainability.

The development of methods for combining the 3 pillars of sustainability with special attention on the environmental evaluation is presented in this thesis. It is new that LCA also covers parameters of water quality and in addition to the standard impact categories also includes freshwater withdrawal impacts on a local scale. The main contributions of the thesis are methods to include the effects of water hardness and freshwater withdrawal in addition to the environmental evaluation of the standard LCA. Finally, in the last part of the thesis (chapter 4) the environmental evaluation is combined with economy and society in a joint decision support system.

Dansk sammenfatning

Bæredygtighedsevaluering af vandforsyningssystemer er vigtig at inkludere i beslutningsprocessen, når nye teknologier eller vandressourcer vurderes med henblik på ibrugtagning. Baggrunden for at skifte teknologi kan være mange og vidt forskellige. I Danmark er en væsentlig motivation de lovgivningsmæssige begrænsninger, der pålægges den tilgængelige grundvandsressource, da grundvand er den oftest anvendt ressource til vandproduktion.

Livscyklusvurdering (LCA) er et omfattende og dominerende beslutningsstøtteværktøj til miljøevaluering, der er i stand til at evaluere vandsystemer fra vugge til grav. Dette første formål i denne PhD-afhandling var at vurdere miljøpåvirkningen af vandforsynings teknologier. LCA blev anvendt til at sammenligne miljøpåvirkningen af Københavns vandforsyning, som den er i dag med relevante alternative cases, som tages i betragtning i forbindelse med den fremtidige vandforsyning. Det blev fundet vigtigt at have korrekte systemafgrænsninger sådan at de udvalgte cases er sammenlignelige. LCA blev også fundet anvendeligt til at evaluere effekterne af vandkvalitetsparametre såsom vandets hårdhed. Det andet formål var, at evaluere teknologierne i forhold til deres bæredygtighed og hertil blev et beslutningsstøttesystem udviklet vha. en multi-kriterie metode og applikeret på studiet.

I PhD-afhandlingen er en LCA udført af den nutidige drikkevandsforsyning (base case) og 4 alternative cases til vandforsyning. Standard LCA'en viser at regn- og vejvands opsamling er den mest miljøvenlige teknologi efterfulgt af de cases som anvender grundvand som ressource. Den mindst favorable case er afsaltning af havvand. Regn- og vejvandsopsamling og afsaltning af havvand har en markant lavere miljøpåvirkning i driftsfasen sammenlignet med udgangspunktet pga. effekter af reduceret hårdhed af vandet. Reduceret hårdhed betyder blandt andet et reduceret forbrug af elektricitet i husholdninger. For at udføre en jævnbyrdig sammenligning af miljøpåvirkningerne er det nødvendigt at inkludere effekter af vandets hårdhed, når vandforsyninger med forskellige hårdheder sammenlignes.

Dog er der en væsentlig mangel i standard LCA-værktøjet, da det ikke dækker påvirkningen af indvinding af ferskvand som f.eks. grundvandsindvindingen. Derfor er en eksisterende metode til at evaluere påvirkningen af vandforbrug på en regional skala videreudviklet og applikeret på lokale grundvandsdeloplande

hvor grundvandet er indvundet til København. Lokale data er fundet i den nationale implementering af det europæiske vandrammedirektiv. Ved at inddrage påvirkningerne af ferskvandsindvindingen i standard LCA'en ændres rækkefølgen af de evaluerede cases delvist sådan at regn- og vejvandsopsamling og afsaltning af havvand er signifikant mere fordelagtige sammenlignet med de grundvandsbaserede cases. Dette viser vigtigheden af at integrere påvirkningerne af ferskvandsindvindingen i miljøevalueringen.

Der er behov for et beslutningsstøttesystem, der inddrager alle identificerede og relevante kriterier når valget står mellem adskillige teknologier til drikkevandsforsyning. I dette PhD-arbejde blev der udviklet et beslutningsstøttesystem, der kaldes ASTA (akronym for: Assess the most SusTainable Alternative), og som er baseret på multi-kriterie metoden analytic hierarchy process. ASTA inkorporerer kriterier fra de 3 bæredygtighedsdimensioner – miljø, økonomi og samfund – også kaldet kategorier i ASTA. De 4 vandforsyningsteknologier til København blev evalueret gennem beslutningsstøttesystemet ASTA og resultatet peger på den mest bæredygtige vandforsyningscase, hvilket dog afhænger af vægtningen af bæredygtighedskategorierne.

Dette PhD-studie viser, at når den højeste vægt er givet til miljø er regn- og vejvandsopsamling den mest bæredygtige case efterfulgt af afsaltning af havvand. Når den højeste vægt er givet til økonomi og samfund er den mest bæredygtige alternative case kompenserende foranstaltninger efterfulgt af enten regn- og vejvandsopsamling eller afsaltning. For alle 3 sæt af vægte er casen ny kildeplads den mindst bæredygtige.

Denne afhandling beskriver udvikling af metoder til at forbinde de 3 søjler af bæredygtigheds-begrebet med særligt vægt på miljøevaluering. Det er nyt at LCA også inddrager effekter af vandkvalitet og udover standard LCA miljøpåvirkningskategorierne også inddrager påvirkningen af det lokale miljø af at indvinde ferskvand. Hovedbidraget i afhandlingen er beskrivelse af eller udvikling af metoder til at inddrage effekter af hårdt vand og ferskvandsindvindingen sammen med miljøevalueringen i den standardiseret LCA. Endeligt kombineres miljøevaluering med økonomi og samfund i et samlet beslutningsstøttesystem i afhandlingens sidste del (kapitel 4).

Contents

Abbreviations and terms

The abbreviations found below are used throughout the thesis. They are presented by the full name the first time encountered in the thesis and afterwards referred to by the abbreviation. The list is meant as a help for the reader if there is a need for refreshing an abbreviation.

Abbreviations	Full name
AHP	Analytic hierarchy process
ASTA	Assess the most sustainable alternative
CE	Copenhagen Energy (water utility)
CF	Characterization factor
CSR	Corporate social responsibility
DSS	Decision support system
DST	Decision support tool
EDIP	Environmental design of industrial products
EoL	End of life
EU-WFD	European Union water framework directive
EWR	Environmental water requirements
FWI	Freshwater withdrawal impact
LCA	Life-cycle assessment
MCDA	Multi-criteria decision analysis
PET	Person equivalent targeted (the unit of weighted LCA results)
ROD	Rank order distribution weights
WR	Renewable water resource
WSI	Water stress indicator
WTA	Withdrawal to availability ratio
WU	Water use
WW	Waterworks
WWTP	Wastewater treatment plant

Terms

MCDA is also seen used as an abbreviation for multi-criteria decision aid, which is equivalent to multi-criteria decision analysis.

Where possible the term "water supply system" is used but occasionally the system was extended to also include sewage, hence "water system" was found appropriate to use.

1 Introduction

The production and deliverance of water supply is as any other production today met with requirements or intentions focusing on declaration of environmental impacts, carbon (CO_2-emissions) and water footprinting, green growth, etc. Therefore it is in the interest of the water utilities to evaluate the product according to such intentions and also to demonstrate how the evaluations have led to a certain decision affecting e.g. the planning of water supply systems.

Water supply in Denmark is based on groundwater abstracted from well fields situated on primarily rural or agricultural land. This is also the case for the capital of Denmark, Copenhagen, where water is abstracted from groundwater sources located outside the city limits, transported to the nearest waterworks (WW) where it is treated in terms of aeration and sand filtration before distributed to the City for urban purposes such as household consumption, industry and recreation (**Fig**. 1.1). The first waterworks were built more than 150 years ago, so the water supply system as we know it today is well-established (Københavns Energi A/S, 2009). As with many other water systems around the world the Danish system is also met with wishes for evaluating the impacts of the production.

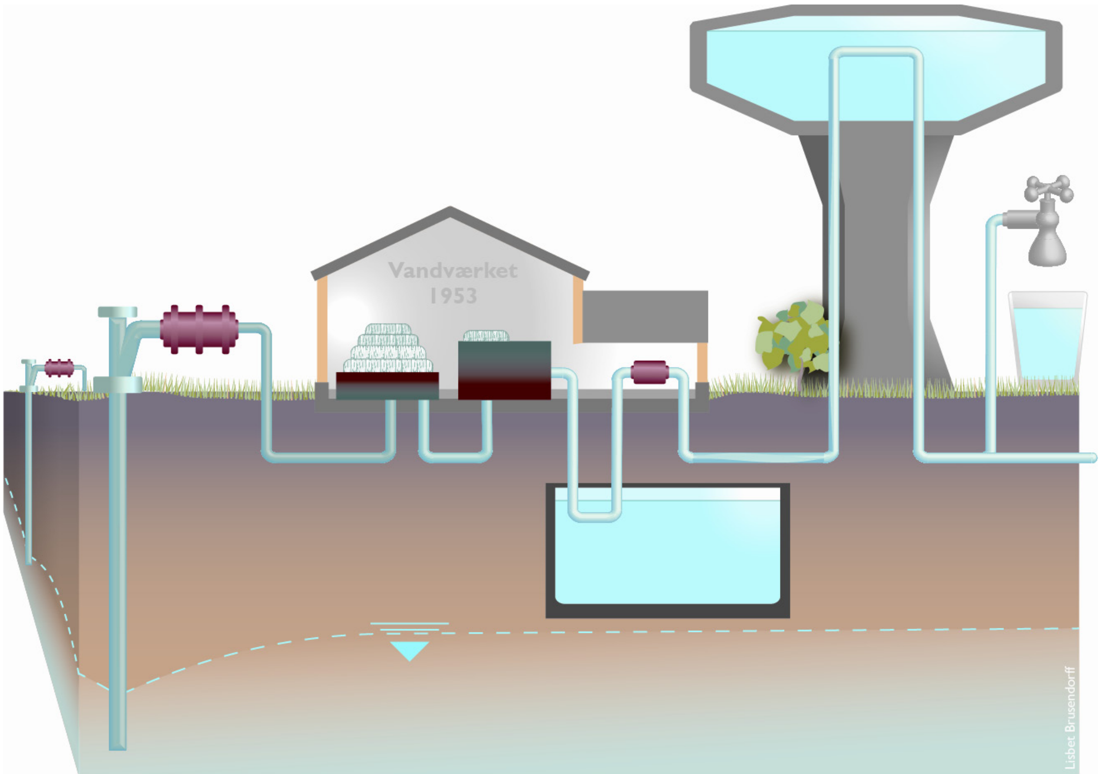

Figure 1.1. A sketch of a typical Danish water supply system where groundwater is abstracted from well fields, treated at the waterworks before distributed to the customers in the City. At the waterworks simple treatment consisting of aeration and sand-filtration takes place.

1.1 Environmental evaluation by Life-cycle assessment

Life-cycle assessment (LCA) is a decision support tool (DST) capable of providing the decision maker with an evaluation of the environmental performance of a product or service as e.g. water supply systems (Hauschild, 2005). Internationally LCA is being used to assess the environmental impacts of water systems (Lundie *et al.*, 2004; Lassaux *et al.,* 2007) e.g. to aid a decision on choosing between several technologies for water supply (Raluy *et al.*, 2005a,b; Stokes & Horvath, 2006; Lyons *et al.*, 2009). The application of LCA to water systems is still developing as these systems are rather complex and the LCA must cover all relevant environmental impact categories (Chapter 2).

For many years the Danish drinking water production based on groundwater has been thought of as an environmentally friendly water production system due to its simple treatment (Vandets vej, 2012). This was confirmed in an LCA of 7 technologies for water supply stating that groundwater abstraction is an environmentally good way of producing drinking water when compared to other water supply technologies (reviewed in *Godskesen et al. (I)*). The study from *Godskesen et al. (I)* only considered the treatment processes and did not look into whether the application of LCA to water supply systems covered all relevant processes for carrying out a complete environmental evaluation. Therefore, a need remained to apply LCA to water supply systems including all relevant processes. For instance the impacts of different water quality parameters such as water hardness (Rygaard, 2010) or environmental impacts form withdrawal of freshwaters are not included in the standard LCA and this is an area of development (see **Table** 3.2.1).

1.2 Impact of withdrawing freshwater

The impact of withdrawing water is placed high on the global agenda both due to a worldwide focus on freshwater availability (Alcamo & Gallopín, 2009; European Environment Agency, 2012) but also due to legislation emphasizing the importance of protecting freshwater environments (European Union, 2000). The European water framework directive (EU-WFD) is being implemented in the EU-member states by the national river basin management plans which among other parameters regulate the water flow requirements for water courses and the utilizable amount of water in each freshwater compartment, including groundwater bodies (Danish Nature Agency, 2011).

In Denmark the implementation of EU-WFD has revealed that groundwater is not as abundant a resource as often believed (European Environment Agency, 2007) especially since the river basin management plans for Denmark states that 65% of the renewable groundwater resource should be allocated to the freshwater environments. The data behind the Danish river basin management plans have been used by The Geological Survey of Denmark and Greenland (Henriksen *et al.,* 2008) to demonstrate that the exploitation of groundwater varies across the country and it is shown that the eastern part where Copenhagen is situated, a situation of overexploitation is occurring (**Fig**. 1.2).

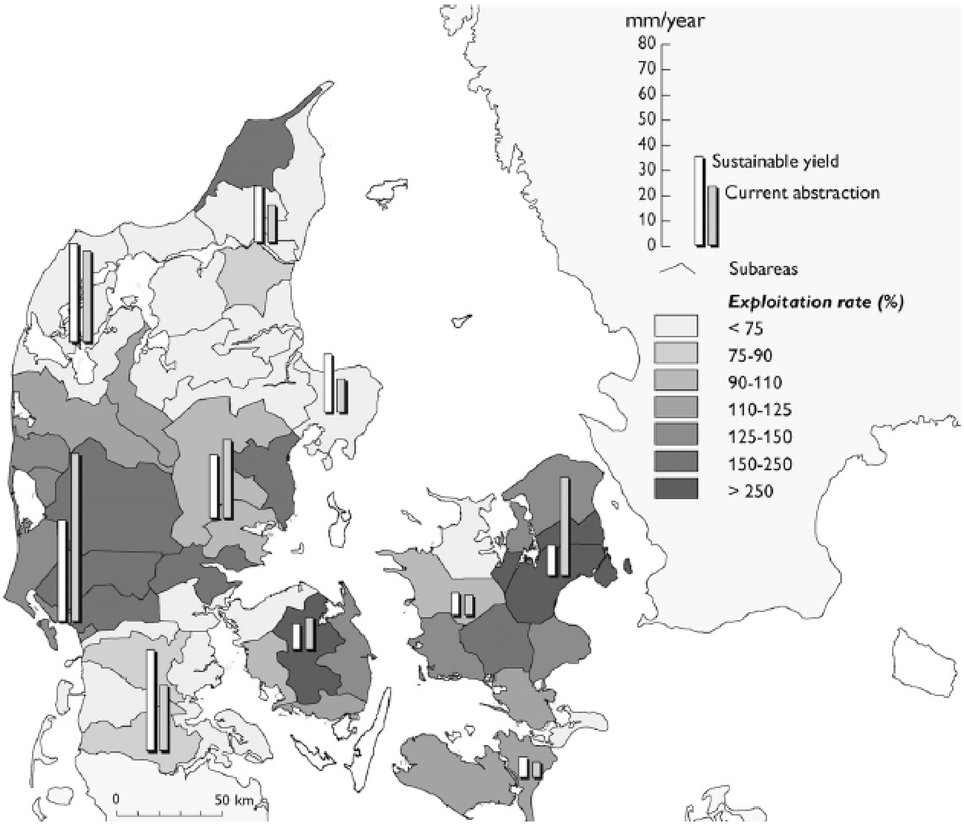

Figure 1.2. Groundwater resource availability status. Light areas have water available as the sustainable yield is above current exploitation; grey areas describe areas where current abstraction and sustainable yield balance. Dark areas show areas with over-exploitation (from Henriksen *et al.*, 2008).

The limitations put on the groundwater has prompted the water utilities e.g. Copenhagen Energy (CE) to revise whether the water production should be based on other water resources than the nearby groundwater catchments or introduce new approaches to sustain the water withdrawal permissions in order to meet the city’s water demand.

1.3 Pollution of groundwater bodies

Other activities are also limiting the uncontaminated groundwater resource since agricultural use of pesticides has resulted in pollution of groundwater catchments by pesticide metabolites (Geological Survey of Denmark and Greenland, 2011). The discovery of pesticides in the groundwater is a challenge for CE because drinking water is produced without treatment process aimed at removing xenobiotic substances. So far utilities have handled pollution by pesticides by moving well fields to groundwater bodies without the unwanted substances and a few utilities have made the decision to add a treatment step of filtration by granular activated carbon to remove the pesticides.

1.4 Other requirements for decisions in a water utility

Today the utilities are met with a growing number of requirements or intentions to demonstrate that the decisions being made on how to run the business live up to different criteria. Three of them are already mentioned above which are evaluations of environmental impacts, impacts on the freshwater resources from where the groundwater is withdrawn and pollution by unwanted substances such as pesticides. Other requirements for the water supply production which the utilities face are:

- The company's own or regional goals of reaching CO_2 neutrality (CE has a goal of reducing the company's CO_2-emissions with 60% in 2020) (Københavns Kommune, 2011),
- Environmental product declaration which also is being applied on utility systems (Københavns Energi A/S, 2012),
- Water foot-printing focusing on how much water is consumed to produce a given product through a life-cycle perspective (Hoekstra *et al.*, 2011) or water use impact assessments which are focused on the effects of withdrawing water from an environment and the local effects of the withdrawal also through a life-cycle perspective (see Chapter 3)
- Corporate social responsibility (CSR) which a company like CE is obligated to report to annually and e.g. CE has chosen to follow UN's global compact guidelines focusing on activities within areas of human rights, labour, environment and anti-corruption (UN, 2007)

- The Danish government's plan for green growth where initiatives focusing on development of technologies, environmental changes in production, cooperations, etc. are encouraged and subsidized (Danish Government, 2009)
- Sustainability based on the 3 pillars environment, economy and society as a term which e.g. CE wishes to promote in order to show to their customers that the company puts sustainability high on the agenda. This also requires stakeholder involvement as in keeping the dialog with the customers intact and include this in the decision making process

1.5 Decision support tools and systems

Hajkowicz & Collins (2007) reviewed multi-criteria decision analysis (MCDA) methods in the water sector and found that MCDA is a widespread and growing tool within the water sector. MCDA methods are capable of aiding the decision maker in incorporating requirements or intentions as mentioned above (section 1.4) in the decision making process. To include them in the decision making a decision support tools (DST) such as LCA or MCDA for evaluating the selected requirements also called criteria is helpful. If the decision is to rely on more than one criterion a decision support system (DSS) can be constructed to incorporate the selected criteria and end up with a transparent decision support result from where arguments for making the decision can be derived (Goodwin & Wright, 2009).

If the utility of CE is to decide that a new resource or approach is necessary for water production for Copenhagen then there is a need for DSTs and a DSS to identify which water supply technology to choose combining the environmental evaluation with the freshwater withdrawal impacts and also capable of introducing other criteria as listed above. It is this need for decision support material which has been the driver for this research.

1.6 Objective and research questions

The main objective of this industrial PhD study is to develop an environmental assessment method for water supply built on Life-cycle assessment also covering the impacts of freshwater withdrawal (the recycling diagram around the globe where water scarce areas are highlighted in red). A second objective has been to integrate this further development of LCA into a Sustainability assessment by developing a decision support system relying on the 3 pillars of sustainability – environment, economy and society. The 2 objectives of the PhD study are illustrated in **Figure** 1.3.

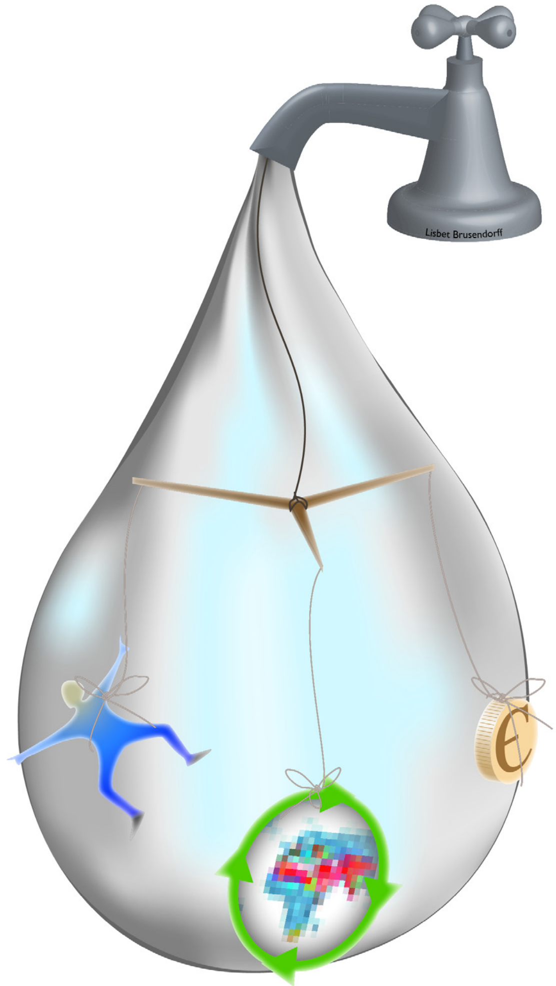

Figure 1.3. Graphical abstract of the objectives of the PhD study: "Sustainability evaluation of water supply technologies" where sustainability is defined as the 3 dimensions – environment, economy and society. Environmental evaluation is built on LCA also covering the impacts of freshwater withdrawals which in the diagram are presented by a recycling diagram around the globe where water scarce areas are highlighted in red. Economy is indicated by a euro-coin and society by a person. All 3 dimensions are integrated into a joint sustainability decision support system shown by the mobile hanging from the tap with the 3 symbols of sustainability.

The 4 main research questions addressed in the thesis within these objectives are:

1. What are the strengths and shortcomings of applying life-cycle assessment for carrying out an environmental assessment of a water supply system? This is evaluated by considering water systems in Copenhagen.

2. How is the environmental impact of withdrawing freshwater for water production integrated with the life-cycle assessment methodology?

3. What is the environmental impact when considering both the standard life-cycle assessment categories and the Freshwater withdrawal impact catego-

ry of water technologies for Copenhagen relying on groundwater and non-freshwater resources?
4. How are the environmental impacts combined with the other aspects of sustainability in order to identify the most sustainable alternative for water supply in Copenhagen?

1.7 Structure of the thesis

The thesis is structured as follows:

Chapter 1 presents the introduction to the research area and the questions processed during the PhD followed by this outline of the thesis.

Chapter 2 settles why LCA is a strong tool to use for environmental evaluation of water systems. This is followed by relevant observations encountered while carrying out the LCAs of water systems of this PhD work.

Chapter 3 presents the modification of an established method for assessing freshwater use impact and the application on the case study in this research.

Chapter 4 describes the development of the decision support system named ASTA which combines the evaluation of the environment, both the standard LCA and FWI, with the other categories of sustainability.

In **Chapter 5** the conclusions drawn in this PhD are presented which lead to answering the research questions outlined in this chapter 1.

Chapter 6 outlines the perspectives on future work within this research area.

In **Chapter 7** all references used in this thesis are listed alphabetically.

In **Chapter 8** the 4 scientific papers produced during the thesis are enclosed.

2 Life-cycle assessment of water supply technologies

Life-cycle assessment (LCA) is considered the most comprehensive approach for quantitative assessment of the environmental impacts of a product or system capable of including processes in a life-cycle perspective often quoted as processes from "the cradle to the grave" (Hauschild, 2005). LCA has also been referred to as a holistic approach since it covers all stages in a life cycle, **Fig**. 2.1.

LCA was originally developed for assessing the environmental impacts of products but was also found applicable for services. LCA has been applied to assess environmental impacts of different technologies for both water supply and wastewater systems (section 2.1) but is still in the beginning of discovering the full capabilities of application to water systems.

Fig 2.1. A Life-cycle assessment covering all stages in a life cycle from 1) Extraction of raw materials over 2) Manufacturing of a product or system by material processing, manufacturing and assembling to 3) Use phase and finally the 4) End of life treatment.

A clear strength of the LCA methodology is that it covers all emissions and consumptions of resources throughout the life-cycle of a product or as in this PhD a service such as water supply. While carrying out the LCA all processes from extracting raw materials are included, over manufacturing of the given product or part of the system to the use stage which is usually the longest period in time of the lifespan of the product or system. The last part of the LCA is the End of Life

(EoL) treatment where materials are disposed or reentering a new life-cycle by recycling. If transport of materials or products is occurring it must also be included in the LCA (Wenzel *et al.*, 1997).

The International Organization for Standardization (ISO) has standardized an LCA framework consisting of 4 steps: 1) Definition of goal and scope; 2) Inventory analysis; 3) Impact assessment and finally 4) Interpretation of results (ISO, 2006). The 4 steps are often illustrated similar to **Fig**. 2.2.

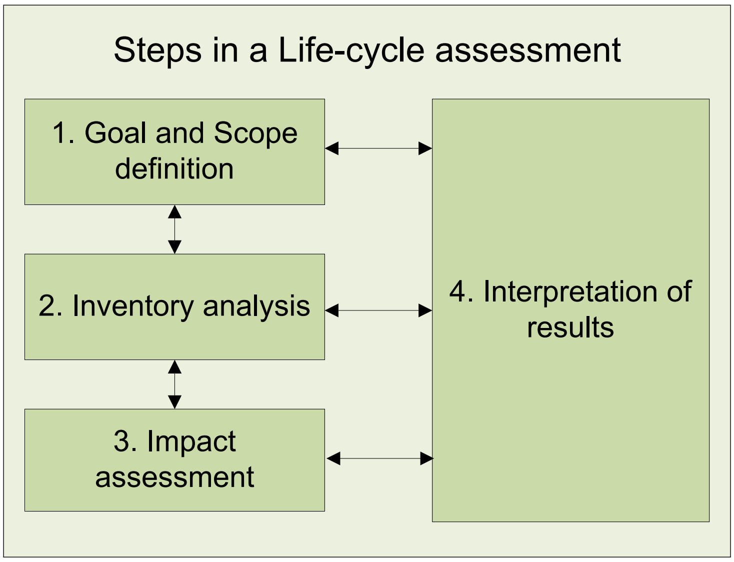

Figure 2.2. Steps in Life-cycle assessment (modified according to ISO, 2006))

The 1st step is the definition of the goal and scope where the intended aim and use of the LCA is described. It also contains the system boundaries making sure that if the LCA is to be used for comparative decision making then the system boundaries must be set so the comparisons are equal. All data inventory must be quantified according to a functional unit (FU) which determines the reference unit of the LCA study.

In the 2nd step the inventory analysis is performed which covers gathering all inputs and emissions occurring throughout the life-cycle (**Fig**. 2.2.). This is often a rather time consuming step as an LCA practitioner often encounters that data are not always easily accessed.

The 3rd step translates the input (e.g. resources, materials, energy) and output (e.g. emissions, substances, waste) of the inventory analysis into the impact categories divided into environment, toxicity and resources. In more details the Impact assessment step consists of 4 steps which are: 3.a) *Selection of impact categories and classification* where the categories representing the system's relevant impacts are identified; 3.b) *Characterization* where the impact of each emission is modeled through impact pathway in a common score e.g. kg CO_2-equivalents for the global warming impact category. The amount of the emission is multiplied by a characterization factor which is determined for each emission. The impacts from all emissions contributing to global warming can then be summed; 3.c) *Normalization* is the step where the impact scores of each impact category is related to a common reference e.g. in the EDIP method (Environmental design of industrial products) the categories are normalized in relation to the annual contribution to the category from 1 average person in the region, converting the normalized result to the so-called personal equivalent (Wenzel *et al.*, 1997); and finally 3.d) the weighting step is where the relative weight of the impact categories are assigned allowing for aggregation of the impact categories in to a one-score result. The impact categories showing a high impact in this PhD work are global warming, acidification, nutrient enrichment and photochemical ozone formation which after weighting according to the EDIP-methodology can be aggregated in a one-score result (**Fig.** 2.3). The one score result is often easier to communicate, however some information might be overlooked (Lundie *et al.*, 2004).

The impact assessment can be related to a global, regional or local scale depending on the scale where the impact takes place. When used correctly it is an advantage that the impact's effect is validated and predicted at the scale it occurs (Hauschild & Potting, 2005).

In the final 4^{th} step the results are interpreted meaning that the LCA result is evaluated according to the overall goal of the study. Sensitivity and uncertainty analyses are also a part of this step (ISO, 2006).

As indicated by the arrows in **Fig**. 2.2. the 4 steps are considered iterative steps which means that interpretation of the steps will most likely lead to reconsidering and going through the steps once more.

2.1 Application of LCA to water systems

2.1.1 International LCA publications

Internationally LCA has a longer history of being applied in the water sector. It is found that relatively few studies are published on LCA of water supply even though the number of publications is rising due to the environmental concerns and growing water stress situations around the world demanding an evaluation of environmental impacts including the effects of water withdrawal.

Publications have also been made on the entire urban water cycle. For instance an LCA of the Sydney water planning was carried out to evaluate several initiatives to bring down the environmental impact of the urban water cycle covering water supply and wastewater systems. The study included several scenarios for changing water supply and wastewater systems and the outcome is a result aimed at decisions regarding future planning and projects of the complex water system (Lundie *et al.*, 2004). Lassaux *et al.* (2007) also carried out an LCA of a water system from the well fields to the wastewater treatment plants. The study concludes that the 3 stages that contribute significantly to the global environmental load are: water discharge, wastewater treatment operation and, to a lesser extent, the building of the sewage system. Even though wastewater carries the highest environmental impact when considering the urban water cycle LCA of drinking water supply still gives us the opportunity to improve the environmental performance of water supply and should be a compulsory phase of future drinking water planning (Vince *et al.*, 2008).

Raluy et al. (2005a, b) compared several desalinations technologies and import of water from a distant river to a local water body. The papers enable us to compare different variations of desalination and also underline that transfer of water is not always the best solution due to energy consumption and rigidity of a project establishing a long distance distribution system. Also, it needs to be considered that desalination technology is evolving noteworthy (Raluy *et al.*, 2005a; Raluy *et al.*, 2005b). Stokes & Horvath (2006) compared desalination, wastewater reclamation and water import in a 2 case study in California. Desalination has the highest environmental impacts in comparison to wastewater reclamation and water import. A similar conclusion was reached in a study also comparing desalination, wastewater reclamation and water import in Arizona (Lyons *et al.*, 2009).

Studies on production of bottled water which are comparable with centralized drinking water supply e.g. for Copenhagen are also relevant to look at since people under given circumstances prefer to buy bottled water for consumption instead of drinking water from the tap. When comparing the results from this PhD of drinking water as produced today by CE with studies of CO_2-emissions for bottled water (Niccoluci *et al.*, 2010; Jungbluth, 2006) the environmental benefits of centralized drinking water supply becomes clear. In the mentioned studies bottled water production emits between 0.14 to 0.18 kg CO_2-equivalents/L when including water intake, production of the bottle and transport.

Water supply based on groundwater as in Copenhagen from source to tap emits 740-920 times less CO_2-equivalents/L and the hypothetical case of desalinated water in Copenhagen emits 110-140 times less CO_2-equivalents/L (**Table** 2.1). This comparison emphasizes that when it comes to energy consumption centralized water supply is preferable, especially when the water source is groundwater but also when it is seawater even though drinking water production based on seawater requires more energy consuming processes.

Table 2.1. Emissions of CO_2 from production of 1L of water from bottled water or centralized drinking water supply.

Reference	**System**	**Country of study**	**Kg CO_2-eq/L**
Jungbluth, 2006	Bottled water in non-returnable PET bottle	Switzerland	1.8E-1
Niccoluci *et al.*, 2010	Bottled water in non-returnable PET bottle	Italy	1.4E-1
Godskesen et al. (III)	Centralized drinking water supply, groundwater based	Denmark	1.9E-4
Godskesen et al. (III)	Centralized drinking water supply, desalination of seawater	Denmark, hypothetical	1.3E-3

2.1.2 Danish LCA applications and interests

When this PhD work started in 2009 only a few studies had been conducted on LCA of the Danish water sector. This PhD identified 3 Danish studies of 3 water systems and a review covering the 3 studies was published in *Godskesen et al. (I)*. One of the studies concludes that groundwater based drinking water supply is environmentally preferable compared to other more energy consuming technologies. This is also confirmed in the LCA of water supply technologies in this PhD work where the groundwater based technologies and Rain- & stormwater harvesting show a lower environmental impact than Desalination of Seawater (**Fig**. 2.3).

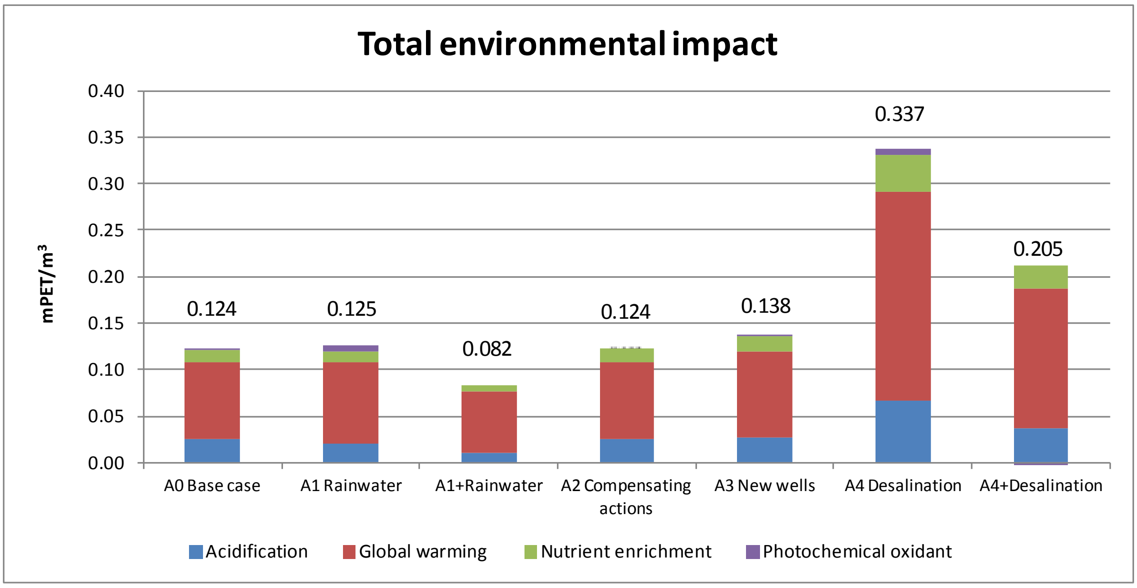

Figure 2.3. The results of an LCA presenting total environmental impacts of the base case technology (A0) and the 4 cases of alternative water supply technologies (A1-A4). The 2 "+cases" indicates that the effects of reduced water hardness in households are included *(Godskesen et al. (III)*).

In this PhD 4 alternative cases for water supply (A1-A4) are included in a case study which is both evaluated according to environment by LCA (this chapter) and sustainability by the ASTA decision support system (DSS) (Chapter 4). The cases are compared to the base case alternative (A0) which is the water production of today for Copenhagen. The cases are chosen due to their relevance for solving the water shortage in Copenhagen as implied by the EU-WFD and since they seem possible to introduce in the near future. The functional unit of the LCA study is production of water which fulfills the EU-WFD's water flow requirements for water courses in the catchments where groundwater is withdrawn and replaces 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. In *Godskesen et al. (III)* a more comprehensive description of the base case and the 4 alternative cases is given.

However, the LCA (**Fig**. 2.3) shows that when including the positive effects in the households of the reduced water hardness the environmental impacts are reduced for case A1 Rain- & stormwater harvesting (see A1+) and for case A4 Desalination of seawater (see A4+). The environmental impacts of desalination are still higher than the groundwater based technologies but not as severe as found by others (Lyons *et al.*, 2009).

In *Godskesen et al. (I)* the LCA of 7 technologies for drinking water supply is criticized for not addressing the impact of withdrawing water and the consequences it has for the freshwater resources but it is not a part of the standard LCA yet. The LCA of 3 technologies for non-potable water production showed that for non-potable production of water, facilities harvesting rainwater has the lowest environmental impact and ends up in a net environmental benefit since the rainwater is prevented from being discharged directly into the combined sewers. For the comparison of local and central sewer overflow options the LCA shows that it is important to consider all environmental impacts of the LCA and not only the greenhouse effect since the total environmental impacts are important for the preference of either the local (low CO_2-emissions but higher contribution to the impact category nutrient enrichment) or central (higher CO_2-emissions but lower contribution to the impact category nutrient enrichment) facilities.

Furthermore, the experience from reviewing LCA in a Danish context is that LCA is a strong tool which is in its early stage for environmental assessment of water systems and has the potential to become even more widespread and developed, also in Denmark. Incentives for incorporating LCA results into the decision making process could be external requirements such as the climate neutrality, CSR, environmental product declaration, etc.

2.2 Lessons learned from conducting LCAs of water systems

This section contains 3 main observations which in this PhD project were found important for the LCA work of water systems. The main observations are data quality, system boundaries and impacts on freshwater resources.

2.2.1 Data quality

There are many challenges of carrying out a proper LCA and this work points at the importance of acquiring good quality data and setting appropriate system boundaries especially when the aim is to compare two or several cases by LCA (Wenzel *et al.*, 1997; Halog & Manik, 2011).

Regarding data quality it was found a great advantage of this PhD project that it has been carried out in close cooperation between the Technical University of Denmark and the water utility of Copenhagen, CE. This gave relatively easy access to knowledge, research and experience based data. By spending time in the water utility spotting the right persons for getting access to data became a skill which was important to develop. Most of the data rely on experience based data from the water utility and also best available estimations and approximations especially since the LCAs also cover data of other processes than water systems that might even be hypothetical.

2.2.2 System boundaries

By conducting the LCAs included in this PhD of the 4 alternative cases for water supply and of introducing central softening of drinking water at waterworks it was encountered that system boundaries must be placed with great care to make the comparisons based on the results from the LCA trustworthy.

When conducting the LCA of the base case water supply technology and 4 alternative cases for Copenhagen it was found that the combined sewers in the City which transports the discharge to the wastewater treatments plants (WWTP) where it is treated has an effect on the system boundaries. The A1 case, rain- & stormwater harvesting, prevents the rain and stormwater from being discharged into the combined sewers which differs from the other cases which do not interfere with rain- and stormwater management. Therefore the system boundaries had to be placed so this difference was taken into account. That is why this work (**Fig**. 2.3) shows that rain- & stormwater harvesting is environmentally beneficial. Others have found that rainwater harvesting has a higher environmental impact than e.g. import of freshwater (Crettaz *et al.*, 1999).

In *Godskesen et al. (II)* the LCA of central softening at waterworks of drinking water proves that when introducing central softening at waterworks which is an activity consuming energy and chemicals, the negative effects of central softening are compensated for in the households where several positive effects of the reduced water hardness are encountered (**Figure** 2.4).

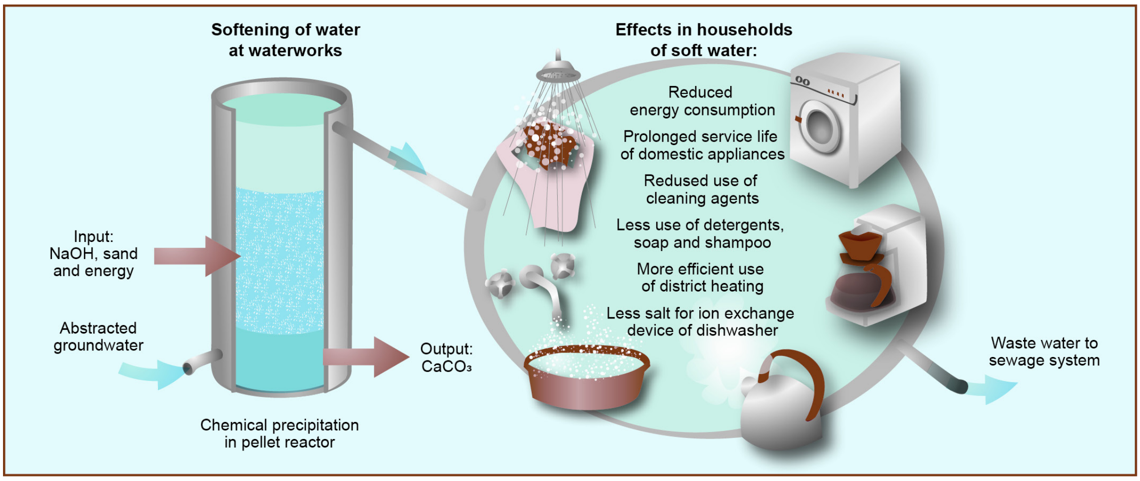

Figure 2.4. Processes occurring at waterworks and in the households when central softening of drinking water is introduced (*Godskesen et al. (II)*).

The environmental negative effects (softening processes at the waterworks) are exceeded by the positive effects in the households (prolonged service life of washing machine, dishwasher, coffee maker and kettle; reduced consumption of energy, cleaning agents, laundry detergent, soap and shampoo; etc.) with a softening depth of 22 mg/L as $CaCO_3$ (the softening depth's break-even point) (**Figure** 2.5). This is a low break-even point and in accordance with Van der Bruggen *et al.* (2009) who found an economic break-even point of a similar study of 50 mg/L as $CaCO_3$.

The conclusion of *Godskesen et al. (II)* is that from an environmental viewpoint it is preferable to reduce the water hardness of very hard water supplies. It also emphasizes that the effects of water hardness are essential to include within the system boundaries of LCAs of different water supply technologies resulting in deliverance of water of different hardness. This is a significant improvement of the method compared to the LCAs reported in *Godskesen et al. (I)*.

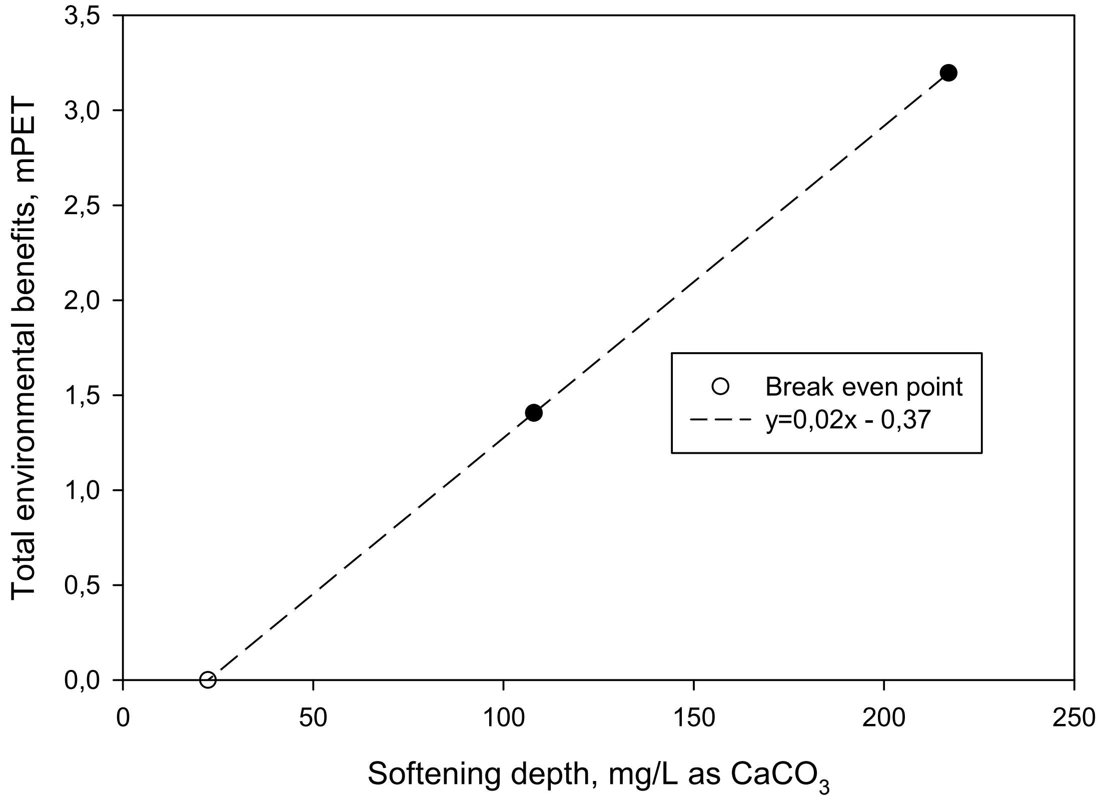

Figure 2.5. Total environmental benefit as a function of the softening depth. The break-even point is the softening depth from where it becomes environmentally beneficial to soften drinking water and is the intersection point of the x-axis (*Godskesen et al., II*).

The work in *Godskesen et al. (III)* shows that water quality parameters are essential to include within the LCA system boundaries. For the case of Copenhagen the groundwater based drinking water supply (A0, A2 Compensating actions and A3 New well fields) results in very hard drinking water (362 mg/L as $CaCO_3$ or 20 ^{o}dH). The groundwater based cases are compared with 2 cases, A1 rain- & stormwater harvesting and A4 desalination of seawater, which share the similarities that they deliver water of a lower hardness (171 and 108 mg/L as $CaCO_3$ or 10 and 6 ^{o}dH) and rely on resources which are not freshwater.

When conducting the standard LCA this work also shows that including the effects of the lower water hardness as savings has an effect on the outcome of the LCA, see **Fig.** 2.6 (and also **Fig**. 2.3).

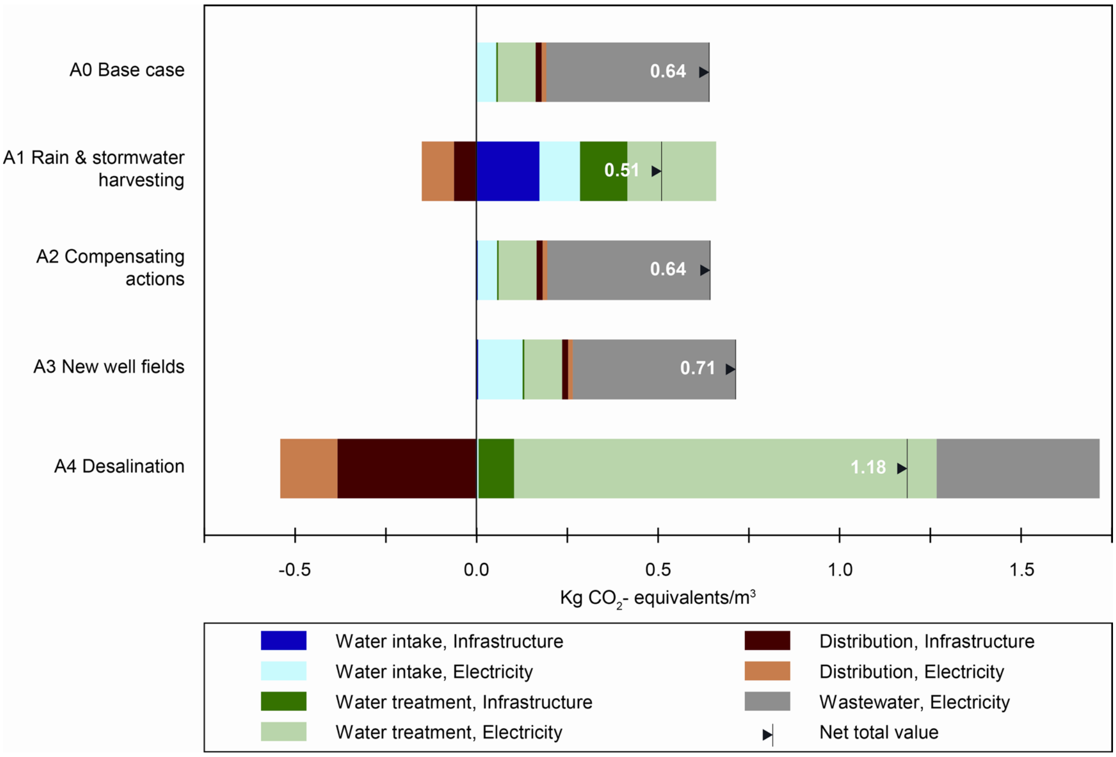

Figure 2.6. Distribution over the life cycle of processes contributing to global warming potential for the base case and the 4 alternative cases for water supply (*Godskesen et al., III*).

The figure presents the contributions from processes in the LCA to the impact category global warming. It is seen that for the groundwater based cases (A0, A2, A3) electricity to treat wastewater is causing a large part of the contribution to global warming. For the A1 case concrete for building the infrastructure consisting of basins is causing a substantial part of the global warming. For desalination (A4) it is electricity consumption during use stage which has a large contribution.

The net total value is lower than the end of the bar for A4 (40%) and A1 (35%) in **Figure** 2.6 due to the environmental positive effects in the households of the lower water hardness. The negative values of the cases A1 and A4 of "Distribution, Electricity" (**Fig.** 2.6) covers the electricity savings per m^3 water delivered due to reduced deposits of limescale on heaters in household appliances. "Distribution, Infrastructure" covers savings due to prolonged service life of the 4 before mentioned domestic appliances and reduced consumption of cleaning agents, laundry detergent, soap and shampoo, etc.

2.2.3 Impacts on freshwater resources

The work of this PhD thesis also focused on how to address the impacts of freshwater withdrawal on the resources from where the water is withdrawn. As will be described in details in chapter 3 many others have before this work mentioned that doing an environmental evaluation of water systems e.g. by use of the LCA tool without taking the effects on the freshwater environments into account is insufficient (see Chapter 3).

2.3 Summary of application of LCA

By looking on the international and Danish publications it is seen that LCA is applied to water supply systems and is a dominant and therefore strong tool for comparing different water supply technologies. The experiences in relation to LCA when doing this PhD are presented in **Table** 2.2. divided into good quality of data, setting the right system boundaries and impact categories in the LCA.

Table 2.2. Summary of impacts to include or consider when doing an LCA

	Impacts to include or consider
Data	Data of good quality, close dialog with real life systems is beneficial for the LCA practitioner
System boundaries	System boundaries should consider differences between the cases for comparison such as 1) discharge of rain- and stormwater and 2) water quality exemplified by water hardness
Presentation of the LCA result	The standard LCA impact categories: global warming; acidification; nutrient enrichment; and photochemical ozone formation where found of importance when working with water systems
LCA impacts	The impacts of freshwater withdrawal is not included in the standard LCA and should be included otherwise (chapter 3)

3 Freshwater withdrawal impact

Across the World water production is based on various sources of raw water which after treatment is distributed as drinking water. An example of a city taking many resources in use is Melbourne, Australia who for a long period in time has been relying mainly on import of water from reservoirs in the mountains (Sharma *et al.*, 2009). Oligotrophic lakes or reservoirs are often placed at a large distance from the supply area but the transport is often compensated by the simple treatment which is sufficient due to self-purification in the reservoir (Moel *et al.*, 2006). In Melbourne other sources of water than the reservoirs are also used as water supply such as treated sewage and stormwater which is distributed for non-potable and even potable purposes (Yarra Valley Water, 2012), and soon also seawater which after desalination processes are distributed to the citizens (State Government of Victoria, Australia, October 14th 2012). The water supply system of Melbourne is highly resilient as many sources are in use and can be turned up or down according to e.g. drought, periods with high precipitation, increased urbanization, etc.

In Europe 70% of the drinking water is on average based on groundwater (Navarrete *et al.*, 2008) and in Denmark groundwater is the only source used for centralized water supply and only very few rainwater harvesting systems exist (Rygaard *et al.*, 2009). Henriksen *et al.* (2008) found that the groundwater withdrawal exceeds the sustainable yield in the eastern part of Denmark and the impacts on the freshwater environments are observed by water flows in water courses which are below natural situations. It is this effect of groundwater withdrawal on flows of water courses which are regulated by the newly implemented EU-WFD (European Union, 2000).

The impacts of water withdrawal can be narrowed down to the freshwater resources since saline water and other types of non-freshwaters are not considered in shortage (Brown & Matlock, 2011; Gleick, 2009). The focus on freshwater scarcity is an approach often adopted by e.g. the water footprint concept (Hoekstra *et al.*, 2011) and methods of assessing the impacts of water use (see section 3.2).

Before presenting other studies' (section 3.2) and this PhD's (section 3.3) suggestion on how to assess the impacts of freshwater withdrawal the water stress indicator is explained as it plays an important role in many of the methods.

3.1 Water stress indicator

Smakhtin *et al.* (2004) presented a method for establishing the relationship between renewable water resources (WR), total water use (WU) and the environmental water requirements (EWR) of the same catchment by the water stress indicator (WSI). The EWR states the amount of water required for the maintenance of freshwater dependent environments and Smakhtin *et al.* (2004) estimated global distribution of EWRs and also estimated the global WSIs (**Fig**. 3.1.1).

The WSI is defined by:

$$WSI = \frac{WU}{WR - EWR} \qquad \text{(Equation 1)}$$

given in annual volumes. If a WSI exceeds 1, the basin is categorized as "Environmentally water scarce", and if WSI is below 0.3 as "Environmentally water safe" (**Table** 3.1).

Table 3.1. 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

For the Scandinavia basin a relatively high EWR of 35% is estimated indicating that the basins require a large amount of water to maintain the freshwater environments' status and when estimating the WSI the study finds that Denmark on average has a water stress situation categorized as environmentally safe (**Fig**. 3.1) (Smakhtin *et al*., 2004). A similar estimation of water stress of the world reached the same conclusion of no water stress in Scandinavia (Boulay *et al.* (2011)). However, the challenge is that when considering water situations on a national or river basin scale the freshwater withdrawal's local effects is not taken into account. By applying the life-cycle approach a local scale is generally preferred to integrate for impacts having an effect found at the local scale (Hauschild & Potting, 2005) as it is the case with freshwater withdrawal.

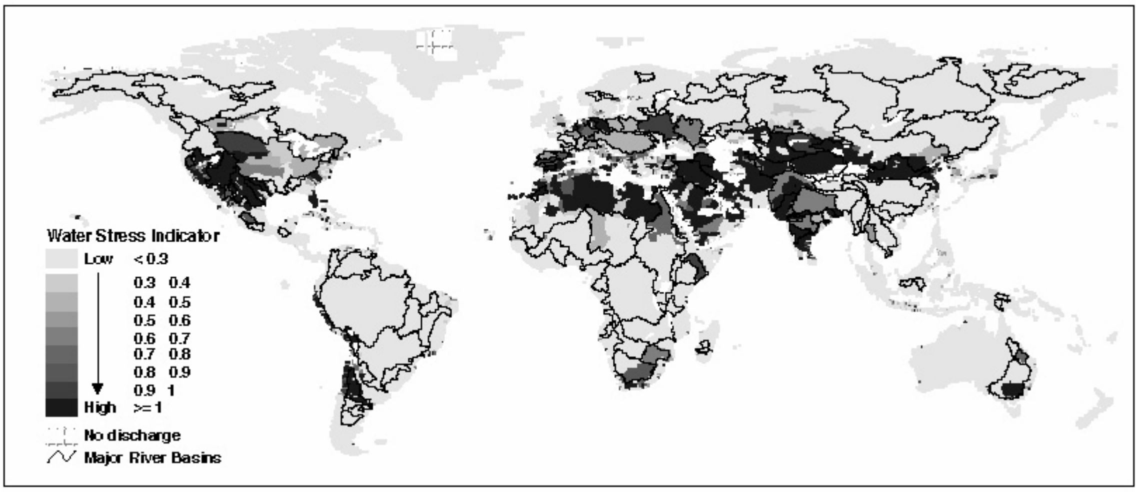

Figure 3.1. A map of global water stress indicators (WSI) which takes environmental water requirements into account (Smakhtin *et al.*, 2004).

Therefore this PhD work chose to consider the local impacts of withdrawing groundwater to focus on evaluation and prediction of the actual effects on the relevant groundwater bodies. However, it has been suggested that the scale must not be more detailed than e.g. river basin since this is an operational level for the LCA procedures especially when gathering data (Koehler, 2008). In this work data of good quality and resolution was found in the national River basin management plans of the EU-WFD and therefore scaling down to the single groundwater bodies was found operational as it will be demonstrated in section 3.3.

Table 3.2. Calculation of water stress indicators (WSI) for water withdrawal scaled according to regional groundwater bodies for freshwater (ground- and surface water) (*Godskesen et al. (IV)*).

	Size of area (km^2)	**Water stress indicator (WSI)**
Local groundwater catchments, Urban area		
Copenhagen (CE's area)	app. 3,000	1.43
Århus	772	1.49
Local groundwater catchments, Rural area		
Vidå-Kruså	1,100	0.28
Bornholm	588	0.05
Larger scale groundwater catchments		
Sjælland (incl. Copenhagen)	7,450	1.37
Denmark	43,000	0.25

By applying the definition of WSI to groundwater bodies in Denmark it is seen that on average the water situation is environmentally safe as the country on average obtain an average of 0.25 (**Table** 3.2). However, it also becomes obvious that the WSI differs dramatically within the country as some groundwater bodies are categorized as environmental water scarce as is the case for the areas where CE withdraws water (a WSI of 1.43). Aggregating catchments for a larger area (Sjælland - Copenhagen and nearby rural area bound by the sea) still results in water stress (WSI 1.37). The second largest city in Denmark also has a situation of water stress (WSI of 1.49). Moving to rural areas results in low WSIs (0.05 – 0.28) indicating withdrawals which are environmentally safe. In **Figure** 3.2 a map of Denmark showing the WSIs calculated on data from all 23 river basin management is presented. The figure shows that the situations of environmentally water scarcity are occurring primarily in the eastern part of the country and in Århus (the pink area in the big blue part). Also, the island Fyn is partly water stressed.

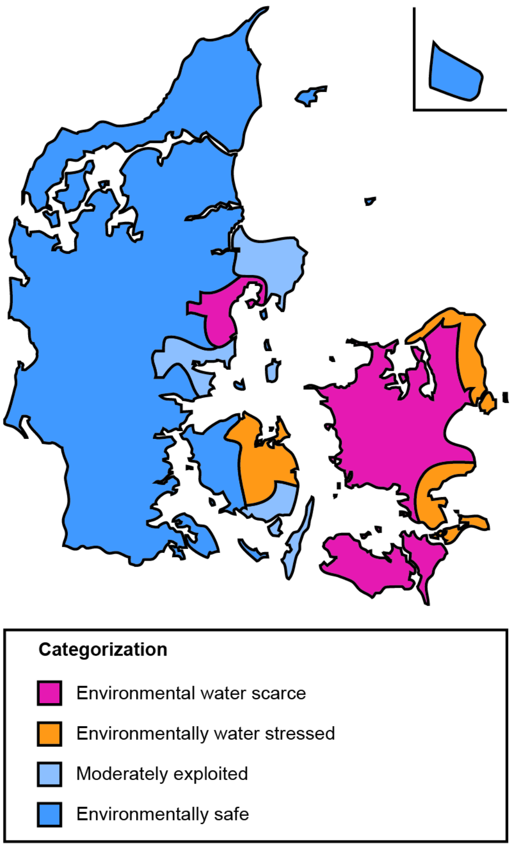

Figure 3.2. A map of water stress indicators (WSI) of Denmark. Calculations are based on data from the 23 national river basin management plans. Categorization is according to **table** 3.1

The large variation in WSI for a small country like Denmark shows the necessity of downscaling since this is where we find the magnitude of the impact on the local groundwater bodies and distinguishing groundwater from surface water when calculating impacts of freshwater withdrawal.

3.2 Assessing water use in Life-cycle assessment

The EDIP method is the method used for the standard LCA in this PhD. From the development of the EDIP method water is considered a resource and included in the modeling. Water is treated as any other consumption of resources in the EDIP method meaning that the total amount of water is possible to abstract from the LCA-model. However, this does not reflect the actual impact on the local groundwater body which is relevant as described in section 3.1 and a development of a method for considering water scarcity is not yet incorporated in the EDIP method.

Up until 2009 the topic of freshwater use and its impacts on the freshwater resources from where the water is withdrawn received limited attention in LCA. Since then some methods have been proposed but the development is still in its infancy.

By studying selected references within this area an overview of the methods is presented in **Table** 3.3. The table describes how the impacts of freshwater withdrawal is characterized (e.g. the characterization factor, CF) and what type of assessment the method uses.

Milà-i-Canals *et al.,* (2009, 2010) differentiate between types of water use in the life-cycle inventory as green water (soil moisture), blue water (ground- and surface water) and fossil blue water (non renewable groundwater). The work suggests WSI as the characterization factor. A study is published using this method for comparing the difference between growing broccoli in Spain and in the UK. The study shows that broccoli produced in the UK during the warm months and frozen for consumption in winter has smaller water related impacts than broccoli imported from Spain (Milà-i-Canals *et al.*, 2010).

Table 3.3. Selected references of how to assess water consumption in life-cycle assessment. The methods considering water as an environmental impact category can either rely on the midpoint (effects contributing to environmental impact category) or endpoint approach (effects assigned to areas of protection such as human health, ecosystem quality and resource consumption). The abbreviations which are not introduced before are described in the following text.

Reference	Characterization factor	Water treated as:	Mid (M)- or Endpoint method (E)
EDIP-method (Wenzel *et al.*, 1997)	$= \frac{\text{Total water consumption}}{\text{Lifespan} \cdot \text{available} \frac{\text{water}}{\text{person} \cdot \text{year}}}$	a resource without taking water scarcity into account	-
Milà-i-Canals *et al.*, 2009	$\text{CF} = \text{WSI} = \frac{\text{WU}}{(\text{WR}-\text{EWR})}$, or $\text{CF} = \text{WTA} = \frac{\text{WU}}{(\text{WR})}$	an environmental impact category;	M
Lévová & Hauschild, 2011	$\text{CF} = (\frac{\text{WU}}{\text{WR}-\text{EWR}})^{(WR/(2xEWR))}$	an environmental impact category;	M
Pfister *et al.*, 2009	$\text{CF} = \frac{1}{1 + e\hat{}(-6.4 \cdot WTA\left(\frac{1}{0.01} - 1\right))}$	an environmental impact category;	M & E
Bayart *et al.*, 2010	$\text{CF} = \alpha \cdot U \cdot Q \cdot (1 - CA)$	an environmental impact category;	M & E
van Zelm *et al.*, 2010	$\text{CF} = \sum_{n=i}(\text{FF}i \cdot \text{EF}i)$	an environmental impact category;	E

Another study used the method proposed by Milà-i-Canals to assess the freshwater withdrawal impact of transferring freshwater in the Ebro river project over very long distances and compared it to alternative water supplies based on reuse and desalination (the Aqua Programme). They showed that the Aqua Programme has a 49% lower impact on the freshwater resources than the water transfer of the Ebro river (Muñoz *et al.*, 2010).

Lévová & Hauschild (2011) presents a method similar to Milà-i-Canals. The main difference between the 2 studies is that Lévová & Hauschild adds a power of $\frac{WR}{2 \cdot EWR}$ to the WSI resulting in a mathematical expression which increases the CF exponentially when the water withdrawal (WU) approaches the renewable water resource (WR).

The method suggested by Pfister and colleagues (2009) is a comprehensive impact assessment of freshwater withdrawal on both mid- and endpoint level. On midpoint level a regional water to availability ratio (WTA; $WTA = \frac{WU}{WR}$) is introduced which serves as input to the CF. Both the mid- and endpoint methods are further developed into 3 categories of damage to human health, damage to ecosystems and damage to resources.

Bayart *et al.* (2010) introduced a freshwater accounting and impact assessment method which is based on water quality, resource type (ground- or surface water). The method enables the quantification of losses and gains of different freshwater types. The CF is calculated as seen in **Table** 3.3 where α is calculated by WTA, U is the number of potential uses depending on freshwater type and quality and the quality factor Q denotes the quality of the consumed freshwater based on energy demand required to transform the water into drinking water. The compensation ability (CA) is also incorporated stating the adaptation to increase water scarcity based on socio-economic parameters.

Van Zelm *et al*. (2010) developed characterization factors expressing the groundwater withdrawal's impact to the ecosystem damage in the Netherlands. The CF is calculated by means of a fate (FF) and effect factor (EF). The fate factor describes the change in drawdown due to a change in groundwater withdrawal and expresses the time required for groundwater replenishment. The effect factor describes the groundwater level response curves of potential plant species richness constructed based on the soil moisture requirements of 625 plant species.

The references (**Table** 3.3) have in common that they suggest a method for assessing impacts of freshwater withdrawal and describes how the methods become operational in an LCA. None of the methods has been adopted into the standard LCA but hopefully soon, a method will be accepted of the LCA framework.

A critical review of water foot-printing and addressing water use in an LCA is found in Berger & Finkbeiner (2010). The review addresses the challenge in acquiring detailed inventory data, inclusion of local water scarcity as well as different definitions on types of water use accounted for. When it comes to estimating water scarcity on a local level Berger & Finkbeiner (2010) claims that the trade-off between precision and applicability needs to be addressed since high resolution data is needed in order to estimate water stress on a local level. This PhD study suggests a local approach relying on data from the national authorities which is relatively easy to access.

3.3 Development of FWI and application

Since a method of how to assess the impacts of water withdrawal or water use is not adopted into the ISO standard of LCA, this PhD work takes an existing method and further develops it. The further development is needed primarily due to scaling down of data on water availability and use from regional water sheds to local groundwater bodies. Also the development leads to focusing on solely the groundwater resources instead of the entire freshwater resources (ground- and surface water).

In this section this PhD's suggestion of how to include impacts of freshwater withdrawal (FWI) is presented in section 3.3.1 and the results when including the FWI in the LCA of a case study is included in section 3.3.2.

3.3.1 Development of FWI

In this PhD the freshwater withdrawal impact (FWI) is included in addition to the standard environmental impact categories in the LCA by modifying the water use impact method developed for industry by Lévová & Hauschild (2011). The method was originally developed using date from regional water sheds to calculate the characterization factor but here it is applied to local groundwater bodies where data is found in the river basin management plans.

The method is further integrated into the LCA by adding a normalization and a weighting step in accordance with the EDIP methodology. Treating the freshwater withdrawal as an environmental impact category allows for comparison with the already established LCA impact categories e.g. the impact category “global warming”.

The freshwater withdrawal impact is 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.

$$FWI = Q \cdot CF \qquad \textit{(Equation 2)}$$

Within the 4 phases of a standardized LCA the FWI method involves 3 special considerations since the FWI is not yet standardized: 1) Quantification from a life-cycle perspective of volume groundwater withdrawn to produce the functional unit; 2) Determination of characterization factors; and 3) Normalization and weighting.

Quantification of freshwater withdrawn

The volume of withdrawal of freshwater (Q, [m^3]) for a given production e.g. water supply is calculated in the inventory of the LCA. The volume should include information about the volume withdrawn for the production (Q_W, [m^3]), the volume which is returned to the same water body as where withdrawn (Q_{OUT}, [m^3]), the total volume of available water in the groundwater body (Q_{TOT}, [m^3]), and the volume of water needed for dilution of the discharged pollution to the original water quality (Q_{DIL}, [m^3]). The Q is defined as follows:

$$Q = Q_W - Q_{OUT} + \left(Q_{OUT} \cdot \frac{Q_{IN}}{Q_{TOT}}\right) + Q_{DIL} \qquad \textit{(Equation 3)}$$

By this formula Q includes the positive effects caused by discharging water back to the water body and also the negative effects of removing the water from the water body (Q_W), of changing water quality (Q_{DIL}), an of causing a time delay between water withdrawal and discharge (the parenthesis).

Characterization factor

In the characterization step the freshwater use impact is converted into its potential impact on the freshwater environment. The characterization factor (CF) is calculated according to Lévová & Hauschild (2011):

$$CF = \left(\frac{WU}{WR-EWR}\right)^{(WR/(2xEWR))} \qquad \textit{(Equation 4)}$$

The water use (WU), renewable water resource (WR) and environmental water requirements (EWR), [km^3/y], are extracted from the local river basin management plans.

CF's are calculated for all local water catchments identified in the River basin management plans and a weighted average representing the total abstraction of CE is calculated according to the volume withdrawn in each region. Hereby CF's are based on local measures of sensitivity of freshwater withdrawal and FWI is characterized to express the contribution to the standard environmental impacts from water withdrawal.

Normalization and weighting

The results for FWI are normalized by dividing with the normalization reference for the local region. Development of a regional normalization reference is done by multiplying the total water withdrawal originating from groundwater with the regional CF and dividing by the region's population (Statistics Denmark, 2012). The total groundwater withdrawal in the region is reported each year to a national water database (Geological Survey of Denmark and Greenland, 2012) gathering withdrawals from water supplies, industries, agriculture, etc. The normalization step converts FWI into the common metric PE (person equivalent) as the other environmental impact categories within the LCA.

The last step is weighting where the normalized impact score is multiplied by a weighting factor reflecting the seriousness of the impact category. 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) is assumed for FWI. The low weight of FWI opens for investigation of the importance of FWI. A lower weighting is not possible in the EDIP method and can only occur if another approach than distance-to-target is applied. The weighting allows for aggregation of FWI with the other weighted environmental impact categories of the LCA.

3.3.2 Application of FWI to the case study

The FWI method is applied to the same case study which also is evaluated by LCA, see section 2.1. In the case study FWI is calculated for both the base case alternative (A0) and the 2 alternative cases (A2, A3) relying on groundwater as the resource for water supply as well as the 2 cases taking in non-freshwaters as A1 (harvest of rain- and stormwater) and A4 (desalination of seawater).

The quantification of freshwater withdrawal (Q) is done by considering the volume of water withdrawn for water supply and the volume of water used throughout the life-cycle for establishment of the facilities needed and wasted water. For the cases A1 and A4 based on non-freshwater the raw water withdrawn for production are not included since these have no impact on the groundwater bodies. However, it is assumed that additional water used throughout the life-cycle originates from local groundwater bodies.

The characterization factors are calculated for the areas where CE has well fields. A general environmental water requirements (EWR) is stated by the Danish EPA as 65% of WR for the whole country without consideration of the specific site (Danish Nature Agency, 2011). This relatively high EWR is considered a precautionary decision and EWR has been estimated lower for the surface and groundwater catchments in the region (Smakhtin *et al.*, 2004; Pfister *et al.*, 2009).

The results of the standard LCA and the FWI for the base case water supply and the 4 alternative water supply technologies shows that the contribution from FWI to the total environmental impact is substantial (-0.02 – 14.9 mPET) (**Figure** 3.3) compared to the standard impact categories (0.08 - 0.20 mPET).

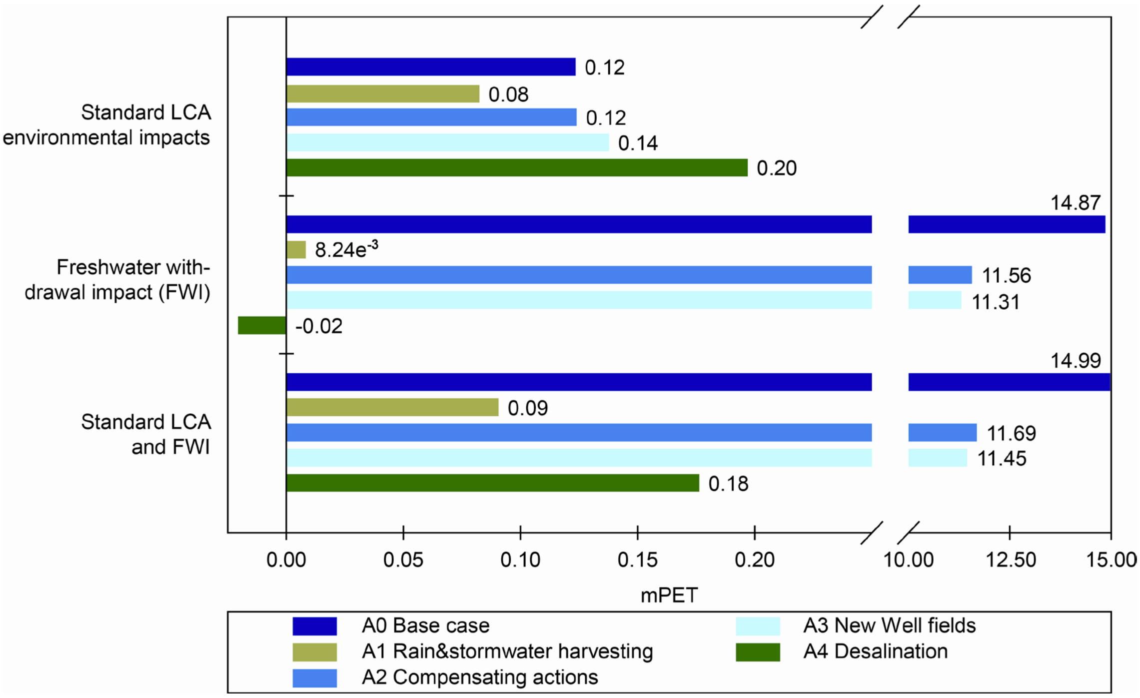

Figure 3.3. Weighted impact results for standard LCA environmental impacts and FWI for the base case and 4 alternative cases for water supply. The upper bars are the result from a standard LCA, followed in the middle by FWI and at the bottom the sum of the two.

The high importance of FWI 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 high impact of FWI underlines the importance of incorporating impacts on freshwater in the decision making process within the water sector.

The results also shows that by including the FWI the cases relying on non-freshwaters are preferable compared to the groundwater based cases for water supply.

3.4 Summary of freshwater withdrawal impact

Suggestions are made on how to address freshwater use impacts in a life-cycle perspective but so far there is not a standardized way of integrating the impacts into LCA. By calculating the WSIs of a small country like Denmark it was found that even though there appears no water stress on a national level water stress or scarcity may be occurring on the local scale. Therefore an existing method (Lévová & Hauschild, 2011) was developed (FWI) and applied in this PhD thesis using data from the national River basin management plans on a local scale which is where the impacts on the environment occur (section 3.3 and *Godskesen et al. (III)*). The FWI was applied to the case study of the base case water supply and 4 alternative cases (A0-A4) along with the standard LCA.

Both *Godskesen et al. (I)* and the standard LCA result, **Fig**. 3.3, show that groundwater based drinking water is environmentally a low-impact technology when the impacts of freshwater withdrawal are not taken into account (upper part of **Fig**. 3.3). When we include the effects of freshwater withdrawal the rank ordering of the cases favors the cases relying on non-freshwater sources such as Rain- & stormwater harvesting (A1) and Desalination (A4) - Desalination goes from last to second most preferable case when including FWI and the groundwater based technologies (A0, A2, A3) ends up as the least preferable water supply technologies (lower part of **Fig**. 3.3).

4 Sustainability evaluation of water supply technologies

The term “sustainable development” is often quoted from the Brundtland Commission (WCED, 1987) as: “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs”. In 1992 this definition of sustainable development was concretized a step further as a balance of three dimensions: environmental protection, economic growth, and social development (UNEP, 1992).

It is this definition of sustainability we have used as a model for the development of the decision support system (DSS) ASTA (section 4.2) which integrates the 3 dimensions or as called in this work, sustainability categories – environment, economy and society – and various relevant criteria belonging to the categories.

In general the strength of a DSS is that it combines the evaluation of a number of cases on 2 or more criteria by using multi-criteria decision analysis (MCDA). When multiple criteria (e.g. environment, economy, and society) are included in an evaluation the MDCA calculates the weighting also called substitution rate or capacity for trade-off between the selected criteria by applying mathematical algorithms and then points at the optimal solution among the cases (Goodwin & Wright, 2009; Chen *et al.*, 2012; Rowley *et al.*, 2012). In *Godskesen et al. (IV)* it is concluded that another relevant strength of the DSS is that it produces a result which can be presented to the decision maker, who then can see the effect of changing the weights on the results and argument why the final decision is made by using the transparency of the result when presented as suggested in this work.

Before describing the development of the decision support system (section 4.2) a review is conducted by pointing out relevant references of why multi-criteria decision analysis is found useful to evaluate water systems.

4.1 Multi-criteria decision analysis in the water sector

4.1.1 Aiding a decision

Decision making within water systems often cover multi-objective problems which means that many objectives or criteria needs to be taken into account. Multi-criteria decision analysis (MCDA) is oriented towards aiding a decision on

Table 4.1. A review of selected studies using Multi-criteria decision analysis to aid a decision on identifying the optimal solution.

Water system or other system	Multi-criteria decision analysis method(s)	Environmental assessment method	Observations in relationship to this thesis	Reference
Studies on framework for sustainability assessment				
Australian Water Industry	Lists various MCDA methods for assigning weights: e.g. linear additive model, simple multi-attribute rating method, strategic advisor, AHP and outranking	LCA is emphasized as a strong tool	This is a thorough description of how to construct a DSS build on sustainability and takes the reader through recommended steps. Stakeholder involvement is encouraged	Lundie *et al.*, 2006; Lai *et al.*, 2008
Biofuel supply chain networks (applicable to other systems)	Lists various MCDA methods for determining weights and for stakeholder participation	Suggests LCA	The study gives a good background of how to incorporate sustainability and further develop the combination into a software	Halog & Manik, 2011
Sustainability studies within the water sector				
New developments to facilitate selection of combinations of water savings strategies and technologies in the UK	Scores criteria by using a scale of 0-5	Scores criteria by using a scale of 0-5	Simple but thorough evaluation of the system	Makropoulos *et al.*, 2008
Water resource planning in a watershed in South Korea	AHP is used to calculate weights of criteria (of 2 levels) of sustainability of water resources in the water shed	Freshwater quality and conservation are the environmental criteria, evaluated by experts	A method for finding the most sustainable water resource which shares similarities with the ASTA DSS as also combines sustainability criteria into one value	Kang & Lee, 2011
Reservoir system for the storage of surface flows in Serbia	Uses AHP to assign weights to the criteria in the study	Defines environment as water available in the reservoir	Brief description of the MCDA	Opricovic, 2009

Urban water resources in Tianjin, China	Uses AHP to assign weights to the criteria in the study	Defined as power consumption, land occupation, sewage unit, consumption of scarce resources	Well described development of sustainability assessment method	Xiaoqin, 2009
Other studies within the water sector				
Drinking water treatment to reduce water hardness/ central softening in the Netherlands	Lack a description of the MCDA method used	An LCA is carried out of the two suggested treatments	Interesting combination of LCA and other criteria, unfortunately the MCDA is not described very closely	Sombekke *et al.*, 1997
Municipal WWTP in Harbin, China	AHP is used for determining weights of impact categories in the LCA	LCA in combination with process based and input-output based life-cycle inventory	Using AHP to determine LCA weights makes the weightings very relevant for the study but difficult to compare with other LCA studies	Fanyu *et al.*, 2010
Water resources for water supply in Jordan	AHP is used for determining weights and scores of the cases upon criteria	Assessed by AHP as the other criteria	An interesting study using AHP to score and weight criteria	Jaber & Mohsen, 2001
Water resource planning in Brazil	AHP is used for determining weights and scores upon criteria	Defined as water resource		Garfi *et al.*, 2011
Flood risk management of the Yangtze River	Analytical network process is used for short term flood management options	Environment is defined as flood risk management		Levy, 2005

a choice between several options or cases and has been applied in many cases within water management. Hajkowicz & Collins (2007) found that MCDA is a widespread and growing tool within the water sector and in their non-exhaustive review they found 113 studies published upon MCDA and water since 1973. A majority of the studies dealt with water resource planning.

Within the water sector MCDA has been found useful and still is used to both determine weights among criteria and scores of cases upon criteria. Before describing the relevance of MCDA for determining weights and scores a review of recent applications of MCDA in the water sector is presented (**Table** 4.1). The table is divided into sections of 1) Framework studies which uses MCDA for setting up a decision support system (DSS) for sustainability assessment, where MCDA is primarily used for eliciting weights thereby combining categories of sustainability e.g. the sustainability framework for the Australian water industry; 2) Water system case studies which uses MCDA for eliciting weights or scores upon a criteria to reach sustainability; and 3) Water system case studies where MCDA is used to meet another goal than sustainability assessment e.g. environmental assessment.

4.1.2 Determining weights among criteria

In any decision making process depending on more than 1 criterion there is a need to evaluate the weight of the criteria before a decision can be made. If the weighting is not carried out by a systematic approach it will usually be done intuitively which does not encourage a transparent decision. There are several MCDA methods for determining the trade-off between criteria, and it is this trade-off that results in a value called a weight, which tells us the importance of the criteria (Goodwin & Wright, 2009; Lai *et al.*, 2008).

When there is more than one category or criterion in a level of the DSS (4.1) the weights between them need to be determined.

For instance Sombekke *et al.*, 1997) used MCDA to combine the results of an LCA with other criteria (quality and public health, reliability, landscape, economy, etc.) when choosing between 2 types of water treatment for reducing water hardness at the waterworks (central softening). MCDA methods are also recommended for combining multiple criteria in the framework for decision support systems aimed at making a sustainable decision as described in the work of Lundie *et al.* (2006) and Halog & Manik (2011).

Several studies suggest MCDA to evaluate water resources planning and management and there exist standardized methods where e.g. the analytic hierarchy process (AHP) is used to determine the weights assigned to different criteria in order to identify the most sustainable water resources in the water catchment (Kang & Lee, 2011).

4.1.3 Determining scores of cases upon criteria

MCDA can also be used for assigning scores of alternatives (level 4, **Fig**. 4.1) upon a criterion (level 3, **Fig**. 4.1) which is exemplified in **Fig**. 4.1 where level 4, the alternatives, needs to be evaluated upon each criterion.

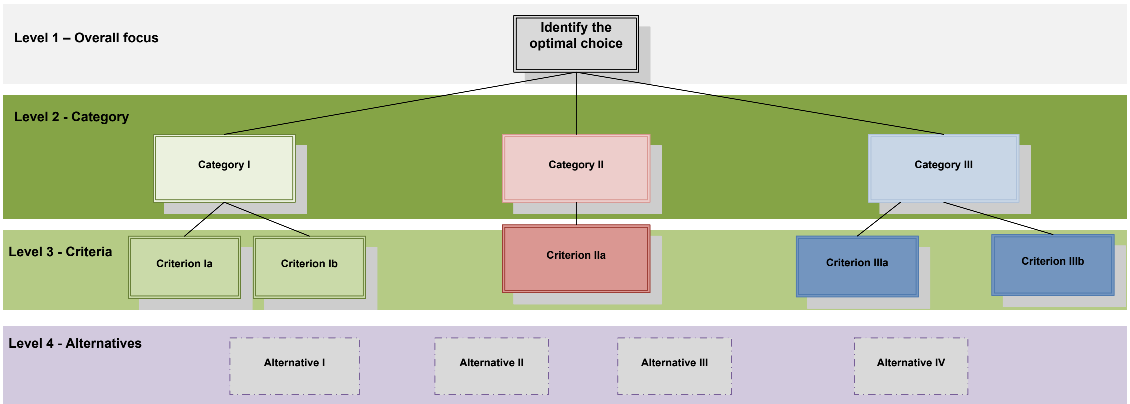

Figure 4.1. A decision support system where the goal is to identify the optimal choice by dividing the decision into 3 categories which are further divided into 5 criteria. It is possible to have more levels if e.g. the criteria needs to be further divided in to sub-criteria which can also be called indicators.

Some MCDA methods are applicable for assigning scores but also other assessment methods can be incorporated into DSS. For instance if environment or economy are incorporated then well-established methods or tools to assess cases by, e.g. LCA and cost-benefit analysis (CBA), can be used (Sombekke *et al.*, 1997; Fanyu *et al.*, 2010; *Godskesen et al. (IV)*). This is preferable because standardized frameworks like CBA and LCA are more precise than MCDA methods. However, if an LCA or CBA is not within hand MCDA methods can also be used to determine scores of the cases (Jaber & Mohsen, 2001; Makropoulos *et al.*, 2008) which is a good estimate of the scores of the alternatives upon the criteria.

This review of selected studies shows that DSS constructed by MDCA methods are capable of combining multiple criteria into a joint decision support system or result where the focus is to identify the most sustainable option or simply just preferable option based on predefined criteria. The table also shows that MCDA is a widespread and often used tool both within water resource planning but recently also within urban water systems (Makropoulos *et al.*, 2008; Fanyu *et al.*, 2010; Jaber & Mohsen, 2001). When it comes to the suggested DST for environmental assessment LCA is the dominant and most comprehensive method used in the review of selected references.

4.2 ASTA decision support system

As this PhD work is inspired by the 3-dimensional definition of sustainability a decision hierarchy was developed where the aim is to Assess the most SusTainable Alternative – the so called ASTA decision support system (ASTA DSS) (**Fig**. 4.2).

The first level in the hierarchy consists of the 3 sustainability categories (environment, economy and society); the second level consists of the criteria within the categories and the third level holds the indicators which all cases (lowest level) are evaluated upon. The cases were chosen due to their relevancy for solving the water stress currently occurring in Copenhagen.

The ASTA DSS is combined by 2 MCDA methods which are the rank order distribution weights (ROD) and the analytic hierarchy process (AHP). The ROD method is used for determining the weights of the sustainability categories (level 2) and criteria (level 3) and the AHP method is used for determining the scores of the indicators (level 4) of the society category.

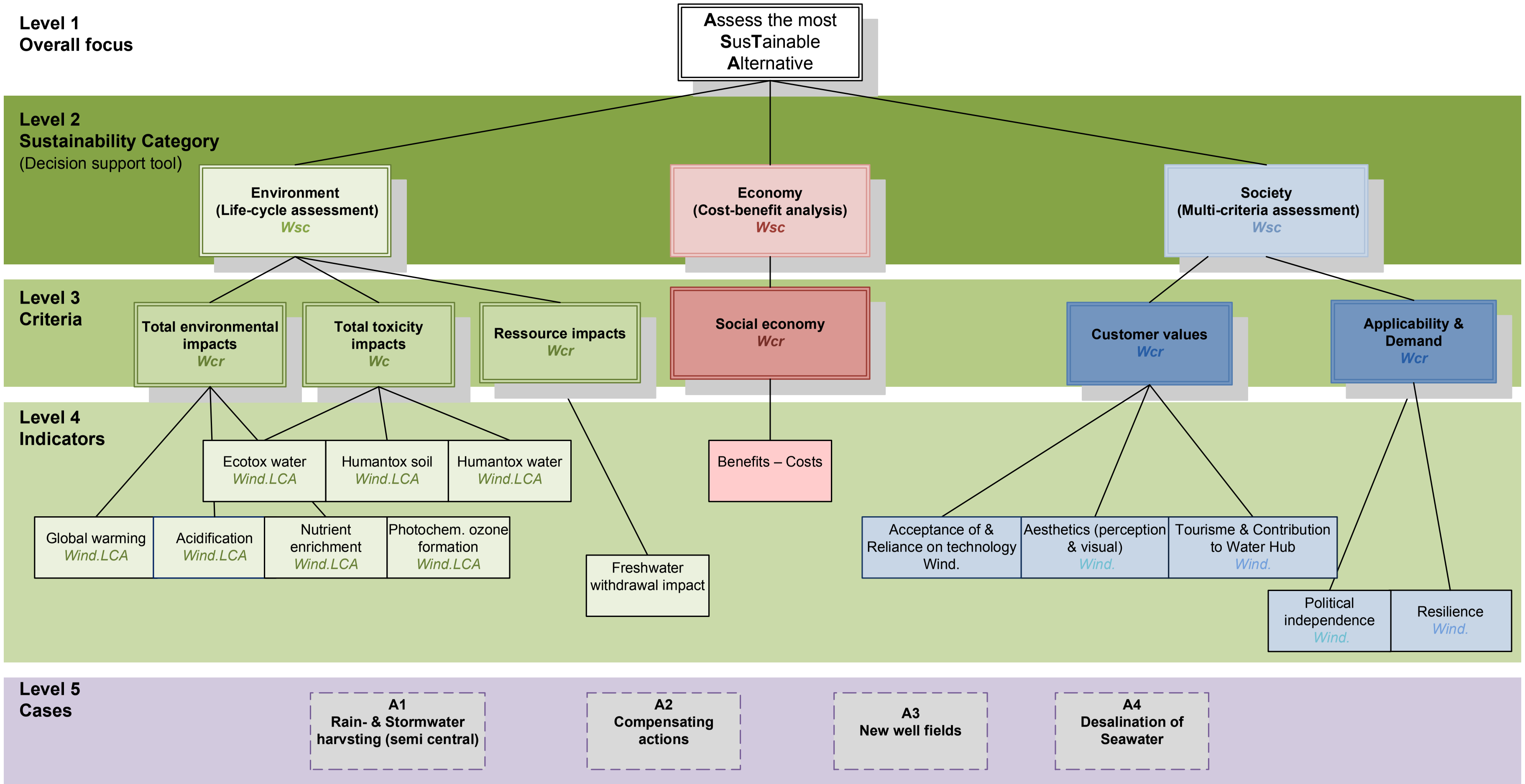

Figure 4.2. The ASTA decision support system built on the 3 sustainability categories (environment, economy and society) and further divided into criteria and indicators upon which alternatives are scored. ASTA is an acronym for Assessing the most SusTainable Alternative.

The 2 MCDA assessments were carried out at a stakeholder workshop August 17th 2012 where identified relevant stakeholders for the water sector were invited. A total of 17 stakeholders participated at the workshop of which 4 participants came from the utility and the rest from: The Danish Nature Agency (the authority implementing the EU-WFD), The Danish Competition and Consumer Authority, The Danish Water and Wastewater Association, The Danish Water Forum, Researches of Hydrology and Environment, Engineering consultancy, The Ecological Council and a water customer.

A closer description of the determination of weights followed by introduction to the 3 sustainability categories of the ASTA DSS is described below.

4.2.1 Use of rank order distribution weights to determine weights

In the ASTA DSS weights are determined when there is more than one sustainability category (environment, economy and society) or criteria at the same level which is the case for total environmental impacts (3 criteria), total toxicity impacts (3 criteria), customer values (3 criteria) and applicability & demand (2 criteria).

The determination of weights is carried out at a stakeholder workshop where relevant stakeholders for the topic are invited. The MCDA method chosen for assigning weights is the ROD weights due to its accuracy as surrogate weights (Roberts & Goodwin, 2002) and the relatively straight forward way of rank ordering performed at e.g. a stakeholder workshop.

The ROD weights are defined according to the number of criteria in the specific weighting of criteria (see calculation of ROD weights in *Godskesen et al. (IV)*).

Prior to the workshop we had identified 3 sets of rank ordering, each defined by their highest ranked category: environment, economy or society. The stakeholders were asked to group according to their first priority of sustainability category and then within a 20 minute period in the groups make negotiations on how the rest of the categories and criteria should be rank ordered. After the rank ordering processes the weights were assigned to each sustainability category or criteria by use of the ROD weights (**Table** 4.2) still keeping the 3 sets intact.

Table 4.2. Rank ordering of sustainability categories and criteria divided in 3 sets and the determination of weights by Rank Order Distribution (ROD) (*Godskesen et al. IV*).

Sustainability Category *Criteria*		**Set 1** Most important: Environment		**Set 2** Most important: Economy		**Set 3** Most important: Society
Environment	0.52		0.32		0.32	
Total environmental impacts		0.15		0.32		0.32
Total toxicity impacts		0.32		0.15		0.15
Resource impacts		0.52		0.52		0.52
Economy	0.15		0.52		0.15	
Operation & maintenance		1.00		1.00		1.00
Society	0.32		0.15		0.52	
Customer values		0.31		0.31		0.69
Applicability & demand		0.69		0.69		0.31

From **table** 4.2 it is noted that all 3 sets of weights agreed on freshwater withdrawal impact having the highest importance of the environmental criteria. This demonstrates the high importance of freshwater consumption identified for the case study of this PhD project and is in agreement with the focus e.g. the politicians and researchers express today in terms of political documents (European Environment Agency, 2012), European regulations (European Union, 2000) and also the interest in integrating freshwater consumption into the LCA methodology (section 3.1).

It was noted at the workshop that the 3 predefined sets of rank ordering made it easier for the stakeholders to reach agreement.

The weighting procedure is a challenge as the stakeholders are basically asked to determine the importance of e.g. 1 ton CO_2-emissions per capita compared to 1 m^3 of freshwater withdrawal per capita. An advantage of the rank ordering is that it appears simple as the stakeholders are not asked to add a specific value or total to the criteria but simply rank order the criteria (Rowley *et al.*, 2012; *Godskesen et al., (IV)*).

Figure 4.3. The stakeholder workshop showing stakeholders negotiating the final rank ordering of the criteria. This photo is from the group with the predefined set of rank ordering where environment was ranked highest.

4.2.2 Assigning scores to the 3 sustainability categories by use of the analytic hierarchy process

Environment

The sustainability category environment is built upon the results of an LCA according to the EDIP (Environmental design of industrial products) method divided into 3 criteria: environmental impacts; toxicity impacts; and resource consumption. The indicators of environmental impacts are the global warming, acidification, nutrient enrichment impacts and photochemical ozone formation which are weighted according to the EDIP method allowing for aggregation into total environmental impacts (Wenzel *et al.*, 1997). Likewise the total toxicity impacts cover the ecotoxicity in water and human toxicity in water and soil which also are also weighted and aggregated.

The third criterion is resource consumption where the impact of withdrawing water for the purpose of water production is the main activity having a relatively large impact on the water resource from where water is withdrawn. As described in section 3 of this thesis only freshwater is considered as a limited resource since rain- & stormwater falling in the city and seawater is in abundance. Therefore the freshwater withdrawal impact (FWI) is included in the ASTA DSS as the only resource hence most important when assessing technologies for water supply.

The LCA result of the criteria environment is per definition presented so that a high impact (which is negative) results in a high score. The ASTA DSS follows the opposite approach where a good environmental performance is presented by a high score hence a high environmental impact results in a low score in the ASTA DSS.

In *Godskesen et al. (III)* the FWI is weighted according to the distance-to-target method (Wenzel *et al.*, 1997) by setting a non-precautionary weight of 1 meaning that the political target for the impact on the freshwater of water withdrawal is already met which is a clear underestimate of the water stress situations around the world today. The weighting makes it possible to compare the FWI with the standard LCA impact categories which showed that the FWI has a high importance since its value is much higher than the values for the other categories. In *Godskesen et al. (IV)* the weighting of FWI in terms of resource consumption (here is only considering FWI) in comparison to the total environmental impacts and the total toxicity impacts is determined at the stakeholder workshop. At the workshop the stakeholders clearly demonstrated that FWI is the main concern among the 3 criteria of environment as it obtained the highest weight (0.52) in all 3 sets of weights (**Table** 4.2)

Economy

The recommended method for the economic evaluation is to carry out a cost-benefit analysis and integrate it into the DSS as done for the environment category with the results from the LCA.

In the case study of the 4 water supply technologies in *Godskesen et al. (IV)* focus was solely on the costs of the utility and based it on previously studies of projects similar to the 4 cases carried out internally in CE.

Society
The LCA and CBA were carried out by a specialist whereas the indicators belonging to the Society category were assessed by stakeholders at a stakeholder workshop (**Fig**. 4.3).

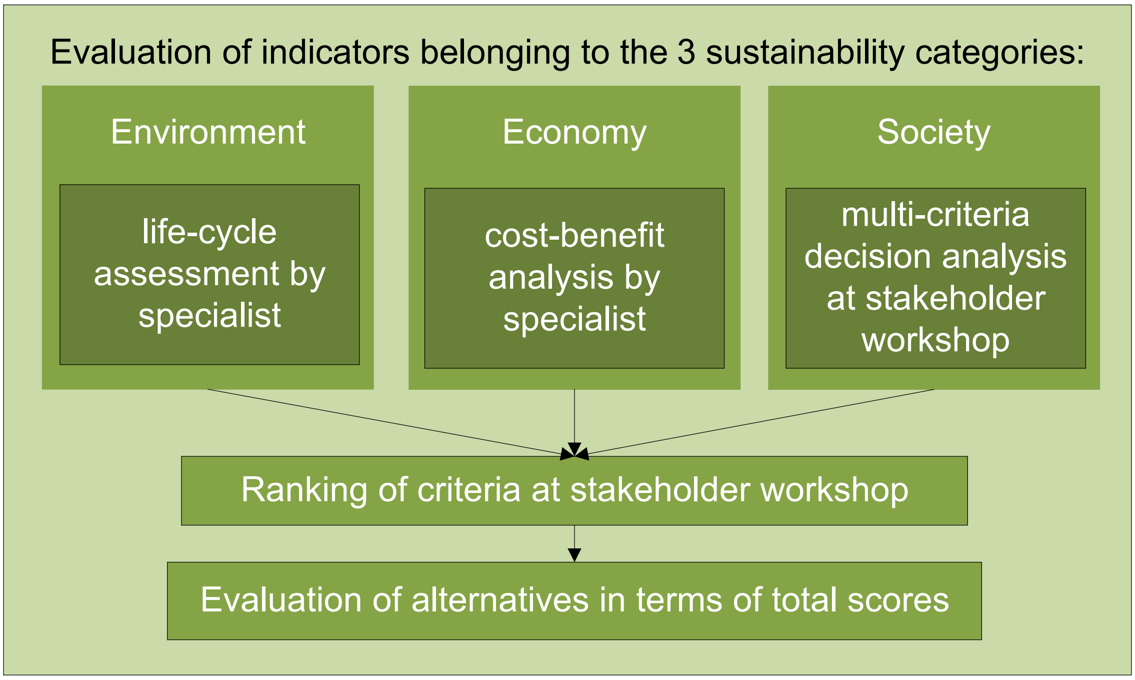

Figure 4.3. The framework of the ASTA-model showing the processes and people involved in the decision making process (*modified according to the ASTA-model from Jensen et al., 2012*).

The analytic hierarchy process (AHP) was applied to score the cases upon each indicator. In AHP, preferences between 2 cases were determined by making pair-wise comparisons of one indicator at a time (Saaty, 2006).

According to the AHP method the comparisons were done using the verbal value scale (Saaty, 2006) consisting of 5 verbal definitions and the intermediates (Fig. 5 in *Godskesen et al. (IV)*). In a joint effort of all stakeholders at the stakeholder workshop each pair-wise comparison was assigned a value. The relative score of each case was found by calculating the geometric mean, G, of the decision matrix

4.2.3 Combining the results from the 3 Sustainability Categories and presenting the result from the ASTA-model

Before the results of the 3 sustainability categories are combined in the ASTA DSS the results are normalized. The normalization step serves the purpose of converting the results to a common scale comparable with all indicators of the ASTA DSS. In this PhD study normalization is defined as dividing the score of each case of an indicator by the sum of the scores of the 4 cases of the same indicator which means the score is expressed as a proportion of the sum of all scores (Rowley *et al.*, 2012). Hereby we consider the study on a local scale consisting of the 4 involved cases. After the normalization step the Criteria were summed up for each case after multiplying by the weight as the ASTA DSS is developed according to the additive model (*Godskesen et al. (IV)*).

Table 4.3. Relative scores from the assessment of 4 cases of water supply technology using indicators divided into criteria and sustainability categories (*Godskesen et al., IV*).

Sustainability Categories / *Criteria*	Indicators	**A1 Rain& storm-water**	**A2 Compen-sating actions**	**A3 New well fields**	**A4 Desali-nation**
Environment					
Total environmental impacts*					
	Global warming, Acidification, Nutrient enrichment and Photochem. ozone formation	0.369	0.253	0.227	0.151
Total toxicity impacts*					
	Ecotoxicity water, Human toxicity soil and water	0.356	0.247	0.229	0.168
Resource impacts					
	Freshwater withdrawal impact	0.636	0.001	0.001	0.362
Economy					
Operation & Maintenance					
	Costs	0.052	0.480	0.286	0.182
Society					
Customer values					
	Acceptance of & reliance on technology	0.059	0.557	0.291	0.093
	Aesthetics (perception & visual)	0.096	0.564	0.303	0.037
	Tourism & Contribution to Water Hub	0.375	0.375	0.125	0.125
Applicability & Demand					
	Political independence	0.373	0.171	0.050	0.406
	Resilience	0.093	0.289	0.114	0.504

*The weighting among the indicators is carried out according to a standardized distance to political target-method incorporated in the Life-cycle assessment.

Before integrating the results of the indicators into the ASTA DSS the various indicators did not point at the same water supply technology as being the most preferable, **Table** 4.3.

The ASTA DSS is capable of assisting the decision maker when choosing the most sustainable case within a given range of cases and according to a predefined problem. The result is presented with a total score and a bar chart showing the contribution from the 3 sustainability categories – and even criteria - of the total score (see **Fig**. 4.4). This serves the purpose of making the decision transparent and well-argumented thereby easy for the decision maker to communicate.

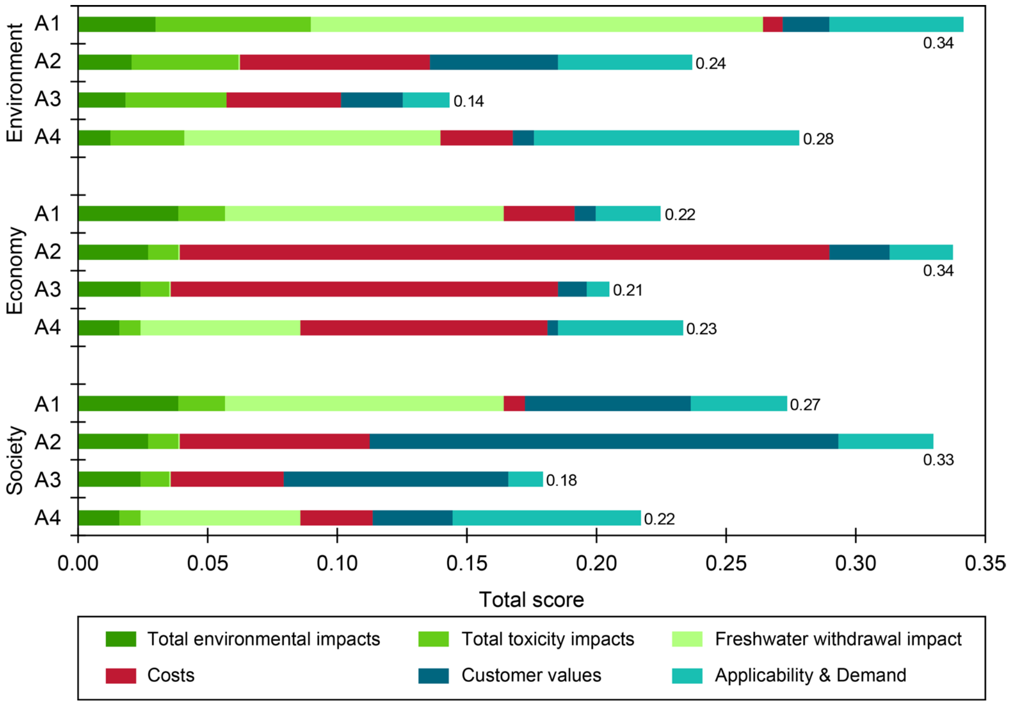

Figure 4.4. The final results of the multi-criteria assessment combining the results of the 6 criteria: Total environmental impacts; Total toxicity impacts; Freshwater withdrawal impact; Costs; Customer values and Applicability & demand. The cases assessed are: A1 Rain- & stormwater harvesting, A2 Compensating actions, A3 New well fields and A4 Desalination of seawater. The 3 sets of weights are presented in separate groups of bars where the highest ranked sustainability category was environment, economy or society (*Godskesen et al., IV*).

Having assessed the 4 water supply technologies for Copenhagen according to the described ASTA DSS, the results point at one preferable water supply technology for each set of 3 rank ordering of weights. However, the result also showed that the result depends upon the weighting.

This study (**Fig**. 4.4) shows that when the highest weight was assigned to environment then the rain- & stormwater harvesting case (A1) is the most sustainable followed by desalination of seawater (A4). When the highest weight was assigned to economy or society then the most sustainable alternative is the case compensating actions case (A2) followed by either rain- & stormwater harvesting or desalination.

For all 3 sets of weighting the new well fields case (A3) has the lowest sustainability.

By integrating sustainability assessment as described for the ASTA DSS a joint decision support result is obtained where the contribution from each sustainability category and criteria is easy to follow in the aggregated result. The result gives the decision maker the opportunity to change the weights and thereby see the robustness of his or her decision. More importantly, the result of the ASTA DSS delivers a transparent and well-argumented decision support which is easy to communicate to the audience.

4.3 Summary of DSS for sustainability assessment

MCDA is a DST capable of eliciting scores to criteria and also when used as a framework to combine multiple and various criteria into a joint DSS. In our development of the ASTA DSS the focus was to assess the most sustainable option by combining environmental evaluation assessed by LCA, economic evaluation assessed by cost-benefit analysis and social evaluation by the MCDA method AHP. In ASTA the weighting between the sustainability categories and criteria is determined by ROD weights. The result from the ASTA DSS gives the decision maker a transparent decision support result which is easy to communicate and provides arguments for the decision.

LCA is identified by many and also in this PhD work as the most dominant and comprehensive and therefore strongest DST when it comes to the environmental evaluation.

MCDA is a growing method within the water sector as many has observed the strengths of the DST. Within the water resource planning MCDA has been widely used and recently MCDA is also being used within urban water systems.

The stakeholder workshop was an effective way of assigning weights and eliciting scores of alternatives upon criteria. However the stakeholder workshop can be a time consuming element and therefore should be planned carefully.

5 Conclusions

This thesis presents an overview of environmental evaluations by Life-cycle assessment (LCA) of water supply systems and an integration of freshwater withdrawal into the standard LCA. The impacts of freshwater withdrawal are generally gaining more and more interest but are especially relevant when working with water supply - an activity which by definition consumes a relatively large volume of water. The thesis also takes the assessment a step further by integrating the environmental evaluation including the freshwater withdrawal impact with the 2 other categories of sustainability: economy and society, into one joint decision support system.

To our knowledge, it is the first time a DSS built on MCDA is developed for water supply systems including LCA of water quality changes, as in this study with the effects of reduced water hardness, and the impacts of withdrawing freshwater.

Environmental evaluation by LCA

The standard life-cycle assessment tool is developed to present the impacts categorized into selected environmental impact categories and is proven to deliver strong decision support material. However, since this PhD thesis focused on water supply systems, we found 2 shortcomings: 1) when the goal is to compare water supply technologies it must be emphasized that the compared cases provide a comparable water quality e.g. water hardness. Otherwise, the effects of the different qualities such as water hardness are missing and should be included; and 2) impacts of withdrawing freshwater are not included in the standard LCA.

Water hardness is especially relevant for Copenhagen since water supply is based on groundwater situated on chalk aquifers resulting in distribution of very hard water and a comparison with a technology providing water of reduced hardness must take this into account. Freshwater withdrawal is necessary to address e.g. by integrating impacts of freshwater withdrawal into the standard LCA.

Integrating the freshwater withdrawal impacts into the standard LCA

This PhD study suggests a method for extending the standard LCA methodology with impacts of freshwater withdrawal by further developing an existing method for freshwater withdrawal impact on freshwater resources, originally developed for assessing industrial freshwater use at a regional scale. The freshwater withdrawal impact (FWI) is integrated into the LCA based on data from the EU-WFD on local groundwater bodies followed by normalization and weighting according to the EDIP LCA methodology.

The strength of this method is that it operates at the local scale of the groundwater including local freshwater interactions instead of operating on regional or national levels. This is important for larger regions e.g. nations where the amount of available freshwater and the pressure on the local freshwater resources (depending on population density and rainfall) are significantly different within the region. That is the case for Denmark where the water resource is limited near Copenhagen which also is an area with high population density.

Life-cycle and freshwater withdrawal impact assessment of 4 cases

In this PhD a standard LCA of the drinking water supply technology of today and 4 alternative cases for water supply technologies was conducted. The system boundaries of the study covered the entire urban water system from water intake, water treatment, over distribution of water including effects of reduced water hardness in the households to transport and treatment of wastewater. The standard LCA points at the rain- & stormwater harvesting case as the most environmentally friendly technology followed by the 3 cases relying on groundwater abstraction. The rain- & stormwater harvesting has the lowest environmental impact mainly due to the combined sewers in this part of the city making the harvesting environmentally preferable as it prevents the rain from being discharged into the sewers where it is transported to and treated at the WWTP. The least favorable case is desalination of seawater.

When incorporating the FWI in addition to the standard LCA impact categories the rank order is partly reversed as rain- & stormwater harvesting and desalination are significantly more preferable compared to the groundwater based cases. This shows the importance of integrating impacts of freshwater withdrawal in the environmental evaluation.

Development of a decision support system focusing on sustainability

Multi-criteria decision analysis was identified as a strong, widespread and growing tool for creating decision support aid combining multiple criteria also within the water sector.

We developed the decision support system ASTA by combining 2 MCDA methods according to the additive model: 1) ROD for determining the trade-off between criteria (in the ASTA-model referred to as sustainability categories and criteria) and thereby calculating a weight and 2) AHP for scoring cases upon indicators belonging to the 2 criteria of society.

The ASTA-model combines the 3 sustainability categories and the subdivided criteria and indicators into one joint decision support result. When the result of the ASTA-model is presented to the decision maker it provides the opportunity to see the influence of changing the weights of the sustainability categories and criteria and most important delivers a transparent and well-argumented decision support which is easy to communicate a decision by.

6 Perspectives

The knowledge gained in this PhD can be used for future environmental evaluation of water systems in Copenhagen Energy, Denmark and internationally. This PhD shows the importance of a holistic approach when considering the water system to be assessed and always consider if the cases are comparable and if the LCA or DSS include all relevant impacts.

6.1 Significance of this PhD work

This work demonstrates that it is important to include effects of freshwater withdrawal when evaluating water systems but the method can be applied to environmental evaluations of other products and systems e.g. together with the standard LCA. An important step is to integrate FWI or similar methods into the standardized LCA so it by default is considered as an impact category when performing an LCA, equivalent to the well-established global warming impact category.

This work also proves that development of a decision support system is possible by combining results from an LCA and multiple other criteria and a framework is described in terms of the ASTA DSS. Understanding and using results from a DSS as ASTA must be based on dialog with the decision makers as the results from ASTA as well as from an LCA are not always straight forward to interpret and use within the time limits of a decision. Once understood, the results from the LCA covering FWI and the ASTA DSS provide the decision makers with arguments of an environmental and sustainability evaluation of water systems making a decision transparent.

6.2 Suggestions for future research

The development of FWI opens the door for evaluating the impacts of freshwater withdrawal for a business e.g. a water utility. Water utilities in Denmark are stating their CO_2-emissions of the water supply system but the focus on the utility's water use impact (such as FWI) must also be considered. The CO_2-emission and FWI could be conflicting as for instance for Desalination of Seawater which carries a low FWI but a high carbon foot-print. The decision of whether the utility should focus on e.g. carbon foot-printing or FWI is important to address and develop methods to consider more aspects than the weighting methods suggested in this PhD (section 3.3 and 4.2.1). It is likely that the future will require assessments of freshwater withdrawal even for energy producing companies that formerly mainly have focused on the CO_2-emissions.

In this work effects of water hardness were assessed by LCA. Other effects of water quality parameters such as micro nutrients, minerals, taste, odor and contamination could also be relevant to assess by LCA or other relevant decision support tool e.g. economic evaluation or risk assessment.

An evaluation with the ASTA DSS could also be used for deciding whether polluted groundwater should be treated and used for drinking water production as described in the introduction as the risk of contamination of groundwater by agricultural use of pesticides is increasing.

Also a further development of technology for groundwater based water supply which compensates for the effects of groundwater withdrawal (more than what is described in the A2 case) is encouraged. This could be an advantage for the groundwater based water supply as it would lead to a better evaluation of impacts of freshwater withdrawal.

Finally, better local estimations of the water requirements of the environment (EWR) than the generic 65% applied to the entire nation in the current Danish River basin management plans is identified as a research area of great importance.

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8 Papers

I. Godskesen B., Zambrano K. C., Trautner A., Johansen N. B., Thiesson L., Andersen L., Clauson-Kaas J., Neidel T. L., Rygaard M., Kløverpris N. H. and Albrechtsen H. (2011). Life cycle assessment of three water systems in Copenhagen - a management tool of the future. *Water Science and Technology*. **63**, issue 3, 565-572.

II. Godskesen B., Hauschild M., Rygaard M., Zambrano K. and Albrechtsen H.-J. (2012). Life cycle assessment of central softening of very hard drinking water. *Journal of Environmental Management*. **105**, 83-89.

III. Godskesen B., Hauschild M., Rygaard M., Zambrano K. and Albrechtsen H.-J. Life-cycle and freshwater withdrawal impact assessment of water supply technologies. *Submitted manuscript.*

IV. Godskesen B., Hauschild M., Rygaard M., Zambrano K. and Albrechtsen H.-J. A method for Multi-criteria evaluation of water supply technologies to identify the most sustainable case for Copenhagen. *Manuscript.*

In the thesis the scientific papers are cited as e.g. *Godskesen et al. (IV)*.
The papers are not included in this web-version, but can be obtained from the library at DTU Environment.

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