Chapter 33
LCA of Drinking Water Supply

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Abstract Water supplies around the globe are growing complex and include more intense treatment methods than just decades ago. Now, desalination of seawater and wastewater reuse for both non-potable and potable water supply have become common practice in many places. LCA has been used to assess the potentials and reveal hotspots among the possible technologies and scenarios for water supplies of the future. LCA studies have been used to support decisions in the planning of urban water systems and some important findings include documentation of reduced environmental impact from desalination of brackish water over sea water, the significant impacts from changed drinking water quality and reduced environmental burden from wastewater reuse instead of desalination. Some of the main challenges in conducting LCAs of water supply systems are their complexity and diversity, requiring very large data collection efforts, with multiple sources of information, many of them not public and requiring cooperation. Important for product and system LCAs with substantial water use, it is emphasized that standard life cycle inventory databases do not reflect the significant variance in environmental impacts of water supply across locations and technologies.

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33.1 Introduction

33.1.1 Water Consumption and Water Treatment Technologies

Water supply systems are unique for every region around the globe. They are based on a variety of water resources and technologies. Importantly, some of them have been based on the same traditional technologies for more than 100 years, while others are rapidly changing to cope with the urban development. The differences are also large between neighbouring countries. For example, while Denmark is 100% based on groundwater abstraction for its water supply, the neighbouring countries Sweden and Germany were sourcing just 22 and 61%, respectively of their water supply from groundwater in 2010. Instead of groundwater these countries use a variety of surface water, spring water and artificially recharged groundwater (IWA 2014). Other countries are now heavily reliant on water reuse and desalination, for example Spain, USA, Israel, Singapore and Saudi Arabia (IWA 2014; Tal 2006; GWI 2010). Desalination and reuse are increasingly used and the rapid development is underlined by the rapid growth in desalination capacity around the globe (Fig. 33.1).

33.1.2 Water Systems Growing Complex

There is a wide variety of water systems, which may interact with many processes and systems (Fig. 33.2). Although, water systems normally include: production (abstraction and treatment or desalination), transmission and distribution of water to various users, each process may apply various technologies, and the systems may

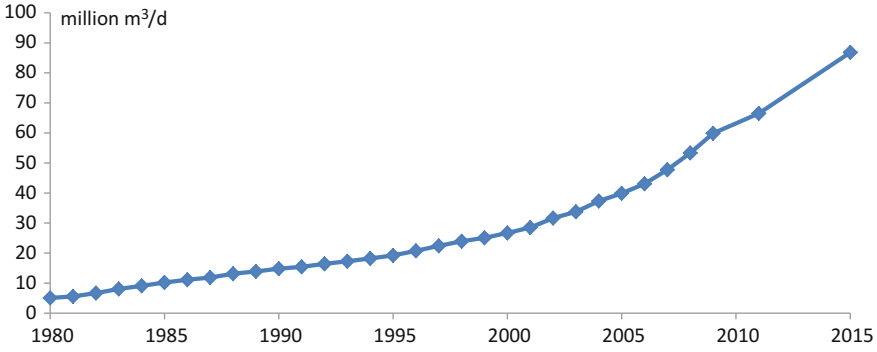

Fig. 33.1 Installed capacity of desalination plants registered by International Desalination Association. *Source* Pankratz (2010) and http://idadesal.org/desalination-101/desalination-by-the-numbers/

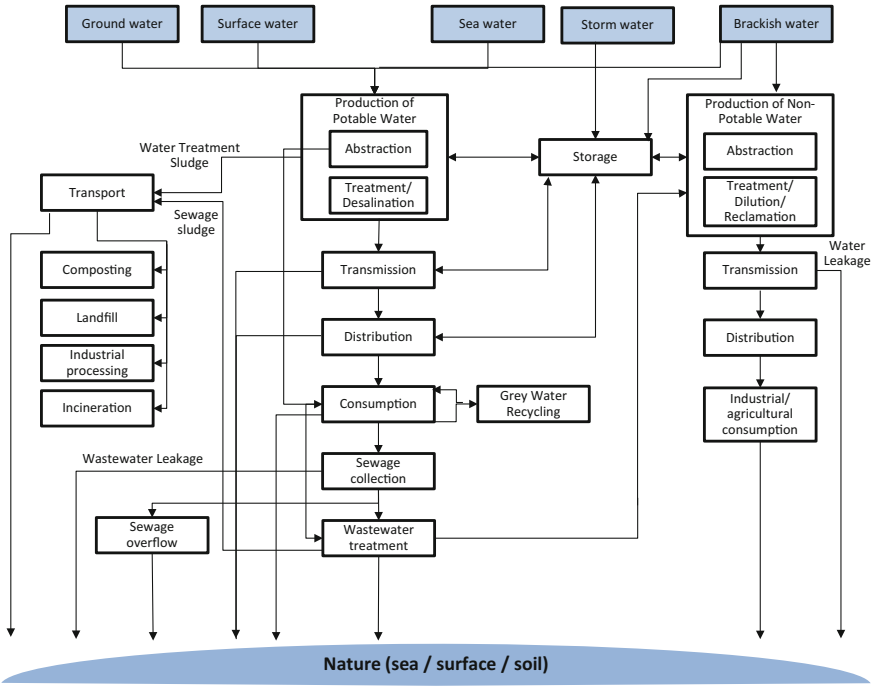

Fig. 33.2 General water supply chain. Adapted from Meron et al. (2016)

use multiple resources and multiple output water qualities for different users. In order to account for the different environmental profiles of water production pathways, Hospido et al. (2013) proposed the concept of water supply mix for the example of irrigation in Spain and inspired by the concept of the electricity mix. Water losses throughout the supply system also vary considerably and can range between 5 and 55% (Ratnayaka et al. 2009), thus may have an important effect on systems' impact. The environmental performance of water systems can therefore greatly vary.

From a systems perspective, the new sources of water and combinations of new and traditional water treatment technologies makes planning decisions difficult. Multiple water resources and differences in the direct and indirect impacts on the environment from each process in the system are complex aspects to consider in the process of finding the best solution for a particular situation. To complicate things, the drivers of change in water systems also push in the direction of having systems with multiple water qualities, treatment technologies and resources in use at the same time. For example, until now, Danish water utilities have managed urban water systems based on groundwater abstraction, simple low-intensive treatment, distribution of one water quality (drinking water). After use, a one-stringed sewer system would divert wastewater to central treatment plants before discharging the treated wastewater to the recipients. Now, water utility managers foresee a

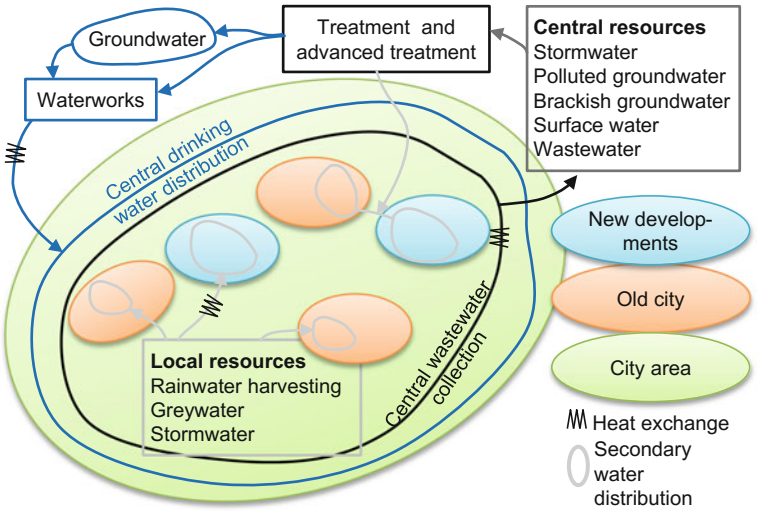

Fig. 33.3 Visions for the future urban water systems in larger cities in Denmark as developed by the two biggest Danish water utilities Aarhus Vand and HOFOR. The water systems are foreseen to become increasingly complex and cover multiple water sources, a mix of central and decentralized systems and vary between old and new parts of the city (Rygaard et al. 2012)

diversification of their water systems that include distribution of multiple water qualities, decentralized handling of wastewater and reclamation of wastewater for distribution for non-potable purposes (Fig. 33.3). Also decision support in much more water scarce areas around the world such as China and Australia have dealt with the difficult choice between a vulnerable, but simple water system and a more robust but significantly more complex diversified water system (Kenway et al. 2011; Lane et al. 2015; Li et al. 2016). In such cases LCA provides insight to the environmental trade-offs between future water supply scenarios.

33.1.3 Water Supply Technologies: Traditional and New Possibilities

With the development in especially membrane filtration processes, it has become common practice for many water supplies to treat water that just a couple of decades ago was considered economically infeasible to use. Back then, most water suppliers based their production on simple treatment techniques such as aeration, flocculation and filtration with activated carbon and sand filters, and disinfection by chlorine. These techniques are adequate to remove many common unwanted substances, for example methane and hydrogen sulphide, iron, organic pollutants, and to deactivate or remove pathogens. With newer treatment techniques like membrane filtration and advanced oxidation methods it is possible to treat wastewater and

remove salt from ocean water to make it suitable for drinking. Potable wastewater reuse, seawater and brackish desalination can now be established at total costs around 0.5–2 US$ per produced m^3 water, which is similar to production costs of more simple and traditional water treatment (Greenlee et al. 2009; Rygaard et al. 2011; Wols and Hofman-Caris 2012). However, aeration and simple filtration requires little energy and few other resources in the operation, while removing salts from water using reverse osmosis requires advanced membranes, high pressure pumps and chemicals to keep the membranes clean. Typical simple groundwater treatment requires around 0.3 kWh/m^3 while state-of-the-art desalination of ocean water requires around 2.5–7 kWh/m^3 produced (Rygaard et al. 2011; Plappally and Lienhard 2012). Shifting from traditional and simple treatment technologies to more advanced treatment gives access to huge additional water resources in the wastewater stream and seawater. On the other hand, it can have significant impact on the material and energy use in the production of water.

Membrane-based treatment technologies can produce very clean product water with essentially no pollutants and minerals in it. This may be particularly beneficial for some industry processes demanding ultraclean water. The option of remineralizing the demineralized water makes it possible to optimize water quality for specific uses, e.g. drinking water with a certain mineral content (Birnhack et al. 2008; Rygaard et al. 2011a).

33.2 Literature Review

In urban water management, LCA is found to be the most dominant and appropriate tool to assess the environmental impacts (Godskesen et al. 2013). Other tools such as carbon and water footprint are also being used but they are not as comprehensive as they only focus on one or two environmental aspects and might not cover the entire life cycle from cradle to grave.

LCA has been applied in the water sector for years and numerous LCA studies of water processes and subprocesses have been reported. Publications have been made on the abstraction, production, transport and distribution, and on entire urban or regional water systems. These studies lead to various conclusions. A meta-analysis of water supply systems and subsystems has confirmed that there is a large variation in the impacts of water supply systems. For example, global warming potential ranges between 0.16 and 3.4 kg CO_2-eq per m^3 of supplied water (Meron et al. 2016).

33.2.1 LCA to Identify Hot Spots in Water Supply

Several studies have shown that water production has the highest contribution to the impacts of the entire water supply system (Friedrich et al. 2009; Godskesen et al.

2013; Lemos et al. 2013; Tarantini and Ferri 2001; Uche et al. 2013), and desalination in particular (Del Borghi et al. 2013). Only a few publications specifically report the contribution of the abstraction and transport and distribution subsystems to the impact of entire water supply systems, although in some cases they may also have significant contribution. For example, in Tarragona, Spain (Amores et al. 2013), and in Lasi, Romania (Barjoveanu et al. 2014), the distribution subsystem has the highest impacts in all categories except eutrophication due to pumping electricity consumption.

Activities affecting water used at households were also shown to be important. For example, water boiling to improve water quality after its deterioration through the distribution subsystem has the highest contribution to the impacts of the supply system in Hanoi, Vietnam (Homäki et al. 2003). The impacts of activated carbon-based filter to improve water quality at domestic level are also considerably higher scores than the impacts of the centralized water supply in Milan (Nessi et al. 2012). Environmental impacts of household activities can be reduced if water is softened at the treatment stage (Godskesen et al. 2012).

The importance of electricity consumption in LCAs of water supply systems has been reported in many studies (Lemos et al. 2013; Lundie et al. 2004; Tarantini and Ferri 2001; Lane et al. 2015). Energy is also found to be a significant factor in water supply subsystems: in abstraction (Buckley et al. 2011), in production through treatment of freshwater (Buckley et al. 2011; Igos et al. 2014; Lyons et al. 2009; Racoviceanu et al. 2007), in desalination (Lyons et al. 2009; Raluy et al. 2005a; Stokes and Horvath 2006; Tarnacki et al. 2012; Uche et al. 2013), in pumping (Amores et al. 2013) and in landfilling sludge in the case of wastewater reclamation (Li et al. 2016).

Energy also has an important contribution to the environmental impacts of water through background processes. The production of treatment chemicals (Bonton et al. 2012; Buckley et al. 2011) and materials for construction of decentralized water supply systems (Godskesen et al. 2013) are reported to have significant impacts.

Production technologies were also studied and compared. Large variation was reported in the impacts of water production. For example, the average Global Warming Potential (GWP) of thermal desalination have been found to be about ten times the average of reverse osmosis desalination's GWP, and about 100 times higher than freshwater technologies' GWP (Meron et al. 2016). Raluy et al. (2005a, b) studied several desalination technologies and import of water from a distant river to a local water body. The paper underlines that even though desalination has high energy requirements it has become competitive and transfer of water is not always the best solution dependent on energy needs for long distance transport.

Within the process of freshwater treatment, chemicals production may play an important role (e.g. Barrios et al. 2008). Yet in some cases chemicals had low contribution (Arpke and Hutzler 2006; Tarantini and Ferri 2001; Jeong et al. 2015).

The contribution of the materials and construction of the distribution infrastructure may be significant and up to 60% of the overall impact of distribution, while only up to 15% of the abstraction impacts and up to 20% of the production

impacts (Meron et al. 2016). Infrastructure construction is shown to have only limited contribution to the total impact of sea water desalination (Raluy et al. 2005b; Uche et al. 2013) and of groundwater treatment plants (Igos et al. 2014; Uche et al. 2013), but infrastructure does represent a significant contribution to the impact of water distribution (Barjoveanu et al. 2014; Slagstad and Brattebø 2014; Uche et al. 2013; Jeong et al. 2015). A study of the impact of pipes compared different materials used in the water transport and distribution network, using several impact categories. The study showed that the installation stage is especially relevant for constructive solutions with smaller pipe diameters (e.g. 90 mm diameter HDPE), whereas the production of the pipe becomes more relevant with larger pipe diameters (e.g. 200 mm diameter HDPE). The reduction of environmental impacts involves the optimisation of the trench dimensions and the process of installation as well as the selection of pipe materials with lower environmental impacts in the production stage (Sanjuan-Delmás et al. 2014).

Several LCAs studied the impacts of urban rainwater capture as an option to supplement or replace water demand from centralized water supply systems. These studies show that rain harvesting can reduce environmental impacts in some cases (Godskesen et al. 2013) whereas in some locations rain water harvesting is not the best choice (Mithraratne and Vale 2007; de Haas et al. 2011). Rain tank impacts are mainly due to electricity consumption (de Haas et al. 2011; Mithraratne and Vale 2007; Angrill et al. 2012) and in some cases infrastructure, depending on which materials are used (e.g. concrete or plastic) (Mithraratne and Vale 2007; Angrill et al. 2012).

33.2.2 LCA of Water Reuse

In several studies LCA was applied to study the environmental impacts of water reuse. Tertiary treatment has a relatively low impact compared to the impact of the entire wastewater treatment plant, as well as compared to desalination (Pasqualino et al. 2011). Production from freshwater sources has also been shown to have similar impacts to tertiary treatment (Meneses et al. 2010). Reclaimed wastewater that replaces freshwater resources used for irrigation may reduce the environmental burden of the water system, compared to systems without reuse (Fang et al. 2016). Wastewater reclamation, water transfer, and desalination were compared in different locations including California (Stokes and Horvath 2006), Arizona (Lyons et al. 2009) and northern China (Li et al. 2016). In all these studies desalination has the highest environmental impacts in all of the impact categories, except in the freshwater withdrawal impact. In summary, LCA has been used to show the reduced environmental burden from water systems turning towards water reuse, instead of expanding surface water treatment or turning to desalination.

LCA studies have also highlighted the need for looking beyond standard impact categories, like carbon footprint, and include toxicity impacts in the decision-making. For example, a study compared eco-toxicity of four alternatives

for use of wastewater after secondary treatment: no-reuse, direct use, and use after two different tertiary treatment technologies based on ozonation. From the ecotoxicity perspective, use after tertiary treatments is the best choice. The study emphasized also that LCAs of wastewater reusing systems assessing toxicity should include wastewater pollutants such as heavy metals, pharmaceuticals and personal care products, which can contribute above 90% of the toxicity impact (Muñoz et al. 2009).

33.2.3 LCA as a Tool in Water Supply Management

The previous sections have shown how LCA have revealed the environmental burden of various water systems and included processes and technologies. LCA is also used in cases where there is a lack of water and need for strategic choices in the planning of future water supplies. One good example of the typical application of LCA in water supply management is the comparison of possible solutions to water scarcity, where two or more water production scenarios are considered. Muñoz and Fernández-Alba (2008) showed that a shift from ocean water to brackish groundwater could significantly reduce the environmental impact from water supply operations. They found that desalinating groundwater with salt content of 15 g/L reduces environmental impacts to nearly half of a seawater-based desalination plant treating water with salt content of 36 g/L. The difference is mainly explained by the electricity consumption in both cases. Similarly, several other cases have used life cycle thinking approaches in decision support before changing the water systems with the aim to obtain a better environmental performance in the utilization of water resources, water treatment technologies, etc. (Rygaard et al. 2014). Another example is an LCA of the Sydney water planning aiming to evaluate several initiatives and to bring down the environmental impacts. The study included several scenarios for changing water supply and wastewater systems and the outcome is a decision support tool for future planning of the complex water system (Lundie et al. 2004).

33.2.4 Tap Versus Bottled Water

Under some circumstances consumers prefer to buy bottled water instead of drinking water from the tap, but what is the environmental perspective on this choice? A comparison of an LCA on centralized drinking water production for Copenhagen, reported in Godskesen et al. (2013) with studies of CO_2-emissions for bottled water in Niccoluci et al. (2010) or Jungbluth (2006) reveals the environmental benefits of centralized drinking water supply in terms of carbon footprint. In the mentioned studies bottled water production emits between 0.14 and 0.18 kg CO_2-eq/L when including water intake, production of the bottle and transport. Water supply based on groundwater as in Copenhagen from source to tap emits

Table 33.1 Climate change impacts from production and distribution of 1L of water from bottled water or centralized drinking water supply (Godskesen et al. 2013)

References	System	Country of study	kg CO_2-eq/L
Jungbluth (2006)	Bottled water in non-returnable bottle	Switzerland	0.18
Niccoluci et al. (2010)	Bottled water in non-returnable bottle	Italy	0.14
Godskesen et al. (2013)	Centralized groundwater based drinking water supply	Denmark	0.00019
Godskesen et al. (2013)	Centralized drinking water supply, desalination of seawater	Denmark, hypothetical	0.0013

740–920 times less kg CO_2-eq/L, and even the hypothetical case of desalinated water in Copenhagen emits 110–140 times less CO_2-eq/L (Table 33.1). Similarly, Botto et al. (2011) found that tap water had ecological and carbon footprints 300 times less than bottled water. This comparison emphasizes that when it comes to carbon footprint, centralized water supply is strongly preferable, especially when the water source is groundwater but also when it is seawater even though desalination processes require much more electricity even in the Copenhagen case for 2013, which is a system relying heavily on fossil fuels.

33.2.5 Case Study of Four Technologies for Drinking Water Supply in Copenhagen, Denmark

Water supply in Denmark is based on groundwater abstracted from well fields located 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 and transported to the waterworks where it is treated by aeration and sand filtration before distribution. The basic structure of Copenhagen's water supply was established more than 150 years ago, and the structure remained largely unchanged until now apart from additional well fields and waterworks.

The European Water Framework Directive (EU-WFD) is implemented in the EU-Member States through River Basin Management Plans which among other parameters regulate the water flow requirements for rivers and streams and the utilizable amount of water in each freshwater (ground- and surface water) compartment (European Commission 2012). The implementation has revealed that groundwater is not an abundant resource when the requirements to the quality of the freshwater environment have to be met as stipulated in the EU-WFD, and the water utility in Copenhagen has been forced to seek new water resources or new approaches to sustain the water withdrawal permissions in order to supply the city

with sufficient water for urban purposes. One could say that the Copenhagen water scarcity is more political than physically founded when compared to other more water stressed areas in the Mediterranean, region, Northern Africa, or India where freshwater resources are far more scarce and often overexploited (Smakhtin et al. 2004; Gleeson et al. 2012) putting pressure on water supplies to shift to other water sources than freshwater. As an example the water service providers in Melbourne built a desalination plant due to a severe drought and an increase in the number of inhabitants. The building of the desalination plant was finalized in 2012. In a case study for the Copenhagen region, we identified four relevant options for water supply which fulfil the EU-WFD and which can either alone or as a mix constitute the future water supply. We performed an environmental evaluation using LCA on the four options since environmental performance is a well-established criterion and should per se be included in any optimization of future supply options in search for the optimal water supply solution.

In this case study system boundaries need to be placed so the LCA also includes effects of changed water quality in the households which is relevant when evaluating water systems delivering water of different water hardness (Godskesen et al. 2012). Also, some of the proposed alternatives are located in areas with combined sewers which means that rain and wastewater are transported in the same sewer system. Therefore, system boundaries should reflect this difference among the alternatives. Finally, the impacts of the water supply system on freshwater resources can be very important in relation to water supply and a method for this was further developed with local specificity for the Copenhagen region (Godskesen et al. 2013).

33.2.5.1 Cases

The four cases were: A1 rain- and stormwater harvesting, A2 compensating actions, A3 new well fields and A4 desalination. The existing system was also included as the base case A0, enabling us to compare the environmental impacts of the four alternatives with today's water production. We defined the functional unit as: Replacing 1 m^3 of potable drinking water as of today in a way that fulfils the EU-WFD's water flow requirements. Schematic diagrams of the options and their location in relation to the urban area are shown in Fig. 33.4.

The LCA was performed according to the ISO 14044 standard procedure (ISO 2006) also including a weighting step. The systems were modelled with the GaBi 4.4 software delivered by PE International and environmental impacts were assessed using EDIP 1997 (Wenzel et al. 1997).

A0 Base Case

In 2009 the city of Copenhagen (population of 0.52 million) used a total volume of 29.8 million m^3 drinking water. The water was abstracted from groundwater

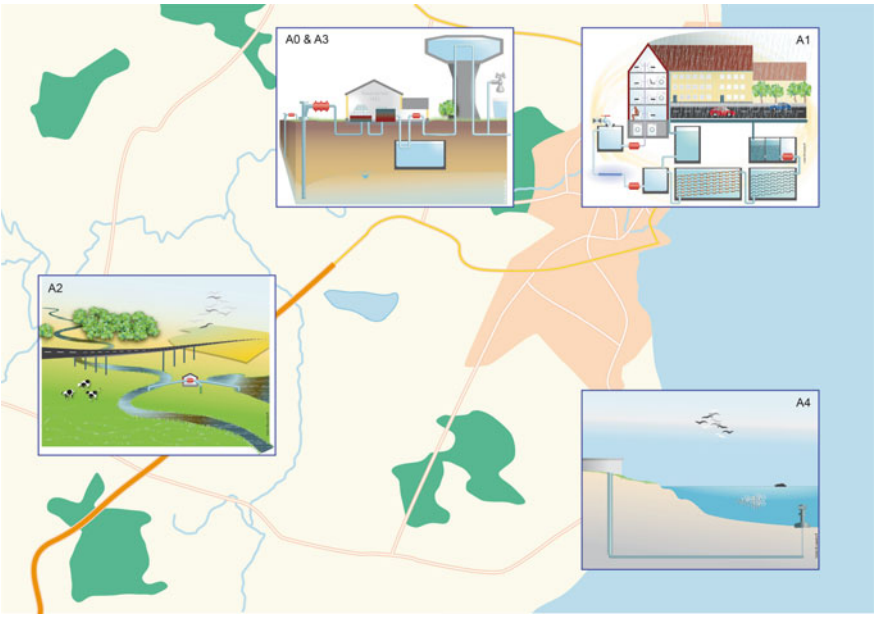

Fig. 33.4 The four options included in the case study: *A0* base case relying on groundwater abstraction; *A1* rain- and stormwater harvesting from several blocks; *A2* compensating actions consisting of water transfer in the affected catchment areas; *A3* establishing well fields 20 km further away from the waterworks; *A4* desalination of seawater from Øresund. The background is a hypothetical map but it emphasizes where the alternatives are located in relation to the urban area (*dark orange*) (Godskesen et al. 2013)

sources located outside the city, requiring only simple treatment at the waterworks in terms of aeration and sand filtration before distribution. During aeration CH_4 and H_2S are emitted and these emissions are also included in the LCA. The water abstraction, treatment and distribution consume only 0.27 kWh per m^3 drinking water. Since the groundwater originates from chalk aquifers the hardness of the water is 362 mg/L as $CaCO_3$ and it is categorized as very hard drinking water (USGS 2012). Primary data from the Copenhagen water supply on use of materials and auxiliaries for water supply was used in the assessments. After use drinking water is considered as wastewater and is transported via combined sewers to the wastewater treatment plants where it is treated before discharged to the Sea (Øresund). Electricity consumption for wastewater transportation is based on average consumption in the period 2007–2009 and modelling of the processes at wastewater treatment plants is based on registered data for consumptions from 2005 to 2009 (Danva 2010).

A1 Rain- and Stormwater Harvesting

In the A1 case rain- and stormwater is considered harvested from an urban area of 68,500 m^2 (roof area 20,200 m^2; main road area 8500 m^2) populated by 1000 residents and 200 employees. The water is of non-potable quality and is used for flushing toilets and washing clothes. The case is hypothetical as it does not exist but was designed and dimensioned as a potential option (Petersen 2011). Rainwater is collected from the roofs of residential and office buildings and led to an underground basin (750 m^3). Stormwater from main roads is collected in large pipes (Ø1000 mm) and led to a basin established in connection with a clarifier and pumping station controlling the flow. The clarifier separates oils from the water before it passes through a dual porosity filter. In the dual filtration, stormwater floats by gravity over a layer of $CaCO_3$ particles where suspended solids, heavy metals and PAHs are adsorbed and thereby removed (Jensen 2009). Afterwards the treated stormwater is mixed with rainwater and stored in a basin. Prior to distribution back to the buildings the water is UV-treated.

A2 Compensating Actions

Compensating actions included transfer of water from lakes and groundwater compartments with surplus of groundwater to water courses where the water flow is reduced due to the water utility's groundwater abstraction. Also included was reestablishment of wetlands from agricultural land. Besides these compensating actions A2 included all processes in the base case (A0).

A3 New Well Fields

Assuming that it would be possible for the water utility to find well fields with a surplus of available groundwater according to the EU-WFD within an additional distance of 20 km, the new well fields case (A3) is equivalent to the base case A0 but with addition of a 20 km longer pipeline from well fields to the waterworks. In comparison, in A0, water is transported 5 km. The longer distance means increased electricity consumption for pumping of abstracted groundwater.

A4 Desalination

Copenhagen is situated at the entrance to the Baltic Sea (Øresund) with brackish water, and desalination of seawater is thus an option. The treatment plant is considered to be located 5 km south of the city. First, water is filtrated mechanically (150 μm) to remove large particles, a coagulant is added and pH adjusted and the water is ultra-filtrated whereby 10% of the water is lost and returned to Øresund

after separation of dry matter. Anti-scaling chemicals are added before the water passes through a two-step reverse osmosis membrane. Finally, calcium hydroxide is added and the water UV treated. The water has a hardness of 108 mg/L as $CaCO_3$ when distributed as drinking water.

33.2.5.2 Methodological Challenges

This case study gives examples where system boundaries must be defined with great care to make the comparisons based on the results from the LCA trustworthy.

33.2.5.3 Water Hardness

Although, central softening at waterworks uses energy and chemicals, the case study showed that these negative effects are more than compensated for by positive effects of reduced water hardness encountered in the households (Fig. 33.5).

The negative environmental effects in the study originate from the softening processes of chemical precipitation of $CaCO_3$ in a pellet reactor at the waterworks. The positive effects located in the households are, e.g. prolonged service life of household equipment like washing machine, dishwasher, coffee maker and kettle; and reduced consumption of energy, cleaning agents, laundry detergent, soap and shampoo. Thus, from an environmental viewpoint it is preferable to reduce the water hardness at the waterworks of very hard water supplies. Decentralized softening of water was not included in our study. The study emphasizes the importance of including effects of changed water hardness in the LCA scoping, when the choice of water supply technologies produces different hardness and therefore causes effects of importance for the overall environmental assessment.

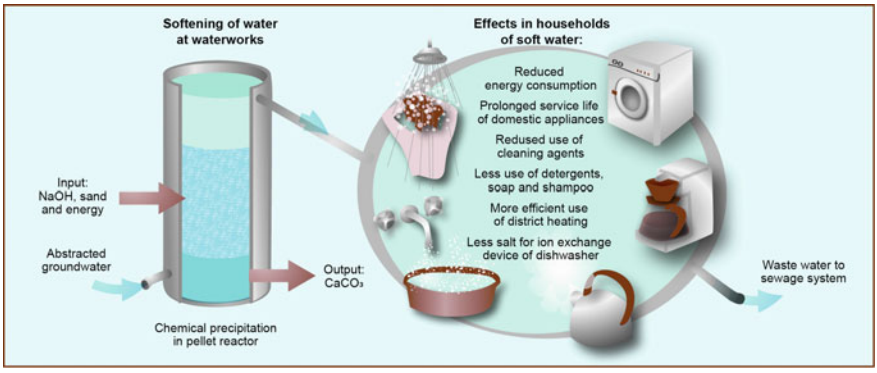

Fig. 33.5 Processes occurring at waterworks and in the households when central softening of drinking water is introduced (Godskesen et al. 2012)

In the case study of alternative technologies for water supply the cases A1 (rain- and stormwater based supply) and A4 (desalinated seawater) deliver water of a lower hardness (171 and 108 mg/L as $CaCO_3$ respectively) compared to the drinking water in the base case (A0) (362 mg/L as $CaCO_3$). For desalination of seawater (A4) consideration of the beneficial effects of the lower water hardness reduces the environmental impacts by approximately 40% while the rain- and stormwater case (A1) shows a reduction of environmental impacts by 35%—results not shown here but can be found in Godskesen et al. (2013). However, desalination (A4) is still the technology with the highest impact though not as severe when the effects of reduced hardness are included (Table 33.2).

Table 33.2 Normalized impact scores per 1 m^3 water delivered by the four options to replace 1 m^3 of potable water, grouped after Environmental impacts, Toxicity impacts and Resource consumption (Godskesen et al. 2013)

	A0 Base case	A1 Rain- and storm-water	A2 Compensating actions	A3 New well fields	A4 Desalination
Environmental impacts, µPET (person equivalent targeted, weighted result)					
Total environmental imp.	124	82	124	138	205
Global warming	82.5	65.5	82.8	91.9	151.4
Acidification	24.6	10.3	24.7	27.5	36.3
Nutrient enrichment	14.5	7.6	14.5	16.2	23.6
Photochem. ozone form	1.9	−1.5	1.9	2.2	−6.5
Toxicity impacts, µPET (person equivalent targeted, weighted result)					
Total toxicity imp.	176	126	180	194	181
Ecotoxicity water chronic	63.7	24.9	64.8	70.1	85.7
Human toxicity soil	69.9	69.8	70.3	78.7	58.8
Human toxicity water	42.4	31.0	45.2	44.9	36.1
Resource consumption, µPR (person reserve)					
Chromium	17.3	−34.1	17.4	17.3	−38.3
Copper	0.05	−3.0	0.057	0.063	−5.3
Hard coal	2.6	1.2	2.6	2.9	5.1
Natural gas	1.7	1.1	1.7	1.9	2.4

33.2.5.4 Combined Sewers

When conducting the LCA of the case study it was found that the combined sewers in the city which transport the discharge (rain and wastewater) to the wastewater treatment plants where it is treated also have an effect on the system boundaries.

The decoupling of the rain- and stormwater from the sewer system is a significant environmental advantage of A1 as electricity consumption for transport and treatment of sewage water is reduced. Therefore, the system boundaries had to be defined so that this difference is taken into account. Hence, this work (Table 33.2) shows that rain- and stormwater harvesting in areas with combined sewers is environmentally beneficial while other authors have found that rainwater harvesting in areas with separate sewer systems (rain and wastewater is handled in separate sewer systems) has a higher environmental impact than, e.g. import of freshwater (Crettaz et al. 1999).

When the modelled system is expanded to include the wastewater system, the strongest environmental impacts originate from wastewater treatment mainly due to the high electricity consumption for treating wastewater (Godskesen et al. 2011; Lundie et al. 2004). Therefore, we found that it is important to include the wastewater system when collecting rain- and stormwater in areas with combined sewers.

33.2.5.5 Results of the Case Study of Alternative Technologies for Water Supply

The results for the alternatives differ markedly for the different impact categories (Table 33.2) and show that the rain- and stormwater harvesting option (A1) has the lowest total aggregated environmental impact (82 μPET/m^3). The cases relying on groundwater abstraction (A0, A2 and A3) have environmental impacts of 124–138 μPET/m^3. A1 has a low environmental impact mainly due to the role of combined sewers and the positive effects of reduced water hardness in the households. Desalination has the highest total environmental impact score (205 μPET/m^3), primarily due to the high electricity demand of this technology.

The environmental impact category with the highest importance is global warming potential (Table 33.2). The contribution from water treatment is higher for A4 compared to the others (Fig. 33.6). The alternatives relying on groundwater abstraction (A0, A2, A3) show very similar patterns with little contribution from water production and more than 50% from wastewater transport and treatment in the global warming impact category and total environmental impact. If wastewater treatment had not been included, these three options would have had the lowest impact, but then they would not have been comparable since the rain- and stormwater harvesting reduces the amount of wastewater to be treated. This emphasizes the importance of a thorough assessment of proper system boundaries (in this case by including the combined sewers and wastewater treatment processes), functional unit, etc. in the preparation of an LCA (ISO 2006).

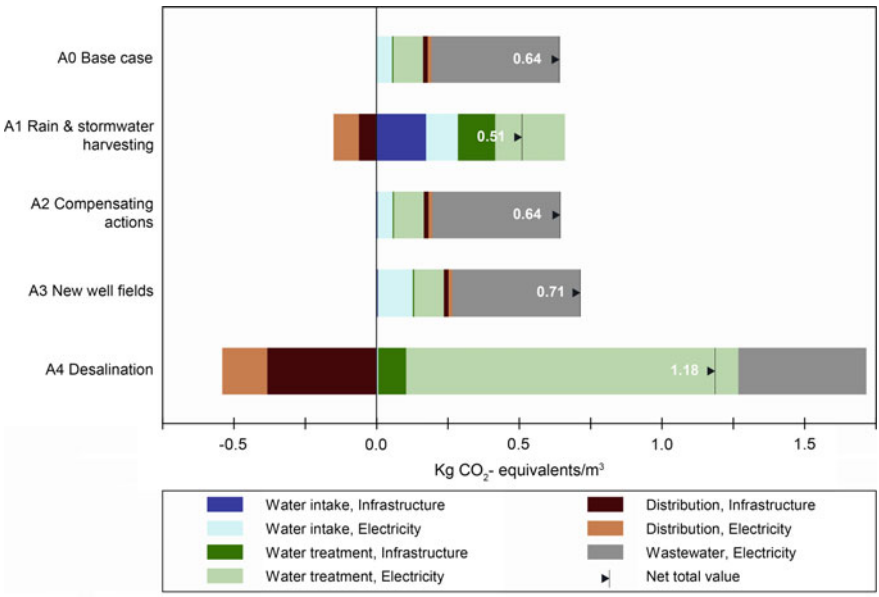

Fig. 33.6 Distribution over the life cycle of contributions to global warming potential for the base case and the four alternative options for water supply (Godskesen et al. 2013)

In conclusion, the LCA showed that the rain- and stormwater harvesting scenario (A1) has the lowest environmental impact (82 μPET/m^3) followed by the options relying on groundwater abstraction (124–138 μPET/m^3), and that A4 Desalination (205 μPET/m^3) has a noteworthy increase in total environmental impacts. If the rain- and stormwater is not harvested it is led to combined sewers in the city which makes it environmentally beneficial to prevent it from discharging into the sewers, e.g. by harvesting and recycling for non-potable purposes. Figure 33.6 shows by the reduction in environmental impacts (negative numbers which reduce the environmental impacts of A1 and A4) that it is essential to include the beneficial effects of reduced water hardness in households when comparing the environmental impacts of water supply cases leading to water of different hardness.

33.3 Specific Methodological Issues for the Application of LCA to Water Supply

33.3.1 General

Following the ISO standard 14044 (ISO 2006) most LCA studies report objectives as part of the goal and scope description, as well as functional unit and system boundaries definitions. However, a widely accepted standard of a uniform set of

indicators to describe the water supply system under study is still missing. Each study therefore describes the studied system in a different way, in many cases missing important descriptors. As a minimum, it is recommended to include the following descriptors:

- Analysed region population and its area
- Total length of pipes
- Distances between abstraction and production, and average distance between production and consumers
- Average difference in height from production to consumers
- Water losses
- Energy mix of electricity
- Details of the water sources and their respective share of contribution
- Production technologies in place, their capacity, and actual supply
- Product water quality

33.3.2 Goal and Scope

Published case studies of LCA of water supply indicate that the goal is often to compare different technologies for water supply in order to identify the most environmentally sound technology for water production or water supply system (Lundie et al. 2004; Lassaux et al. 2007; Klaversma et al. 2013; Godskesen et al. 2013; Stokes and Horvath 2006; Lyons et al. 2009). The goal may also be to identify hot spots in the system allowing for optimizing the environmental performance.

Studies use different functional units (FU). The most common is one m^3 of water produced at the period of time for which the analysis is valid, at the user or at the end of the process. For example, the most common FU for the entire water supply systems is one m^3 of potable water at the consumer tap. Another example of the definition of a FU would be the annual consumption of water at the end user.

When infrastructure is the focus of the LCA FUs may take another form. For example, a study on reverse osmosis membranes used one membrane module as FU (Lawler et al. 2015) and a study on pipes used a metre of pipe network (Herz and Lipkow 2002; Sanjuan-Delmás et al. 2014). Such definitions may serve adequately the specific systems, in which they were used, but they are not applicable for comparison between systems or case studies, in which case the specific FU should be linked to the commonly used FUs.

Quality of source and product water can vary substantially and should therefore be reported. Owens (2001) proposed water quantity and quality indicators to make LCAs compatible with environmental management and reporting systems.

When carrying out the case study of water technologies for Copenhagen it was found that the service life of different components in the system differ and therefore it is important to carefully go through each component and gather data or

best available estimates on the expected service lives. This applies to components such as pumps, different types of pipes (polyethylene, polypropylene, concrete, cast iron, etc.), materials used in building of waterworks (bricks, concrete, steel), etc.

33.3.3 Inventory and Product System Modelling

The system boundaries of studies of water supply systems vary by the life cycle stages included in each analysis: infrastructure construction, operation, maintenance and demolition. Studies also vary in the included activities: material production, material transportation, equipment use and energy production (Meron et al. 2016).

Some studies of recycling systems include raw wastewater treatment (e.g. Tangsubkul et al. 2005; Pasqualino et al. 2011 Lyons et al. 2009; Li et al. 2016) while some studies start only with the secondary effluent entering tertiary treatment (Muñoz et al. 2009; Meneses et al. 2010; Stokes and Horvath 2006). A few studies do not report LCA results of water supply systems and the wastewater collection and treatment separately, due to availability of aggregated data only. For example, the study of Aveiro (2008) in Portugal (Lemos et al. 2013), and of the city of Atlanta (2005–2009) in the USA (Jeong et al. 2015) report the distribution of water and collection of wastewater together because electricity monitoring could not be separated. Having a more detailed monitoring system of electricity consumption as well as other operational data can be an important recommendation to water systems managers, which enable more accurate LCAs in the future.

A review of studies analysing rainwater harvesting tanks showed considerable difference between ex-ante theoretical calculations and measured data from established systems. Where the theoretical calculation had a median electricity consumption of 0.2 kWh/m^3, the median measured data was 1.4 kWh/m^3 (Vieira et al. 2014). This shows the importance of establishing better data inventories based on actual measured data rather than generic estimations. Therefore, it is recommended to collect actual data from the water supply system for the LCA modelling. If data is unavailable literature values and estimates may be used. Upstream and downstream background data is usually available in the LCI databases such as GaBi, Ecoinvent, etc.

In the case study of water technologies for supplying the city of Copenhagen the system boundaries where placed to reflect equal effects of the water hardness of the drinking water. This had a significant effect on the results of the LCA especially in the global warming potential impact category. The case study shows that system boundaries must be defined so the alternatives compared in the LCA are equal also when it comes to product water quality.

33.3.4 Impact Assessment

Various LCIA methods were used in different studies, including CML 2000 (e.g. Barjoveanu et al. 2014), CML 2001 (e.g. Li et al. 2016), and CML-IA (e.g. Muñoz and Fernández-Alba 2008; Meneses et al. 2010; Amores et al. 2013), ReCiPe (e.g. de Haas et al. 2011; Jeong et al. 2015; Slagstad and Brattebø 2014), Eco-indicator 95 (Mohapatra et al. 2002), Eco-indicator 99 (e.g. Uche et al. 2013), IPCC GWP 2007a (e.g. Uche et al. 2013), IMPACT 2002+ (e.g. Bonton et al. 2012), USES-LCA (e.g. Muñoz et al. 2009; Tarantini and Ferri 2001), USEtox (e.g. Li et al. 2016) or EPD 2013 (e.g. Del Borghi et al. 2013). Most papers use a variety of units to present the impacts, whereas some papers transform the results to a single unit such as "eco-point" (e.g. Raluy et al. 2005a; El-Sayed et al. 2010; Uche et al. 2013) and EDIP's "person equivalent" (Godskesen et al. 2011).

Several studies have pointed out the uncertainties resulting from using early stage impact models (Jeong et al. 2015; Lane et al. 2015; Zhou et al. 2011). A comprehensive LCIA harmonization for GWP-100 showed that the maximum difference between GWP scores obtained with different LCIA methods is 7%, while in some impact categories, such as human toxicity and marine ecotoxicity, variability between different LCIA methods is very high and scores are incomparable (Meron et al. 2016). Selection of impact models is important and future research is required in order to generate an agreed set of models.

Impact categories to describe water depletion have been the subject of many studies. Many have expressed the volume of freshwater withdrawn for water supply, (Sharma et al. 2009; Lundie et al. 2004; Lane et al. 2015; Jeong et al. 2015; Li et al. 2016) e.g. by water foot-printing (Hoekstra et al. 2011) where water is considered a resource for man rather than an environmental media with environmental impacts when withdrawn. More recent methods have been suggested to integrate freshwater use into the LCA methodology by treating freshwater consumption as an environmental impact category with an impact on the freshwater environment (Núñez et al. 2016) and human health (Boulay et al. 2015b). The relative Available WAter REmaining (AWaRe) indicator was developed by the Water Use in LCA (WULCA) working group of the UNEP-SETAC Life Cycle Initiative as a (proxy-) midpoint indicator to assess the environmental performance regarding freshwater consumption (Boulay et al. 2015a). The indicator aims to represent the potential of water deprivation, to humans or ecosystems, based on the assumption that the less water remaining available per area, the more likely another user will be deprived (Boulay et al. accepted). Further details on water consumption LCIA can be found in Sect. 10.15.

Reporting impacts of water supply systems in the water use category is important because water supply systems are the major source of direct impacts in this category and without it any impact assessment of products that use water will be incomplete.

To compare the significance of various impact categories of water supply systems, a normalization analysis of 10 supply system models and 15 production

systems has been carried out using ReCiPe (H) V1.12/World (Meron et al. 2016). The highest value is associated with marine ecotoxicity, with consistently highest values in nine of the ten models of water supply systems. Normalized values of freshwater ecotoxicity, freshwater eutrophication, fossil depletion, human toxicity, and GWP follow. Other impact categories have considerably lower scores.

33.3.5 Interpretation

It is recommended to include a sensitivity and uncertainty analysis. In the study of drinking water technology for Copenhagen a sensitivity analysis on the future prediction of the Danish electricity mix for the years 2020 and 2050 evaluated the changes in the global warming potential impact category and showed that global warming potential values will decrease and other impact categories will be higher compared to the others (Godskesen et al. 2013). Similarly to the electricity mix, the scarcity of freshwater resources will change in the future due to population increase (demand) and climate change (local availability) as demonstrated for Spain by Núñez et al. (2015), which may be of significance for studies with longer time horizons. Therefore, a sensitivity and uncertainty analysis may change the outcome of the results and also affect the interpretation of the LCA.

33.4 Concluding Remarks and Outlook

LCAs of water supply systems are of growing importance as an increasing number of regions in the world rely less on nature (rain) and shift to more treatment intensive water resources, e.g. desalination of sea or brackish water. It has been shown that the differences among water supply systems result in significant variation in environmental impacts. However, site-specific LCAs of regional supply systems have been carried out only in a limited number of regions, mostly in Europe.

Studies of systems in water-stressed regions are therefore needed. In particular, it is important to carry out studies of supply systems in regions where desalination is heavily used. LCAs of water supply systems in rapidly developing countries (e.g. India, Brazil, Indonesia, Turkey) are also needed as the impacts of their water supply systems may be significantly different from the impacts identified in available studies.

Using standard LCI databases is a common practice although impacts of water supply systems can vary significantly (Meron et al. 2016). In the assessment of products that consume large amounts of water, using datasets from other regions may result in misleading conclusions. Relying on correct selection from available studies can serve as a basis for receiving more accurate results than straightforward use of standard datasets.

Our case study and the work of others show that LCA is useful for assessing the environmental impacts of water supply technologies and it provides a platform for integrating environmental considerations in the decision-making process and planning of future water systems. When conducting LCA of water supply it is important that:

- the system boundaries are defined carefully so that compared alternatives are fully comparable, e.g. shares the same product water quality
- a typical functional unit could be the annual consumption or supply of one m^3 of water at the end user
- a hot spot analysis is performed to better understand where and what processes in the water supply system contribute most to the environmental impacts;
- impacts of freshwater use are considered. This is especially relevant to include when working with water supply systems because of the intrinsically large use of water
- an uncertainty and sensitivity analysis is carried out that accounts for data availability, estimations versus measured data and also considers the future predictions of electricity mix and water scarcity.

LCA can also be used for integrating environmental aspects in the decision-making process within other areas of water systems. In Copenhagen the water utility is using LCA to reach better overall environmental performance of the water utility through:

- Evaluation of alternative options for supplying a new neighbourhood under development in Copenhagen with non-potable water
- Evaluation of stormwater management solutions
- Water supply strategy development, e.g. the choice of establishing new well fields and waterworks within the city limits or extending the water import from well fields and waterworks located 30–50 km outside the city.

LCA is not only relevant for the analysis of future urban water management. As for most other production activities, water utilities are also met with requirements or intentions to declare environmental impacts, carbon and water footprint, green accounting, etc. Therefore, it is in the water utility's interest to evaluate their production and transport of water, as well as handling of wastewater to provide transparent efficiency measures, decision support for daily operations that thoroughly covers environmental aspects.

To reach a full sustainability assessment, LCA can be combined with an economic and social evaluation, such as multi-criteria decision analysis (Sombekke et al. 1997; Lundie et al. 2006; Lai et al. 2008; Godskesen 2012). The combination of these criteria completes the three-dimensional sustainability approach as suggested by the first political definitions of sustainability (WCED 1987; UNEP 1992).

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