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Desalinated water in urban water supplies – a systems approach to identify optimal drinking water composition

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Technical University of Denmark DTU

Desalinated water in urban water supplies

- a systems approach to identify optimal drinking water composition

Martin Rygaard

DTU Environment
Department of Environmental Engineering

PhD Thesis
June 2010

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Preface

This thesis presents the outcome of a PhD project carried out at Department of Environmental Engineering, Technical University of Denmark. The project was supervised by Associate Professor Philip J. Binning and Professor Erik Arvin.

The thesis is based on five scientific journal papers and excerpts from a book:

I. P. J. Binning, M. B. Hauger, M. Rygaard, A. M. Eilersen, and H.-J. Albrechtsen, Rethinking the urban water management of Copenhagen, Water Practice and Technology, 1 (2006).

II. M. Rygaard, H.-J. Albrechtsen, and P. J. Binning, Alternative water management and self-sufficient water supplies, IWA Publishing, London, UK, 2009. (Book excerpts)

III. M. Rygaard, H. J. Albrechtsen, and P. J. Binning, Increasing urban water self-sufficiency: New era, new challenges (submitted).

IV. M. Rygaard, E. Arvin, and P. J. Binning, Indirect economic impacts in water supplies augmented with desalinated water, Water Science and Technology (in press).

V. M. Rygaard, E. Arvin, and P. J. Binning, The valuation of water quality: Effects of mixing different drinking water qualities, Water Research, 43 (2009) 1207-1218.

VI. M. Rygaard, E. Arvin, A. Bath, and P. J. Binning, Designing water supplies: optimizing drinking water composition for maximum economic benefit (submitted).

In the thesis these texts are cited as Rygaard et al. (II). The texts are not included in this www-version, but can be obtained from the DTU Environment library: Library, Department of Environmental Engineering, Technical University of Denmark, Miljoevej, Building 113, DK-2000 Kgs. Lyngby, Denmark, (library@env.dtu.dk).

April 2010, Martin Rygaard

Acknowledgements

I would like to thank my supervisors Philip and Erik for the efforts they have put into this work. Erik came up with the original idea to look at indirect impacts from changes to water supplies and continued to provide great ideas up to the very last minute. Philip kept the focus and path clear for me whenever it was needed. If my work has any long lasting quality, I owe it very much to them. Special thanks to Hans-Jørgen Albrechtsen from DTU Environment for his collaboration and support on the project on the future of the water supply of Copenhagen.

The PhD was conducted with support from a grant from the Technical University of Denmark. Additional support was provided by Københavns Energi who funded project work conducted in parallel to the PhD. Travel funding to Australia for the case study and conference funding was provided by Otto Mønsteds Fond.

I would also like to thank my colleagues at DTU Environment, Københavns Energi, CSIRO Land and Water, and Andrew Bath from Water Corporation who all have contributed greatly to my work.

Martin Rygaard
April 2010

Tak til alle mine bagmænd,
der mander mig op
Især Frida og Signe

Summary

The use of alternative water supply technologies like desalination and wastewater reclamation are growing rapidly all over the world. These treatment techniques make drastic changes to the water chemistry and there is a potential for optimizing and designing drinking water composition. This thesis describes the drivers and implications of using alternative water supply techniques in urban water supplies. A new method for valuing the impacts of changed water quality has been developed. The water quality impacts include effects on health (cardiovascular disease, atopic eczema, dental caries), lifetime of assets (washing machines, dish washers, water heaters and distribution system), laundry detergent consumption, and effects on bottled water sales. The economic impacts are compared with changed production costs, costs of water resource management, costs of remineralization options, and potential costs of mitigating green house gas emissions from water production. Results from two cases from Copenhagen (Denmark) and Perth (Western Australia) show that the benefits of the introduction of desalinated water remineralized with magnesium and fluoride can exceed changes in production costs, costs of remineralizing the water, and costs of mitigating green house gas emissions. Desalinated water without added magnesium and fluoride is predicted to have a negative impact on the societal economy. Based on the results from the two case studies a new set of optimum water quality criteria is proposed.

Dansk resumé

Alternative vandforsyningsteknologier som afsaltning og genanvendelse af spildevand er i hastig vækst over hele verdenen. De nye teknikker giver adgang til nye vandressourcer og medfører også mulighed for store ændringer i det leverede vands kemi. Dette skaber et potentiale for en optimering af sammensætningen af drikkevandet. Denne afhandling beskriver drivkræfterne bag udviklingen af alternative vandforsyningsteknikker og evaluerer effekter af af teknikkernes implementering. Afhandlingen præsenterer ligeledes en ny metode til at værdisætte påvirkninger skabt af en ændret vandkvalitet. Metoden inkluderer påvirkninger af sundhed (hjertekarsygdomme, atopisk eksem og karies), levetid af materialer (vaskemaskiner, opvaskemaskiner, varmevekslere og vandforsyningens distributionsnet), vaskemiddelforbrug og påvirkninger af flaskevandssalg. De økonomiske påvirkninger sammenlignes efterfølgende med ændrede produktionsomkostninger, potentielle omkostninger ved vandressourceforvaltning, omkostningen af remineralisering, og potentielle omkostninger ved afhjælpning af drivhusgasudledinger fra vandproduktionen. To casestudier fra København og Perth (Australien) viser, at indførelse af afsaltet vand remineraliseret med magnesium og fluorid kan medføre økonomiske fordele for samfundet, der er større end de ekstra produktionsudgifter og eventuelle udgifter til afhjælpning af drivhusgasudledning. Omvendt viser resultaterne også, at afsaltet vand uden magnesium og fluorid kan have en negativ påvirkning af samfundsøkonomien. Baseret på de to casestudier foreslås nye retningslinier for en optimal vandkvalitet.

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1 Introduction

A major challenge for water supply managers is to meet demands for good, clean and safe drinking water. Managers have a diverse range of supply options from traditional sources like conventional groundwater and surface water resources, to newer and rapidly developing options such as desalination, water reuse and rainwater harvesting. Modern membrane treatment techniques make otherwise unusable resources available for drinking-water purposes and are rapidly falling in cost. Membrane desalination increases the potential for closing the water loop in cities and increasing water self-sufficiency of urban areas (Rygaard et al. II). However, these new techniques often have relatively high energy costs compared to conventional water treatment (Rygaard et al. III) and can create other challenges by drastically altering water chemistry (Rygaard et al. IV & V). The cost and implications of such changes are significant and so the environmental, social and economic impacts must be assessed.

The main goal of a modern water utility is to supply: "*Good safe drinking water that has the trust of consumers*" (Bonn Charter, International Water Association 2004). To protect current and future generations water supplies must be designed to be sustainable from an economical, environmental and social perspective. Some of the key principles in the Bonn Charter are relevant for this thesis. Drinking water management should: consider the *whole water cycle*, including *water and land interactions*; consider the *risks at all points* in the system; disseminate information and knowledge in *open, transparent and honest* ways; and ensure that supplied water is *safe, reliable and aesthetically acceptable*.

These principles are reflected in the system analysis approach used in this thesis. Any change in the water supply system will have a broad range of impacts on the quality of the water supplied and hence on consumers. These impacts can be categorized as follows (Figure 1.1):

- *Health and nutrition*. Health is directly affected by chemical micropollutants such as atrazine and arsenic, and microorganisms such as *Legionella.* For good reasons guidelines for drinking water quality specifically address the importance of delivering water that meets specific criteria for these contaminants (World Health Organization 2004). However, drinking water may also posses nutritional value for our health, with the beneficial effect of fluoride on dental caries being the best example (Griffin et al. 2007).

- *Resources and environment*. Ecosystems, drinking water resources, and recreational values are at risk due to over-exploitation of freshwater resources. Drought may directly threaten the reliability of the water supply, and a public and political wish to protect ecosystems limits the amount of water available for withdrawal (European Parliament and Council 2000). Intensive water treatment also affects ecosystems and consumes scarce resources, for example via power generation based on fossil fuels (Sims et al. 2007).

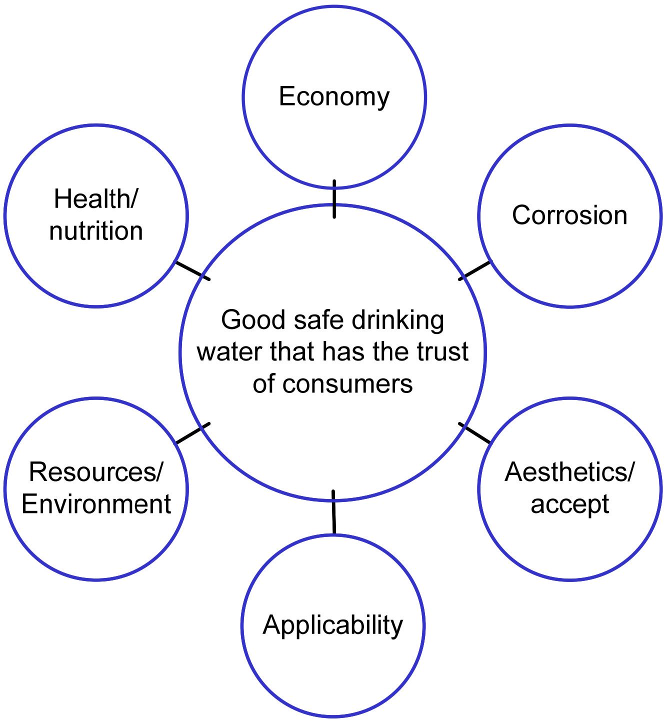

Figure 1.1. Major categories of impacts from changes to urban water supply related to the goal of the International Water Association's Bonn Charter (International Water Association 2004).

- *Applicability*. Applicability considers how suitable water is for different purposes. For example, hard water will leave stains on tableware, glass and increase rigidity of clothing.
- *Aesthetics and acceptability*. Peoples' perception of water is directly related to its taste, its history, and their trust in water authorities (Lou et al. 2007; Syme & Williams 1993).

- *Corrosion*. Although deterioration of water assets, appliances, and pipes is a major problem, corrosion does not get the attention from the water profession justified by the magnitude of the resultant costs (Edwards 2004). For example, saline water may corrode and shorten lifetime of appliances and piping systems (Characklis 2004).
- *Economy*. Utilities may focus on the production costs in evaluations of the economic feasibility of changes in water management (Dore 2005), but little attention is paid to the costs of sub optimal water quality.

To meet the recommendations of the Bonn Charter, integrated assessments of changes to water supply systems should consider all the impacts shown in Figure 1.1.

1.1 Why focus on membrane desalination?

The thesis focuses on membrane (reverse osmosis) desalinated water. Membrane desalination is a particularly interesting example of an alternative water supply option for at least three reasons: 1) The desalination industry has seen a dramatic development and growth over the past few decades, 2) desalination is a relatively intensive treatment technique compared to conventional freshwater treatment, and 3) membrane desalination has a potential to dramatically change the product water quality compared to conventional sources.

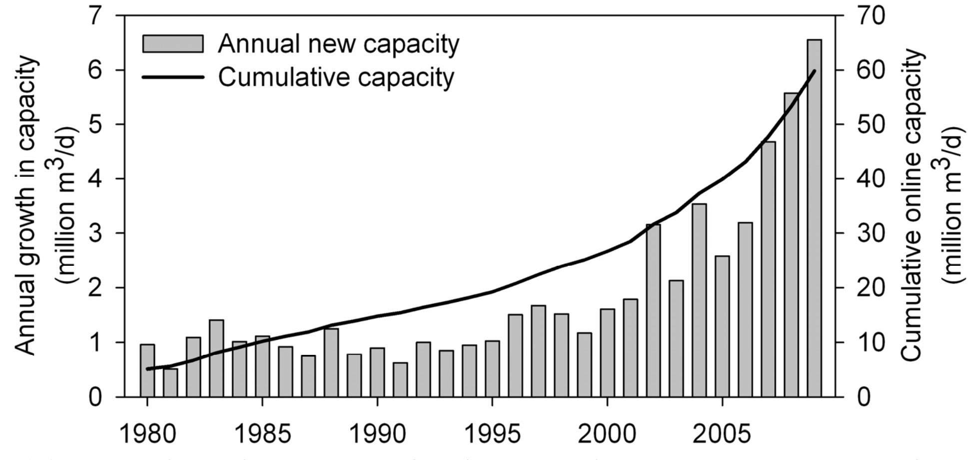

Figure 1.2. World's registered desalination capacity growth and cumulative desalination capacity 1980 to June 2009 (Pankratz 2010).

Over the last few decades desalination has grown from a total capacity installment of 9.8 million m^3/d in 1980-89 to 35 million m^3/d in 2000-2009 (Figure 1.2). By June 2009 the total registered capacity was 63 million m^3/d. For comparison, 520,000 persons in Copenhagen use less than 0.1 million m^3/d. Reverse osmosis treatment is the most widespread desalination technique in Europe (Fritzmann et al. 2007) and large scale reverse osmosis plants are now situated in all parts of the world, including the Middle East, South East Asia, Australia, Europe and North America (Pankratz 2010). The increased use of desalination technologies is due to its increasing efficiency and decreasing costs (Rygaard et al. III; Service 2006). The production of drinking water from typical seawater now requires less than 4 kWh/m^3 and costs have been reported to be as little as US\$0.5/m^3 (Dreizin 2006). Still there is intensive research going on to improve the technology even further. Among the development goals for the industry are to develop reverse osmosis membranes that allow increased water fluxes, increased salt rejection, and also reduce maintenance costs by making the membrane surface resistant to fouling (Service 2006).

Desalination is a treatment intensive process (Figure 1.3). Forcing seawater through a reverse osmosis membrane requires careful pre-treatment, dosing of chemicals, high water pressures, post-treatment and waste disposal. In places where water supply is based on treated fresh water resources, desalination will be a big change in treatment intensity.

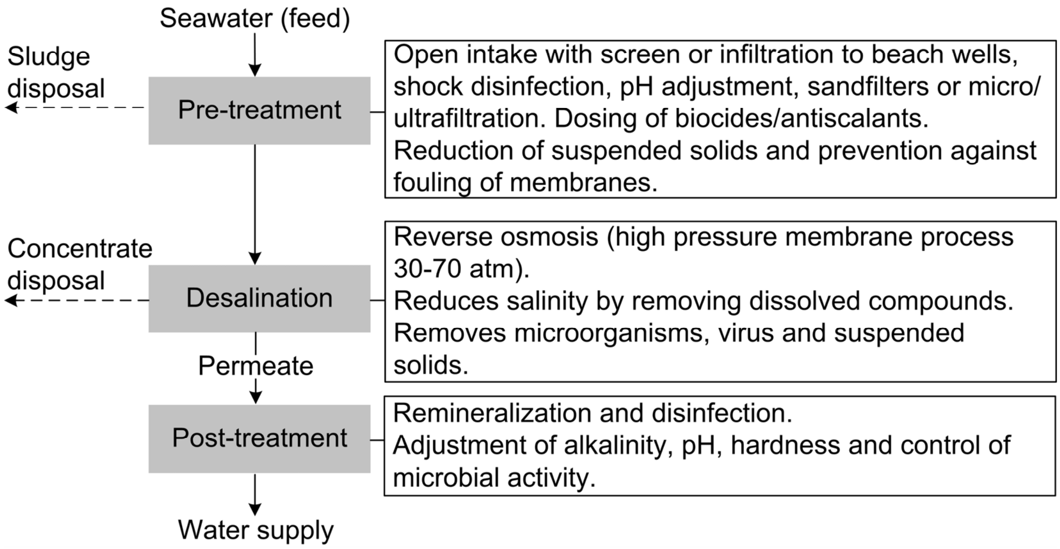

Figure 1.3. Typical reverse osmosis seawater desalination (Fritzmann et al. 2007; see examples in Rygaard et al. II).

Reverse osmosis typically removes the majority of minerals from the water. The permeate stream must therefore be remineralized to be palatable and non-corrove to materials in contact with the water (Delion et al. 2004; Withers 2005). The combination of demineralization and remineralization provides a potential for adjusting and optimizing the supplied drinking water quality.

Although the focus of this work is on membrane desalination, it should be noted that the thesis has a much broader relevance. Water treatment processes that de- or re-mineralize water like reverse osmosis and lime dosing are used widely in the water supply sector. Reverse osmosis is used in Orange County, California to reclaim wastewater (Rygaard et al. II) and nano-filtration is suitable for removal of pesticides and other micropollutants (Berg et al. 1997) and can also be used for softening (Schaep et al. 1998). It has been estimated that 18% of the world's desalination capacity is used for other purposes than treating brackish water and seawater, i.e. treating river water, wastewater, and pure water (Pankratz 2010). Another example is pellet reactors used for softening which change the water composition before distribution in water supply systems (Harms & Robinson 1992) .

Many researchers are seeking methods to optimize these water treatment techniques for efficiency and reliability. Fewer are looking at where we are heading with the significant advancements. This thesis explores the implications of increasing urban water self-sufficiency through various water treatment techniques and concepts. A focus is on the economic impact of changes to the drinking water quality. Membrane desalination for drinking water supply is discussed as an example of a technique used for increasing water self-sufficiency.

1.2 Objective

> *The main objective of this PhD study is to develop new systems analysis techniques for evaluating the consequences of water quality changes in water supply due to the use of alternative water resources, especially membrane desalinated water.*

Three main questions are addressed:

1) What are the drivers and implications of increasing urban water self-sufficiency? Self sufficiency is an important trend in urban water supply where cities aim to reduce dependence on import of water by using alternatives to conventional water supply, such as desalination.

2) What are the environmental, economic and social impacts of distributing different drinking-water qualities? The term "impacts" refers to the positive and negative outcomes of water quality parameters on the environment, health, society, economy etc. The thesis will explicitly address varying mixtures of conventionally treated surface/groundwater and saline water resources desalinated through reverse osmosis treatment. Which factors must be considered in a holistic analysis of a water supply system that is partially based on desalinated water? How is such an assessment prepared?

3) Given knowledge of the impact of changes to water supply, is there an optimum water quality? Is it possible to achieve the optimum by mixing desalinated water with conventional sources?

The assessments and analyses required for question 2 and 3 are illustrated by two case studies considering the design of a Danish and an Australian water supply system.

2 A new era for urban water supply

The first objective of this thesis is to explain the drivers and implications of increased water self-sufficiency in cities. Water self-sufficiency is another term for decreased dependence of external water imports, which is seen as a new era for urban water supplies (Rygaard et al. III). This development is relevant to investigate for two reasons: 1) A large number cities around the world have already decreased their dependence on water imports (Rygaard et al. II). 2) Examples have shown that water self-sufficiency often involves a change from conventional treatment to more advanced water processes and more intensive treatment techniques, for example desalination and wastewater reclamation.

Desalination and wastewater reclamation are often employed to increase urban water supply self-sufficiency. The reasons for this can be illustrated by the analysis of future water scenarios for Copenhagen (Binning et al. I). In that paper a water balance for Copenhagen reveals that four types of water supply are possible for the city if it is to be independent of water import: desalination, wastewater reclamation, rainwater harvesting, and surface/groundwater water. However, available surface and groundwater within the City of Copenhagen can supply less than 10% of the total drinking water demand. Studies have shown for other cities that local rainwater harvesting may supply 8-50% of the current household water demand. Rainwater harvesting is primarily limited by its intermittent nature and required reservoir volume (Pickering et al. 2007; Rygaard et al. III). Independency from water imports is therefore likely to be based on desalination or wastewater reclamation.

Binning et al. (I) developed nine very different scenarios for Copenhagen’s future water supply based on the premise of complete water self-sufficiency. One extreme scenario was the central desalination of seawater to supply the entire city and another scenario proposed closing the water loop within single buildings using high tech localized water reclamation similar to requirements for long space missions (Tansel et al. 2005). Although all nine scenarios would require substantial changes in Copenhagen’s structure, numerous examples of alternative water management are found outside Denmark. Around the world cities have been through significant developments away from reliance upon water imports to a high dependency on local water resources (Rygaard et al. II). For example in Wulpen (Belgium), Berlin (Germany), Orange County (California), and

Windhoek (Namibia) wastewater reclamation contributes to the local drinking water supply. These and other examples are described in Rygaard et al. (II). The examples show that wastewater reuse, desalination and rainwater harvesting are being widely used for water supply as alternatives to conventional freshwater resources. Rygaard et al. (III) focuses on this development and provides a definition of water self-sufficiency, a proposal of categories of drivers behind alternative water supplies, and a discussion of challenges that comes with increased self-sufficiency.

2.1 Water self-sufficiency

One of the best examples of urban water self-sufficiency is from Singapore where the National Water Agency PUB has a goal of making the island self-sufficient with water (Rygaard et al. II). Increasing water self-sufficiency is also related to concepts of localized water management, i.e. management of the drinking water, rainwater and wastewater within local neighborhoods. Localization is considered a crucial component of integrated water management and low impact urban design and contrasts starkly with the conventional strategy of maximum separation of water sources, wastewater, stormwater from the public (van Roon 2007).

The concept of water self-sufficiency lacks a formal definition, however a Local Water Independency Ratio (LWIR) has been proposed as *LWIR = internal water supply/total used water* (Han & Kim 2007). Internal water supply includes any water resource available within the region, including river flows. Here the water self-sufficiency ratio is defined as (Rygaard et al. III):

$$\textit{Water self-sufficiency ratio}\ \text{area}\ i = \frac{\text{Amount of water sourced within area}\ i}{\text{Total water demand in area}\ i} \qquad (1)$$

Here water sourced within an area is limited to water reuse and rainwater sourced within the area and desalinated water from local shores. In other words, the term *water self-sufficiency* is used to describe independence from any imported water resources from neighboring areas. In this definition, river flows from catchments outside of the city do not contribute to water self-sufficiency. For selected cities water self-sufficiency ratios have been found to range between 15 and 81% (Figure 2.1).

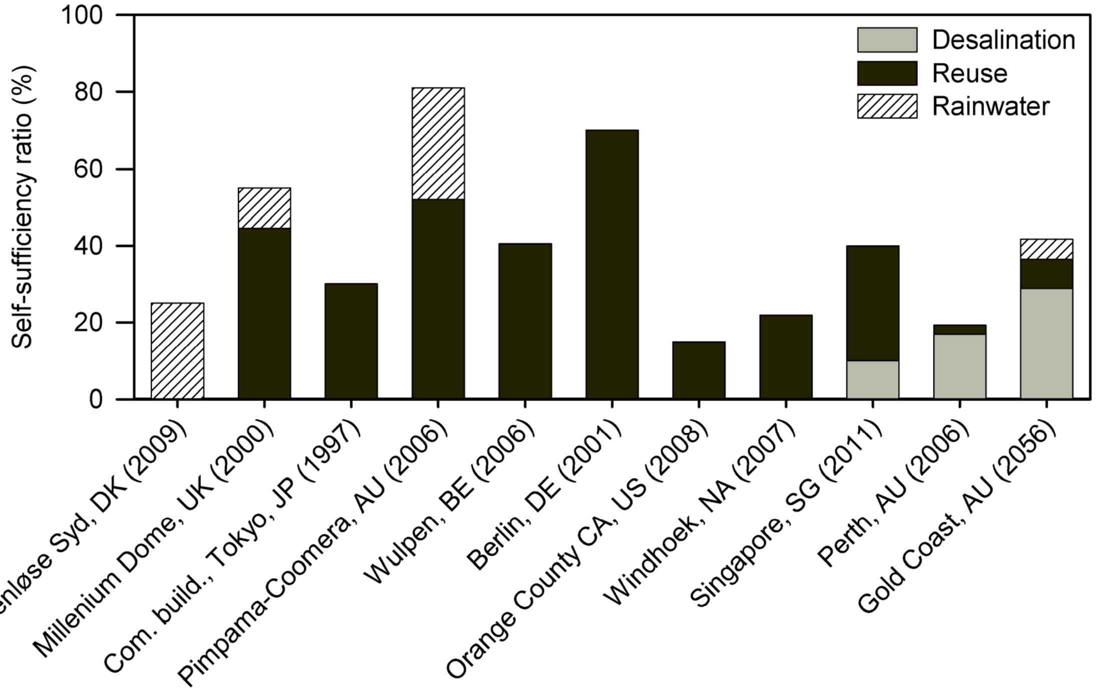

Figure 2.1. Percentages of water sourced from desalination, water reuse and rainwater harvesting in selected cities (Rygaard et al, III). Dates refer to year of planned or reported self-sufficiency ratios.

The question "*what drives urban areas towards water self-sufficiency*?" is addressed in the following.

2.2 Drivers

Alternative water management and increased self-sufficiency is driven by multidisciplinary issues (Table 2.1). Notably, drivers are not limited to the need for more water caused by population growth or droughts. Drivers are also political, infrastructure capacity limitations, and demands from industry. For example, Singapore has a strong political will to make the island independent of water imports from Malaysia (Luan 2010). Major investments in local industry and educational institutions illustate a broad commitment across different sectors of Singapore to reduce waste of all water on the island, including seawater, rainwater, urban stormwater and wastewater. Different institutions and companies are supported by the government with the aim to make Singapore an international hub for water industry and water education (Rygaard et al. II & III). Self-sufficiency in Singapore might have started out as a result of an indirect lack of water (driver 2b, Table 2.1), but since then *the sectoral system* (5, Table 2.1) has become a major driver.

Table 2.1. Driving forces behind water reuse, desalination and rainwater collection in water supply Rygaard et al. (III).

1. ***Direct lack of water*** caused by
    a. Drought (reduced resource availability)
    b. Population growth (increased demand)
2. ***Indirect lack of water*** caused by policy changes:
    a. Increased emphasis on environmental flows (nature restoration)
    b. Wish to be independent of water imports (from surrounding areas/other countries)
3. ***Constrained infrastructure*** limiting capacity for water supply and drainage
4. ***Demand for high quality water*** from industry
5. ***The sectoral system*** governed by commercial, organizational and institutional interactions

The drivers shown in Table 2.1 often lead to a focus on management options such as the efficient use and optimized allocation of water resources (Bouwer 2000). However, drivers 2-5 often cannot be addressed via management options alone and so alternative water management concepts like membrane treatment and desalination are of growing importance to the water sector. It is therefore important to investigate the implications of water self-sufficiency based on these particular treatment techniques.

2.3 Self sufficiency, energy use and public perception

Self sufficiency has two important implications: Energy use and public perceptions, which must be carefully managed if new approaches are to succeed.

A change from conventional sources like groundwater to alternative water management concepts like wastewater reclamation and desalination is likely to increase the energy demand significantly (Figure 2.2). The importance of energy consumption is supported by environmental life-cycle assessments. It has been found that electricity causes more than 90% of the assessed environmental impacts from water production based on desalination of brackish water and seawater (Munoz & Fernandez-Alba 2008; Vince et al. 2008).

It is therefore essential to include changes in energy consumption and possible environmental impacts from power generation in the assessment of water supply alternatives. The issue is included in the assessment of optimum water composition (chapter 4).

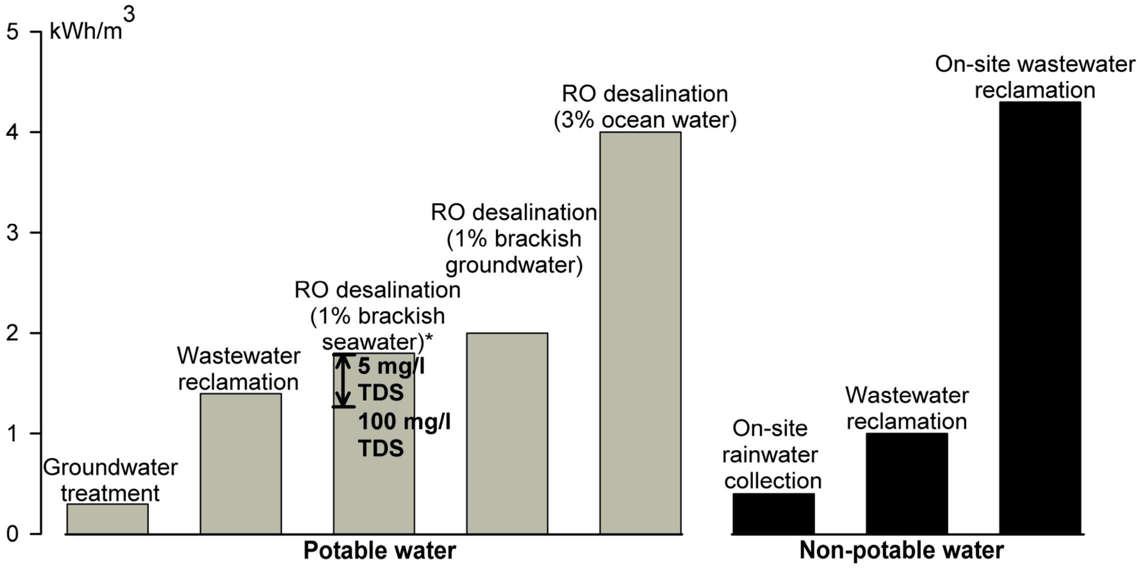

Figure 2.2. Typical energy consumption for various water treatment options. Figure 4 in (Rygaard et al III) modified with energy requirements for desalination in Copenhagen (modelled in IMSDesign (Hydranautics 2008), 1% salinity brackish water from the Baltic Sea). *Energy use depends on product water quality requirements for total dissolved solids, either <100 mg/l or <5 mg/l.

Convincing the public that reclaimed wastewater is safe to drink can be challenging, but in several cases it has been done (Rygaard et al. II & III). The discussion in Rygaard et al. (III) indicates that accept of drinking water with an unclean history is a matter of trust in relevant agencies and the decision making process rather than confidence in technical parameters, such as treatment processes (Russell & Lux 2009; Syme & Williams 1993). The issue of public perception is included in the assessment of optimum water composition for drinking water (chapter 4).

3 Valuing impacts of changed water quality

The second objective of this thesis is to determine the environmental, economic and social impacts of distributing different drinking-water qualities. The list of available impact assessment tools used in water supply system analysis is long, but two tools have received particular attention from the water community: Environmental lifecycle assessment (LCA) (Lundie et al. 2004; Munoz & Fernandez-Alba 2008; Raluy et al. 2005; Tapia et al. 2008; Vince et al. 2008) and cost-benefit analysis (CBA) (Brunson et al. 2005; Characklis 2004; Dreizin 2006; Khan et al. 2008; Van der Bruggen et al. 2009). These references discuss the pros and cons of different water quality and/or treatment techniques. However, it has not been possible to find any study that combines health and corrosion impacts from changed mineral levels in drinking water with other costs and benefits from water production. The thesis addresses this deficiency (Rygaard et al. IV-V).

3.1 Life cycle assessment and cost-benefit analysis

Environmental lifecycle assessment is a widely used tool for analyzing environmental impacts (Hauschild 2005). It is often used for consequential assessments which addresses differences between the environmental impact of scenarios. Consequential life cycle assessment focuses on changes rather than absolute values (Ekvall & Weidema 2004). Although lifecycle assessment employs a strong methodology (Finnveden et al. 2009), it has limitations for use in water supply: 1) The method has a strong focus on emissions to the environment and resource consumption and does not easily incorporate nutritional effects associated with drinking water's mineral content. 2) Until recently the method did not incorporate fresh water abstraction. Even with the recent developments (Pfister et al. 2009), local ecological impacts due to freshwater and seawater abstraction are not included. Lifecycle assessments have not yet considered corrosion or aesthetic impacts.

Cost-benefit analysis (CBA) is another decision support tool and it has a higher degree of flexibility than lifecycle assessment. Cost-benefit analysis was developed for welfare economics and is used to analyze whether social benefits outweigh social costs. Benefits and costs are aggregated across the entire society, which means that winners and losers might not be the same persons (Pearce et al. 2006). It is flexible because any effect that can be assigned a monetary value can be included. Unfortunately this flexibility also introduces a great deal of uncertainty and ambiguity in the interpretation of the results, for example the valuation of ecosystems or human life is very controversial. Cost benefit-analysis have been used to assess economic benefits of water fluoridation (Brunson et al. 2005), desalination of seawater (Dreizin 2006), desalination of brackish water (Characklis 2004; Characklis et al. 2005), and water softening (Van der Bruggen et al. 2009).

3.2 A new valuation tool

With these assessment tools in mind a new method for valuation of changes in water quality is developed. The method borrows the convenient measure of monetary units from cost-benefit analysis and impacts are evaluated as changes from a base scenario, as in consequential lifecycle assessment. The new method is outlined in Rygaard et al. (IV) and further developed in Rygaard et al. (V & VI). A similar approach to impact assessment is found in air pollution research (European Commission 2005; Matus et al. 2008). Impact predictions are based on concentration-response relationships derived from the literature. The relationships are used to estimate the potential change from the current situation, as seen from society's viewpoint.

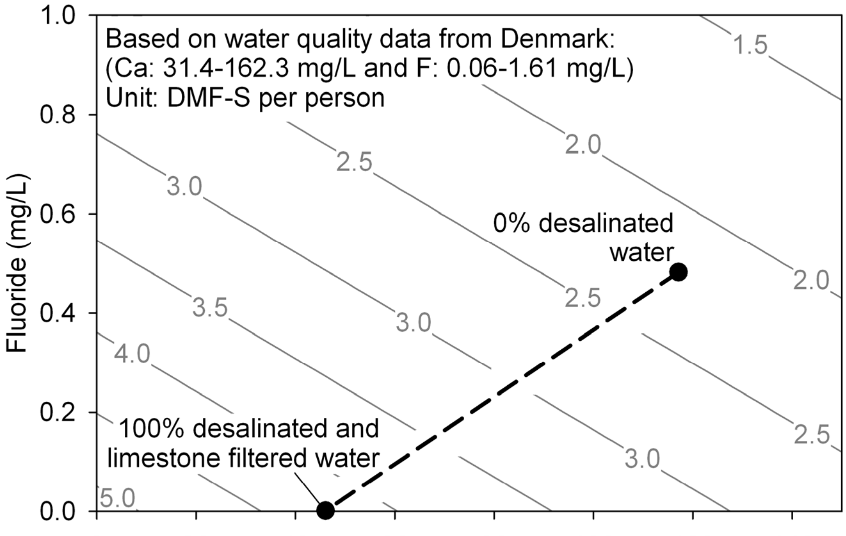

Figure 3.1. Concentration-response relationship for calcium/fluoride and dental caries. Caries is measured in Decayed, Missing, and Filled Surfaces (DMF-S). Dotted line shows predicted DMF-S with groundwater replaced by limestone filtered desalinated water in Copenhagen. Relationship from (Bruvo et al. 2008).

The new method can be illustrated by considering two scenarios for Copenhagen: 1) The current groundwater based water supply, and 2) a future scenario where the entire city relies on 100% desalinated water. A concentration-response relationship for fluoride/calcium versus dental caries is then used to predict current (2.2) and possible future number (4.3) of Decayed, Missing, and Filled Surfaces (DMF-S) per person (Figure 3.1). It is a significant increase of 94%. Given the number of persons affected and the average annual cost of maintaining a filled tooth surface, it is possible to estimate the total annual economic impact from the predicted 94% increase in DMF-S. According to the calculations in Rygaard et al. (VI) the total impact on dental caries due to a change to 100% desalinated water in Copenhagen is a net benefit of €-0.3±0.2 per m^3 delivered water (a negative benefit is a cost). The principle can be used to assess the following additional impacts: atopic eczema, cardiovascular diseases; lifetime of washing machines, dish washers, water heater/heat exchangers, and the distribution system; and laundry detergent consumption. The first concentration-response relationships were derived in Rygaard et al. (IV) and more were added in Rygaard et al. (V). With 50% groundwater replaced by desalinated water in Copenhagen, the impact of water quality changes are found to be between €-0.11±0.06 and €0.15±0.04 per m^3 delivered to Copenhagen (Figure 3.2).

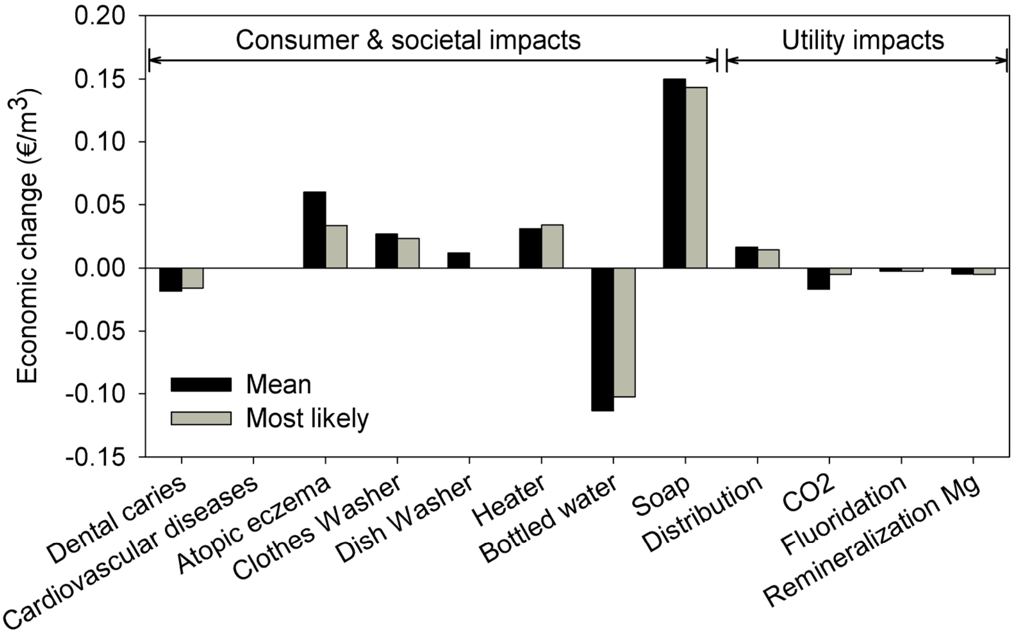

Figure 3.2. The predicted economic impacts when 50% of conventional sources are replaced with desalinated seawater remineralized with fluoride and magnesium. A possible off-set for the cost of CO_2-emissions is also shown. Based on Rygaard et al. (V).

3.3 Estimating uncertainties

Some of the impacts of drinking water quliaty assessed in this thesis are still debated. For example, the protective effect of drinking water magnesium content against cardiovascular disease is considered by WHO (Cotruvo & Bartram 2009), but has recently been both rejected (Morris et al. 2008) and confirmed (Catling et al. 2008). The validity of empirical data collected for appliances in the U.S. (Ragan et al. 2000) for the lifetime of North European and Australian appliances can also be discussed (Rygaard et al. V). Similar uncertainties must be addressed for other parts of the assessment.

These uncertainties are incorporated in the model by the use of a triple estimate method known as the *Successive Principle* (Lichtenberg 2000). This method is outlined in Rygaard et al. (V). In short the method builds on three estimates of the impact: a *most likely value* and *minimum/maximum* estimates. The extreme estimates are interpreted as the impact values that with 99% confidence will not be exceeded. If the confidence interval is skewed around the most likely value, the predicted mean impact is accordingly adjusted (Figure 3.2). The use of this triple estimate technique in water supply management is new and has two important advantages for impact assessment: It allows for subjective expert judgment and adjusts the mean economic impact for any skewness in the evidence underlining the impact assessment.

3.4 Limitations to the valuation of water quality effects

To avoid risk of ambiguity and to maintain transparency only direct cost are included and the assessment does not account for intangible costs, such as *value of a statistical life* or *value of a life year*. Using direct costs ensures transparency of the method, but it has the disadvantage of underestimating the value of health impacts. A recent review found numerous pollution studies where the value of life dominated the economic impact (Pearce et al. 2006). In the valuation of health impacts, direct costs are assessed as a cost of illness. Ideally the cost of illness includes all cost components related to the counseling and treatment of patients. In reality, however, few studies include all possible components and it is difficult to determine a standard cost of illness (Clabaugh & Ward 2008). In this PhD project the cost of illness is based on public sources where the quoted values depend on the original definition of costs used.

Possible feedback mechanisms (Finnveden et al. 2009) are also neglected here. For example, money saved from reduced household expenditure on appliance renewal and detergents can be used on other goods and services, which have their own environmental and economic impacts. Such re-bound effects have been assessed in other studies (Hertwich 2005; Thiesen et al. 2008) but are not included here.

Finally, a number of water quality related impacts have not been included in the assessment. Most of them have been omitted due to lack of data for establishing concentration-response relationships. Some of these omitted impacts are:

- *Temperature and taste preferences*. Customers prefer cold water, but apart from that, the few available taste studies have found ambiguous preferences in relation to mineral content. There seems to be indications that people most prefer the taste of drinking water they are used to (Lou et al. 2007; Nancarrow et al. 2003; Turgeon et al. 2004).
- *Disinfection*. pH, temperature and natural organic matter are known to affect disinfection efficiency (Nikolaou & Lekkas 2001; Sadiq & Rodriguez 2004). Rygaard et al. (VI) conclude that an improvement of disinfection efficiency is likely after the introduction of desalinated water.
- *Other nutrient related diseases*. Recent reviews of nutrients in drinking water consider several conditions that are potentially affected by water quality. The reviews emphasize that drinking water impacts on dental health and cardiovascular disease are emphasized are particularly significant (Cotruvo & Bartram 2009; World Health Organization 2005). But other diseases may also be important, for example, one issue ignored by WHO is the hardness-atopic eczema relation described in Rygaard et al. (IV & V). The method presented in this thesis can be extended to other nutrients and diseases as concentration-response relationships become available.
- *Failure rates and related damages*. The lifetime models of piping system and appliances only account for changed replacement rates. Reducing the amount of total dissolved solids in drinking water is likely to decrease the cost of maintenance, parts replacement, and water damages. Unfortunately, cost-damage data describing this relationship is not available and so it was not included in this assessment.
- *Heat losses and pressure losses*. It has been argued that calcium carbonate scaling causes heat loss in water kettles, water heaters, and other

appliances with heating elements (Merkel 1998; Van der Bruggen et al. 2009). Van Bruggen et al. (2009) found significant energy savings when scaling is reduced. Unfortunately, details of the underlying empirical evidence are not included in the publications. Similarly scaling causes pressure losses in piping systems, but this issue has not been investigated here. It seems is likely that reduced calcium carbonate scaling will lead to reduced heat and pressure losses and will contribute to the overall benefit of desalination.

- *Chemical consumption and wastewater treatment.* A long list of household and industry chemicals are dosed according to hardness, buffering capacity, and alkalinity levels of drinking water. Here only laundry detergent is considered as an indicator of potential changes in chemical consumption. Similarly, the nitrification process in wastewater treatment requires a minimum alkalinity (Henze et al. 2002). The eventual need for alkalinity addition at wastewater treatment plants requires consideration.

When interpreting the results of this thesis and in the further development of the method, it is important to bear in mind these limitations. However, this thesis provides the widest selection of impacts of changed water quality in a single analysis to date. The limitations discussed here can be overcome by incorporating the method in a more conventional cost-benefit analysis and environmental lifecycle assessment.

4 Determining optimal water quality

The final objective of the thesis is to determine whether there is an optimal water quality and determine whether is it possible to achieve the optimum by mixing desalinated water with conventional sources. The demineralization and remineralization options available at desalination plants mean that the effects of changed water quality described in the previous chapter can be controlled, thereby creating a potential for optimizing drinking water quality.

Optimization has a long tradition within water resources management, with the major goal being to allocate water for different uses in a catchment for maximum benefits for humans and ecosystems (Loucks & Beek 2005).

4.1 Optimal water composition: earlier studies

Optimization has been used to find optimal water quality in water water supplies. For example, the mixing of desalinated water and surface water in a groundwater based supply in Tampa Bay (Florida) was the focus of an extensive research program (Taylor et al. 2005). The project aimed to minimize metal release and monochloramine dissipation by controlling water quality. It was found optimal to restrict groundwater to <60% in the final blends due to copper release caused by the high alkalinity (225 mg/l as $CaCO_3$) of the groundwater source. It was also recommended that mixing of approximately equal amounts of surface and desalinated water be avoided because such combinations lead to increased lead and iron release due to high sulfate content in surface water (180 mg/l) and high chloride content in the desalinated water (50 mg/l) (Imran et al. 2006). Notably, the paper did not model options for adjusting the desalination treatment and the optimization was limited to considerations of the pipe infrastructure and did not include health impacts. A similar narrow focus on water quality effects on distribution infrastructure has been repeated in a recent review of research needs within water quality effects (Imran et al. 2009).

Desalination is now becoming the cornerstone of Israeli water management (Tal 2006). Lahav & Birnhack (2007) have developed new quality criteria for desalinated water based primarily on process engineering considerations and considerations of corrosion potentials. Their new criteria also agrees with agricultural requirements (Yermiyahu et al. 2007). The research group argues for remineralization to high alkalinity levels (>100 mg/l as $CaCO_3$) instead of the common criteria of 50 mg/l. Increased alkalinity improves chemical stability in the distribution system (Lahav et al. 2009) and maintains process stability at wastewater treatment plants (Lew et al. 2009). Another new recommendation is to restrict calcium content to 80-120 mg/l as $CaCO_3$, which is a significantly narrower span than stated in international guidelines (Table 4.1) (Birnhack & Lahav 2007). The new Israeli criteria primarily consider corrosion effects and blending options with existing fresh water resources. Health impacts are not included.

A study from Belgium considers the costs and benefits of central softening of drinking water (Van der Bruggen et al. 2009). They found that softening would cause increased operations costs for the water utility (€0.13/m^3) but save the customers €0.65 per delivered m^3 if the water hardness is reduced from 470 to 150 mg/l as $CaCO_3$. This finding clearly indicates that softer water is preferable to hard water. However, the assessment did not consider health effects and focused only on impacts related to water hardness and related production costs.

Characklis (2004) conducted a cost-benefit analysis comparing the extra costs of desalination with the benefits from reduced salinity of water. Salinity reduction was predicted to increase the lifetime of appliances, distribution systems etc. His results showed that the extra costs of desalination are generally beneficial for places in Texas with raw water salinities above 710 mg/l, with results depending on water treatment plant size and other factors. Parts of the empirical evidence forming the basis for Characklis' assessment were up to 30 years old (Tihansky 1974). A newer study (Ragan et al. 2000) provided evidence for a more modest impact per mg/l change in salinity compared to the studies of the 1970's. Ragan et al. argued that the difference was due to improved statistical analysis of lifetime data combined with improved material choice in appliances. Both studies provided evidence that optimal water quality for asset lifetime is achieved by minimization of total dissolved solids content. Impacts on health and the environmental impacts of desalination were not considered.

The studies summarized above show that previous water optimization methods have considered a very narrow set of optimization criteria. A method for assessing the combined impact of health effects, corrosion, and detergent consumption is a new to the field of "optimal water quality". The development of this new method is the main topic of Rygaard et al. (V & VI).

4.2 Method for determining the optimal water quality and application to case studies

The water quality optimization method has two steps (Rygaard et al. VI): 1) Possible water qualities are predicted using modeling software and options for remineralization are considered. 2) The predicted economic impacts from changed water quality are combined with the estimated production costs, remineralization costs, and any other cost relevant for the economic impact assessment.

To assess the optimal water composition two case studies have been analyzed. The case studies demonstrate the new assessment method before implementation of desalination (Copenhagen, Denmark) and after desalination has been introduced (Perth, Australia). For the two cases production costs, costs of water resource replenishment, remineralization costs, and costs of CO_2-mitigation are compared with economic water quality impacts (chapter 3).

In Perth marginal productions costs are available through Water Corporation's analysis of future options for Perth's water supply (Water Corporation 2008). The cost projections for Perth include redistribution of water resources to maintain sustainable abstraction rates. Production costs of desalination in Copenhagen are based on a proposed design of a plant desalinating brackish seawater infiltrated from the Baltic Sea (Rygaard et al. 2009). Since groundwater abstraction around Copenhagen exceed ecologically sustainable rates (Henriksen & Sonnenborg 2003) it is chosen to add a shadow cost of groundwater abstraction. The shadow cost of groundwater abstraction is estimated as the potential cost of using reclaimed wastewater to restore river flows around Copenhagen (Rygaard et al. VI). Costs of remineralization with fluoride and magnesium are projected from experiences in other places.

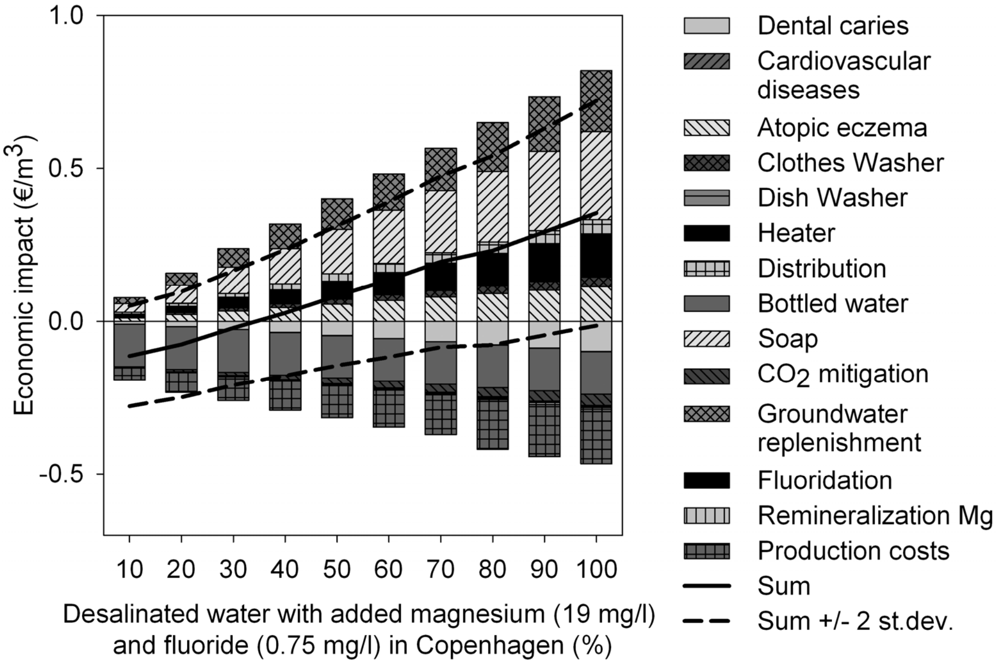

Figure 4.1 Predicted economic impact in Copenhagen with a given amount of desalinated water remineralized with magnesium and fluoride replacing groundwater (Rygaard et al. VI).

An example of the results of the optimization are shown in (Figure 4.1) which shows the economic impact for the Copenhagen case study for various blends of desalinated water and groundwater. The figure shows that replacing more than 30% of Copenhagen's groundwater based supply with desalinated water remineralized with magnesium and fluoride is likely to have an overall positive economic impact for society. The major benefits are reduced soap consumption (up to €0.29±0.08), improved lifetime of distribution system and domestic appliances (€0.22±0.06), and saved groundwater replenishment (€0.20±0.08). These benefits are partly off-set by increased production costs (€-0.18±0.08). Notably, remineralization with fluoride and magnesium, and CO_2-off-set represent a minor economic impact (up to €-0.05±0.03) compared to the other impacts. The modest impact from the energy consumption is reflected both in production costs and CO_2-off-set costs. Although water production electricity consumption increases from 0.3 to approximately 2 kWh/m^3 the consumption in absolute terms is still modest. The City of Copenhagen's total energy use for electricity and heating in households and institutions, but excluding transport was 214 kWh per delivered m^3 in 2008 (City of Copenhagen 2010). Another study has found water supply energy demands to be approximately 3% of total household energy use including transport, even in a seawater based water supply (Semiat 2008).

The results of Rygaard et al. (V & VI) show that the introduction of intensive water treatment like desalination may be beneficial from a societal perspective. However, any intensive water treatment system must be designed carefully. Rygaard et al. (V & VI) show that the introduction of desalination without remineralization is suboptimal and may lead to significant costs for society.

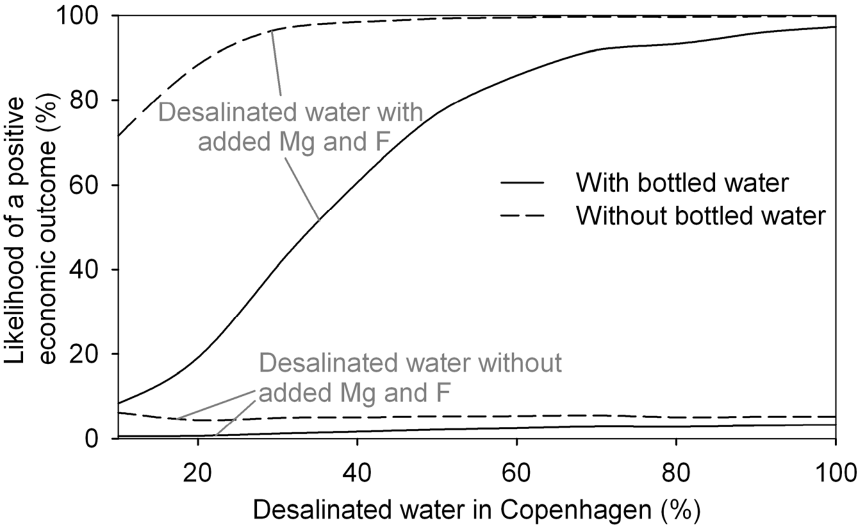

Figure 4.2. Predicted likelihood of a positive economic outcome with desalinated water replacing groundwater in Copenhagen. Based on total economic change including and excluding impact on bottled water sales (Rygaard et al. VI).

All the results are influenced by uncertainty. Assuming the total economic impact to be normal distributed, it is possible to estimate likelihood of a positive outcome (Figure 4.2). Without remineralization with magnesium and fluoride it is unlikely (<5%) that Copenhagen will achieve a positive economic outcome from desalination. A major uncertainty relates to bottled water consumption which reflects the populations trust in the water supply. If bottled water sales are unaffected by changes to water supply systems, then the likelihood of positive economic outcome increases to be above 95% for cases where desalinated water replaces more than 30% of the groundwater (Figure 4.2).

4.3 A new definition of optimal water composition

Most water quality criteria do not set minimum values for most parameters and the range of acceptable concentrations for individual inorganic compounds is quite wide. Water quality standards also vary. For example, is it recommended that total dissolved solids contents are maintained below 1500 mg/l in Danish drinking water (Danish Ministry of the Environment 2007), while in Australia the upper aesthetic guideline is 500 mg/l (Australian Government 2004). According to the Danish database on groundwater quality (GEUS 2008), the Australian guideline is exceeded for a large part of the Danish groundwater resources used for drinking water.

New water supply paradigms such as the de- and remineralizing treatment processes used in desalination plants, water reclamation schemes, and softening processes create the possibility of designing supplied water to meet any desired water quality. It is therefore very relevant to define an optimum water quality to strive for in water production. Based on the water quality impacts (chapter 3) and assessments from Perth and Copenhagen (Rygaard et al. VI) it is proposed to establish a set of optimum water quality criteria for selected parameters (Table 4.1).

Table 4.1. International guidelines for selected water quality parameters compared with the optimum proposed in Rygaard et al. (VI).

Parameter (mg/l)	Danish Ministry of the Environment (2007)	Australian Government (2004)	World Health Organization (2004)	Lahav & Birnhack (2007)	New proposal Rygaard et al. (VI)
Mg	-	-	-	-	>10
Ca	<200	-	-	32-48	40-50
Hardness (as $CaCO_3$)	89-534	<200	-	-	<150
F	<1.5	<1.5	<1.5	-	0.5-1
TDS	<1500	<500	-	-	<200

5 Conclusions

This thesis provides an overview of the reasons for changes in public water supplies and major implications that follow. With focus on membrane desalination, a method has been developed for assessing impacts from changes in water composition and has been applied successfully to two cases in Copenhagen, Denmark and Perth, Western Australia. The results address several gaps in managers' ability to consider the *whole water cycle* and the *risks at all points* (c.f. the Bonn Charter). The new knowledge includes:

A method for the economic evaluation of changes in water composition, based on concentration-response relationships.
The evaluation includes effects on health (cardiovascular diseases, atopic eczema, dental caries), material lifetime (washing machines, dishwashers, water heaters and distribution system), and laundry detergent consumption. In one example, based on a scenario for Copenhagen, it is shown that impacts caused by augmenting Copenhagen's water supply with 50% desalinated water will have a societal impact up to €0.51 (±0.2) per m^3 water delivered. Compared to current production costs (€0.3/m^3), the societal impact of poor water quality is significant.

The method includes an evaluation of production costs, environmental costs (green house gas emission costs and water resource restoration), and possible costs due to changes in consumers consumption of bottled water. Notably, the cost of the CO_2-mitigation is minor relative to the benefits occurring as a result of improved water quality and decreased pressure on fresh water resources. Considerations of CO_2-mitigation in environmental life-cycle assessments and cost-benefit analyses must therefore be complemented by assessment of effects from changed water quality and other effects related to the system.

In general it is assumed that damage to health and assets are underestimated since only direct costs of treatment and replacement is included. Indirect costs such as lost lifetime, water damage etc. will add to the benefits of optimizing drinking water quality. A number of impacts have been omitted from the analysis: temperature and taste preferences; disinfection issues; other nutrient related diseases; appliance and pipe failure rates and related water damage; heat and pressure losses due to scaling; and chemical consumption and operation wastewater treatment. The future inclusion of these indirect costs and omitted impacts is expected to favor lower salinity and hardness levels in drinking water.

Guidelines for an optimal water quality in urban water supplies.

A combination of desalinated water and the low cost of remineralization with calcium carbonate, magnesium and fluoride can be used to design an optimum water composition. Designing water with an optimum composition can lead to a water supply system with a higher value for society when compared to a system designed to simply meet conventional drinking water quality guidelines. Based on the case studies from Copenhagen and Perth, the following optimum water quality criteria are proposed:

	Mg	**Ca**	**F**	**Hardness (as $CaCO_3$)**	**TDS**
mg/l	>10	40-50	0.5-1	<150	<200

Techniques for uncertainty analysis of the economics of water supply systems

The new uncertainty evaluation method uses the *successive principle* for economic assessment developed for civil engineering project management. The simplicity of this approach, combined with the focus on uncertainty distribution, provides a transparent, honest and reliable evaluation and communication of impacts from changed drinking water composition, in line with the Bonn Charter. The successive principle includes a ranking of the impacts by their individual contribution to the total impact uncertainty. According to this ranking, changes to the magnesium content leading to a changed risk of cardiovascular diseases is the most uncertain component of the economic assessment. A better understanding of the link between drinking water magnesium content and risk for cardiovascular disease deserves great attention from the research community.

Overview of the drivers behind and solutions for increased urban water self-sufficiency.

A quantitative definition of urban water self-sufficiency has been proposed. Examples from around the world show how cities already have increased their water self-sufficiency by the use of desalination, wastewater reclamation and rainwater harvesting. In addition to a direct lack of water, four other drivers for water self-sufficiency have been identified. One of the implications of increasing water self-sufficiency is the possible increase of energy consumption for water supply by an order of magnitude. Unfortunately, no single solution provides a panacea for water supply systems; there appears to be no low intensity, publicly acceptable, and climate independent drinking water solution leading to urban water self-sufficiency.

Designing water: A new water supply paradigm

Some intensive treatment techniques including desalination allow the control of mineral contents to meet user specified criteria. Based on the findings in this thesis it is recommended to take advantage of the technology and actively adjust blends and mineral contents to optimize final water quality. This approach can have significant economic benefits when compared to water that just meets water quality criteria.

6 Perspectives

This PhD thesis has shown the importance of considering the entire water supply system from resource abstraction to consumption of water. Such a holistic assessment requires specialist knowledge from different disciplines including economics, process engineering, health care, corrosion science, ecology and the social sciences. I believe there is a great potential for further integration of knowledge found in the specialist literature. This knowledge pooling deserves further attention to ensure that integrated assessments, whether they are based on cost-benefit analysis, lifecycle assessment or other decision support tools, are genuinely holistic.

Engineering is primarily build on exact science, but flexible assessments like the one proposed here allow for inclusion of more relative knowledge. It is possible to build what-if scenarios and include impacts of doubtful nature. For example by posing the question: If bottled water sales are affected, what is the impact? We might never be able to provide the correct answer but we may become a little more enlightened by knowing the answer to the question: Do bottled water sales matter?

6.1 Suggestions for future research

I would like to emphasize that a better understanding of the nutritional value of drinking water is greatly needed. Public water supply reaches the entire population and new water treatment techniques manipulate mineral contents, so it is important to improve our understanding of any nutritional effects.

It is also relevant to further develop the concept of ‘optimum water quality’. With legal requirements that allow wide ranges of water qualities, this thesis proposes that we distinguish between *adequate, good* and *excellent* drinking water quality. Utilities considering changes to water supply treatment or management strategies must also consider options for cost-effectively improve water quality beyond legal requirements. The establishment of a generic framework for definition of optimum water quality based on local conditions is suggested. Such framework should ideally include many more parameters than those considered in this thesis.

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Appendices

I. P. J. Binning, M. B. Hauger, M. Rygaard, A. M. Eilersen, and H.-J. Albrechtsen, Rethinking the urban water management of Copenhagen, Water Practice and Technology, 1 (2006).

II. M. Rygaard, H.-J. Albrechtsen, and P. J. Binning, Alternative water management and self-sufficient water supplies, IWA Publishing, London, UK 2009. (Book excerpts)

III. M. Rygaard, H. J. Albrechtsen, and P. J. Binning, Increasing urban water self-sufficiency: New era, new challenges (submitted).

IV. M. Rygaard, E. Arvin, and P. J. Binning, Indirect economic impacts in water supplies augmented with desalinated water, Water Science and Technology (in press).

V. M. Rygaard, E. Arvin, and P. J. Binning, The valuation of water quality: Effects of mixing different drinking water qualities, Water Research, 43 (2009) 1207-1218.

VI. M. Rygaard, E. Arvin, A. Bath, and P. J. Binning, Designing water supplies: optimizing drinking water composition for maximum economic benefit (submitted).

The texts are not included in this www-version, but can be obtained from the DTU Environment library:

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