Indirect economic impacts in water supplies augmented with desalinated water

M. Rygaard, E. Arvin and P. J. Binning

ABSTRACT

Several goals can be considered when optimizing blends from multiple water resources for urban water supplies. Concentration-response relationships from the literature indicate that a changed water quality can cause impacts on health, lifetime of consumer goods and use of water additives like softeners. This paper describes potential economic consequences of diluting Copenhagen's drinking water with desalinated water. With a mineral content at 50% of current levels, dental caries and cardiovascular diseases are expected to increase by 51 and 23% respectively. Meanwhile, the number of dish and clothes washer replacements is expected to decrease by 14%. In economic terms these changes are equal to 24–85% of water production costs in 2005. Our calculations further indicate that the economic impact from changing the water quality can be at least as significant as the change in operating costs going from fresh water based to desalinated water supply. Large uncertainties prevent the current results from being used for or against desalination as an option for Copenhagen's water supply. In the future, more impacts and an uncertainty analysis will be added to the assessment.

Key words | cost, desalination, drinking water, health, quality

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INTRODUCTION

Water supplies can optimally blend multiple water resources to meet one or more goals. In practice, the blend ratio often reflects the available water resources rather than an integrated assessment of the resource, its quality and the application of the water. For example, in Europe much attention is now directed towards resource exploitation and the goals for the aquatic environment set by the EU Water Framework Directive. In the search for new resources desalination is often mentioned as viable option. Desalinating water can provide product water dramatically different from water of conventional treatment methods. This is especially true in water supply systems delivering water of high salinity and hardness. Optimized blending of desalinated and conventional sources has been performed with the goal of preventing excessive corrosion in the supply network (Imran *et al.* 2006) or reducing wear on domestic appliances due to high salinity levels

(Characklis *et al.* 2005). However, other goals can be considered. Here, we describe possible consequences of diluting water supplied to Copenhagen City, Denmark, with desalinated water. The costs of delivering a mixture of conventional water resources and desalinated water are compared with the potential economic impacts of the changed water quality. The study is a first step in a complete integrated assessment of the consequences of delivering desalinated water to Copenhagen City.

Copenhagen City's water supply

Copenhagen City's current water supply is mainly ($>95\%$) based on water imported from chalk aquifers around the urban area, supplemented by a minor surface water abstraction. The main supplier of drinking water, Copenhagen Energy, delivered an average of 55 million m^3/y to

approximately one million persons in the Greater Copenhagen area in 2005. Chemical properties are shown in Table 1. The production costs in 2005 were $0.34 \, €/m^3$ excluding costs associated with the distribution of water.

The aquifers have come under increasing pressure for legislative reasons (EU Water Framework Directive), groundwater contamination and increasing population. One possible way to relieve the stressed fresh water resources is by augmenting the water supply with desalinated water.

Membrane filtration is currently not used in the Danish public water supplies. Hence, no local cases can serve as basis for estimates of costs and technical implications of desalinating water in Denmark. One study estimated costs of nine desalination scenarios for Copenhagen (Rygaard & Tengnagel 2005). The scenarios included desalination of brackish groundwater, surface water or seawater delivering up to 12 million m^3/y. Production costs depend to a high degree on production scale in favor of larger systems (Figure 1). The scale of economics can be approximated by an inverse first order relationship as shown in the figure. The empirical relationship suggests that there exists a lower boundary for the production costs around $0.55 \, €/m^3$, where economy of scale no longer influences the price. However, this boundary will change with any fluctuation in energy prices, labor costs or capital costs, but also if plant location or design change significantly.

Impact of changed water quality

From a literature review a range of impacts related to distributed water quality was compiled and grouped in categories based on common features. It is feasible to construct four main categories of impacts. For each category a single or

Table 1 │ Average properties of water delivered to Copenhagen City in 2005. Data from Copenhagen energy

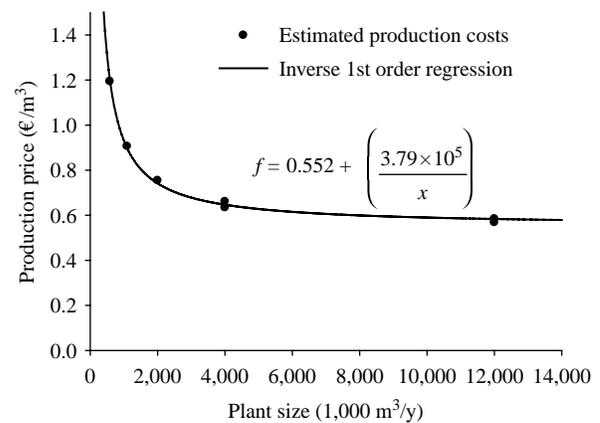| Parameter	Concentration (mg/l)
Hardness (as $CaCO_3$)	373
Ca^{2+}	115
Mg^{2+}	21
F^-	0.36
TDS	558

Figure 1 │ Estimated production costs for 7 desalination scenarios in Copenhagen and fitted inverse 1st order regression. Cost estimates from (Rygaard & Tengnagel 2005).

few impacts were chosen to illustrate the importance of including that impact category in the planning of water supply systems.

First category was "health and nutrition" where it was chosen to focus on the long term nutritional health impacts of the supplied drinking water. This is valid assuming that the supplied water complies with international guidelines of drinking water quality at all times and poses no acute toxicological effects on human health. The World Health Organization mentions calcium, magnesium, fluoride, sodium, copper, selenium and potassium as being potentially significant to people's nutritional status (World Health Organization 2005). Greatest attention has been given to the first three. Calcium and magnesium are often considered the main contributors to total hardness of the water, which in several cases have been shown correlated with a range of diseases. Two of these are cardiovascular diseases and atopic eczema, which we use to illustrate the impact on the health care economy.

"Applicability" covered non ingestive uses of water, e.g. impacts occurring in the practical use of water in housekeeping, industry etc. It included the suitability of the water for cleaning purposes and the need for adding softeners or other additives before use. We used detergent consumption in washing machines as an example of the economic impact from the application of water.

"Corrosion" included the technical aspects related to corrosion in distribution systems and wear on installations in households. Wear on domestic clothes and dish washers

were used to illustrate the economic importance of their life time.

A fourth category could have been "aesthetics and acceptability". It refers to impacts on taste, staining of tableware, rigidity of newly washed clothes. Such a category could also include abstract issues like people's perception of the water and its origin. This category is difficult to assess quantitatively. Therefore only the first three categories were considered for the results presented here.

External benefits and costs

Estimates of economic impacts from changed water quality require that a cause-effect relationship has been identified and verified. Strong cause-effect relationships are established when the association is found in many independent studies, the association persists when possible lurking variables are accounted for, and there is a plausible explanation for cause and effect (Petruccelli *et al.* 1999). In our study the criteria for including at cause-effect relationship were relaxed a little. This was done to include significant potential impacts and highlight the need for verification of cause-effect relationships.

METHOD

To delimit the analysis 2005 was used as a base year for the calculations and the geographical scope was limited to Copenhagen City. In 2005 this municipality had 502,000 inhabitants living in 273,000 households. The total water consumption in Copenhagen City was 32.6 million m^3.

Production costs

It was assumed that the unit cost of conventional supply remains constant at 0.34 €/m^3 even after 50% of the supply is substituted by desalinated water. The total production price C_{tot} [€/m^3] was thus found as the sum of the cost of conventional water treatment and desalinated water:

$$C_{\text{tot}} = (1 - \text{DW}) \times 0.34\,\text{€/m}^3 + \text{DW} \times (0.55\,\text{€/m}^3$$

$$+ (3.8 \times 10^5\,\text{€})/(\text{DW} \times 32.6 \times 10^6\,\text{m}^3/y))$$

DW was the desalination ratio; the share of desalinated water in the water supply to Copenhagen:

$$\text{DW} = \frac{\text{Desalinated water production (m}^3/y)}{\text{Total water delivery (m}^3/y)}$$

Economic impacts from changed water quality

When a cause-effect relationship was identified a concentration-response relationship was established. For a water supply system this is similar to dose-response relationships used in ecotoxicology and air pollution research. Here, we adopted the method used in air pollution research (European Commission 2005) and sought to establish linear relationships of the form:

$$R_i = s_i \times dc_i \times P_i$$

where R_i is the response [e.g. number of cases/value per year] of impact category i, s_i is the slope of the concentration-response curve, dc_i is the change in concentration of relevant compound(s) from reference conditions, and P is the size of affected population. A scenario where Copenhagen's water is diluted to 50% of current mineral concentrations was considered. This reflects the situation were groundwater is mixed 1:1 with desalinated water without re-mineralization.

Several approaches and frameworks to assess indirect economic impacts exist and there are on-going discussions of their applicability and interpretation of results (Pearce *et al.* 2006). To avoid price setting of intangible costs and to keep the analysis transparent we focused on direct costs, e.g. cost of illness for health impacts, and did not include externalities like the value of lost life years etc. This means that the cost calculation became a conservative measure and provided results that are lower than the real economic burden on society.

RESULTS

In the following the established concentration-response relationships and cost estimates are presented. A summary of costs of each impact type is presented in the end of the section (Table 2).

Table 2 │ Summary of costs of each impact type. For comparison: if 50% of the water supply in 2005 were replaced with desalinated water, the production costs is expected to increase with 0.12 €/m³ to 0.46 €/m³

	Cases in Copenhagen City 2005	Expected change in cases if 50% desalinated water		Cost per case	Total economic impact in Copenhagen 2005 if 50% desalinated water	
		(No.)	(%)	(€)	(10^6 €)	(€/m³)
DMF-S (dental caries)	1.1×10^6	560,167	51	−6	−3.5	−€ 0.11
Hospitalizations related to cardiovascular diseases	1.1×10^4	2,531	23	−3,733	−9.4	−€ 0.29
Annual prevalence of atopic eczema among 0–11 year olds	4.3×10^3	−3,460	−81	−718	2.5	€ 0.08
Estimated detergent consumption (clothes only)	–	–	–	–	3.8	0.12
Annual clothes and dish washer replacements	3.9×10^4	−5,232	−14	−683	3.6	0.11

Production costs

If 50% (DW = 0.5) of Copenhagen City's water production in 2005 were replaced with desalinated water the expected production costs would rise to 0.46 €/m³, excluding costs associated with the distribution of water.

Health and nutrition

Water hardness and cardiovascular diseases

Researchers have recently concluded that 50 years of research have not been able to definitively confirm or reject a negative correlation between water hardness and the risk of cardiovascular diseases (Monarca *et al.* 2006). However, the hypothesis that consumption of hard water is associated with a somewhat lowered risk of suffering from cardiovascular diseases is probably valid. The association is considered weak and there seem to be consensus that the magnesium content is the main cause of the lowered risk. Out of several possible concentration-response relationships from the literature it was chosen to use one based on the association between drinking water content of magnesium and the risk of cardiovascular diseases. A Swedish concentration-response relationship for magnesium content and mortality from ischemic heart disease was used. Rylander *et al.* (1991) found that the relative risk of men dying from ischemic heart disease decreases with 0.022 per mg/l change in magnesium level of

drinking water. We assumed that this relationship based on a specific cardiovascular disease can be used to describe the general variation of all cardiovascular/circulation diseases due to changes to the magnesium content in drinking water. This relationship was considered particularly relevant since Sweden is a country with socioeconomic and demographic conditions similar to Denmark. In 2005 the average price per hospitalization related to circulation was € 3,740 (Ministry of the Interior and Health 2006). 2.2% of Copenhagen's population were hospitalized with this diagnose (Statistics Denmark 2007).

Atopic eczema

Some evidence suggest that water hardness can increase prevalence of atopic eczema (McNally *et al.* 1998; Miyake *et al.* 2004). McNally *et al.* (1998) found that 1-year period prevalence (occurrence within the last year) of atopic eczema among English 4–11 year olds was significantly higher in areas with high water hardness, both before and after adjusting for typical demographic and social confounders. Prevalence among 11–16 year olds was not significantly correlated with water hardness. For our purpose linear correlations between the eczema prevalence and water hardness was used to establish a concentration-response relationship (Figure 2). The average slope of the curves gives an absolute 0.029% increase in eczema prevalence per unit change in water hardness.
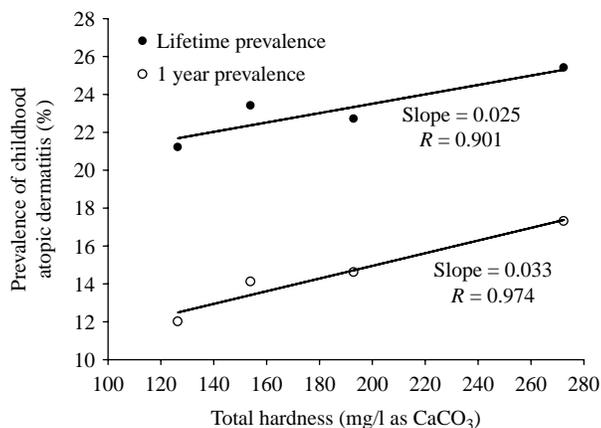
Figure 2 | Prevalence of childhood atopic dermatitis in the UK plotted against the average water hardness in each of their four hardness categories (McNally *et al.* 1998). A linear regression is fitted to estimate the slope of the dose-response curve.

Prevalence of atopic eczema can be difficult to diagnose and different criteria exist. Lifetime-prevalence among Danish schoolchildren has been found to be 18–21%, while 1-year period prevalence was found to be 6.7% among 12–16 year old Danish adolescents (Mortz *et al.* 2001; Olesen *et al.* 2001). We assumed that 6.7% of Copenhagen's 0–11 year old (total 63,694) had atopic eczema in year 2005. It was also assumed that the prevalence of atopic eczema for that age group was affected by the drinking water hardness by an absolute 0.03% increase per unit change in water hardness. Actual treatment costs for atopic eczema are unknown, but typical hospitalization costs for allergies in general were rated at € 718 per case in 2005 (Ministry of the Interior and Health 2006).

Calcium and fluoride content and dental caries

Fluoride concentration in drinking water is negatively correlated with dental caries and positively correlated with fluorosis (Clarkson & McLoughlin 2000). As the drinking water in Copenhagen has fluoride concentrations well below the WHO maximum guideline value (1.5 mg/l), only effects on dental caries have been considered. Dental caries is measured in Decayed Missing and Filled Surfaces per person (DMF-S). Calcium levels in drinking water can also have an effect on dental caries. A Danish study found that variation in DMF-S values among 15-year adolescents
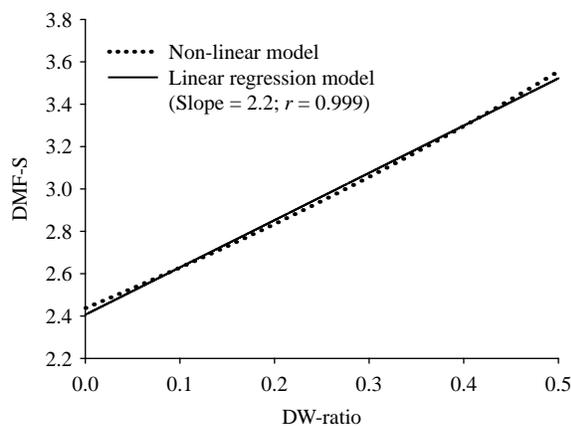

Figure 3 | Nonlinear model (Bruvo *et al.* 2008) and fitted linear regression on the relationship between fluoride and calcium levels at changing desalinated water ratios in Copenhagen and DMF-S values.

could be described by the expression (Bruvo *et al.* 2008):

$$DMF\text{-}S = \exp(1.05 - 0.18 \times ([F^-] - 0.33)/0.25 - 0.11$$
$$\times ([Ca^{2+}] - 83.53)/25.63)$$

For the calcium and fluoride levels in question the change in DMF-S is approximately linear (see Figure 3), with a slope of 2.2 per unit change in desalination ratio. A simple dental plastic filling costs € 29–51 (2005 prices, Ministry of the Interior and Health (2007)). Here we used the average cost of filling (€ 40) and a replacement rate of 1 per 6.5 fillings per year.

Application and use of water

Soap consumption

Soap consumption is different from the other impacts since the actual amounts used are unknown and also the size of the detergent market in Denmark is unknown. However, assuming that people follow the dosage guidelines on the packages it was possible to estimate expenses per wash cycle. The detergents are sold with recommendations of dosage according to the hardness of the local water supply. Based on estimated costs of one washing cycle for three different water hardness categories it was chosen to make a linear relationship between the water hardness and expected costs (Figure 4). The annual number of washing cycles per person is highly uncertain, but it has previously
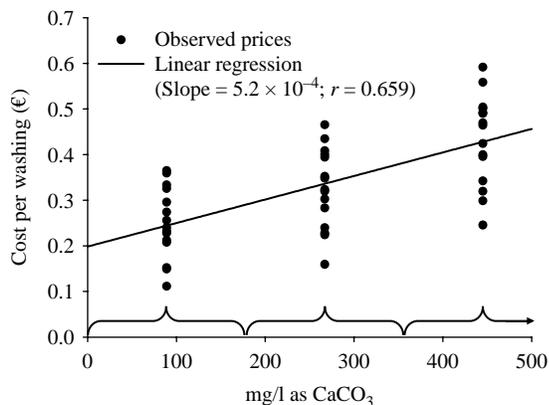
Figure 4 | Prices of 15 different detergent brands from (Andreasen & Stubsgaard 2002). Price per dosage if following recommendations on package for the three hardness levels 0–10°dH, 10–20°dH and >20°dH (adjusted to 2005 prices).
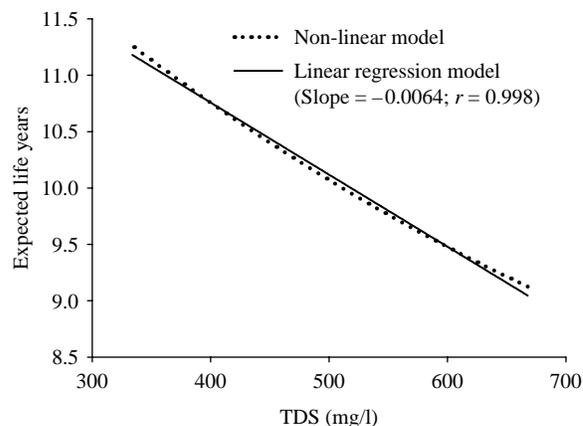

Figure 5 | Non-linear model and fitted linear regression on the relationship between salinity levels and expected life time of domestic dish and clothes washers. Non-linear model from (Characklis 2004).

been assumed to be 78 cycles per person (Andreasen & Stubsgaard 2002).

Corrosion

Corrosion of domestic appliances

Only a preliminary assessment of the water quality's impact on the lifetime of domestic appliances was conducted. American studies have shown that drinking water salinity may have a significant impact on the life time of appliances like dish and clothes washers. Characklis (2004) gathered a selection of salinity impacts on domestic appliances. He used the following expression to estimate expected life time of dish and clothes washers:

$$\text{Life [years]} = 4.6 \times 10^{-6} \times [\text{TDS}]^2 - 1.1 \times 10^{-2} \times [\text{TDS}]$$

$$+ 14.42$$

For the salinity levels in question the dose-response can be assumed linear with a decrease of 0.0064 years per unit change TDS (Figure 5). Respectively 79 and 56% of Danish households had dish and clothes washers in 2005 (Statistics Denmark 2007). The machines were assumed to have an average lifetime of 11 and 12 years respectively and the expected cost is 683 € per machine.

Comparison of costs

Replacing 50% of the water supply with desalinated water will reduce the magnesium content from 21 mg/l

to 10.5 mg/l. From the relationship presented above the change is expected to add $0.022 \times 10.5 = 0.23$ to the risk of cardiovascular diseases. This response adds 2,169 (23%) to the annual 11,000 cases of cardiovascular diseases in Copenhagen City. Multiplying the change with the average hospitalization price (3,733 €) the annual economic impact becomes −8.1 million € (0.25 € per delivered m³). A summary of the results is presented in Table 2.

DISCUSSION

By replacing 50% of the conventional water supply with desalinated water the economic impact from each of the impact categories ranged from 0.08 €/m³ to 0.29 €/m³. This equals 24 to 85% of the conventional production costs in 2005. The desalination was expected to add 35% to the production costs. Thus all of the impacts presented here provide significant values in an overall assessment of the economic performance of the water supply system. But how confident can we be of the results? Several issues contribute to the uncertainty of the results. First of all, the production costs of desalinated water were based on limited available scenarios for desalination in Copenhagen. In Israel and at larger scale the costs of desalination are now down to 0.34 €/m³, 38% lower than values used for comparison in our study (Tal 2006). Phasing out 50% of the current groundwater abstraction requires significant changes of

wetlands around Copenhagen. The implications of such changes have also not been considered here.

There exist various possible concentration-response relationships for each impact category. For example, other relationships can be derived for the relation between hardness/magnesium content and cardiovascular diseases. It is also uncertain how valid the association between magnesium and ischemic heart disease among men is to describe all kinds of cardiovascular diseases. Age, gender, race, diet patterns etc. is known to have influence too and it is unclear whether generalizations can be justified or not (Monarca et al. 2006).

The literature search also revealed a vast amount of possible cause-effect relationships not included here. To name a few relations it would be relevant to consider for future studies: minerals and osteoporosis (Simonen & Laitinen 1985), desalination and bottled water consumption (an aesthetical issue), and corrosion of public/domestic piping systems (Imran et al. 2006). For example, copper release has been shown positively correlated with alkalinity in pipe rig tests (Edwards et al. 1996; Taylor et al. 2005).

A possible problem of the method presented here is that responses are all measured in absolute values and not relative to the background or base case occurrences. It is unlikely that water hardness explains 81% of the prevalence of atopic eczema in Copenhagen since children in regions with soft water also have atopic eczema (Bjorksten et al. 1998). Calculating a relative change instead would reduce the impact, while another method of estimating prevalence would alter the relative sizes of the impact. For transparency it was chosen not to alter between absolute and relative changes in our analysis, but it points out an important issue in the further development of the method.

Finally the economic assessment is a complicated and controversial task. We limited the costs to direct hospitalization or treatment costs, which alone can be difficult to define and obtain. Certainly changed life time/quality, lost work ability, medicine expenses, special diet requirements, etc. would contribute to the economic impacts too. The importance of these issues has been shown in the research on externalities from energy production (European Commission 2005).

CONCLUSION

The work presented here shows a beneficial use of dose-response relationships in the planning of water systems. It has been shown that mineral content of drinking water may affect economies to a degree that is comparable to or even exceeds differences in production costs. The choice of water resources should therefore also include an assessment of potential impacts from changing the delivered water's mineral content, even though the water fulfills legislative requirements. The results presented here must be verified by an uncertainty analysis. On this background and the issues raised in the discussion, we can not use the results presented here to support or reject desalination as a solution for Copenhagen City. We will merely point out the possible large economic implications of changing the mineral content of the delivered water in Copenhagen City.

So far, the results can be used as an indication of which impacts that matters and require further analysis. Further investigations should include other impacts like corrosion of public and domestic piping.

Despite the uncertainties (and because of them) more attention towards indirect cost and benefits seems justified. Public water supplies have the characteristic that the service reaches every home and company of the city and even small effects on the individual level can add up to significant amounts as we have shown here.

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