VU Research Portal

Evaluating the costs of desalination and water transport

Zhou, Y.; Tol, R.S.J.

published in
Water Resources Research
2005

DOI (link to publisher)
10.1029/2004WR003749

document version
Publisher's PDF, also known as Version of record

Link to publication in VU Research Portal

citation for published version (APA)
Zhou, Y., & Tol, R. S. J. (2005). Evaluating the costs of desalination and water transport. *Water Resources Research*, *41 (3)*(W03003). https://doi.org/10.1029/2004WR003749

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:
vuresearchportal.ub@vu.nl

Download date: 18. Sep. 2021

WATER RESOURCES RESEARCH, VOL. 41, W03003, doi:10.1029/2004WR003749, 2005

Evaluating the costs of desalination and water transport

Yuan Zhou[1]

International Max Planck Research School of Earth Systems Modeling, Hamburg, Germany

Richard S. J. Tol[2,3]

Research Unit Sustainability and Global Change and Center for Marine and Atmospheric Science, Hamburg University, Hamburg, Germany

Received 18 October 2004; accepted 29 December 2004; published 2 March 2005.

[1] Many regions of the world are facing formidable freshwater scarcity. Although there is substantial scope for economizing on the consumption of water without affecting its service level, the main response to water scarcity has been to increase the supply. To a large extent, this is done by transporting water from places where it is abundant to places where it is scarce. At a smaller scale and without a lot of public and political attention, people have started to tap into the sheer limitless resource of desalinated water. This study looks at the development of desalination and its costs over time. The unit costs of desalinated water for five main processes are evaluated, followed by regressions to analyze the main influencing factors to the costs. The unit costs for all processes have fallen considerably over the years. This study suggests that a cost of \$1/m^3 for seawater desalination and \$0.6/m^3 for brackish water would be feasible today. The costs will continue to decline in the future as technology progresses. In addition, a literature review on the costs of water transport is conducted in order to estimate the total cost of desalination and the transport of desalinated water to selected water stress cities. Transport costs range from a few cents per cubic meter to over a dollar. A 100 m vertical lift is about as costly as a 100 km horizontal transport (\$0.05–0.06/m^3). Transport makes desalinated water prohibitively expensive in highlands and continental interiors but not elsewhere.

Citation: Zhou, Y., and R. S. J. Tol (2005), Evaluating the costs of desalination and water transport, *Water Resour. Res.*, *41*, W03003, doi:10.1029/2004WR003749.

1. Introduction

[2] Water is a crucial resource for survival and growth of life, as well as sustaining the environment. However, the vast majority of water on the earth is too salty for human use. Ninety-seven percent of the Earth's water is found in the oceans, with a salt content of more than 30,000 mg/L [*Gleick*, 2000]. Water, with a dissolved solids (salt) content below about 1000 mg/L, is considered acceptable for a community water supply [*Buros*, 2000]. Because of the potentially unlimited availability of seawater, people have made great efforts to try to develop feasible and cheap desalting technologies for converting salty water to fresh water.

[3] A variety of desalting technologies has been developed over the years, including primarily thermal and membrane processes. The main thermal processes include multistage flash evaporation (MSF), multiple effect evaporation (ME), and vapor compression (VC). The membrane processes contain reverse osmosis (RO), electrodialysis (ED) and nanofiltration (NF). The MSF and RO processes dominate the market for both seawater and brackish water desalination, sharing about 88% of the total installed capacity [*Wangnick*, 2002] (Figure 1). Raw water with different qualities has been treated in desalting plants, dominated by seawater and brackish water [*Wangnick*, 2002] (Figure 2). Seawater is desalted often by various thermal processes and also by RO, whereas brackish water is treated by means of mainly RO and ED.

[4] Desalination of brackish and seawater has been expanding rapidly in recent decades, primarily to provide water for municipal and industrial uses in arid, semiarid or water-short areas. It is driven by water stress generated from limited water resources and ever growing demands for water. Continuous progress in desalination technology makes it a prime, if not the only, candidate for alleviating severe water shortages across the globe [*Ettouney et al.*, 2002]. The market is also driven by the falling costs of desalination, which are due to the technological advances in the desalination process [*Tsiourtis*, 2001]. Until 2002, over 15,000 industrial-scale desalination units, with a total capacity of 32.4 million m^3/d, had been installed or contracted worldwide. Among them, nonseawater desalination plants contributed with 13.3 million m^3/d, while the capacity of the seawater desalination plants reached 19.1 million m^3/d [*Wangnick*, 2002].

---

[1] Also at Research Unit Sustainability and Global Change and Center for Marine and Atmospheric Science, Hamburg University, Hamburg, Germany.

[2] Also at Institute for Environmental Studies, Vrije Universiteit, Amsterdam, Netherlands.

[3] Also at Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA.

Copyright 2005 by the American Geophysical Union.
0043-1397/05/2004WR003749\$09.00

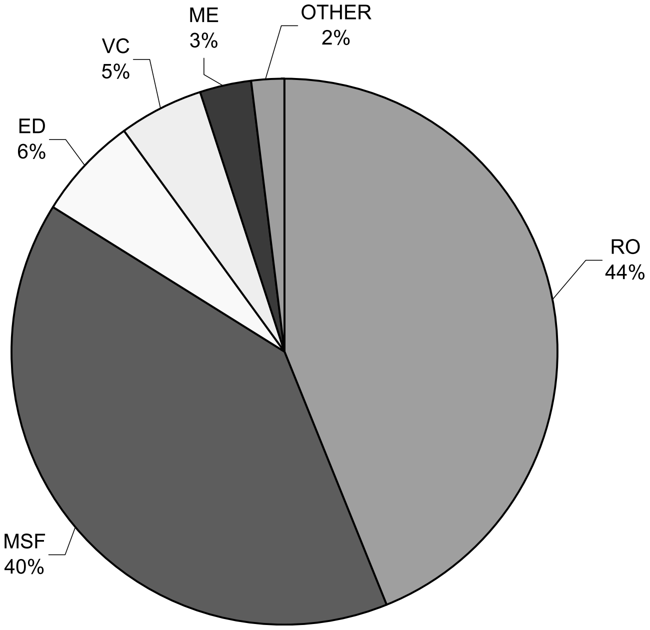

Figure 1. Installed desalting capacity by process. See color version of this figure in the HTML.

[5] The costs of water produced by desalination have dropped considerably over the years as a result of reductions in price of equipment, reductions in power consumption and advances in system design and operating experiences. As the conventional water supply tends to be more expensive due to overexploitation of aquifers and increasing contaminated water resources, desalted water becomes a viable alternative water source. Desalination costs are competitive with the operation and maintenance costs of long-distance water transport system [*Ettouney et al.*, 2002]. This study defines the main economic parameters used in estimation of desalination costs and calculates the unit costs of desalted water for five main processes based on simplified assumptions. It then uses multiple regression to estimate the trends of unit costs over time and analyze the significant factors that affect the cost of desalination. Moreover, in this study a literature survey on the costs of water transport is conducted in order to estimate the total cost of desalination and the transport of desalinated water to where water is short.

2. An Overview of Desalination Costs by Various Processes

[6] The costs of desalination vary significantly depending on the size and type of the desalination plant, the source and quality of incoming feed water, the plant location, site conditions, qualified labor, energy costs and plant lifetime. Lower feed water salinity requires less power consumption and dosing of antiscale chemicals. Larger plant capacity reduces the unit cost of water due to economies of scale. Lower-energy costs and longer plant period reduce unit product water cost.

[7] The primary elements of desalination costs are capital cost and annual running cost. The capital cost includes the purchase cost of major equipment, auxiliary equipment, land, construction, management overheads, contingency costs etc. The capital costs for seawater desalination plants have decreased over the years due to the ongoing development of processes, components and materials. Annual running costs consist of costs for energy, labor, chemicals, consumables and spare parts. A typical breakdown of running costs for thermal processes is that the ratio of energy: chemicals: labor equals 0.87:0.05:0.08 [*Wangnick*, 2002]. The energy costs play a dominant role for thermal processes. Distillation costs will fluctuate more than RO with changing energy costs. In regions where the energy is fairly expensive, RO is a favorable choice compared to any other thermal processes due to its lower energy consumption.

[8] To provide the overview of the desalination costs worldwide, we evaluate the unit costs for the main processes based on rough assumptions. All the plants rated at 600 m^3/d per unit or more for the five main processes of *Wangnick* [2002] are included in the calculation. The report provides information on land-based desalting plants rated at more than 100 m^3/d per unit and contracted, delivered or under construction as of the end of 2001. The report is considered to be the most comprehensive and complete of its kind worldwide though not high quality especially in providing more detailed information on single plant. The data set should be handled with caution since there are no other data sets available to cross check on it. The data regarding desalting plants include country, location, total capacity, units, process, equipment, water quality, user, contract year and investment costs. The detailed annual running costs are not available for the plants so it is hard to differentiate what kind of costs exactly are included and how. The total costs are assumed to be split up into 40% capital costs for interest and depreciation on the investment and 60% of running costs, referring to *Wangnick* [2002]. The load factor is assumed to be 90% for all the plants. These assumptions are the same for all desalination techniques, again for want of better information. We use the work by *Wangnick* [2002] despite the crudeness of the data. The alternative would be to build our own database that may have higher quality

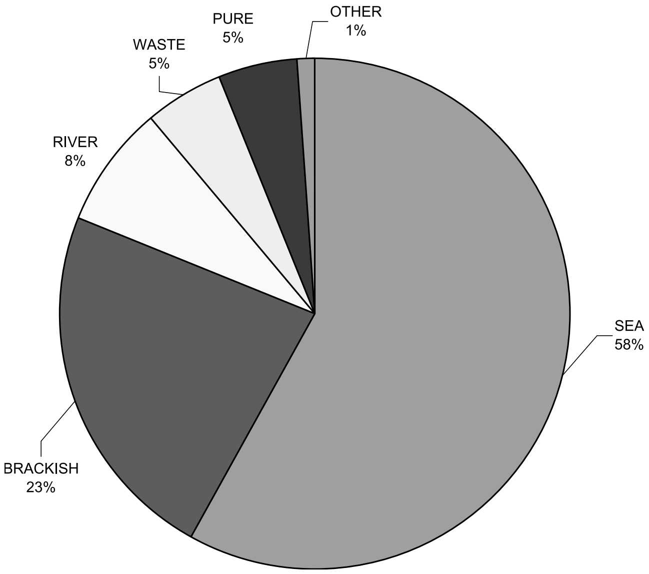

Figure 2. Installed capacity by raw water quality. See color version of this figure in the HTML.

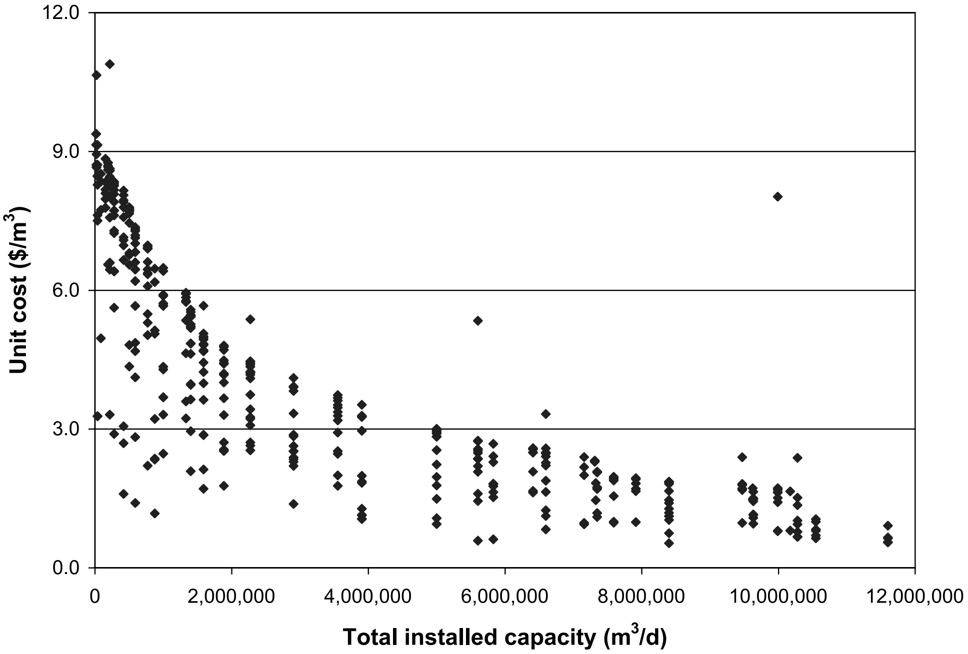

Figure 3. Unit costs versus total installed capacity by the MSF process. See color version of this figure in the HTML.

and more detailed cost data, but which would also have a much smaller number of observations, have a more limited geographic scope, and cover a much shorter period of time.

[9] The annual amortized capital costs are obtained by multiplying the costs by an amortization factor, given as follows:

$$C = P \times i \times (1+i)^{n-1} \Big/ [(1+i)^{n} - 1]$$

where C is amortized annual capital cost, P the investment in the original year, i the annual discount rate, and n the economic plant life. In this study, a discount rate of 8% and a plant life of 30 years are applied for amortization for all the cases. For the purpose of comparison, all unit costs are given in terms of 1995 US dollars calculated based on the United States Consumer Price Index. The cost data and our calculation are available on the Web (http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/Models.htm).

2.1. Costs of the MSF Process

[10] This study considers 442 desalting plants using MSF processes worldwide from year 1957 to 2001, with a total capacity of 12.6 million m^3/d. The process accounts for the second largest installed desalting capacity in the world next to RO. The major consumers of MSF are in the Middle Eastern and North African (MENA) countries, such as Saudi Arabia, United Arab Emirates, Kuwait, Libya and Iran. The main users of desalinated water are municipality, industry and power plants. The majority of plants are designed to treat seawater.

[11] Figure 3 illustrates the unit costs of all the desalting plants using the MSF process over the total cumulative installed capacity. The unit cost has been reduced substantially since the initial stage of MSF technology. The average unit cost has fallen from about \$9.0/m^3 in 1960 to about \$1.0/m^3 at present, which indicates that there has been a great improvement of MSF technology. The average annual reduction rate of unit costs has been about 5.3% in last 40 years.

[12] We use regression methods to estimate the unit costs of these desalting plants. The original data for the plant include the location, the year, the plant capacity and raw water quality. The calculated data include unit costs and the total cumulative installed capacity. The major consumers for MSF are located in the Middle East and North Africa (MENA), therefore regional dummies are included to analyze the significance of location differences. The raw water quality dummies are also included. The model for this process is specified in (1).

$$\mathrm{F(UNITC) = G(TIC, CAP, YEAR, MENA, SEA)} \qquad (1)$$

where UNITC is the average unit cost of desalting one cubic meter of water, TIC refers to the total cumulative installed capacity, which reflects the expansion of desalting plants over time. CAP is the capacity of a single plant. YEAR is the contract year of the plant. ME&NA is the regional dummy, and SEA is the raw water quality dummy. The model was estimated with OLS for two different equations, namely semilog and double log. Since TIC and YEAR are correlated and nonstationary, we estimate separate equations with either (but not both) explanatory variable. UNITC cointegrates with both TIC and YEAR, and TIC and YEAR cointegrate with each other. Statistical techniques for multicointegration have yet to be developed [cf. *Banerjee et al.*, 1993; *Chatfield*, 2004], except when there is strong prior information [*Tol and de Vos*, 1998], which we lack in this case. Note that the two alternative regressions have a different interpretation. With YEAR as an explanatory variable, costs reductions are due to technological progress outside the water desalination industry. In contrast, with TIC as an

Table 1. Unit Cost Estimation Results[a]

Variable	Log-Log Model 1	Log-Log Model 2	Semilog Model 1	Semilog Model 2	Log-Log (Energy Adjusted) Model 1	Log-Log (Energy Adjusted) Model 2
Constant	6.93[b] (38.96)	798.76[b] (38.73)	1.21[b] (14.85)	109.49[b] (36.65)	5.83[b] (29.11)	672.22[b] (31.36)
TIC	−0.35[b] (−30.22)		−1.71E-07[b] (−33.95)		−0.26[b] (−20.21)	
YEAR		−105.02[b] (−38.59)		−0.06[b] (−36.31)		−88.33[b] (−31.22)
CAP	−0.16[b] (−12.85)	−0.14[b] (−13.30)	−2.21E-06[b] (−7.93)	−2.14E-06[b] (−8.01)	−0.17[b] (−12.19)	−0.14[b] (−13.24)
MENA	0.10[b] (2.76)	0.05 (1.54)	−0.06 (−1.85)	−0.05 (−1.41)	0.21[b] (4.94)	0.17[b] (5.05)
SEA	0.63[b] (7.35)	0.69[b] (9.54)	0.73[b] (8.74)	0.68[b] (8.57)	0.66[b] (29.12)	0.73[b] (9.71)
R^2 adjusted	0.77	0.84	0.78	0.80	0.64	0.78
F value	369.37	571.16	393.55	445.83	195.08	397.89
Log likelihood	−161.29	−85.85	−150.44	−130.84	−213.46	−102.99
n	442	442	442	442	442	442

[a] The t statistics are in parentheses. Read −1.71E-07 as -1.71×10^{-7}.
[b] Significance is at the 0.01 level.

explanatory variable, cost reductions are due to technological progress inside the water desalination industry through learning by doing. The estimation results are presented in Table 1.

[13] The regressions show that all the variables but MENA are statistically significant in unit cost estimation. The negative values imply that the unit cost declines with the increase of the variables. As TIC represents the total installed capacity of all the desalting plants, the decline of the unit cost can be explained as a result of the technological development and gained experiences. CAP also influences the unit cost of a plant, as the cost tends to be lower with the increase of plant capacity due to economies of scale. It is thus suggested from this study that seawater desalting plants using the MSF process will be economically favorable to have a larger capacity. However, the correlation is not obvious for plants with a capacity less than 50,000 m^3/d [*Zhou and Tol*, 2004]. YEAR is significant, reflecting that the technology change outside the sector also plays an important role in the cost reduction over time. The positive value of SEA implies the higher unit cost for seawater desalting than for other raw water quality.

[14] According to the regression results, the unit cost will continue to decrease with the increasing cumulative capacity and over the time. The double log estimation with TIC suggests a total installed capacity elasticity of −0.35, that is, for every 1% extension of the total installed capacity, the unit costs decrease by 0.35%. For the year 2001 alone, the total contracted capacity has increased by about 8%. That would mean a decrease of unit cost by 2.8%. The study also indicates an elasticity of −0.16 for the plant capacity, that is, increasing returns to scale.

[15] As energy cost played such a significant role in the total cost of desalination, one may wonder why the curve in Figure 3 does not reflect the oil crisis in the 1970s, which had led to the dramatic increase of oil prices. The reason is that the above estimation is conducted irrespective of energy prices due to lack of information on actual energy consumption for all the plants. In order to get an idea of how the energy prices may influence the whole cost of desalination, we report a sensitivity analysis by calculating the unit cost over time based on the correlation between energy costs and oil prices. Although some plants run on natural gas instead of oil, here we take only oil prices since the gas price typically follows the oil price. One may argue that the production costs of plants would not be affected by changes in oil prices because the Middle Eastern countries, where most desalination plants are located, have plenty of cheap oil and gas. However, the market price reflects the "opportunity cost" incurred for not selling oil and gas. The crude oil prices are obtained from the Web sites of the Office of Transportation Technologies (http://www.ott.doe.gov) and the Energy Information Administration (http//www.eia.doe.gov). We assume that the energy costs account for 50% of the total cost in the year 1995, and then correlate the energy cost in a particular year with oil prices of the time. If the oil price doubles in that year compared to 1995 level, then the energy cost also doubles. Figure 4 illustrates the unit costs of MSF plants with and without adjustment for oil prices. Without oil prices, there is a comparatively neater trend than with prices adjustment. Figure 4b shows clearly higher costs during the period 1970–1985. Since 1990, the unit costs are more or less similar in 4a and 4b. This analysis indicates that one could expect more or less similar fluctuations of costs for other thermal processes such as ME and VC and perhaps a smaller scale of fluctuations for membrane processes. The regression using log-log model was conducted again with oil prices adjusted data and the result was presented in Table 1. Clearly, there is a less correlation for the energy-adjusted data and it also suggests a less total installed capacity elasticity and the significance of plant locations (MENA).

[16] Because of the crudeness of data, it is difficult to come up with a realistic analysis of energy costs for all the plants. This analysis is presented here for illustrative purposes only. For the rest of the paper, energy costs are not adjusted particularly with oil prices for desalination cost estimation.

2.2. Costs of the RO Process

[17] The RO process has become more popular during the past decades due to advancing technology and falling costs. It should be noted, though, that RO plants are more difficult to operate than other types of desalination plants, the main attraction being costs. The operating cost of RO plants has been reduced, thanks to two developments: (1) lower-cost, higher-flux, higher salt-rejecting membranes that can efficiently operate at lower pressures and (2) the use of pressure recovery devices [*Gleick*, 2000]. This study contains 2514 desalting plants using RO processes worldwide, with a total capacity of 12.7 million m^3/d since the 1970s. The

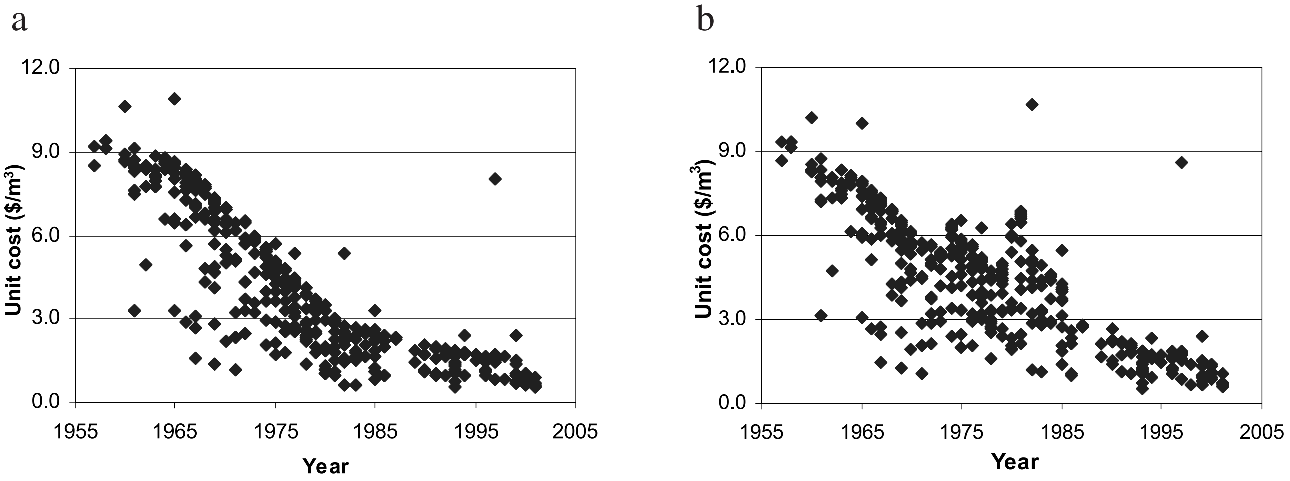

Figure 4. Sensitivity analysis of unit costs regarding energy costs. (a) Without oil prices. (b) With oil prices. See color version of this figure in the HTML.

process has become to have the largest installed desalting capacity throughout the world. RO is often used to treat less saline water, such as brackish, river and wastewater. Since the last decade, it has been increasingly applied for seawater as well and has become competitive to thermal processes. Till 2001, a breakdown of capacity according to feed water quality is that the ratio of brackish: seawater: river and pure: other is about 40:14:40:6. The users include municipal and industrial use, power plants and also tourism.

[18] Figure 5 shows the unit costs of all desalting plants using RO processes over the total cumulative installed capacity. The different feed water qualities are indicated with different symbols. In general, the unit costs for seawater are the highest, followed by waste, brackish, and river and pure water. Raw water quality plays an important role in the costs of RO desalination. The average unit costs of RO processes have declined from \$5.0/m^3 in 1970 to less than \$1.0/m^3 today. Figure 5 also shows that the unit costs for seawater desalination are still above \$1.0/m^3 while the costs for desalting brackish, river, and pure water has been reduced to less than \$0.6/m^3 level. Note that recent tenders costs of large seawater RO indicate even lower costs. For instance, some field estimates suggest a cost of \$0.55/m^3 for a large RO project in Florida [*Ettouney et al.*, 2002]; more recent cost proposals such as for the Ashkelon desalination in Israel have included costs as low as \$0.52/m^3 [*Busch and Mickols*, 2004].

[19] Essentially we did similar regressions to estimate the unit cost as for the MSF process. The major consumers for RO are located quite dispersedly worldwide such as in the USA, Saudi Arabia, Spain, Japan and Korea, which give no information about grouping countries, therefore the regional dummies are excluded. Various raw water qualities such as

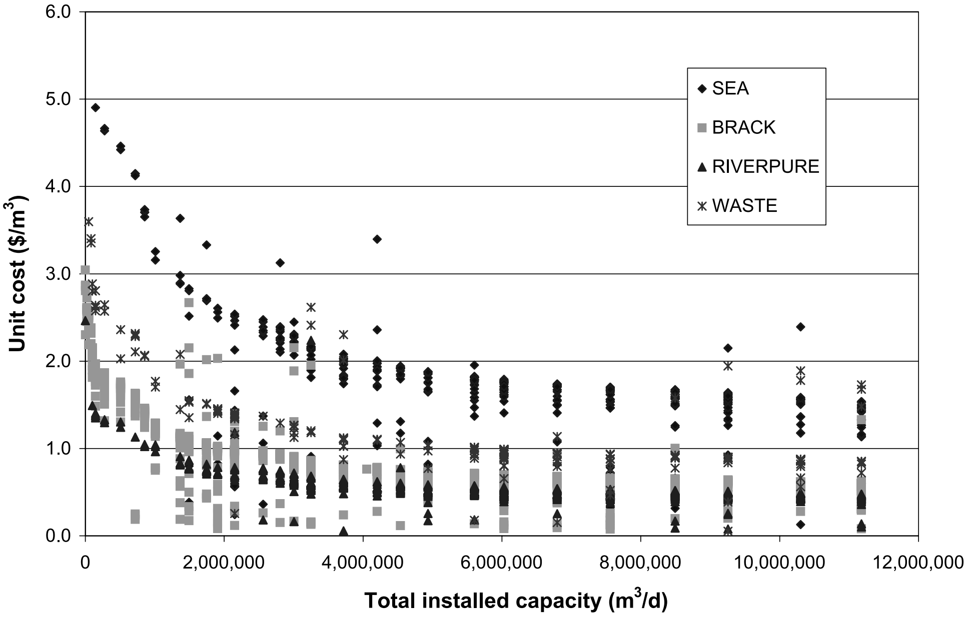

Figure 5. Unit costs versus total installed capacity by the RO process. See color version of this figure in the HTML.

Table 2. Unit Cost Estimation Results[a]

	Log-Log		Semilog	
Variable	Model 1	Model 2	Model 1	Model 2
Constant	5.19^{b} (53.99)	652.68^{b} (47.42)	0.60^{b} (19.66)	88.66^{b} (47.84)
TIC	−0.29^{b} (−50.20)		−9.03E-08^{b} (−36.85)	
YEAR		−85.81^{b} (−47.34)		−0.04^{b} (−47.77)
CAP	−0.10^{b} (−15.85)	−0.09^{b} (−14.42)	−3.55E-06^{b} (−6.72)	−3.74E-06^{b} (−7.89)
SEA	0.50^{b} (17.82)	0.50^{b} (17.02)	0.46^{b} (13.89)	0.49^{b} (16.19)
BRACK	−0.41^{b} (−16.17)	−0.42^{b} (−15.89)	−0.38^{b} (−12.66)	−0.41^{b} (−15.16)
RIVERPURE	−0.66^{b} (−25.17)	−0.67^{b} (−24.86)	−0.70^{b} (−22.74)	−0.66^{b} (−23.76)
R^2 adjusted	0.72	0.71	0.62	0.69
F value	1322.63	1216.75	813.19	1122.73
Log likelihood	−639.38	−716.31	−1050.91	−787.04
n	2514	2514	2514	2514

[a] The t statistics are in parentheses.

[b] Significance is at the 0.01 level.

brackish, sea, river, pure, and wastewater are included. The model specification is in (2).

$$F(\mathrm{UNITC}) = G(\mathrm{TIC}, \mathrm{CAP}, \mathrm{YEAR}, \mathrm{SEA}, \mathrm{BRACK}, \mathrm{RIVERPURE}) \tag{2}$$

where SEA, BRACK, and RIVERPURE refer to seawater, brackish water and river plus pure water dummies. Wastewater and brine water are in category OTHER, which does not show in the equation. The regression results for double-log and semilog models are presented in Table 2.

[20] The results show that all the variables are statistically significant at the 0.01 level. The negative coefficient values of TIC and CAP imply a lower unit cost with the increase of the total installed capacity and the plant capacity, which is similar to the estimation of MSF. Raw water qualities give both positive and negative values. The positive coefficient value of SEA implies that there is a higher unit cost for seawater desalination than OTHER (wastewater). Negative coefficient values of BRACK and RIVERPURE indicate a lower unit cost for brackish, river, and pure water than wastewater. Moreover, RIVERPURE (−0.66) shows a smaller value than BRACK (−0.41), which implies that the unit cost of desalting river & pure water is lower relative to that of brackish water. These results make sense in that cleaner and less saline water requires relatively less energy than low-quality water in treatment process.

[21] The double-log regression results suggests a total installed capacity elasticity of −0.29, which means that for every 1% extension of the total installed capacity, the unit costs fall by 0.29%. For the year 2001 alone, the total contracted capacity has increased by about 13%, which would mean a fall of unit cost by 3.77%. It also indicates an elasticity of −0.10 for the plant capacity, which is lower than for MSF.

2.3. Costs of the ME, VC, and ED Processes

[22] Three other processes, namely multiple effect evaporation (ME), vapor compression (VC) and electrodialysis (ED), also contribute significantly to desalination. ME and VC are thermal processes applied mainly to seawater desalination while ED is a membrane process often used to desalt less saline water. According to *Wangnick* [2002], there are about 143 desalting plants using the ME process worldwide, with a total capacity of 907,000 m^3/d and 289 desalting plants using the VC process with a total capacity of about 1.4 million m^3/d. The VC process was introduced in the 1970s, later than MSF and ME. It was generally used for small- and medium-scale seawater desalination but has been developed rapidly in recent decades. In addition, the report comprises 427 desalting plants by the ED process, with a total capacity of 1.3 million m^3/d.

[23] Figures 6–8 show the unit costs of each process over the total installed capacity. The cost of desalination by the ME process has fallen from \$10.0/m^3 in the 1950s to about \$1.0/m^3 today. For the VC process, the cost has also decreased considerably over time, from \$5.0/m^3 in 1970 to about \$1.0/m^3 at present. As to the ED process, it is remarkable that it has a relatively lower cost than other processes. The average unit cost has gone down from \$3.5/m^3 in the 1960's to less than \$1.0/m^3 today. One reason is that brackish water was largely used as feed water. However, the costs seem to go up a bit at the end of the curve, it is because there are a few plants with unknown water quality, which can be wastewater or even seawater. For brackish water desalination, the average unit cost by ED is about \$0.6/m^3 at present.

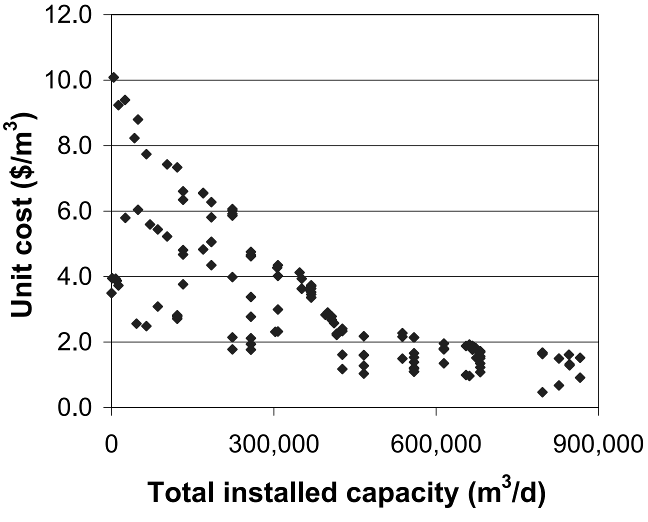

Figure 6. Unit costs by the ME process. See color version of this figure in the HTML.

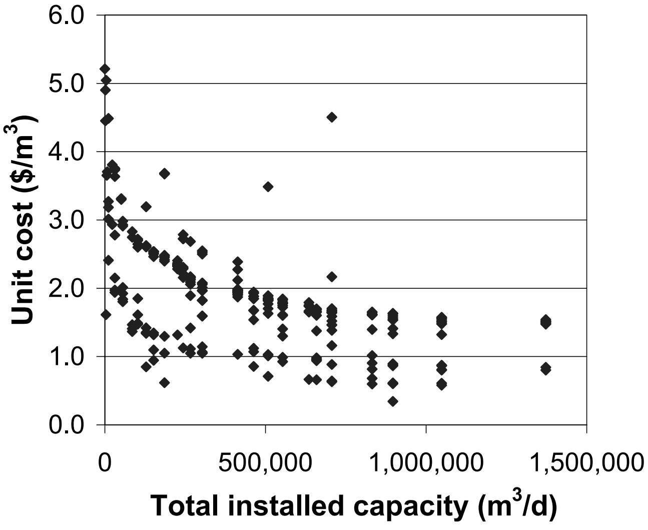

Figure 7. Unit costs by the VC process. See color version of this figure in the HTML.

[24] Similar regressions were conducted for these three processes as well. Given the dispersed spatial distribution of major consumers, the regional dummies are not included. SEA and OTHER are included as water quality dummies for the ME and VC processes while BRACK and OTHER are taken for the ED process. The estimation results with double log function for each process are presented in Table 3. For ME and VC processes, all the explanatory variables are significant at the 0.01 level. For the ED process, however, it is somewhat surprising that brackish water is not significant, which indicates that the unit costs are independent from raw water quality (excluding seawater). The regression results also suggest an elasticity of the total installed capacity of −0.40 for the ME process, −0.26 for VC, and −0.38 for ED. ME and ED learn faster than MSF and RO and may potentially challenge the two dominant technologies; VC is a slow learner and may never be used for anything but niche applications.

[25] To summarize, the unit cost of desalination has fallen considerably since the past 50 years. It was due to the advancing technology in desalination and membrane fields as well as accumulated experiences. The MSF process is still the leading process in seawater desalination, followed by VC and ME processes. The unit cost of desalting seawater has been reduced to about $1.0/m^3$ or less. RO and ED processes are most often used to treat brackish, waste, and river water. The unit cost of desalting brackish water has fallen to about $0.6/m^3$. Because of the lower costs the expansion of the total capacity of RO plants has been pronounced during the last few years. Particularly for seawater RO, recent tenders have indicated lower costs of large seawater RO plants. RO has shown the great potential to become the most economical process for seawater desalination in the future. As technology and practices grow, the cost of desalination will further decrease.

3. Costs of Water Transport

[26] An extensive search of the scientific literature revealed that little has been published on the costs of transporting water. A few informal interviews with engineers made clear that cost information is held by engineering companies and is considered to be commercially sensitive. The literature search also revealed that most of the few articles that discuss water transport costs refer back to *Kally* [1993]. *Kally* [1993], however, only sketches the cost estimates, referring for details back to earlier reports in Hebrew. It does contain a few useful estimates, though, particularly with regard to the costs of transferring water from the Nile to Gaza. Our estimates below should be treated with great caution, however.

[27] Transporting 100 million cubic meters (MCM) of water per year over a distance of 200 km would cost 21.4 cents/m^3. Of this, 4.0 cents/m^3 are for the purchase of Egyptian water, and 5.2 cents/m^3 for lifting the water some 100 m. Consequently, it costs 6.1 cents/m^3 per 100 km to transport water. If the transfer scheme would be extended to 500 MCM, total costs would fall to 19.8 cents/m^3 and transport costs to 5.3 cents/m^3 per 100 km. The unit costs of energy and water purchase would not be affected by the extension. This suggests a capacity elasticity of transport cost of 0.92, that is, for every 1% extension of capacity, total costs increase by 0.92% and unit costs fall by 0.08%.

[28] *Kally*'s [1993] cost estimates make clear that horizontal distance is not the main driver of water transport costs, but the vertical distance is. *Kally* [1993] implicitly makes this point a number of times, but unfortunately does not present cost estimates for alternative lift heights. We therefore assume that the costs of pumping water are linear in the height pumped, in line with Kally's assumption on the energy costs of lifting water.

[29] In his discussion of a possible Red Sea–Dead Sea transfer (for hydropower), *Kally* [1993] provides the effects of soil type and transfer mode on costs. The Nile-Gaza transfer is by canal in soft but stable soil. If the soil is rocky, transport costs would be 13% higher, and if the soil is sandy, costs would be 175% higher. Transporting water by pipe would lead to a cost increase of 271%, while a tunnel would cost 108% more than a canal.

[30] *Gruen* [2000] provides estimates of water transport costs from Turkey to Turkish Cyprus. A 78 km pipeline with a capacity of 75 million m^3 a year would deliver water

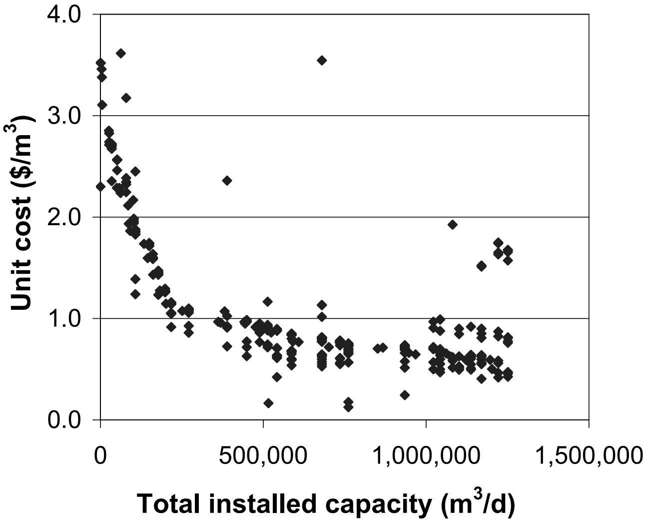

Figure 8. Unit costs by the ED process. See color version of this figure in the HTML.

Table 3. Unit Cost Estimation Results[a]

	ME (Log-Log)		VC (Log-Log)		ED (Log-Log)	
Variable	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Constant	6.06[b] (16.26)	684.72[b] (30.80)	4.53[b] (21.35)	727.39[b] (18.20)	5.42[b] (25.08)	677.53[b] (23.88)
TIC	−0.40[b] (−15.76)		−0.26[b] (−17.75)		−0.38[b] (−26.87)	
YEAR		−0.90[b] (−30.73)		−95.59[b] (−18.16)		−89.15[b] (−23.86)
CAP	−0.08[b] (−2.85)	−0.09[b] (−4.99)	−0.13[b] (−7.04)	−0.12[b] (−6.54)	−0.08[b] (−5.09)	−0.07[b] (−3.91)
SEA	0.74[b] (9.52)	0.76[b] (16.54)	0.44[b] (11.31)	0.39[b] (9.94)		
BRACK					0.0006 (0.02)	−0.03 (−0.71)
R^2 adjusted	0.67	0.88	0.60	0.61	0.68	0.63
F value	94.86	347.57	146.05	148.97	298.47	240.38
Log likelihood	−52.31	20.34	−44.80	−54.55	−65.80	−99.37
n	142	142	288	288	427	427

[a] The t statistics are in parentheses.

[b] Significance is at the 0.01 level.

at 25–34 cents/m^3. According to Kally's data, the horizontal transport alone would cost 16 cents/m^3, while effectively lifting the water by 300 m (the sea between Turkey and Cyprus is at least 1000 m deep) would raise the price to 34 cents/m^3. However, Kally uses an 8% discount rate, while Gruen uses a 4% discount rate; Kally reports that investment and operation and maintenance have an equal share in the costs of transporting water. Correcting for this, Kally's data suggest a cost of some 26 cents/m^3. The cost estimates of *Kally* [1993] seem to be consistent with those of *Gruen* [2000].

[31] *Uche et al.* [2001] report the costs of transporting water in the National Hydrological Plan of Spain. This would involve canals of 900 km long, transporting 1000 million m^3 of water from the Ebro to Barcelona and Southern Spain. *Uche et al.* [2001] estimate that this can be done at some 36 cents/m^3 if a 4% discount rate is taken. On the basis of *Kally*'s [1993] data, the horizontal transport alone would cost at least 52 cents/m^3. Kally's estimates seem to be on the high side.

[32] *Hahnemann* [2002] discusses the Central Arizona Project, which brings some 1800 million m^3/yr from the Colorado river to amongst others Phoenix and Tucson, a horizontal distance of some 550 km, and a vertical distance of some 750 m. *Kally*'s [1993] data suggest that this would cost some 74 cents/m^3, but *Hahnemann* [2002] reports an otherwise unspecified marginal cost of only 5 cents/m^3.

[33] *Liu and Zheng* [2002] estimate the costs of transferring water of the Yangtze to China's north. They provide most detail about the eastern route, which is in a more advanced stage of planning than the middle and western routes. The total amount of water transferred is 32 billion m^3/yr, although only less than a fifth of that will reach the final destination. The main canal would be 1150 km long, and the water would need to be pumped 65 m high. *Liu and Zheng* [2002] estimate the costs at 10–16 cents/m^3; using *Kally*'s [1993] estimates, we find this to be 38 cents/m^3. However, Liu and Zheng's estimates only include capital; according to Kally, operation and maintenance are of the same order of magnitude as investment costs. Moreover, Liu and Zheng apparently use a zero discount rate, and part of the eastern route uses already existing canals. This suggests that the costs estimated by Liu and Zheng are in fact slightly above Kally's estimates.

[34] In sum, the cost estimates of transporting water by *Kally* [1993] are the most detailed in the open literature. Comparing these estimates to those of other studies suggests that Kally may have been overly pessimistic. However, most of these studies are ex ante engineering studies of government projects, which suggests that the actual costs would have been higher. Therefore we continue to use Kally's estimates.

4. Potential of Desalination

[35] Seawater desalination plants are typically located in the coastal area. However, not all the water scarce regions are close to the coast, which generates a need to transport

Table 4. Cost of Desalinated Water to Selected Cities

City, Country	Distance, km	Elevation, m	Transport, c/m^3	Desalination, c/m^3	Total, c/m^3
Beijing, China	135	100	13	100	113
Delhi, India	1050	500	90	100	190
Bangkok, Thailand	30	100	7	100	107
Riyadh, Saudi Arabia	350	750	60	100	160
Harare, Zimbabwe	430	1500	104	100	204
Crateus, Brazil	240	350	33	100	133
Ramallah, Palestine	40	1000	54	100	154
Sana, Yemen	135	2500	138	100	238
Mexico City, Mexico	225	2500	144	100	244
Zaragoza, Spain	163	500	36	100	136
Phoenix, United States	280	320	34	100	134
Tripoli, Libya	0	0	0	100	100

water from desalination plants to where water is needed. In this study, we calculate the total cost comprising the cost of desalination and the cost of transporting desalinated water to the nearest point of distribution. Here we estimate only the cost of source water, not the ultimate costs to the end users. The costs for different end uses vary according to the system of distribution, blending and purification. For agriculture, the cost is perhaps similar to the cost presented here, but for potable water the cost could be increased as much as $\$0.1/\mathrm{m}^3$ (the cost of additional treatment).

[36] Table 4 contains some sample calculations for the costs of desalinated water in selected water-stressed cities. We assume a transport of 100 MCM/yr. Transport costs are assumed to be 6 cents per 100 km horizontal transport plus 5 cents per 100 m vertical transport. Distances and elevations are taken from the Times Atlas of the World. The calculations are illustrative only.

[37] The costs of desalination, here assumed to equal 100 cents/m^3, are typically larger than the costs of transport. Indeed, one needs to lift the water by 2000 m, or transport it over more than 1600 km to get transport costs equal to the desalination costs. Thus desalinated water is only really expensive in place far from the sea, like New Delhi, or in high places, like Mexico City. Desalinated water is also expensive in places that are both somewhat far from the sea and somewhat high, such as Riyadh and Harare. In other places, the dominant cost is desalination, not transport. This leads to relatively low costs in places like Beijing, Bangkok, Zaragoza, Phoenix, and, of course, coastal cities like Tripoli.

5. Conclusions and Discussions

[38] In energy-rich, arid and water-scarce regions of the world, desalination is already an important option. As with all new technologies, progress in desalinating water has been rapid. Whereas it cost about $\$9.0/\mathrm{m}^3$ to desalinate seawater around 1960, the costs are now around $\$1.0/\mathrm{m}^3$ for the MSF process. For RO, the most popular method, the costs have fallen to $\$0.6/\mathrm{m}^3$ for brackish water desalination. There is no reason to believe that the trend will not continue in the future. However, it should be noted that the costs of desalination still remain higher than other alternatives for most regions of the world.

[39] Transporting water horizontally is relatively cheap while the main cost is lifting it up. We find that desalinated water could be delivered to Bangkok and Beijing for $\$1.1/\mathrm{m}^3$, to Phoenix for $\$1.3/\mathrm{m}^3$ and to Zaragoza for $\$1.4/\mathrm{m}^2$. These are probably competitive prices at the moment, and they may well fall in the future. However, getting water to New Delhi would cost $\$1.9/\mathrm{m}^3$, to Harare $\$2.0/\mathrm{m}^3$, and to Mexico City $\$2.4/\mathrm{m}^3$. Desalinated water may be a solution for some water-stress regions, but not for places that are poor, deep in the interior of a continent, or at high elevation. Unfortunately, that includes some of the places with biggest water problems.

[40] It should be noted that desalination processes are accompanied by some negative impacts on the environment. The environmental costs associated with desalination, such as production of concentrated brine and carbon dioxide emissions, are not considered in the study due to lack of data. From the literature, the cost of brine disposal is estimated to be 4–5% of the capital cost for a seawater RO plant [*Hafez and El-Manharawy*, 2002], which is well within the margin of error of our data. In the case of inland brine disposal, brine removal costs can be a more significant portion of desalination costs (10–25%) depending on the circumstances. Therefore, when considering options for massive implementation of desalination, environmental impacts will have to be internalized and to be minimized by proper planning.

[41] In line with desalination, water reuse and recycling are considered and applied increasingly to provide extra usable water. Combining strategies of wastewater reuse and desalination technology makes it possible to convert wastewater into high-quality water that suits various users in industry and agriculture. Wherever there is water stress, the improvement of water use efficiencies should be considered in the first place, but its marginal costs should not exceed the marginal costs of enhancing the water supply through desalination.

[42] The analysis presented here provides a general trend of costs under rough assumptions. The selection of most appropriate technology and approach for a particular plant should therefore be based on the careful study of site-specific conditions and economics, as well as local needs. The cost analysis could be improved by having a more detailed and precise running costs for all the desalting plants. For instance, if we know actual energy costs for each plant, the cost estimates would be more realistic. This could be done by collecting a relative smaller amount of plants with high-quality data. It would also be interesting to have information on the costs of delivering desalinated water on a geographically explicit basis throughout the world. If we would know the costs of water supply from all other sources for a region, we could then evaluate the potential of desalination. This would require further study in the field.

[43] **Acknowledgments.** Financial support by the Michael Otto Foundation for Environmental Protection is gratefully acknowledged. Uwe A. Schneider provided valuable comments for improving the paper. The comments and suggestions from two anonymous reviewers are highly appreciated. All errors and opinions are ours.

References

Banerjee, A., et al. (1993), *Co-integration, Error Correction, and the Econometric Analysis of Non-stationary Data*, Oxford Univ. Press, Oxford.

Buros, O. K. (2000), The ABCs of desalting, report, 2nd ed., Int. Desalination Assoc., Topsfield, Mass.

Busch, M., and B. Mickols (2004), Economics of desalination—Reducing costs by lowering energy use, *Water Wastewater Int.*, *19*(4), 18–20.

Chatfield, C. (2004), *The Analysis of Time Series*, 6th ed., CRC Press, Boca Raton, Fla.

Ettouney, H. M., et al. (2002), Evaluating the economics of desalination, *Chem. Eng. Prog.*, *98*, 32–39.

Gleick, P. H. (2000), *The World's Water 2000–2001, The Biennial Report on Freshwater Resources*, Island, Washington, D. C.

Gruen, G. E. (2000), Turkish waters: Source of regional conflict or catalyst for peace?, *Water Air Soil Pollut.*, *123*, 565–579.

Hafez, A., and S. El-Manharawy (2002), Economics of seawater RO desalination in the Red Sea region, Egypt. part 1. A case study, *Desalination*, *153*, 335–347.

Hahnemann, W. M. (2002), The Central Arizona Project, *Working Pap. 937*, Div. of Agric. and Nat. Resour., Univ. of Calif., Berkeley.

Kally, E. (1993), *Water and Peace: Water Resources and the Arab-Israeli Peace Process*, Greenwood, Oxford, U. K.

Liu, C. M., and H. X. Zheng (2002), South-to-north water transfer schemes for China, *Water Resour. Dev.*, *18*(3), 453–471.

Tol, R. S. J., and A. F. de Vos (1998), A Bayesian statistical analysis of the enhanced greenhouse effect, *Clim. Change*, *38*, 87–112.

Tsiourtis, N. X. (2001), Desalination and the environment, *Desalination*, *141*, 223–236.

Uche, J., et al. (2001), Hybrid desalting systems for avoiding water shortage in Spain, *Desalination*, *138*, 329–334.

Wangnick, K. (2002), 2002 IDA worldwide desalting plants inventory, *Rep. 17*, Int. Desalination Assoc., Topsfield, Mass.

Zhou, Y., and R. S. J. Tol (2004), Implications of desalination for water resources in China—An economic perspective, *Desalination*, *164*, 225–240.

R. S. J. Tol, Research Unit Sustainability and Global Change and Center for Marine and Atmospheric Science, Hamburg University, D-20146 Hamburg, Germany.

Y. Zhou, International Max Planck Research School of Earth Systems Modeling, Bundesstrasse 55, D-20146 Hamburg, Germany. (yuan.zhou@dkrz.de)