NEW YORK STATE

PUBLIC SERVICE COMMISSION

--X

Proceeding on Motion of the Commission :
to Examine United Water New York, Inc.'s : Case 13-W-0303
Development of a New Long-Term :
Water Supply Source :

--X

MOTION FOR A PRUDENCE INVESTIGATION
ON BEHALF OF THE
TOWN OF RAMAPO

July 9, 2014

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INTRODUCTION

In its Notice Seeking Comments and Scheduling Conference (Issued May 22, 2014) ("Notice"), the Commission noted that

> … any determination of imprudence with respect to the development costs can best be made after a determination of need in Case 13-W-0303. To that end, in commenting on the Staff Report on Need interested parties may make a prima facie case of imprudence regarding UWNY's actions related to the long-term water supply source.

Notice at page 2. Accordingly, this Motion on behalf of the Town of Ramapo ("Town" or "Ramapo") that is being filed simultaneously with the Town’s Comments on the Staff Report on Need (“Comments”), will establish that United Water New York, Inc. (“UWNY”) acted imprudently in:

1. Selecting reverse osmosis desalination (“RO desal”) technology for a new long-term water source in the fifth wettest county in New York State;
2. Continuing with the project in the face of declining demand and the knowledge, as early as 2009, that improved circumstances regarding the condition of Rockland County’s aquifer was found by the USGS;
3. Continuing to seek permits for a project that is likely to be never needed[1]; and
4. Not demanding written explanations for professional services provided on the invoices from its major engineering and environmental contractors in violation of the Uniform System of Accounts and paying those deficient invoices.

In short, UWNY was amazingly imprudent in starting,

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[1] In the Town’s companion Comments, it will be argued that pursuing permits for a project that may never be needed is not only wasteful of ratepayer funds but is in all probability a futile exercise since the FEIS cannot not be issued without a demonstration of need. Hence, the permits cannot be obtained without the FEIS.

staying and refusing to stop this controversial project that has unified Rockland County's elected leaders across all parties and its businesses and citizens across all demographics. It is the Town's position that the massive expenditures for this project should not be charged to the ratepayers. Because of UWNY's extraordinary imprudence, all costs associated with this project should be charged to the shareholders.

Even if one were to suspend reality and find *arguendo* that UWNY was not imprudent in its actions in starting this project, then there is still no basis to allow recovery of the expenditures on the Haverstraw Desalination Project. As has been shown in the surcharge Case 13-W-0246, there is no explanation of the services provided for the vast majority of engineering and environmental vendors. How can this Commission allow a surcharge that is premised on such inadequate cost documentation? Not one Commissioner would pay such a detail deficient bill from his or her plumber. And the Commission should use that common sense standard here to deny recovery of any costs that is not supported. This is not in compliance with the Uniform System of Accounts that requires UWNY to keep its books so that all costs charged to ratepayers can be fully reviewed for appropriateness by the Staff and this Commission.

By not requiring detailed explanation of the charges for professional services, UWNY's accounting for this project has been manifestly imprudent. Paying invoices as UWNY has done for over $24 million (and that is only for the top four ($ volume) engineering and environmental firms) is manifestly imprudent and demonstrates that UWNY does not have even rudimentary cost controls in place and that is not only reflective of poor management, but is in itself imprudent.

THE LEGAL STANDARD

Department of Public Service Staff ("Staff") has succinctly summarized the legal standard to be applied to the instant matter in "Proposed Prima Facie Submission Regarding the Prudence of Consolidated Edsion Company of New York, Inc., In its Internal Controls and Failure to Detect Fraud Waste and Abuse in its Capital Program and Operations and Maintenance Expenditures." Staff's submission is set forth in full:

> New York Public Service Law §65(1) requires the Commission to set just and reasonable utility rates. In doing so, the Commission may "consider all factors which in its judgment have any bearing on determining just and reasonable prices, rates and charges as to utility costs."[7] The Commission has the authority to determine whether a utility's costs of service should be borne by the utilities' ratepayers or its shareholders – shareholders are held responsible for those costs that a utility "imprudently" incurred in carrying out its obligation to provide safe and adequate service.[8] "It would be neither just nor

> reasonable for a utility's customers to bear the cost of inefficient management or poor planning."[9]
> The Commission must determine whether "the utility acted reasonably, under the circumstances at the time, considering that the utility had to solve problems prospectively rather than reliance on hindsight" and the burden,
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> 7 See *Matter of Abrams v. Public Serv. Comm'n of State of N.Y.*, 136 A.D.2d 187, 189 (3d Dept. 1988); see also Public Service Law, Article 4, §65 (1), §66(12), §72).
>
> 8 *Matter of Long Island Lighting Co. v. Public Serv. Comm'n of State of N.Y.*, 134 A.D.2d 135 (3d Dept. 1987).
>
> 9 *Id*. p. 143, quoting Consolidated Edison Company of New York, PSC Opn. No. 79- 1 (issued January 16, 1979).
>
> ultimately, is on the utility to "justify its conduct."[10] In the first instance, however, Staff is obliged to demonstrate a tenable basis for imprudence.[11] Staff submits that the information provided below demonstrates the imprudence of Con Edison's decision-making and its failure to follow through with properly conducted and coordinated internal investigations culminating in the arrests of several of its construction management employees for activity that inflated the costs of construction projects from 2000 to 2010 when Con Edison strengthened its internal controls as a result of information learned from the underlying arrests.
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>
> 10 *Id*. p. 143-155.
>
> 11 See *Id*. p. 144.

Here the Town will "demonstrate a tenable basis for imprudence." Indeed, the Town believes that the facts already adduced in the three UWNY proceedings to date: the General Rate Case 13-W-0295; the Surcharge Case 13-W-0246 and this Need Case 13-W-0303 are more than sufficient to find that UWNY has acted in a grossly imprudent manner in the conception and management of this unneeded desalination project.

THE SELECTION OF DESALINATION TECHNOLOGY IN THE FIFTH WETEST COUNTY IN NEW YORK WAS IMPRUDENT PER SE

UWNY was lusting after a capital intensive desalination facility well before the Commission ordered it to develop a new long-term water supply in its 2006 Order. How else was it able to file a report within 30 days of the issuance of the 2006 Order selecting desalination as the preferred choice for a new long-term water supply? The analysis of alternatives presented in its DEIS was inadequate from a professional and common sense perspective. The analyses were rigged to favor RO desal.

The DEIS looked at four alternatives:

1. Process and Operational Alternatives
2. Project Design Alternatives
3. Ambrey Pond Reservoir Alternative
4. Wastewater Reuse Alternative

First, it should be noted that the project goal of an increase in supply of 7.5 mgd was never proven. It was an *a priori* construct probably based on available components and not based on any assessment of the need for an additional 7.5 mgd.

> At this time, United Water is proposing the Haverstraw Water Supply Project because with 30 years of technological advancements in water treatment technology, the Haverstraw Water Supply Project is a more reliable and more financially and environmentally prudent project than the Ambrey Pond project.

See DEIS on page 1-6. Nothing could be further from the truth and UWNY knew that when it drafted the DEIS. A project that has to be shut down if there is an oil spill on the Hudson River or a release of radionuclides from Indian Point cannot be said to be reliable. And to say that the project is more financially prudent is ridiculous on its face. Taking water from Haverstraw Bay and reintroducing concentrated brine to one of the most precious aquatic environments in the Hudson River is hardly environmentally prudent.

Second and of greatest importance, the DEIS did not look at a menu of alternatives that taken together would be able to satisfy the project goals. So for example, the comparison of the Enhanced Water Conservation and Green Infrastructure alternative was compared to whether it would reduce demand by 7.5 mgd and thus was found wanting. Similarly, the Enhanced Leak Management Alternative was also found wanting because it could not reduce demand by 7.5 mgd.

Likewise, the surface water storage alternatives were found wanting because not one could meet the arbitrary 7.5 mgd goal. The increased storage at Lake DeForest would only provide a 0.3 mgd increase in safe yield[2]. The Quarry Reservoir Alternatives were found wanting:

Suffern Quarry	2.8 mgd safe yield increase
Tompkins Cove Quarry	6.1 mgd safe yield increase
Congers-Haverstraw Quarry	3.8 mgd safe yield increase

The latter two quarry alternatives were “not available within the required timeframe.” See DEIS Chapter 18, Table 18-1.[3] Perhaps now that there is time, these alternatives could and should be further investigated by the Rockland County Water Supply Task Force [need exact name].

RO desal is an important technology for those areas of the world that are deficient in fresh water. With an average annual rainfall of 49 inches per year, Rockland County is hardly deficient in fresh water. The selection of RO desal was imprudent from the beginning. This can be shown by the capital and operating costs that were known or could have been known to UWNY. For example, the Southmost desalination facility in south Texas was estimated to cost (in 2006 dollars) $2.36 per 1,000 gallons for a 7.5 mgd.

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[2] It should be noted that the Letchworth Water Treatment Facility is not operating at full capacity year round leaving a potential additional supply of 0.5 mgd.

[3] http://haverstrawwatersupplyproject.com/images/stories/deis%202012/DEIS/DEIS_18_Alternatives_Overview_and_Summary.pdf

> For the Southmost facility, when a commitment was made to build a facility for $26.2 million, an implicit commitment for another $39.1 million (basis 2006 dollars) was also made for Continued and Capital Replacement costs. Investigation into life-cycle costs during the design and planning stages of a desalination facility can assist with determining the least-cost asset configuration to adopt and operational methods to employ.[4]

The source water for the Southmost facility is brackish with about 3,500 ppm of salinity – comparable to the average anticipated for the Haverstraw project. Project construction for Southmost was started in February 2003 and completed 20 months later in September 2004 due to "various delays and challenges during the construction phase." Southmost Report at page 9. The initial construction cost was $26.2 million or $3.49 million per mgd.

This should be compared to the latest cost for the Haverstraw Desalinaton Project at $153 million for 2.5 mgd or $61.2 million per mgd. This is a staggering 17.5 times more expensive on an mgd basis. Indeed, the pre-construction costs for the Haverstraw plant are 2.3 times the entire initial construction cost of the Southmost facility that is three times the size of Phase I for the Haverstraw Desalination plant. If this is not an indication that something went terribly wrong with this

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[4] An Analysis of the Economic and Financial Life-Cycle Costs of Reverse-Osmosis Desalination in South Texas: A Case Study of the Southmost Facility (September 2009) ("Southmost Report") attached hereto as Appendix A.

project, then the Town is at a loss to know what more evidence is needed since the Southmost plant was constructed and in operation well before the 2006 JP was signed. Why did UWNY take advantage of this experience? Why would UWNY develop a cost estimate of $69 million initially for 2.5 mgd facility when one had been built that was three times the size at one-half the cost? If this is not evidence of imprudence, then again the Town is at a loss to determine what would be considered imprudent.

Another paper entitle the Cost of Desalination in Texas is attached hereto as Appendix B. It shows capital costs ranging from $2 to $9.1 million (2011 $) for plants in the 1.2 to 2.5 mgd size range. These plants used brackish source water, not seawater.

ECONorthest – Deficient Capital, O&M and Alternative Cost Comparisons

An April 19, 2002 Report from ECONorthwest, attached hereto as Appendix C, addressed the "cost information: data and the sources of data, analytical methods, assumptions made as part of the analysis, and the comparison of cost information and results across alternatives." The Report at page 1 concluded as follows:

> - *The almost complete lack of transparency and documentation regarding the data, assumptions, and analytical methods used to generate the cost results.* By excluding such basic details, the authors

of the cost sections of the DEIS report results that lack credibility as a source of information for decision makers and stakeholders.

- *The DEIS authors do not use consistent measures of cost effectiveness across all alternatives.* Measuring the cost of the preferred alternative using the method applied to the wastewater reuse alternative shows that the proposed project is not necessarily the most cost effective option.

- *The cost analysis as described in the DEIS does not conform to commonly-accepted standards for measuring and describing cost-effective comparisons among competing alternatives.* The National Research Council and other industry experts provide detailed guidelines for conducting the types of cost-effective analyses at issue in the DEIS. Had the authors of the cost sections of the DEIS following these guidelines they could have produced cost results that decision makers and stakeholders could have confidence in as they deliberate the competing alternatives. Instead, the DEIS cost analysis is analytically deficient.

Lack of Transparency – Capital Costs

The ECONorthwest Report found as follows:

The list of relevant analytical details not included in the two-paragraph summary of project capital costs includes:

- Phase 3 of the project would not happen until after 2030, 18 years in the future. What inflation rate did the analysts use to account for increases in construction costs?
- Likewise, what discount rate did the analysts apply to future costs to calculate the present value of future costs?
- What are the individual line items, or categories, in the cost calculation?
- What are the contingency and design costs?

- Does the analysis include all the relevant costs of new or upgraded infrastructure upon which the operation of the proposed project would rely?
- At what capacity did the analysts assume the plant would operate?
- What analytical assumptions or data account for the low and high cost estimates?
- What data sources and other analytical assumptions does the analysis rely on?
- What are the major risks and uncertainties associated with the cost calculation and how do they affect the results?

This is an extraordinary list of questions that are not answered in UWNY's DEIS. And because desalination of estuarine water is so uncommon, the answer to these questions is even more important. The Congressional Research Service, in an August 15, 2011 Report entitled: Desalination: Technologies, Use and Congressional Issues (Nicole T. Carter) stated: "The cost of desalination remains a barrier to adoption. Like nearly all new freshwater sources, desalinated water comes at substantially higher costs than existing sources." That report is attached hereto as Appendix D and will be referred to as the CRS Report.

The CRS Report notes that the cost competitiveness of RO desal is heavily dependent on the cost of electricity.

> Additionally, the electricity consumed in desalination has greenhouse and other emissions associated with it. Price and emissions have driven many desalination proponents to investigate renewable energy supplies and co-location with power plants.[footnote omitted] As electricity becomes more expensive, less electricity-intensive options (such as conservation, water purchases, and changes in water pricing) increase in competitiveness relative to desalination.

CRS Report at 3. The CRS Report also notes other health risk concerns:

> While the quality of desalinated water is typically very high, some health concerns remain regarding its use as a drinking water supply. For example, the source water used in desalination may introduce biological and chemical contaminants to drinking water supplies that are hazardous to human health, or desalination may remove minerals essential for human health. For example, a health concern about boron has been raised in relation to seawater desalination; this is an uncommon concern for traditional water sources. Boron is know to cause reproductive and developmental toxicity in animals and irritation of the digestive tract, and it accumulates in plants, which may be a concern for agricultural applications.
>
> There are concerns about boron in the freshwater produced from seawater desalination because the boron levels after basic reverse osmosis commonly exceed current World Health Organization health guidelines and the U.S. Environmental Protection Agency (EPA) health reference level. Boron can be removed through treatment optimization, but that treatment could increase the cost of desalted seawater. Boron is one of a number of potential health concerns requiring further attention and investigation as seawater desalination is used in large-scale application for water supply; for example, microorganisms unique to seawater and algal toxins may also pass through reverse osmosis membranes and enter the water supply.

CRS Report at 4 – 5. The CRS Report also notes that

> The application of desalination in the United States is also challenged by the use of estuarine water in many of the facilities being contemplated. Estuarine water, which is a brackish mixture of seawater and surface water, has the advantage of lower salinity than seawater. Application of desalination to estuarine water is uncommon, with the facility in Tampa being the largest of its kind in the United States. The presence of surface water (which tends to be more contaminated than seawater) in estuarine water may complicate compliance of desalinated estuarine water with federal drinking water standards. (emphasis added).

CRS Report at 5. Returning the ECONorthwest report concludes that

> The lack of transparency and documentation combined with the relatively large spread between the estimated low and high construction costs for the proposed project raises questions regarding the source of the cost results. Specifically, readers are left to wonder as to the data, assumptions, and analytical methods that the DEIS authors used to generate a cost estimate that varies by $50 million dollars, or by 36 percent relative to the low-cost estimate.

ECONorthwest Report at 4.

Of some interest is the fact that the federal government has authorized spending on R & D [cite CRS Report], but there is no evidence that UWNY sought any such grants from the federal government or any other program. This omission constitutes imprudence and is similar to UWNY's gross negligence in not seeking property tax reduction through economic obsolescence adjustments as the Commission found in the very recent rate Order.

O&M Costs – Not Transparent

The ECONorthwest Report is equally critical of the way UWNY presented the Operating and Maintenance Costs on pages 4 to 5:

> The DEIS description of operating costs of the proposed project is similarly meager. The entire subsection on operating costs (Section 2.4.4.2.) reads as follows:
>
> > "Upon completion, the Proposed Project would incur life-cycle costs during the course of its operations. These operating costs arise from the Project's need to consume electricity, gas, and process materials. In addition, the Project would require ongoing maintenance and periodic equipment repairs and replacement. The estimated annual life-cycle cost of operating the Proposed Project, excluding depreciation, personnel and property tax expenses, would be approximately $2.2 million per year during Phase 1, increasing to $4.0 million during Phase 2, and $5.6 million per year at completion. The cost estimates were prepared based on the baseline design described in this chapter and using generally accepted scientific and engineering practices."8
>
> Much of the criticism above regarding the lack of transparence and documentation in the analysis of capital costs applies to the analysis of operating or life-cycle costs for the proposed project. This is especially true for three operating costs that industry experts report as being particularly important: energy costs, the costs of managing salt concentrate, and the costs of membrane replacement.9 Specific to electricity costs, the CRS report states, "Uncertainty in electricity prices ... creates significant uncertainty in the operating costs of desalination facilities, which influences the technology's attractiveness as a water supply." A full accounting of operating costs for the proposed project would include not only the current and future costs of electricity to operate the facility, but also the cost

of electricity to pump water upslope from the water source to the plant. A related cost is the cost of carbon emissions associated with the energy demand and other aspects of operating the proposed project.[10] Specific to the costs of concentrate management, a report on desalination by the National Research Council states, “... when low-cost concentrate management methods are not available, brackish groundwater desalination costs can reach or exceed seawater desalination costs.”[11] On this topic the author of the CRS report concluded, “For inland brackish desalination, significant constraints on adoption are the uncertainties and the cost of the waste concentrate disposal.”[12] Specific to the costs of membrane replacement, another industry expert states, “The major maintenance cost [of a desalination plant] pertains to the frequency of membrane replacement, which is affected by the feedwater quality.”[13] The authors of the cost sections of the DEIS provide no information on if or how they accounted for these and other uncertainties that can affect the operating costs of the proposed project, and the resulting costs to ratepayers.

Deficient Cost Comparison of Alternatives

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[8] DEIS, page 2-43.

[9] Carter, 2011; Committee on Advancing Desalination Technology, National Research Council. 2008. Desalination: A National Perspective. The National Academies Press. ISBN: 0-309-11924-3, http://www.nap.edu/catalog/12184.html. (NRC, 2008); Younos, Tamim. 2005. “The Economics of Desalination,” Journal of Contemporary Water Research & Education, 132: 39-45. University Council on Water Resources. December.

[10] Carter, 2011, page 4. [11] NRC, 2008, page 153. [12] Carter, 2011, page 5.

The ECONorthwest report also found that the cost comparisons among alternatives were deficient.

> The analysis of the cost of alternatives to the proposed project exhibits the same analytical deficiencies we describe above. The DEIS includes major costs of alternatives without documenting data sources, analytical assumptions, or methods. For example, the section of DEIS Appendix 18A.2 on wastewater reuse alternatives provides some details on the potential demand for wastewater reuse, but little to no information on the cost calculations for these alternatives. In a specific example, the DEIS authors assume without explanation a contingency factor for construction costs of 50 percent.14 A reader is left to wonder how the authors concluded that the wastewater reuse alternatives warrant such a high contingency factor. Because of the almost total lack of information on the costs analysis, decision makers and stakeholders will not know the extent to which assumptions about the contingency factor and other costs overstate the true cost of a wastewater alternative. For comparison we note that the DEIS section on the cost of the proposed project has no information on a contingency factor. Relevant analytical questions include: did the analysis of the proposed project include a contingency factor? If so, what percent?
>
> The analytical deficiencies described above render the cost sections of the DEIS almost useless for those interested in understanding or independently verifying the analysis that produced the cost results reported in the DEIS. But perhaps the most significant omission from the cost analysis is the lack of transparency and documentation regarding how the construction and operations and maintenance costs of the proposed project would impact ratepayers. The DEIS authors report their conclusions as to the costs to ratepayers, but—similar to their other cost results—provide no details as to the data, methods, or assumptions they used to generate their results.

UWNY’s DEIS Does Not Conform to Commonly Accepted Standards

The ECONorthwest Report was highly critical of the fact that

> The cost analysis reported in the DEIS does not conform to commonly accepted standards for reporting and describing cost-effectiveness comparisons among competing alternatives. The National Research Council (NRC) and other industry experts provide detailed guidelines for conducting the types of cost-effectiveness analyses at issue in the DEIS. For example, a NRC book on desalination includes a chapter on describing the costs and benefits of desalination facilities. [footnote omitted]. Among the cost information that the NRC reports for desalination that the DEIS does not include:
>
> - annualized capital costs
> - parts/maintenance
> - chemicals
> - labor
> - membranes
> - energy costs
> - concentrate management

ECONorthwest at 8. The ECONorthwest report concludes as follows:

> In contrast to the analytically-deficient cost information in the DEIS, an analysis that followed the guidelines described above, and, or, used one of the industry-accepted models—and clearly reported the relevant data, methods and assumptions—would yield cost results that decision makers and stakeholders could have more confidence in as they deliberate the competing alternatives. Given the analytical deficiencies in the DEIS, we urge regulators to consider conducting an independent review of the cost analysis reported in the DEIS, engage a consultant familiar with industry-accepted standards for cost analyses of desalination plants to revise the analysis reported in the DEIS, or both. Based on the experience

> of the Tampa desalination plant, the author of the CRS report recommends such oversight for proposed desalination plants. "... [T]he Tampa project illustrates some of the risks of working with private water developers and lowest-bid contracts without sufficient external review and accountability mechanisms."[footnote omitted].

Spending on Pre-Construction Increased While Demand Decreased

The Annual Average Day Demand peaked in 2005 to 2007 and then started to decline though 2010 the last year shown in the DEIS. But that decline continued in 2011, 2012 and 2013. It was imprudent for UWNY to not update these statistics while the DEC was reviewing the DEIS. It was also imprudent to continue to claim that the project was immediately needed when the statistics showed otherwise.

Contracts with Engineering and Environmental Vendors were Apparently Open-Ended with no Controls or Performance Metrics

Because the contracts with the major engineering and environmental vendors: Black & Veach, AKRF, CDM and HDR were never produced even under the protective order, the record in this case is bereft of any information on the nature of those contracts other than by implication. Apparently, there were no controls or performance metrics.

This can be inferred from a review of the public and confidential portions of Exhibit 1. There are no credits – not a single one over the seven years this project was under pre-construction development. One cannot even characterize these contracts as "turnkey" that can include BOO(T) (Build-Own-Operate (-Transfer)) or another popular alternaive Engineering-Procurement-Construction (EPC).

In "Capital cost estimation of RO plants: GCC countries versus southern Europe", attached hereto as Appendix E, the authors (Loutatidou, Chalermtha, Marpu and Arafat) developed a cost estimation model based on a 950 plant data set including both SWRO (sea water reverse osmosis) and BWRO (brackish water reverse osmosis) that were built under EPC contracts between 1985 and 2013. These plants were located in GCC (Gulf Cooperation Council) countries and southern Europe. The cost of each EPC contract was converted into United State Dollars and then escalated to 2013 using the Consumer Price Index. It was found that 96% of the EPC cost variance was explained by the size of the project and this was true for both SWRO and BWRO plants in both regions.

The paper uses cubic meters per year of finished water to measure capacity. So the Haverstraw Desalination

Project, Phase I, of 2.5 million gallons a day must be converted to cubic meters per year. There are 264.17 gallons in a cubic meter. Therefore, a 2.5 million gallon per day facility produces 9,463.6 cubic meters per day or 3.45 million cubic meters per year. To facilitate comparison, using scientific notation, this is 3.45E+06. Looking at Figure 3 from the paper, one sees that the EPC cost in 2013 dollars for that size plant is approximately $34.5 million in southern Europe and somewhat less in the GCC region. The Haverstraw Desal plant is therefore going to cost 4.4 times more than plants built in southern Europe or in the Gulf region. This is further evidence of imprudence.

The paper notes that there were three contractors for BWRO plants in each region that obtained the majority of the contracts. In the GCC region: Veolia, Al Kawther and General Enterprises and in southern Europe: Culligan, Tedagua and Osmo Systemi. The paper found that

> This implies that the CAPEX of an RO plant is not strongly dependent on the choice of EPC company contracted. One exception is seen in the case of BWRO plants contracted in southern Europe. Here, it appears that the choice of a certain EPC contractor (Culligan) has often led to the development of BWRO plants with normalized capital below that of the other two leading companies (Tedagoa and Osmo Systemi).

The record is silent on whether UWNY asked any of these leading contractors to bid on the design and construction of the Haverstraw desalination project. So this is further evidence of imprudence to use firms without substantial desalination engineering and construction experience, especially since UWNY touts its parent's extensive international experience.

UWNY Was Imprudent to Continue this Project In View of the USGS Report Findings that It Knew About in 2009.

Not only was demand declining, but it was found that the Rockland aquifer was recharging at a higher rate than expected. UWNY knew the substance of the USGS reports as early as 2009. See transcript page 624 in Case 13-W-0246.

It is Imprudent to Continue to Seek Permits for an Unneeded Project.

Staff appears to want to salvage something of value from this tragic project and so urges UWNY to continue to seek the necessary permits. The problem is both practical and legal. As a practical matter, no agency with jurisdiction is going to waste their limited resources on a project that is not needed anytime soon. As a legal matter, it is highly doubtful that the DEC can complete the FEIS project now that Staff has recommended to the

Commission that UWNY be relieved of the obligation to build a new long-term water supply based on the lack of need.

CONCLUSION

It is abundantly clear that UWNY was committed to building a RO desal plant and then forged ahead under Commission Orders even when the fact supporting those orders had changed significantly. UWNY had an obligation to bring those changed circumstances to the Commission and did not do so and that is further evidence of imprudence. The Town's Motion should be granted and the Commission should commence a prudence investigation immediately.

Respectfully submitted.

on behalf of the
Town of Ramapo
Daniel P. Duthie
Daniel P. Duthie

APPENDIX A

AgriLIFE RESEARCH
& EXTENSION
Texas A&M System

TEXAS A&M UNIVERSITY

COLLEGE OF AGRICULTURE
AND LIFE SCIENCES

TR-295
2009

An Analysis of the Economic and Financial Life-Cycle Costs of Reverse-Osmosis Desalination in South Texas:
A Case Study of the Southmost Facility

By:
Allen W. Sturdivant
M. Edward Rister
Callie S. Rogers
Ronald D. Lacewell
Joseph W. "Bill" Norris
Jesus Leal
Jose Garza
Judy Adams

Texas Water Resources Institute Technical Report
September 2009

Texas Water
Resources Institute
make every drop count

TR-295
September 2009

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Texas Water Resources Institute
Texas AgriLife Research
Texas AgriLife Extension Service

An Analysis of the Economic and Financial Life-Cycle Costs of Reverse-Osmosis Desalination in South Texas:

A Case Study of the Southmost Facility

September 2009

Texas Water Resources Institute Report:
TR-295

by:
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Cover photo by Sturdivant (2007).

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This report relies heavily upon primary data developed, maintained, and provided by NRS Consulting Engineers (NRS) of Harlingen, TX, the Brownsville Public Utilities Board (BPUB) of Brownsville, TX, and the Southmost Regional Water Authority of Brownsville, TX. We thank these collaborators, for without their assistance, this particular work would not have been possible. Further, since the methodology used in this analysis mimics that of another spreadsheet model (i.e., RGIDECON$^{©}$, as documented in Rister et al. 2009), we would like to again reiterate our appreciation to all the individuals noted in that document for their assistance.

Editor's Note

This report is an update to an earlier article (Sturdivant et al. 2007) which also reported on the Southmost facility. The results presented herein are more comprehensive and reflect newer information which provides a more accurate analysis.

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Table of Contents

Table of Contents, continued

Item **Page**

List of Figures

List of Tables

List of Tables, continued

An Analysis of the Economic and Financial Life-Cycle Costs of Reverse-Osmosis Desalination in South Texas:

A Case Study of the Southmost Facility

Abstract

Desalination provides a supply alternative for potable water for many communities, along with possible defenses against security threats potentially affecting clean water supplies. The economic and financial life-cycle costs associated with building and operating the Southmost desalination facility (near Brownsville, TX) in South Texas are investigated using the spreadsheet model DESAL ECONOMICS©. Primary data key to this analysis include actual initial construction costs, annual continued costs (i.e., for source-water acquisition and transport, pretreatment, purification, and delivery), capital replacement expenses, and desalination-process parameters. The input data used reflect the unique location and quality of source water, process-flow design, asset selection and configuration, management structure, local cost rates, and employed operational methods unique to the Southmost facility. Thus, the specific results are only applicable to the Southmost facility for a specific time, but do provide useful information and insight into life-cycle costs for public and commercial desalination facilities in a more general sense.

Annuity equivalent costs are reported (on both a \$/acre-foot (ac-ft) and \$/1,000 gallons of finished water basis, f.o.b. (free on board) municipal delivery point) for seven individual operational/expense areas, as well as for the entire desalination facility. Results are also presented across different cost types, categories, and items. The baseline results are deterministic, but are expanded to include sensitivity analyses of useful life, initial construction costs, annual energy costs, and production efficiency rate, amongst others.

The current estimated total annual life-cycle costs (in 2006 dollars) to produce and deliver desalinated water to a point in the municipal delivery-system infrastructure for the Southmost facility are \$769.62/ac-ft {\$2.3619/1,000 gal.}. These baseline estimates apply to the Southmost facility and are sensitive to changes in the production efficiency level, and costs incurred for energy, chemicals, initial construction, etc. Also, results indicate significant outlays, beyond those of Initial Construction, are involved with desalination. For the Southmost facility, when a commitment was made to build a facility for \$26.2 million, an implicit commitment for another \$39.1 million (basis 2006 dollars) was also made for Continued and Capital Replacement costs. Investigation into life-cycle costs during the design and planning stages of a desalination facility can assist with determining the least-cost asset configuration to adopt and operational methods to employ.

Also included are modifications to certain key data-input parameters that provide 'modified results' which facilitate a more fair basis of comparing facilities and/or technologies. The modified results, which are considered appropriate to use when comparing to similarly-calculated values (for other facilities or technologies), are \$615.01/ac-ft/yr {\$1.8874/1,000 gal./yr} (basis 2006 dollars).

An Analysis of the Economic and Financial Life-Cycle Costs of Reverse-Osmosis Desalination in South Texas:

A Case Study of the Southmost Facility

Introduction

In the 1990s, water emerged as a critical issue for the Texas Lower Rio Grande Valley because of rapid population growth, a prolonged drought, and shortfalls in water deliveries from Mexico over many years.[1] Since that time, opportunities for, and investigations into, easing the stress from limited water (for municipal, industrial, and agricultural users) have taken many paths, with key identified alternatives including:

» water conservation in irrigation district water-conveyance systems,
» on-farm and municipal water-conservation measures, and
» desalination of brackish groundwater and/or seawater.

Alternatives, listed and otherwise, are capable of increasing the available local water supply, either by efficiency improvements in transport or usage, or by manufacturing.[2] Desalinated water is not considered a viable alternative for traditional agricultural irrigation purposes.

When prioritizing and/or selecting among alternatives, a plausible query is "Assuming equivalent quality (relatively speaking), which is the most cost efficient?" An appropriate approach for resolving this question is to identify and define each alternative as a capital investment (i.e., project) alternative, with each project likely differing in its initial and continued costs, quantity and quality of output, expected useful life, etc. Proper implementation of accounting, finance, and economic principles and techniques (i.e., capital budgeting), and consideration of appropriate quality-treatment cost adjustments can transform such data into comparable annual cost measures (e.g., \$/acre-foot or \$/1,000 gallons) for each alternative. Deriving and having comparable (i.e., 'apples-to-apples') costs can be useful in numerous situations, including regional water-resource planning, by highlighting the alternative(s) providing *the most bang-for-the-buck*.[3]

This analysis addresses the economic and financial life-cycle costs of one of the water-supply alternatives for South Texas (i.e., desalination of brackish groundwater), using actual construction and continued costs for an operating desalination facility. The method of analysis

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[1] Shortfalls in water deliveries from Mexico are in reference to The 1944 Treaty, a binational treaty in which the U.S. annually provides Mexico with 1.5 million ac-ft from the Colorado River, while Mexico in return annually provides the U.S. with 350,000 ac-ft from the Rio Grande. As of September 30, 2005, Mexico had paid its water debt which accumulated during 1992-2002 (Spencer 2005).

[2] Here, "manufacturing" refers to desalination as it "makes" potable water from previously unavailable or contaminated water. Another example is water reuse, which can provide potable or non-potable water.

[3] The phrase 'apples-to-apples' is useful lay terminology referring to the annuity-equivalent results being 'adjusted' for time and stated in current (i.e., 2006) dollars, thereby allowing comparisons across projects. Doing so is common among capital-project comparisons and, for example, allows a desalination facility (or component) having a 30-year useful life to be compared with one having a 50-year useful life. That is, the project alternative having the 'most-bang-for-the-buck' will be identified as the one having the lowest per-unit life-cycle cost (or, technically dubbed, the lowest per unit annuity-equivalent cost).

is Capital Budgeting – Net Present Value (NPV) analysis, with the calculation of annuity equivalent measures.[4] Resulting annuity equivalent costs (or 'annualized life-cycle costs') are provided on both a $/ac-ft/year and a $/1,000-gal/year basis.

A "life-cycle" is the length of time a facility "lives"; i.e., the time from whence construction commences until facility decommissioning. Therefore, "life-cycle costs" include all costs involved with the facility – initial construction, future operation and maintenance, and future capital replacement. These costs are expressed in current-year dollars and can be presented as (1) a life-cycle total, (2) an annual, monthly, or daily amount, or (3) a per-unit amount, such as dollars per acre-foot or dollars per 1,000 gallons.

The purpose of this report is to (a) provide a comprehensive economic and financial analysis of the costs of producing and delivering reverse osmosis (RO) desalinated water at an operating facility, and (b) document the template used in this, and subsequent, analyses. The estimates herein are applicable only to this facility for the stated operating circumstances, but provide insight into costs of desalination. By definition, any consideration of water sales revenue or other economic benefit which would act as a 'credit' to offset economic and financial costs would infer a cost/benefit study, and result in an analysis of the *net* costs. In this study, such non-cost items are irrelevant and not included.

Alternatives to Desalination in South Texas

South Texas' dependency on the Rio Grande for its supply of municipal and industrial (M&I) water remains paramount as surface water from the River accounts for about 87% of M&I use (**Table 1**) (Rio Grande Regional Water Planning Group 2001). It is this heavy reliance, in combination with severely-reduced supplies in the mid-to-late 1990s, which sparked stakeholders' interest in desalination, particularly among the River's most downstream users. This interest was subsequently manifested into a recommended supply strategy by the Rio Grande Regional Planning Group (i.e., Region M in the State water-planning process) in 2003.[5]

The second largest supply source in South Texas is groundwater, which provides about 5.8%, while reuse and desalination currently provide about 3.7% and 3.3%, respectively of the region's water (**Table 1**) (Rio Grande Regional Water Planning Group 2001). Surface water from resacas is also listed as a Region M supply alternative, providing about 0.1% of the Region's supply. Other than some rainwater runoff into resacas, the originating supply source for resacas is the Rio Grande, thus diminishing the actual net contribution resacas provide.

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[4] "Capital Budgeting" is a generic phrase used to describe various financial methodologies of analyzing capital projects. Net Present Value (NPV) analysis is arguably the most entailed (and useful) of the techniques falling under Capital Budgeting. The use of annuity equivalents extends the standard NPV analysis method to accommodate comparisons of projects (or desalination facility segments) with different useful lives. The methodology used in the analysis are similar to methods documented in Rister et al. (2009). For more information, refer to the *Summary of Economic and Financial Methodology* section in this report, and Jones (1982); Levy and Sarnat (1982); Quirin (1967); Robison and Barry (1996); and Smith (1987).

[5] The recommendation to include desalination as a supply strategy was made via an amendment (in 2003) to the Water Plan which was originally completed/adopted in 2001 (Norris 2007).

Rainwater harvesting (RWH) is an idea/practice that is expanding in South Texas, although it contributes only a minuscule portion (approximately one-twentieth of 1%) toward M&I water supply in the Region. RWH is not a Region M denoted alternative, but it can serve as a location-specific source of landscape irrigation water, or, with treatment, serve as a source of potable water. Other alternatives (e.g., water transfers within or across basins) are technically possible, but have not been implemented. Thus, the Region is considered to currently have six supply alternatives (**Table 1**).

Table 1. Summary of Water-Supply Alternatives for Municipal and Industrial Users in South Texas, Ranked by Estimated Contribution to Regional Supply, 2006.

Water-Supply Alternatives	Estimated % of Current Regional Supply
1) surface water from the Rio Grande	87.10 %
2) groundwater	5.80 %
3) reuse	3.70 %
4) desalination	3.25 %
5) surface water from resacas	.10 %
6) rainwater harvesting	.05 %

Source: Rio Grande Regional Water Planning Group 2001.

Importance of Economics and Finance

The water provided by each of the above-mentioned alternatives (**Table 1**) represents varying levels of quality (e.g., salinity). Consequently, treatment-cost adjustments may be required to place the final delivery cost of surface water, harvested water, and possibly groundwater on par with the quality of desalinated water. Nonetheless, each is a *supply* alternative. Further, other efficiency-improving capital-project alternatives identified in the introduction (e.g., on-farm and municipal water-conservation measures) can be termed *efficiency* alternatives (i.e., either in water's transport or usage). Though different in their "approaches," both *supply* and *efficiency* alternatives can add to the Region's water supply. Following through with the aforementioned concept of Capital Budgeting, each alternative can be evaluated, compared against each other, and ranked.

Brackish Groundwater Desalination Facility in South Texas

Though multiple brackish groundwater desalination facilities exist (and more are planned) in South Texas, this study is limited to one existing facility near the Gulf of Mexico and the Texas-Mexico border just outside of Brownsville, TX (**Figure 1**).[6] This facility is termed the *Southmost Desalination Facility*, and is owned and operated by the Southmost Regional Water

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[6] Related research by the authors derive life-cycle costs of other brackish groundwater (and a planned seawater) desalination facilities (Boyer 2008), as well as traditional surface-water facilities (Rogers et al. 2009). These studies allow comparisons to be made across facilities and across technologies (Rogers et al. 2008).

Authority (SRWA) – a consortium of six partners which includes: Brownsville Public Utilities Board, City of Los Fresnos, Valley Municipal Utilities District No. 2, Town of Indian Lake, Brownsville Navigation District, and Laguna Madre Water District (Brownsville Public Utilities Board n.d.; Southmost Regional Water Authority n.d.).

Source: Google Earth (2007).

Figure 1. Approximate Location of the Southmost Desalination Facility Near Brownsville, TX and the Gulf of Mexico.

Overview of the Southmost Desalination Facility

The Southmost facility was built to treat brackish groundwater and provide an alternative water supply for the majority of the Southmost Regional Water Authority (SRWA) partners in the southern Cameron County region (Brownsville Public Utilities Board n.d.).[7] With the completion of Phase I in the Summer of 2003, the designed 7.5 million gallons per day (mgd) total output can provide more than 40% of the annual municipal and industrial water needs for the participating entities. Since the facility's components were oversized, output can be expanded two or three times beyond the designed 7.5 mgd (Brownsville Public Utilities Board n.d.; Southmost Regional Water Authority n.d.).

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[7] At the time of the decision to build the Southmost desalination facility, the northern area of Brownsville, TX was experiencing rapid urban growth and faced with having to either build another conventional surface-water treatment facility or a desalination facility. Of the eventual $26.2 million invested in the desalination facility, about $12 to $15 million would have been required to build a surface-water treatment facility (Norris 2007).

The current maximum-designed capacity of the Southmost facility is 7.5 mgd, which is derived by combining 6.0 mgd of RO-processed water with 1.5 mgd of blend source water. Using a 100% production efficiency (PE) rate equates the 7.5 mgd production rate to 8,401 acre-feet (ac-ft) annually. As depicted in **Table 2**, the Southmost facility's actual PE rate has varied due to operational and product-demand interruptions.

Table 2. Annual Output and Production Efficiency (PE) Measures, as a Percentage of Maximum Designed Capacity, for the Southmost Desalination Facility.

Capacity / Fiscal Year [a]	Average Daily Output (mgd) [b]	Total Annual Output (ac-ft)	Resulting Production Efficiency (PE) (% of max. design capacity)
Current Maximum-Designed Capacity	7.500	8,401	100.0 %
Anticipated Capacity [c]	7.050	7,897	94.0 %
Rule of 85 [d]	6.375	7,141	85.0 %
Finance Dept. Forecast for 2007 [e]	6.000	6,721	80.0 %
Modeled Capacity (baseline) [f]	5.100	5,713	**68.0 %**
Production for 2007 [g]	5.047	5,654	67.3 %
Production for 2006	5.068	5,676	67.6 %
Production for 2005	3.665	4,105	48.9 %
Production for 2004 [g]	0.976	1,093	13.0 %

Source: Brownsville Public Utilities Board 2007a.

[a] Fiscal year is from October 1 to September 30.

[b] mgd: million gallons per day.

[c] The production rate anticipated by management and consulting engineers after operational and product-demand interruptions are completely overcome.

[d] Texas Commission on Environmental Quality (TCEQ) mandate 30 TAC §291.93(30) states that when a retail public utility (possessing a certificate of public convenience and necessity) reaches 85% of its capacity as compared to the most restrictive criteria of the commission's minimum capacity requirements in Chapter §290.45 of the TAC, it must submit to TCEQ a service-demand plan, including cost projections and installation dates for additional facilities (Texas Secretary of State 2008). Thus, although a facility may be operable at >85% capacity, it may necessarily be constrained (over the long term) to a lower PE rate as the public entity manages the operations of a portfolio of water supply/treatment facilities (Adams 2007)

[e] As of January 2007 (Brownsville Public Utilities Board 2007b).

[f] The production rate used in the baseline analysis discussed herein.

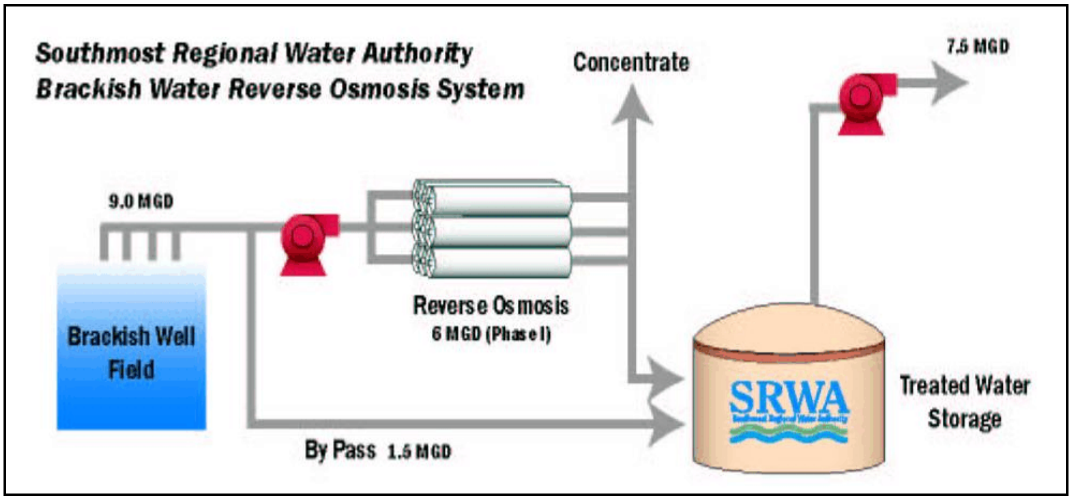
[g] The facility operated for less than twelve months; i.e., production/delivery began in April of 2004, while 2007 only includes 3 months (January - March) of operation. These partial-year data were annualized to provide comparable measures across all four years.

The Southmost facility utilizes brackish groundwater from the Gulf Coast aquifer as its source water (Norris 2007). This source water typically has incoming salinity levels of about 3,500 parts per million (ppm). Once processed, including blending with source water, the finished water from the Southmost facility typically has outgoing salinity levels of 300-475 ppm

(Norris 2007), which is below the 500 ppm maximum level set by the U.S. Environmental Protection Agency for drinking water (Arroyo 2005).[8]

Desalination Process Description for the Southmost Facility

The source brackish groundwater from the Gulf Coast aquifer is obtained using 20 supply wells, in which 18 are primary and two serve as backup. The well field encompasses about 17 acres, with each individual well's depth ranging from 280-300 feet. Connecting the supply wells together and transporting the source water to the main facility requires approximately 15 miles of source-water collection lines (Southmost Regional Water Authority n.d.). Once the source groundwater is pumped and transported via a pipeline to the main facility, the process-flow depicted in **Figure 2** occurs in the Southmost facility (NRS Consulting Engineers n.d.).



Source: Southmost Regional Water Authority (n.d.); Norris (2007).

Figure 2. Graphical Depiction of the Process Flow for the Southmost Desalination Facility.

Pretreatment Process

Pretreatment occurs as the raw, untreated source water enters the main facility. This process consists of cartridge filtration to remove particulate matter and the addition of scale-inhibitor to control salts-scaling. The objective of pretreatment is to control the rate and type of possible fouling that can occur within the membrane elements performing the RO process (NRS Consulting Engineers n.d.). Suspended solids in the source water are removed, prior to the RO system, by a series of five (5) cartridge filters which improve the operation of the subsequent RO membranes. These filters are replaced approximately every four months.

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[8] An alternative source water for the Southmost facility would be seawater, which would have to be piped 30+ miles to the existing facility. Typical incoming seawater would have salinity levels of about 35,000 ppm (Arroyo 2005). There is a proposed seawater-dependant facility project (to be located along the ship-channel in Brownsville, TX, or at a nearby shore-side location) that received $1.34 million funding from the Texas Water Development Board for a pilot plant study (NRS Texas Water News 2006a).

Reverse Osmosis (RO) Process

A series of six booster pumps move the water from the pretreatment cartridge filters to three ‘banks’ (or sometimes referred to as ‘trains’) of pressure vessels, with each configured in a 6:11 array (i.e., total of 198 vessels (3 x 6 x 11)), which remove total dissolved solids (TDS) (**Figure 3**).[9] The booster pumps pressure the pre-treated water against Thin Film Composite membranes housed in each pressure vessel with approximately 180 pounds per square inch (psi), allowing only fresh water to pass through the membrane. Each pressure vessel contains seven elements (i.e., canister filters) which require replacement approximately every six years.

From a water-flow view, each ‘bank’ (i.e., 6 columns and 11 rows) of vessels is ‘split’ into two halves containing 33 pressure vessels each. The pressure vessels are configured such that feed water from the pretreatment cartridge filters enters the initial 22 vessels of each half-bank (i.e., 2:11 array) for the 1st-stage RO process. The concentrate from the 1st-stage then feeds the 2nd-stage RO process which is performed by the next column of 11 pressure vessels (i.e., 1:11 array) in each half-bank (**Figure 3**). This process occurs in each of the three banks of pressure vessels.

Source: Sturdivant (2007).

Figure 3. Three Banks of Pressure Vessels (6:11 array each) at the Southmost Facility, 2007.

Each half-bank of 33 pressure vessels (1st and 2nd stages combined) is designed to produce 1.0 mgd of permeated water. Thus, current designed capacity of permeated water for the Southmost facility is 6.0 mgd (i.e., three banks, multiplied by two half-banks, multiplied by 1.0 mgd per half-bank). The entire RO system operates at a 75% recovery

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[9] The “*6:11*” notation is a way of describing a bank of pressure vessels which has six columns (width) and eleven rows (height). Different configurations of vessels are used in RO operations.

rate, meaning three-fourths of the water which enters the pressure vessels is captured as permeated (i.e., desalted) water (Norris 2007; Adams 2007).[10]

Concentrate Waste Discharge

The 25% volume of water not recovered as permeated water in the RO pressure vessels is salt concentrate waste. Given its close proximity to the Texas Gulf Coast, the Southmost facility has the luxury of a relatively simple and inexpensive disposal issue. The concentrate waste is discharged (Texas Commission on Environmental Quality (TCEQ) permitted) through a 16" (dia.) pipeline into an earthen drainage ditch located adjacent to the Southmost facility and extending to the Laguna Madre.[11] For other, inland facilities, the discharge of concentrate waste is typically more complex and costly (e.g., at the El Paso Kay Bailey Hutchison Plant, the concentrate waste must be pumped into deep wells about 20 miles from the main facility site (Archuleta 2004).

Blend Water

After cycling through the RO pressure membranes, the permeated water, now at 40-50 ppm salinity, is blended with non-permeated (i.e., brackish) blend water (from the pre-treatment process where suspended solids are removed), which is about 1,800 ppm. The blended water has a salinity level of about 300-475 ppm.[12]

The process of over desalting source water via the RO process (to 40-55 ppm) and then blending with 1,800 ppm nonpermeated water to attain product water with 300-475 ppm salinity (vs. permeating to the 300-475 ppm salinity level and not blending) happens for several, planned reasons. One is the booster pumps installed in the Southmost facility provide a constant level of pressure (i.e., not variable-pressure pumps) against the membranes, which require high pressure (i.e., 180 psi) to permeate water. In doing so, approximately 95-98% of the minerals are removed. Tweaking the permeate level is not permissible with the installed equipment/process. Benefits of this approach include (1) a reduced amount of water is pumped from the well field, (2) a smaller and less expensive intake pipeline from the well field to the main facility, (3) reduced chemical usage in the RO process, (4) reduced concentrate waste volume (which is State regulated by TCEQ), and (5) waste-energy recovery from the concentrate waste flow of the first stage to the source flow of the second stage.

pH Adjustment and Disinfection

The blended product water is treated with caustic soda for pH adjustment and chloramines for disinfection of microorganisms (e.g., bacteria, viruses, protozoa) which can cause diseases such as typhoid fever and dysentery (Scranton Gillette Communications, Inc.

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[10] The 75% is obtained by a 50% recovery of the 1st-stage (i.e., in 22 vessels) and 50% recovery in the 2nd-stage (i.e., 11 vessels which use the concentrate from the 1st-stage) for each of the three banks.

[11] The Laguna Madre (translated: “mother lagoon”) is a shallow, salty lagoon that is five miles across at its widest point and stretches for 200+ miles from southern Texas into northern Mexico (**Figure 1**). One of the five saltiest bodies of water on Earth, and considered an extraordinarily rich wetland area, it provides habitat for young finfish, shrimp, shellfish, etc., and is sheltered by a system of barrier islands and mainland beaches (The Nature Conservancy 2006).

[12] Such quality of blended water (i.e., 300-475 ppm) is comparable to conventional treatment of surface water from the Rio Grande (Norris 2007).

2007).[13] Calcium chloride (CaCl) is added to counter extreme product-water 'softness,' and to assist with the pH adjusting process (NRS Consulting Engineers n.d.).[14]

Degasification and Tank Storage

After the post-RO treatments, the product water is pumped into the transfer station clearwell for degasification (i.e., aeration) where "air bubbles" of carbon dioxide are removed. From here, the finished water is pumped into a 7.5 million gallon above ground storage tank.

Delivery of Product Water

From the above-ground storage tank, the product water is pumped via a pipeline to the municipal delivery point approximately two (2) miles away. Plans for a second delivery point to be installed in the near future exist. This will increase the acceptance capacity of the municipal system and thereby reduce demand interruptions of RO-desalinated water from the Southmost facility (i.e., not inhibit the maximum designed capacity).

Construction Period and Expected Useful Life

The construction period for the Southmost desalination facility spanned 20 months between February 2003 and September 2004. Like other capital projects, various delays and challenges were incurred during the construction phase. These issues are discussed in further detail in Norris (2004). Without the unanticipated delays and needed phased-in start-up, Southmost facility management and consulting engineers advise construction could have been achieved in a 12-month period. For this analysis, a 1-year construction period is assumed.[15]

The various civil, electrical, and mechanical components of the Southmost facility are expected to have useful lives ranging from a low of three (3) years for items such as well-field pump motors, to a high of 50 years for structural items such as buildings, storage tanks, concrete, etc. For this analysis, a maximum useful life of 50 years is established for the entire desalination facility. Within that maximum-life limit, however, it is recognized that certain capital items have shorter lives. Thus, intermittent capital replacement expenses (inflation adjusted) are incorporated, as appropriate, to reflect the necessary replacement of such items (e.g., membranes, pumps, motors, etc.) to insure the facility's full anticipated productive term. Other, non-capital expenses, such as electrical switches, valves, etc. are captured in annual operating expenses. Combined, specified capital-replacement and annual-operational expenses provide for a facility that will maintain productive capacity for 50 years.

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[13] That is, when chlorine (Cl) (found in chloramines) is added to water, it forms hypochlorous acid (HOCl), an active disinfectant (Scranton Gillette Communications, Inc. 2007).

[14] Changes to U.S. Environmental Protection Agency (EPA) water-quality standards regarding arsenic, which took effect January 2006, have impacted the Southmost facility (and other municipal water suppliers relying on groundwater). The new requirements reduce the allowable arsenic limit from 50 parts per billion (ppb) to 10 ppb. Realizing a range from 14 to 35 ppb of arsenic, the Southmost facility collaborated with NRS Consulting Engineers to successfully deal with specific properties of the arsenic in the source water by adding 0.15 mg/L of chlorine to oxidize arsenic (III) to arsenic (V). This adjustment to the treatment process resulted in 2 ppb levels of arsenic (i.e., below the new 10 ppb level) in the permeated water (NRS Texas Water News 2006b). Chlorine levels are closely monitored as chlorine can damage the membranes inside the pressure vessels.

[15] The impact of this assumption upon results is very minimal. Results from a scenario with a 2-year (i.e, 24 months) construction period were within 1.9% of the baseline results reported herein. Extrapolating with a 20-month period, suggests results to be within 1.3% of the reported baseline results.

Annual Water Production

The current maximum-designed capacity of the Southmost facility is 7.5 mgd (**Table 2**), which equates to a total annual output of 8,401 ac-ft (with blend water added), assuming a 100% production efficiency (PE) rate. For this analysis, however, allowances are made for typical operational and demand interruptions incurred by such a facility. Imposing the stated 68% PE rate in this analysis is considered appropriate and concurrent with PE levels observed in the most recent fiscal years (i.e., 2006 and 2007) (**Table 2**). The modeled 68% rate equates to 5.1 mgd average daily output, or 5,713 ac-ft annually. This value is held constant during each year of the facility's productive life in the baseline analysis. Other, successive notable rates are listed and discussed further in the table notes.

Initial Construction Costs

Initial construction costs totaled $26.2 million for the Southmost facility and are assumed to be spent before the initial 1-year (assumed) construction period (i.e., in time "zero"). For analysis-detail and desalination-facility-comparison reasons, the total cost is divided into 18 cost-item categories, and dissected into seven individual functional areas common to desalination facilities (**Table 3**). As depicted in **Table 3**, the most cost-intensive area of the Southmost facility is the *Main Facility* ($9,554,574), followed by the *Well Field* ($7,768,525) and *Overbuilds & Upgrades* ($4,168,843) cost areas. When viewed from an individual cost-item perspective,[16] the *Pipeline* ($5,682,754) and *Building & Site Construction* ($5,630,904) items are the largest contributors to total initial construction costs.[17]

Continued Costs

Continued costs facilitate perpetual operations from completion of construction to the end of useful life and are compounded at slightly more than 2.0% annually herein.[18] The continued costs used are based on actual expenses incurred for the Southmost desalination facility during the 2004-2005 fiscal year (FY), with adjustments made to reflect 2006 dollars and anticipated increases in energy and chemical costs for the current fiscal year.[19] That is, FY 2004-2005 expenses are used as a proxy (with increased adjustments to energy and chemical costs) in lieu of unavailable current FY expenses. The continued costs begin in the first year after completion of construction and are thereafter compounded at 2.0+% for each successive year of useful life. For this study, annual continued costs total $1.7 million and are organized into two general categories (**Table 4**):[20]

> Administrative: These annual expenses total $82,148 and account for facility-related expenses which are not included on the Southmost desalination facility's budget, but rather are included on other owner-entity budgets (e.g., Brownsville PUB).[21] For analysis-detail

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[16] Many detailed cost items have been "collapsed" into generalized categories.

[17] The amount and division of initial construction costs into cost-item categories and into facility segments were identified by NRS Consulting Engineers of Harlingen, Texas.

[18] More precisely, the compound rate is 2.043269% and is inferred, as is described later in this document, in the *Assumed Values for Discount Rates and Compound Factor* sub-section.

[19] Fiscal year is from October 1 to September 30.

[20] Operation and maintenance expenses and their allocation into facility segments were identified by Brownsville Public Utilities Board, the contracted operator and major stakeholder.

[21] Such administrative expenses are estimated as 5% of the O&M budget at the Southmost facility (Adams 2007).

and desalination-facility-comparison reasons, this category has been divided into six cost-item categories, as well as separated into seven individual functional areas common to desalination facilities (**Table 4**).[22] The most costly area is the *Main Facility* ($47,357) (**Table 4**).

Operations & Maintenance (O&M): These annual expenses total $1,642,953 and account for facility expenses incurred at the Southmost facility. For analysis-detail and desalination-facility-comparison reasons, this category has been divided into ten cost-item categories, as well as separated into seven individual functional areas common to desalination facilities (**Table 4**). As depicted in **Table 4**, the most costly area is the *Main Facility* ($947,137). When viewed from individual cost items,[23] the *Electrical Power* ($816,347) item is the largest contributor to continued O&M costs.

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[22] Since the administrative costs are estimated, the amount is allocated into only one account (i.e., Administrative Overhead) in **Table 4**.

[23] Many detailed cost items have been "collapsed" into generalized categories.

Table 3. Initial Construction Costs for the Southmost Desalination Facility, Across Individual Functional Areas, in 2006 Dollars.

INITIAL CONSTRUCTION COST ITEM	Individual Functional Areas (i.e., Cost Centers) of the Southmost Desalination Facility							
	Well Field	Intake Pipeline (Well field to facility)	Main Facility	Concentrate Discharge	Finished Water Line & Tank Storage	Delivery Pipeline (to municipal line)	Overbuilds & Upgrades [a]	TOTAL COSTS
Administrative Overhead	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
Building & Site Construction	1,429,009		3,736,706	50,000			415,190	5,630,904
Contingencies								0
Contractor Fees								0
Electrical Equipment	891,192		620,568				167,973	1,679,733
Electrical Service Installation	360,000							360,000
Engineering	1,009,824	450,388	1,288,499	7,363	219,202	386,418		3,361,694
Labor								0
Land	500,944							500,944
Miscellaneous			266,325					266,325
Other - non listed								0
Pipeline		1,529,294				1,312,083	2,841,377	5,682,754
Pre-Project	272,525							$272,525
Pumps								0
RO Equipment & Installation			3,478,265					3,478,265
SCADA [b]	300,000		164,211					464,211
Storage Tank					744,303		744,303	1,488,606
Well Field	3,005,031							3,005,031
TOTAL	$ 7,768,525	$ 1,979,682	$ 9,554,574	$ 57,363	$ 963,505	$ 1,698,501	$ 4,168,843	$ 26,190,993

[a] Captures the ‘whistles & bells' beyond baseline necessities, and some ‘elbow room' for future increased capacity – see footnote 28 in the text.

[b] Acronym for **S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition – hardware and software technology which collects data from sensors at remote locations and in real time sends the data to a centralized computer where facility management can control equipment/conditions at those locations.

Table 4. Baseline Annual Continued Costs, Allocated Across Individual Functional Areas, for the Southmost Desalination Facility, Based on Fiscal Year 2004-2005 Expenses Inflated to 2006 Dollars.

	Individual Functional Areas (i.e., Cost Centers) of the Southmost Desalination Facility							
CONTINUED COST ITEM	Well Field	Intake Pipeline (Well field to facility)	Main Facility	Concentrate Discharge	Finished Water Line & Tank Storage	Delivery Pipeline (to municipal line)	Overbuilds & Upgrades [a]	TOTAL COSTS
ADMINISTRATIVE								
- Administrative Overhead [b]	$ 18,283	$ 204	$ 47,357	$ 184	$ 3,354	$ 8,924	$ 3,842	$ 82,148
- Insurance (public officials)								
- Labor								
- Maintenance								
- Other								
- Vehicles / Rolling Stock								
sub-total	$ 18,283	$ 204	$ 47,357	$ 184	$ 3,354	$ 8,924	$ 3,842	$ 82,148
OPERATIONS & MAINTENANCE								
- Administrative Overhead							62,933	62,933
- Chemical [c]			246,453					246,453
- Concentrate Disposal								0
- Electrical Power [c]	293,885		293,885		57,144	171,433		816,347
- Insurance	8,642		32,409		2,161			43,212
- Labor	36,868	3,687	313,380	3,687	7,374	3,687		368,683
- Maintenance	15,842		44,357			3,168		63,367
- Other							13,911	13,911
- Rental (land, equip., storage)	8,456							8,456
- Vehicles / Rolling Stock	1,959	392	16,653		392	196		19,592
sub-total	$ 365,652	$ 4,079	$ 947,137	$ 3,687	$ 67,071	$ 178,484	$ 76,844	$ 1,642,953
TOTAL	$ 383,935	$ 4,283	$ 999,494	$ 3,871	$ 70,425	$ 187,408	$ 80,686	$ 1,725,101

[a] Captures the ‘whistles & bells' beyond baseline necessities, and some ‘elbow room' for future increased capacity – see footnote 28 in the text.

[b] Expenses incurred at the BPUB for and on behalf of the Southmost facility which are estimated as 5% of the O&M budget at the Southmost facility.

[c] Variable expenses associated with the baseline facility production rate of 68% (see **Table 2**). Production rates above/(below) the baseline necessarily raise/(lower) the total dollar amount of expense.

Capital Replacement Costs

Similar to continued costs, capital replacement costs facilitate perpetual desalination operations, albeit on an intermittent (vs. annual) basis. That is, within the facility's maximum useful life of 50 years, certain capital items wear out and must be replaced intermittently (e.g., every 2, 5, or 10 years). Recognizing the financial reality of inflation, the costs for capital replacement items (which are based on current FY 2006 dollars) are compounded at slightly more than 2.0% annually in this study.[24] **Table 5** depicts the needed capital replacement items, as well as their replacement occurrence and costs, incorporated in this study:

Table 5. Capital Replacement Items, Occurrence, and Costs (basis 2006 dollars) for the Southmost Desalination Facility.

Capital Item	Replacement Occurrence	Cost per Item	No. of Items Replaced Each Occurrence
Well / Pumps	3 years	$10,000	20
Membranes	6 years	$700,000	1

Prior Economic Estimates

A review of the desalination literature reveals many strategic-planning papers and much research focused on Texas, the U.S., and internationally. For brevity's sake, and a contemporary perspective, only select results and studies published or released within the past eight years are discussed here. Although little detail is provided on the methodology of these prior studies, the predominant methods of analysis used by their authors are regression[25] and capital budgeting. Without access to such methodological detail, however, commentary regarding the accuracy, comparability, and/or soundness of prior studies' results cannot be (and is not) made herein.

Many engineering-, economic-, regulatory-, institutional-, and environmental-related factors influence the final product costs of desalination facilities, with most or all factors being the focal point and/or the most-significant item in prior investigations. *Location* of a desalination facility dictates the source water type (i.e., brackish or seawater) and thus has a major impact on the facility's product cost. Illustrating the relevance of this factor, Zhou and Tol (2004) used regression techniques on data gathered from more than 2,500 RO desalination facilities (all over the world) and found that any given seawater RO desalination facility experienced higher per-unit costs than brackish-groundwater-dependant facilities. In Adams, Berg, and Harris' (2000) regression results from three South Texas brackish groundwater RO facilities indicate there is a positive linear relationship between treatment costs and total dissolved solids (TDS) concentration (i.e., impurities) of the source water. Both of these conclusions are arrived at because lower-salinity and higher-quality source water require less frequent filter replacement, lower power consumption, and lower chemical usage (Ettouney et al. 2002).

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[24] More precisely, the compound rate is 2.043269% and is inferred, as is described later in this document in the *Assumed Values for Discount Rates and Compound Factor* sub-section.

[25] Regression analysis is a statistical (i.e., mathematical) technique which seeks to predict the value of a variable, based upon the value or characteristics of other (i.e., generally at least two) variables (Wooldridge 2006).

Energy accounts for a large portion of final product costs. Younos (2005) credits energy as the primary cost difference between desalination of seawater and brackish water. The data show electric power accounts for 11% of total costs for brackish-water dependant facilities and 44% for seawater-dependant facilities. Graves and Choffel (2004) report electricity costs account for about 30% of the total costs for seawater-dependant facilities. Energy is a factor that is highly dependent on the location, as power rates can vary greatly from state to state and country to country. Ettouney et al. (2002) note the cost of electricity ranges from \$0.04 - \$0.09/kWh, with the lower ranges experienced in the Gulf States and the U.S., while European countries experience the higher end of the range.

Seaside desalination facilities typically experience lower *brine-concentrate disposal* costs as they elude costly deep-injection wells. To minimize environmental impacts, however, seaside facilities may be required to pump the concentrate some distance offshore. A detailed look at such costs for a seaside facility is given in Graves and Choffel (2004). They report, for a 25 mgd seawater facility (generating 16.7 mgd of concentrate), disposal costs associated with piping concentrate 1-mile offshore are \$32.59 per ac-ft {\$0.10 per 1,000 gallons} and \$309.59 per ac-ft {\$0.95 per 1,000 gallons} for a 20-mile discharge pipe. For facilities which are unable to utilize the ocean for concentrate disposal, the remaining options include deep-well injections or evaporation ponds. Archuleta (2004), in a study for a potential facility in El Paso, Texas, indicates that deep-well injection would be the most economical choice.[26] Further, Archuleta notes that a conventional evaporation pond covering 772 acres would cost an initial \$41 million, plus an additional \$1 million in annual operation and maintenance costs. Nicot and Chowdhury (2005) discuss the reduction of concentrate-disposal costs associated with using depleted oil and gas fields since the substantial initial costs to dig the deep well can be avoided.

A predominant theme in much of the current literature on desalination is the idea of *economies of scale*.[27] Several reports indicate that increasing the total capacity of the facility decreases the per-unit costs for both seawater- and brackish-water-dependant facilities. Arroyo (2005) estimates that production costs for brackish groundwater facilities range from \$772.27 per ac-ft {\$2.3700 per 1,000 gallons} for a 0.10 mgd RO facility down to \$231.35 per ac-ft {\$0.7100 per 1,000 gallons} for a 10 mgd RO facility. This theme of utilizing economies of "size" to reduce per-unit costs is also noted by Norris (2004) and Archuleta (2004) in which more than one entity collaborated to build one larger facility, rather than multiple, smaller facilities in South Texas and El Paso, Texas, respectively.

Pittman et al. (2004) reported seawater desalination in South Texas was not economically competitive with conventional-treated municipal water. This conclusion was based on a comparison of charges for conventional-treated water in Brownsville, Corpus Christi, and

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[26] The Kay Bailey Hutchison Desalination Plant located in El Paso, Texas began operating in 2007.

[27] Much, if not all, of the current literature refers to 'economies of *scale,*' which is defined as the "expansion of output in response to an expansion of <u>all</u> factors in <u>fixed</u> proportion" (Beattie and Taylor 1985). In the specific case of increasing output capacities of desalination facilities, however, not all production factors (e.g., land, labor, capital, management, etc.) are increased proportionately to attain the increased output. Therefore, the correct term is 'economies of *size*' -- the concept that *economies* (or decreasing marginal and average variable costs) are incurred as output is increased from a non-proportional increase in the 'size' (i.e., level) of some or all factors of production (i.e., inputs). That is, *scale* refers to a proportionate change in all production inputs, whereas *size* refers to a non-proportionate change in some or all production inputs (Beattie and Taylor 1985). A study by Boyer (2008) reports on 'economies of size' in municipal water treatment technologies.

Freeport, Texas which ranged from $527.88/ac-ft to $661.48/ac-ft, with proposed seawater desalination costs ranging from a low of $1,166.55/ac-ft to a high of $1,306.66/ac-ft (**Table 6**). The cost to desalinate brackish groundwater could be considered economically competitive, however, as Norris (2004) states desalinating brackish groundwater at the Southmost facility (located near Brownsville, Texas) costs between $521.36 and $586.53 per ac-ft {$1.6000 and $1.8000 per 1,000 gallons} to treat and deliver (**Table 6**).

Table 6. Select Charges for Conventional-Treated Water and Costs of Desalinated Seawater, and Costs of Brackish-Groundwater Desalination.

	Pittman et al. (2004) [a]				Norris (2004)	
	Conventional-Treated Water Charges		Proposed *Seawate*r Desalination Water Costs		Proposed *Brackish Groundwater* Desalination Water Costs	
Texas City	$/ac-ft	$/1,000 gals	$/ac-ft	$/1,000 gals	$/ac-ft	$/1,000 gals
Brownsville	$661.48	$2.03	$1,306.66	$4.01	$521.36 - $586.53	$1.60 - $1.80
Corpus Christi	$580.01	$1.78	$1,378.35	$4.23	n/a	n/a
Freeport	$527.88	$1.62	$1,166.55	$3.58	n/a	n/a

Source: Pittman et al. (2004), Norris (2004).

[a] Note the conventional-treated values are <u>charges</u>, which may not equate with <u>costs</u> of such water, thus making for a possible imbalanced comparison with seawater desalination costs.

Summary of Economic and Financial Methodology

Like other capital projects, the Southmost desalination facility: (1) required an initial investment (i.e., dollars) to fund initial construction, (2) requires dollars to fund ongoing operations, and (3) provides both a level of productivity and water quality for some number of years into the future. With an expected life lasting into future years and financial realities such as inflation, the time-value of money, etc., the *life-cycle cost* of providing an acre-foot of desalinated water is the appropriate cost measure to be determined. Capital Budgeting – Net Present Value (NPV) analysis, in combination with the calculation of annuity equivalents, is the methodology of choice because of the capability of integrating expected life with related annual costs and outputs, and other financial realities into a comprehensive $/ac-ft/year {or $/1,000 gals/year} *life-cycle* cost. In short, calculating NPV values for dollars and water allows for comparing alternatives with differing cash flows and water production output, while the use of annuity equivalents (of the NPV values) facilitates comparisons of projects with different useful lives. Assumed in the calculations and methodology are zero net salvage value (for land, buildings, equipment, etc.) and a continual replacement of such capital items into perpetuity.

To facilitate a NPV – Capital Budgeting analysis (with annuity-equivalent calculations) of the Southmost facility, agricultural economists from Texas AgriLife Extension Service and Texas AgriLife Research developed the Microsoft$_{®}$ Excel$_{®}$ spreadsheet model DESAL ECONOMICS$^{©}$. This model analyzes and provides life-cycle costs (e.g., $/ac-ft/year) for <u>up to</u> twelve individual functional expense areas, as well as for the entire facility. To the authors' knowledge, and from a literature search, this capability appears unique among economic and financial cost models directed at desalination facilities. DESAL ECONOMICS© is custom built and useful for analyzing and reporting on all desalination facilities, regardless of size, location, etc. Individual expense areas for the Southmost facility are:

1) Well Field;
2) Intake Pipeline (from the well field to the main facility);
3) Main Facility;
4) Concentrate Discharge;
5) Finished Water Line & Tank Storage;
6) Delivery Pipeline (to the municipal delivery point);
7) Overbuilds & Upgrades[28]; and
8-12) *unused*.[29]

Results derived using DESAL ECONOMICS© allow an "apples to apples" comparison to be made across different desalination facilities and/or across individual expense areas of different desalination facilities. Noteworthy of special mention of this model is having the ability to analyze individual expense area results (i.e., detail beyond the 'bottom line' of the entire facility). That is, with a standard 'aggregate' analysis of a desalination facility, one may experience dramatic life-cycle cost differences across facilities, but have no explanation as to the functional cost area(s) which are causing the disparity. By also analyzing the individual functional cost areas, additional useful data is provided – this may highlight the need for a review assessment to see if engineering/construction changes could be made in one or more specific areas toward reducing the composite life-cycle cost.

Also, if the same methodology and factors are used, comparisons can be made with other capital projects which 'add' to the region's available water supply (e.g., on-farm and municipal water-conservation measures, seawater desalination, rainwater harvesting, ponding and retainment, rehabilitation of water-conveyance systems (e.g., Rister, Lacewell, and Sturdivant (2006)), etc.).[30] Ultimately, having comparable costs for all alternatives which add water to a region's supply will provide information useful for prioritizing projects in the event of limited funding, and other varied circumstances.

Though potentially 'different,' the qualities of final-product waters from different municipal treatment facilities are assumed inherently comparable and are not adjusted (for incoming source-water quality, nor outgoing final-product water quality) to facilitate across-facility or across-technology comparisons as (a) all potable-water suppliers are required to meet

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[28] This expense area captures the 'whistles & bells' included in the initial construction costs beyond baseline necessities, and some 'elbow room' for future increased capacity. That is, the Southmost facility is considered a Type A 'cornerstone' building as its equipment and amenities facilitate desalination-related training and meetings beyond the capabilities of a basic, no-frills facility. The associated notoriety has helped to bring the Southmost facility to the forefront of desalination in Texas (Southmost Regional Water Authority n.d.).

[29] The nature of the Southmost facility is such that only seven of the permissible twelve facility segments (i.e., functional areas, or expense areas) within DESAL ECONOMICS© were required for the analysis. Thus, there are unused facility segments in DESAL ECONOMICS© for this particular analysis and report.

[30] Note, the cost-of-saving water via rehabilitation of water-conveyance systems needs to be adjusted for municipal treatment costs to par the quality of Rio Grande surface water with that of desalinated water. Also, ongoing efforts by the authors are focused on analyzing the listed capital project alternatives.

specified quality standards on final-product water such that extreme differences in qualities affecting human health cannot occur, and (b) the comparative costs of attaining the relatively-narrow standards is reflected in the input data for each (e.g., chemical amount and costs, equipment used, and costs for specific operating regimes). That is, as long as costs (via the process-flow design, asset selection/configuration, management structure, local cost rates, and employed operational methods unique to each facility) comparing final-product water (i.e., potable) are used, the unique location **and quality** of the source water are reflected in the life-cycle cost of getting the source water's unacceptable quality level to an acceptable (per State and Federal regulations) quality level for each facility's final-product water. Simply said, the assumption is 'potable water is potable water'. Thus, herein, there are no quality adjustments made to account for differences in incoming or outgoing water quality to facilitate across-facility or across-technology comparisons of potable-water producing facilities.[31]

Assumed Values for Discount Rates and Compound Factor

Much primary data are used in this analysis. Two important discount rates and a compound rate are assumed, however. The discount rate used for calculating the net present values of cost streams represents a firm's required rate of return on capital (i.e., interest). The discount rate is generally considered to contain three components: a risk-free component for time preference, a risk premium, and an inflation premium (Rister et al. 1999).

> Discounting Dollars: Having different annual operating costs and expected lives across facilities (and possibly functional areas) encourages 'normalizing' such flows by calculating the NPV of costs, which requires a discount factor. Since successive-years' costs are increased by an inflationary factor, there is an inflationary influence to consider in the discounting of costs (Klinefelter 2002), i.e., the *inflation premium (I)* and *time (t)* portions of the discount factor should be used.[32] The discount rate used in this analysis is 6.125%, which is consistent with and documented in Rister et al. (2009).
>
> Discounting Water: Having different annual water output and expected useful lives across facilities encourages 'normalizing' such flows by calculating the NPV of production, which requires a discount factor. Since it is incorrect to inflate successive-years' water production, there is no inflationary influence to consider in the discounting of water (Klinefelter 2002), i.e., only the *time (t)* portion of the discount factor should be used. Consultations with Griffin and Klinefelter contributed to adoption of the 4% rate used by Griffin and Chowdhury for the social time value in this analysis (Griffin 2002; Klinefelter 2002; Griffin and Chowdhury 1993).

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[31] Though adjustments (to account for incoming or outgoing water quality differences) are not made herein to facilitate comparing potable-water-producing facilities (or technologies), certain adjustments are needed to properly compare life-cycle costs for raw water from infrastructure rehabilitation (e.g., Rister, Lacewell, and Sturdivant 2006), or invasive weed removal (Seawright 2009), with life-cycle costs for potable water obtained from desalination.

[32] One estimate of a discount rate from a desalination-facility owner's perspective is the cost at which it can borrow money (Hamilton 2002). Griffin (2002) notes, however, that because of the potential government/public funding component of this project, it could be appropriate to ignore the risk component of the standard discount rate as that is the usual approach for federal projects. After considering those views and interacting with Penson and Klinefelter (Penson 2002; Klinefelter 2002), both Texas A&M University agricultural economists specializing in finance, a discount rate of 6.125%, consistent with and documented in Rister et al. (2009), was adopted for use in discounting all financial streams.

Compounding Costs: Inflation is a financial reality with future years' ongoing operational costs. As presented in Rister et al. (2009), use of an overall discount rate of 6.125%, with a 4.000% social time value and a 0% risk premium, infers a 2.043269% annual inflation rate.[33] Thus, nominal dollar cost estimates for years beyond 2006 are inflated at 2.043269% annually.

Results of the Economic and Financial Analysis

Composite results for the economic and financial analysis of the prior data, using the Excel® spreadsheet model DESAL ECONOMICS©, are presented. A summary of aggregate estimated baseline results is presented first, with more results presented across facility segments and then by cost type. Thereafter, brief presentations of key sensitivity analyses for select parameters are provided. Herein, the phrases '*cost-of-producing water*' and '*cost-of-producing-**and-delivering** water*' are often used interchangeably. Since the costs of the Southmost facility analyzed include delivery to a point in the municipal delivery-system infrastructure, the phrase '*cost-of-producing-**and-delivering** water*' is sometimes used to denote the delivery of finished water on an f.o.b. municipal delivery point basis. This should not be confused with household delivery, but only to a point within the municipal delivery-system infrastructure.

Results – Aggregate Baseline

Initial Construction Costs: The total initial construction costs for the Southmost facility (**Table 3**) amount to $26,190,993 in nominal 2006 dollars (**Table 7**). Since these costs are assumed to be incurred immediately prior to commencement of construction, the real value does not require adjustment for time and inflation, and hence equals the nominal value (**Table 7**).

Water Production: Over the 50-year expected useful life, the annual production of 5,713 ac-ft, using the modeled effective capacity of 68% (**Table 2**), will total 285,637 ac-ft on a nominal basis. This value, when adjusted for time at the 4.000% social-preference rate, results in a present-day amount of 118,002 ac-ft. The annuity equivalent of this real value, or 'annualized amount,' is 5,459 ac-ft per year (**Table 7**).[34]

Total Life-Cycle Costs: Summing all facility costs (i.e., initial, continued, and capital replacement) over the 50-year expected useful life result in $195,914,480 in nominal dollars. Adjusting this value for time and inflation at 6.125% results in a real value of $65,281,089 (**Table 7**). This value represents the net total life-cycle costs of constructing and operating the Southmost facility (in 2006 dollars). That is, at the time a commitment is made to fund the initial construction costs of $26,190,993, an additional $39,090,096 (i.e., $65,281,089 minus $26,190,993) in current 2006 dollars is also implicitly committed (**Table 7**).

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[33] Represented mathematically: $\frac{1+6.125\%}{1+4000\%} - 1 = 2.043269$.

[34] Here, *nominal value* (or nominal basis) refers to non-inflation adjusted values, while *real value* (or real basis) refers to values expressed in time- and inflation-adjusted terms, with the benchmark year for both time and inflation being 2006 in this analysis.

Annual Cost Annuity: Calculating the annuity equivalent of the $65,281,089 real value results in an 'annualized cost' of $4,201,075. This real value represents, in current 2006 dollars, the net annual costs of constructing and operating the Southmost facility.[35]

Cost of Producing (and Delivering) Water: To derive the annual *Cost-of-Producing (and Delivering) Water*[36] value on a per ac-ft basis, divide the total cost annuity of $4,201,075 per year by the total water-production annuity of 5,459 ac-ft per year {1,778,701 1,000-gallon units per year}. This results in a baseline annual cost of producing and delivering desalinated water at the Southmost facility of $769.62 per ac-ft {$2.3619 per 1,000-gallons} (**Table 7**). This value can be interpreted as the cost of leasing one ac-ft {1,000 gallons} of water in year 2006. It is not the cost of purchasing the water right for one ac-ft {1,000 gallons} (Rister et al. 2009). Consistent with the methodology presented in Rister et al. (2009), this value represents the costs per year in present-day dollars of producing and delivering one ac-ft {1,000 gallons} of water each year into perpetuity through a continual replacement of the new desalination facility, with all of the attributes previously described.

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[35] For the 'Water Production' and 'NPV of Total Cost Stream' results in **Table 7**, the real-value amounts are less than the nominal-value amounts. This occurs because the continued and capital replacement costs, and water production which occur in the latter years of the facility's life are significantly discounted (at 6.125% and 4.000%, respectively) and thus do not contribute to the summed real total as much as do costs during earlier years. Also, the nominal water-production value makes no distinction of time and allows year 1 (after construction) to have the same impact as year 50. Also, note the 'NPV of Total Cost Stream' values are positive. This infers net costs will be incurred and no off-setting revenues, 'credits,' or positive externalities exist which could exceed the costs; i.e., a negative NPV of total costs would infer a net profit.

[36] 'Delivery' is to a point within the municipal delivery-system infrastructure, not household delivery.

Table 7. Aggregate Baseline Results for Production and Costs for the Seven Facility Segments of the Southmost Desalination Facility, in 2006 Dollars. [a]

Results	Units	Nominal Value	Real Value [b]
Initial Facility Costs	2006 dollars	$26,190,993	$26,190,993
Water Production	ac-ft (lifetime)	285,637	118,002
- annuity equivalent [c]	ac-ft/year		5,459
Water Production	1,000-gal (lifetime)	93,075,000	38,451,045
- annuity equivalent [c]	1,000-gal/year		1,778,701
NPV of Total Cost Stream [d]	2006 dollars	$195,914,480	$65,281,089
- annuity equivalent [c]	$/year		$4,201,075
Cost-of-Producing & Delivering Water [e]	$/ac-ft/year		$769.62
Cost-of-Producing & Delivering Water [e]	$/1,000-gal/year		$2.3619

[a] These baseline results reflect the Southmost facility in its current operating state (i.e., 68% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Determined using a 2.043% compound rate and a 6.125% discount factor for dollars, and a 4.000% discount factor for water.

[c] Basis 2006.

[d] These are the total net cost stream values (nominal and real) relevant to producing RO-desalinated water for the life of the facility as they include initial capital-investment costs, increased O&M and capital replacement expenses, and ignore any value (or sales revenue) of the final water product.

[e] Delivery is to a point within the municipal delivery-system infrastructure, not household delivery.

Results – by Facility Segment

DESAL ECONOMICS© uniquely analyzes and provides comparable life-cycle costs (e.g., $/ac-ft/year) for up to twelve individual functional expense areas and for the entire facility. Here, the above aggregate cost-of-producing (and delivering to a point in the municipal delivery-system infrastructure) water of $769.62 (**Table 7**) is dissected into the seven functional expense areas detailed earlier.[37]

Table 8 shows the NPV of the net cost stream to range from a low of $137,325 for *Concentrate Discharge*, to a high of $32,247,556 for the *Main Facility*. These values signify the relative impact individual components' initial construction and future O&M costs have on costs for the total desalination facility. Also in **Table 8**, the annuity equivalent values are provided for individual components, which range from $8,837/year for *Concentrate Discharge*, to a high of $2,075,247/year for the *Main Facility*. These values are interpreted as the

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[37] DESAL ECONOMICS© can analyze up to twelve individual expense areas. For this analysis, however, only seven individual expense areas were present (and modeled). Other expense areas could be included (e.g., an integrated and dedicated power source such as wind turbine or solar-panel structure, or some other distinguishable functional area not present at the Southmost facility).

annualized costs for each component, inclusive of all life-cycle costs and reported in 2006 dollars (Rister et al. 2009).

A further delineation of the annuity equivalents reveals the economic and financial life-cycle costs range from $24/day for the *Concentrate Discharge* segment, to a high of $5,686/day for the *Main Facility*. The total life-cycle cost for all seven segments equates to $11,510/day. Again, these are the total daily life-cycle costs, reported in 2006 dollars (Rister et al. 2009).

Key annualized cost results presented in **Table 8** are the segmented costs-of-producing water for the seven individual facility components. This table reveals a range in facility segments' cost-of-producing-water values from a low of $1.62/ac-ft/year {$0.0050/1,000-gallons/year} for *Concentrate Discharge*, to a high of $380.18/ac-ft/year {$1.1667/1,000-gallons/year} for the *Main Facility*. In both the aggregate and segmented form, the total annual cost-of-producing water at the Southmost facility and delivering it on a f.o.b. basis to the municipal delivery point is $769.62 per ac-ft {$2.3619 per 1,000 gallons} (**Tables 7** and **8**).

Table 8. Costs of Producing (and Delivering) Water for the Seven Facility Segments of the Southmost Desalination Facility, in 2006 Dollars. [a, b]

		Annuity Equivalents				
Facility Segment	NPV of Cost Stream [c]	($/yr) [d]	($/day) [d]	$/ac-ft/year [e]	$/1,000-gals/year [e]	% of Total Cost
1) Well Field	$17,004,809	$1,094,321	$2,998	$200.48	$0.6152	26.0%
2) Intake Pipeline	$2,068,143	$133,092	$365	$24.38	$0.0748	3.2%
3) Main Facility	$32,247,556	$2,075,247	$5,686	$380.18	$1.1667	49.4%
4) Concentrate Discharge	$137,325	$8,837	$24	$1.62	$0.0050	0.2%
5) Finished Water Line & Tank Storage	$2,418,178	$155,619	$426	$28.51	$0.0875	3.7%
6) Delivery Pipeline	$5,569,592	$358,423	$982	$65.66	$0.2015	8.5%
7) Overbuilds & Upgrades	$5,835,486	$375,535	$1,029	$68.80	$0.2111	8.9%
TOTAL	$65,281,089	$4,201,075	$11,510	$769.62	$2.3619	100.0%

[a] These baseline results reflect the Southmost facility in its current operating state (i.e., 68% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Delivery is to a point in the municipal delivery-system infrastructure, not individual household delivery.

[c] Total costs (in 2006 dollars) throughout the facility's life of producing and delivering RO-desalinated water to a point in the municipal delivery-system infrastructure.

[d] Total costs for ownership and operations, stated in 2006 dollars, and the annuity values for the first column entitled 'NPV of Cost Stream.'

[e] Total 'annualized costs' on a per ac-ft basis (or $/1,000-gals) for each segment.

The proportions of annual cost-of-producing desalinated water at the Southmost facility are depicted for the seven functional areas in **Figure 4**. The respective percentages are those reported in **Table 8**. The most significant segment of the Southmost facility is the *Main Facility*, which contributes 49.4% of the total life-cycle cost. The *Concentrate Discharge* segment constitutes the lowest portion, representing only 0.2% of all life-cycle costs.

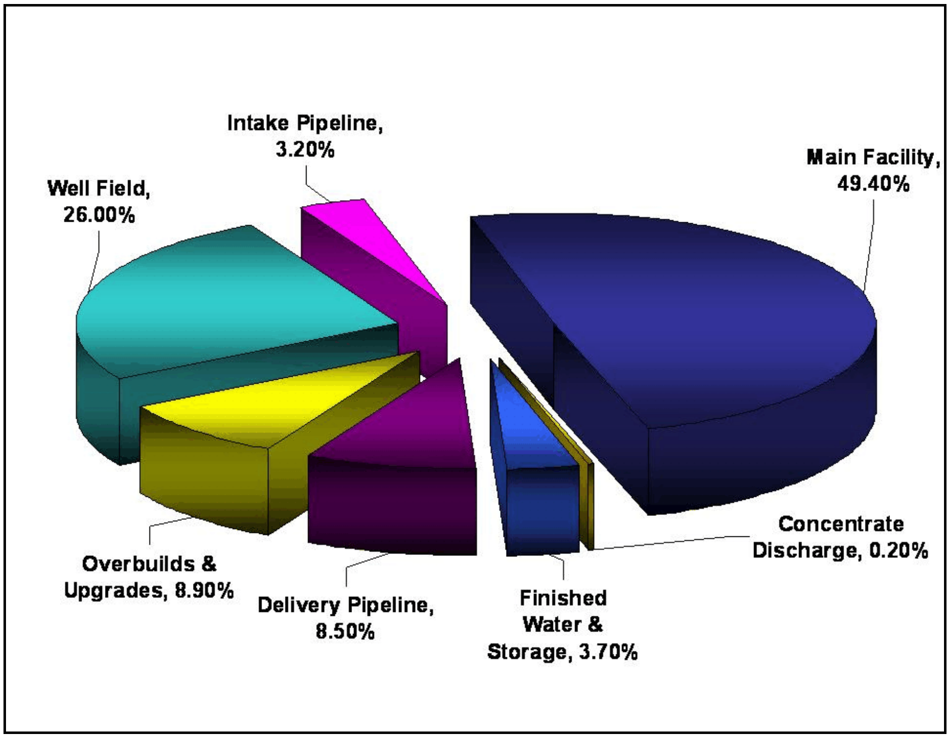

Figure 4. Proportion of Total Life-Cycle Cost, by Segment, for the Southmost Desalination Facility, 2006.

This analysis and presentation of segmented cost-of-producing-water results is believed to be unique among economic and financial analyses, as it goes beyond analyzing the 'bottom line' cost of an entire desalination facility. The segmenting of costs into functional areas (as is done in DESAL ECONOMICS©) allows for both single- and multi-facility analyses:

> Single-Facility Analysis: Within a single-facility analysis, the additional segmented-cost data identify the relative life-cycle costs, which can (a) highlight the need for a review assessment to see if engineering and/or construction changes could be made in a specific area to reduce the composite life-cycle cost (i.e., least-cost engineered design and/or asset configuration), and/or (b) analyze at what annual cost would a desalination-facility owner prefer to out-source a functional segment.[38]
>
> Multi-Facility Analysis: Within a multi-facility analysis, significant cost differences could occur across facilities. With a standard 'bottom line' analysis, there is no explanation as to which of the functional cost area(s) may be causing the disparity. By analyzing the individual functional cost areas, the additional detail provided can highlight the need for a review assessment to see if engineering/construction changes could be made in a specific area to reduce the composite life-cycle cost to a level observed at another similar facility.

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[38] For example, as indicated in Table 8, the *Well Field* costs $200.48 per ac-ft (2006 dollars) to buy, develop, and operate over the course of its life. If a third party were to offer to provide that same task (e.g., supply the source water at a rate based on 2006 dollars), the owner could make a comparison and evaluate the offer's soundness.

Results – by Cost Type, Category, and Item

Also unique regarding results provided by DESAL ECONOMICS© is a presentation of life-cycle cost results differentiated by a breakdown of cost types, categories, and certain specific cost items. **Tables 9a-9c** provide a progression of interrelated results, whose successive presentation gives an increasing concentration of scope.

As revealed in **Table 8**, the total net costs (in 2006 dollars) of producing and delivering RO-desalinated water (by segment) amount to $65,281,089 over the facility's productive life. This total can be attained by summing the net costs for *Initial Construction* ($26,190,993), *Continued* ($35,633,597), and *Capital Replacement* ($3,456,499) (**Table 9a**). The summed total of $65,281,089 is the estimated total amount of money which will be invested and spent on the desalination facility over the course of its life-cycle, expressed in 2006 dollars.

Within **Table 9a**, the $35,633,597 of *Continued* costs are segmented into the two detailed *Administrative* ($1,696,838) and *O&M* ($33,936,759) cost categories. Again, in successive detail of scope, the $33,936,759 in *O&M* costs are dissected into the four detailed *Energy* ($16,862,411), *Chemicals* ($5,090,723), *Labor* ($7,615,483), and *All Other* ($4,368,142) cost items. For each category and item, these values are the estimated total amount of money which will be invested and spent on the facility over the course of its life-cycle, in 2006 dollars.

Table 9a. Total NPV and Annuity Equivalent Costs, by Cost Type, Category, and Item for the Southmost Desalination Facility, in 2006 Dollars. [a]

Cost Type/Category/Item	- - - - NPV of Cost Streams - - - -			- - - Annuity Equivalent Costs - - -		
	"**Total** Life-Cycle Costs" [b]			"**Annual** Life-Cycle Costs" [b]		
	O&M	Continued	Total	O&M	Continued	Total
Initial Construction			$26,190,993			$1,685,486
Continued [c]			$35,633,597			$2,293,151
» Administrative		$1,696,838			$109,198	
» O&M		$33,936,759			$2,183,954	
• Energy	$16,862,411			$1,085,157		
• Chemicals	$5,090,723			$327,607		
• Labor	$7,615,483			$490,084		
• All Other	$4,368,142			$281,106		
Capital Replacement			$3,456,499			$222,438
TOTAL	$33,936,759	$35,633,597	$65,281,089	$2,183,954	$2,293,151	$4,201,075

[a] These baseline results reflect the Southmost facility in its current operating state (i.e., 68% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Basis 2006 dollars.

[c] "Administrative" costs are incurred by the Brownsville Public Utilities Board in association with the Southmost facility, while "Operation & Maintenance (O&M)" costs are incurred at the facility.

Table 9a indicates that significant costs, beyond those of *Initial Construction*, are associated with desalination. For this facility, when a commitment was made to build a facility for $26,190,993, an implicit commitment for an additional $39,090,096 (i.e., $65,281,089 - $26,190,993) (basis 2006 dollars) was also made for *Continued* and *Capital Replacement* costs.

In similar fashion, the associated annuity equivalent costs (or annual life-cycle costs, or "annualized" costs) for the NPV of Cost Stream are presented for each cost type, category, and item on the right-hand portion of **Table 9a**. Here, the "annualized" costs (which are calculated using annuity equivalent measures) are shown to total $4,201,075, with *Initial Construction* costs constituting $1,685,486 of that total. The largest proportion is derived from *Continued* costs of $2,293,151, while *Capital Replacement* costs contribute $222,438 to the annual economic and financial costs. Again, successive cost detail, as explained for NPV of Cost Streams in the preceding two paragraphs, applies.

The successive continuation of results in **Table 9a** is further developed in **Table 9b** where annuity equivalent ("annualized") costs are presented on a per unit basis for both *$/ac-ft/year* and *$/1,000-gal/year* measures. As per **Tables 7** and **8**, the total annual life-cycle costs are $769.62 per ac-ft and $2.3619 per 1,000-gallons. As per the left-portion of **Table 9b**, the per ac-ft life-cycle cost is dissected into *Initial Construction* ($308.77/ac-ft/year), *Continued* ($420.10/ac-ft/year), and *Capital Replacement* ($40.75/ac-ft/year) cost types, summing to an annual per ac-ft cost of $769.62. This is the estimated total amount of money which will be invested and spent annually (per ac-ft) to produce and deliver (to a point within the municipal delivery-system infrastructure) desalinated water from the Southmost facility over the course of its life-cycle, expressed in 2006 dollars. Successive detail for annual per ac-ft life-cycle costs, by cost category and cost item, is found on the left-side portion of **Table 9b**.

The right-side portion of **Table 9b** provides the same type of detailed cost information as discussed in the previous paragraph, but on a dollars per 1,000-gallon basis. The successive and progressive presentation of more detailed results concludes in **Table 9c** where the proportions of per-unit annual life-cycle costs (i.e., $/ac-ft/year and $/1,000-gal/year) are provided for the various cost types, categories, and items.

An earlier comment regarding results in **Table 9a** noted that "*... significant costs, beyond those of Initial Construction, are involved with desalination*," with supporting dollar values indicating the $26,190,993 in *Initial Construction* as being only a partial consideration of the total $65,281,089 in total life-cycle costs for the Southmost facility. As displayed in **Table 9c** below, *Initial Construction* costs constitute an estimated 40% of the total amount of money (basis 2006 dollars) which will be invested and spent on the desalination facility over the course of its life-cycle. Again, the proportion of *Continued* costs which amount to 55% is derived by *Administrative* (3%) and *O&M* (52%) cost proportions. The *O&M* costs consist of 26% *Energy*, 8% *Chemical*, 12% *Labor*, and 18% *All Other* (**Table 9c**). In total, *non-Initial Construction Costs* constitute 60% of the Southmost desalination facility's total life-cycle cost.

Table 9b. Life-Cycle (Annuity Equivalent) Costs – \$/ac-ft/year and \$/1,000-gal/year, by Cost Type, Category, and Item for the Southmost Desalination Facility, in 2006 Dollars. [a]

Cost Type/Category/Item	Annuity Equivalent Costs [b] \$/ac-ft/year O&M	Continued	Total	\$/1,000-gal/year O&M	Continued	Total
Initial Construction			\$308.77			\$0.9476
Continued [c]			\$420.10			\$1.2892
» Administrative		\$20.00			\$0.0614	
» O&M		\$400.10			\$1.2278	
• Energy	\$198.80			\$0.6101		
• Chemicals	\$60.02			\$0.1842		
• Labor	\$89.78			\$0.2755		
• All Other	\$51.50			\$0.1580		
Capital Replacement			\$40.75			\$0.1251
TOTAL	\$400.10	\$420.10	\$769.62	\$1.2278	\$1.2892	\$2.3619

[a] These baseline results reflect the Southmost facility in its current operating state (i.e., 68% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Basis 2006 dollars.

[c] "Administrative" costs are incurred by the Brownsville Public Utilities Board in association with the Southmost facility, while "Operations & Maintenance (O&M)" costs are incurred at the facility.

Table 9c. Percentage of Life-Cycle Costs, by Cost Type, Category, and Item for the Southmost Desalination Facility, 2006.

Cost Type/Category/Item	% of Life-Cycle Costs O&M	Continued	Total
Initial Construction			40 %
Continued			55 %
» Administrative		3 %	
» O&M		52 %	
• Energy	26 %		
• Chemicals	8 %		
• Labor	12 %		
• All Other	7 %		
Capital Replacement			5 %
TOTAL	52 %	55 %	100 %

Results – Key Sensitivity Analyses
The baseline results presented above are deterministic (i.e., absent stochastic elements, or risk considerations in the data input) and are based on specific values for:

(1) actual construction costs,
(2) estimated future years' continued costs (based on FY 2004-2005 as a proxy adjusted to FY 2006, with increases for higher energy and chemical expenses, and assumed 2.0+% inflation),
(3) estimated future years' capital replacement costs (based on 2006 dollars and 2.0+% inflation, and estimated replacement-period occurrences), and
(4) assumed discount rates of 6.125% for dollars and 4.000% for water.

Having data input which are absent stochastic elements does not negate the usefulness of the baseline results. It only means the baseline results are point estimates and, given inexactness in data input, baseline results are not expected to be exactly precise. Further, given the likely range in values for input parameters, a range in results also probably exists. To further the deterministic results presented above, the two-way Data Table feature of Excel® (Walkenbach, pp. 570-7 1996) is used to provide sensitivity analyses on the cost-of-producing (and delivering) water by varying two parameters and leaving all others constant at the levels used in the baseline analysis. Such actions facilitate testing of the stability (or instability) various data input have upon the results.

Most data-input parameters in this analysis are technically suitable for sensitivity analyses. For practical reasons, however, an abridged analysis of sensitivities is investigated and presented. Those input parameters presented are chosen for their likelihood of displaying significantly different results with slight-to-modest changes. Sensitivity results are provided in pairs of tables, where the "a" table depicts annual results on a $/ac-ft/year basis, while the "b" table depicts equivalent results on a $/1,000-gallon/year basis (**Tables 10a-16b**).

Tables 10a-b test the sensitivities across plausible ranges for the **facility's expected useful life** and the **production efficiency rate**. Changes to the expected useful life of 50 years are tested with minus (-) 5-year, 10-year, 15-year, 20-year, 25-year and 30-year variations, while the production efficiency rate is analyzed with variations ranging from a low of 60% to a high of 100% (inclusive of the baseline 68%). Using these variation ranges, sensitivity results for these two data show the annual cost of producing (and delivering) desalinated water ranges from $610.30 to $897.99 per ac-ft in **Table 10a**, and from $1.8730 to $2.7558 per 1,000 gallons in **Table 10b**. As expected, higher production efficiency rates contribute to lower cost-of-producing-water estimates. The impact that length of useful life has depends upon the number of expected useful years; i.e., for useful lives lasting 35 to 50 years, the costs are essentially the same, while useful lives shorter than 35 years tend to increase the costs of producing and delivering desalinated water. The key factor affecting this is the timing of capital replacement costs within the specified useful lives.

Tables 11a-b test the sensitivities across plausible ranges for **initial construction costs** and the **production efficiency rate**. Changes about the baseline initial construction costs of $26,190,993 are tested with +/- $1.0-million, $2.5-million, and $5.0-million variations, while the production efficiency rate is analyzed with variations ranging from a low of 60% to a high of 100% (inclusive of the baseline 68%). Using these variation ranges, sensitivity results for these two data show the annual cost of producing (and delivering) desalinated water ranges from $570.22 to $902.81 per ac-ft in **Table 11a**, and from $1.7499 to $2.7706 per 1,000 gallons in **Table 11b**. As expected, higher production efficiency rates and lower initial construction costs contribute to lower cost-of-producing-water estimates, and vice versa.

Tables 12a-b test the sensitivities across plausible ranges for **annual O&M costs** and the **production efficiency rate**. Changes about the baseline annual O&M costs of $1,725,101 are tested with +/- 10%, 20%, and 30% variations, while the production efficiency rate is analyzed with variations ranging from a low of 60% to a high of 100% (inclusive of the baseline 68%). Using these variation ranges, sensitivity results for these two data show the annual cost of producing (and delivering) desalinated water range from $494.79 to $976.13 per ac-ft in **Table 12a**, and from $1.5185 to $2.9956 per 1,000 gallons in **Table 12b**. As expected, higher production efficiency rates and lower annual O&M costs contribute to lower cost-of-producing-water estimates, and vice versa.

Tables 13a-b test the sensitivities across plausible ranges for **annual energy costs** and the **production efficiency rate**. Changes about the baseline annual energy costs of $816,347 are tested with +/- 5%, 10%, and 20% variations, while the production efficiency rate is analyzed with variations ranging from a low of 60% to a high of 100% (inclusive of the baseline 68%). Using these variation ranges, sensitivity results for these two data show the annual cost of producing (and delivering) desalinated water range from $568.56 to $877.75 per ac-ft in **Table 13a**, and from $1.7448 to $2.6937 per 1,000 gallons in **Table 13b**. As expected, higher production efficiency rates and lower energy costs contribute to lower cost-of-producing-water estimates, and vice versa.

Tables 14a-b test the sensitivities across plausible ranges for **annual chemical costs** and the **production efficiency rate**. Changes about the baseline annual chemical costs of $246,453 are tested with +/- 5%, 10%, and 20% variations, while the production efficiency rate is analyzed with variations ranging from a low of 60% to a high of 100% (inclusive of the baseline 68%). Using these variation ranges, sensitivity results for these two data show the annual cost of producing (and delivering) desalinated water range from $597.70 to $848.61 per ac-ft in **Table 14a**, and from $1.8343 to $2.6043 per 1,000 gallons in **Table 14b**. As expected, higher production efficiency rates and lower chemical costs contribute to lower cost-of-producing-water estimates, and vice versa.

Tables 15a-b test the sensitivities across plausible ranges for **capital replacement costs for RO membranes** and the **production efficiency rate**. Changes about the baseline capital replacement cost for RO membranes of $700,000 are tested with +/- $50,000, $75,000, and $100,000 variations, while the production efficiency rate is analyzed with variations ranging from a low of 60% to a high of 100% (inclusive of the baseline 68%). Using these variation ranges, sensitivity results for these two data show the annual cost of producing (and delivering) desalinated water range from $607.84 to $840.11 per ac-ft in **Table 15a**, and from $1.8654 to $2.5782 per 1,000 gallons in **Table 15b**. As expected, higher production efficiency rates and lower capital replacement costs contribute to lower cost-of-producing-water estimates, and vice versa.

Tables 16a-b test the sensitivities across plausible ranges for **capital replacement periods for RO membranes** and the **production efficiency rate**. Changes about the baseline capital replacement period for RO membranes of once every six (6) years is tested with +/- 1-year, 2-year, and 3-year variations, while the production efficiency rate is analyzed with variations ranging from a low of 60% to a high of 100% (inclusive of the baseline 68%). Using these variation ranges, sensitivity results for these two data show the annual cost of producing (and delivering) desalinated water range from $603.63 to $868.33 per ac-ft in **Table 16a**, and from $1.8525 to $2.6648 per 1,000 gallons in **Table 16b**. As expected, higher production efficiency rates and less-frequent capital replacement periods contribute to lower cost-of-producing-water estimates, and vice versa.

Table 10a. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/ac-ft), by Variations in Expected Useful Life and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (ac-ft) – ($ per acre-foot, per year)								
		5,041	5,461	**5,713**	5,881	6,721	7,141	7,561	7,981	8,401
Expected Useful Life (years)	20	$897.99	$847.03	$820.04	$803.34	$732.35	$703.12	$677.13	$653.88	$632.96
	25	$864.62	$816.81	$791.50	$775.83	$709.23	$681.81	$657.43	$635.62	$615.99
	30	$847.80	$801.81	$777.47	$762.40	$698.36	$671.98	$648.54	$627.57	$608.69
	35	$836.70	$792.07	$768.43	$753.80	$691.63	$666.03	$643.27	$622.91	$604.58
	40	$834.34	$790.32	$767.02	$752.60	$691.29	$666.04	$643.60	$623.52	$605.45
	45	$834.61	$790.97	$767.86	$753.56	$692.77	$667.74	$645.49	$625.58	$607.66
	50	$836.00	$792.60	**$769.62**	$755.40	$694.94	$670.05	$647.92	$628.12	$610.30

Table 10b. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/1,000 gallons), by Variations in Expected Useful Life and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (1,000 gal) – ($ per 1,000-gallons, per year)								
		1,642,500	1,779,375	**1,861,500**	1,916,250	2,190,000	2,326,875	2,463,750	2,600,625	2,737,500
Expected Useful Life (years)	20	$2.7558	$2.5994	$2.5166	$2.4654	$2.2475	$2.1578	$2.0780	$2.0067	$1.9425
	25	$2.6534	$2.5067	$2.4290	$2.3809	$2.1765	$2.0924	$2.0176	$1.9506	$1.8904
	30	$2.6018	$2.4607	$2.3860	$2.3397	$2.1432	$2.0622	$1.9903	$1.9259	$1.8680
	35	$2.5678	$2.4308	$2.3582	$2.3133	$2.1225	$2.0440	$1.9741	$1.9116	$1.8554
	40	$2.5605	$2.4254	$2.3539	$2.3096	$2.1215	$2.0440	$1.9751	$1.9135	$1.8581
	45	$2.5613	$2.4274	$2.3565	$2.3126	$2.1260	$2.0492	$1.9809	$1.9198	$1.8648
	50	$2.5656	$2.4324	**$2.3619**	$2.3182	$2.1327	$2.0563	$1.9884	$1.9276	$1.8730

Table 11a. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/ac-ft), by Variations in Initial Construction Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (ac-ft) – ($ per acre-foot, per year)								
		5,041	5,461	**5,713**	5,881	6,721	7,141	7,561	7,981	8,401
Initial Construction Costs ($'s)	($5,000,000)	$769.20	$730.93	$710.67	$698.13	$644.84	$622.89	$603.38	$585.93	$570.22
	($2,500,000)	$802.60	$761.77	$740.15	$726.76	$669.89	$646.47	$625.65	$607.02	$590.26
	($1,000,000)	$822.64	$780.27	$757.83	$743.94	$684.92	$660.62	$639.01	$619.68	$602.29
	$26,190,993	$836.00	$792.60	**$769.62**	$755.40	$694.94	$670.05	$647.92	$628.12	$610.30
	$1,000,000	$849.36	$804.93	$781.41	$766.85	$704.96	$679.48	$656.83	$636.56	$618.32
	$2,500,000	$869.41	$823.43	$799.09	$784.03	$719.99	$693.63	$670.19	$649.22	$630.34
	$5,000,000	$902.81	$854.27	$828.57	$812.66	$745.04	$717.20	$692.46	$670.31	$650.39

Table 11b. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/1,000 gallons), by Variations in Initial Construction Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (1,000 gal) – ($ per 1,000-gallons, per year)								
		1,642,500	1,779,375	**1,861,500**	1,916,250	2,190,000	2,326,875	2,463,750	2,600,625	2,737,500
Initial Construction Costs ($'s)	($5,000,000)	$2.3606	$2.2431	$2.1810	$2.1425	$1.9789	$1.9116	$1.8517	$1.7981	$1.7499
	($2,500,000)	$2.4631	$2.3378	$2.2714	$2.2304	$2.0558	$1.9839	$1.9201	$1.8629	$1.8114
	($1,000,000)	$2.5246	$2.3945	$2.3257	$2.2831	$2.1019	$2.0274	$1.9611	$1.9017	$1.8483
	$26,190,993	$2.5656	$2.4324	**$2.3619**	$2.3182	$2.1327	$2.0563	$1.9884	$1.9276	$1.8730
	$1,000,000	$2.6066	$2.4702	$2.3981	$2.3534	$2.1634	$2.0852	$2.0157	$1.9535	$1.8976
	$2,500,000	$2.6681	$2.5270	$2.4523	$2.4061	$2.2096	$2.1287	$2.0567	$1.9924	$1.9345
	$5,000,000	$2.7706	$2.6216	$2.5428	$2.4940	$2.2865	$2.2010	$2.1251	$2.0571	$1.9960

Table 12a. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/ac-ft), by Variations in Annual O&M Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (ac-ft) – ($ per acre-foot, per year)								
		5,041	5,461	**5,713**	5,881	6,721	7,141	7,561	7,981	8,401
Annual O&M Costs ($'s)	-30%	$699.64	$660.25	$639.39	$626.48	$571.61	$549.01	$528.93	$510.96	$494.79
	-20%	$744.68	$703.96	$682.40	$669.06	$612.34	$588.99	$568.23	$549.65	$532.94
	-10%	$790.13	$748.07	$725.81	$712.03	$653.45	$629.33	$607.89	$588.71	$571.44
	$1,725,101	$836.00	$792.60	**$769.62**	$755.40	$694.94	$670.05	$647.92	$628.12	$610.30
	+10%	$882.29	$837.53	$813.83	$799.16	$736.81	$711.13	$688.31	$667.89	$649.52
	+20%	$929.00	$882.87	$858.44	$843.32	$779.06	$752.59	$729.07	$708.03	$689.09
	+30%	$976.13	$928.61	$903.45	$887.88	$821.68	$794.43	$770.20	$748.52	$729.01

Table 12b. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/1,000 gallons), by Variations in Annual O&M Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (1,000 gal) – ($ per 1,000-gallons, per year)								
		1,642,500	1,779,375	**1,861,500**	1,916,250	2,190,000	2,326,875	2,463,750	2,600,625	2,737,500
Annual O&M Costs ($'s)	-30%	$2.1471	$2.0262	$1.9622	$1.9226	$1.7542	$1.6849	$1.6232	$1.5681	$1.5185
	-20%	$2.2853	$2.1604	$2.0942	$2.0533	$1.8792	$1.8075	$1.7438	$1.6868	$1.6355
	-10%	$2.4248	$2.2958	$2.2274	$2.1851	$2.0054	$1.9313	$1.8655	$1.8067	$1.7537
	$1,725,101	$2.5656	$2.4324	**$2.3619**	$2.3182	$2.1327	$2.0563	$1.9884	$1.9276	$1.8730
	+10%	$2.7077	$2.5703	$2.4976	$2.4525	$2.2612	$2.1824	$2.1124	$2.0497	$1.9933
	+20%	$2.8510	$2.7094	$2.6345	$2.5881	$2.3908	$2.3096	$2.2374	$2.1729	$2.1147
	+30%	$2.9956	$2.8498	$2.7726	$2.7248	$2.5217	$2.4380	$2.3637	$2.2971	$2.2373

Table 13a. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/ac-ft), by Variations in Annual Energy Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (ac-ft) – ($ per acre-foot, per year)								
		5,041	5,461	**5,713**	5,881	6,721	7,141	7,561	7,981	8,401
Annual Energy Costs ($/year)	-20%	$794.26	$750.85	$727.87	$713.65	$653.19	$628.30	$606.17	$586.37	$568.56
	-10%	$815.13	$771.73	$748.75	$734.52	$674.07	$649.17	$627.05	$607.25	$589.43
	-5%	$825.57	$782.16	$759.18	$744.96	$684.50	$659.61	$637.48	$617.68	$599.87
	$816,347	$836.00	$792.60	**$769.62**	$755.40	$694.94	$670.05	$647.92	$628.12	$610.30
	+5%	$846.44	$803.04	$780.06	$765.83	$705.38	$680.48	$658.36	$638.56	$620.74
	+10%	$856.88	$813.47	$790.49	$776.27	$715.81	$690.92	$668.79	$648.99	$631.18
	+20%	$877.75	$834.35	$811.37	$797.14	$736.69	$711.79	$689.67	$669.87	$652.05

Table 13b. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/1,000 gallons), by Variations in Annual Energy Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (1,000 gal) – ($ per 1,000-gallons, per year)								
		1,642,500	1,779,375	**1,861,500**	1,916,250	2,190,000	2,326,875	2,463,750	2,600,625	2,737,500
Annual Energy Costs ($/year)	-20%	$2.4375	$2.3043	$2.2338	$2.1901	$2.0046	$1.9282	$1.8603	$1.7995	$1.7448
	-10%	$2.5015	$2.3683	$2.2978	$2.2542	$2.0686	$1.9922	$1.9243	$1.8636	$1.8089
	-5%	$2.5336	$2.4004	$2.3298	$2.2862	$2.1007	$2.0243	$1.9564	$1.8956	$1.8409
	$816,347	$2.5656	$2.4324	**$2.3619**	$2.3182	$2.1327	$2.0563	$1.9884	$1.9276	$1.8730
	+5%	$2.5976	$2.4644	$2.3939	$2.3503	$2.1647	$2.0883	$2.0204	$1.9597	$1.9050
	+10%	$2.6297	$2.4965	$2.4259	$2.3823	$2.1968	$2.1204	$2.0525	$1.9917	$1.9370
	+20%	$2.6937	$2.5605	$2.4900	$2.4463	$2.2608	$2.1844	$2.1165	$2.0558	$2.0011

Table 14a. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/ac-ft), by Variations in Annual Chemical Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (ac-ft) – ($ per acre-foot, per year)								
		5,041	5,461	**5,713**	5,881	6,721	7,141	7,561	7,981	8,401
Annual Chemical Costs ($/year)	-20%	$823.40	$780.00	$757.02	$742.79	$682.34	$657.44	$635.32	$615.52	$597.70
	-10%	$829.70	$786.30	$763.32	$749.09	$688.64	$663.75	$641.62	$621.82	$604.00
	-5%	$832.85	$789.45	$766.47	$752.24	$691.79	$666.90	$644.77	$624.97	$607.15
	$246,453	$836.00	$792.60	**$769.62**	$755.40	$694.94	$670.05	$647.92	$628.12	$610.30
	+5%	$839.15	$795.75	$772.77	$758.55	$698.09	$673.20	$651.07	$631.27	$613.45
	+10%	$842.30	$798.90	$775.92	$761.70	$701.24	$676.35	$654.22	$634.42	$616.60
	+20%	$848.61	$805.20	$782.22	$768.00	$707.54	$682.65	$660.52	$640.72	$622.91

Table 14b. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/1,000 gallons), by Variations in Annual Chemical Costs and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (1,000 gal) – ($ per 1,000-gallons, per year)								
		1,642,500	1,779,375	**1,861,500**	1,916,250	2,190,000	2,326,875	2,463,750	2,600,625	2,737,500
Annual Chemical Costs ($/year)	-20%	$2.5269	$2.3937	$2.3232	$2.2795	$2.0940	$2.0176	$1.9497	$1.8890	$1.8343
	-10%	$2.5463	$2.4131	$2.3425	$2.2989	$2.1134	$2.0370	$1.9691	$1.9083	$1.8536
	-5%	$2.5559	$2.4227	$2.3522	$2.3086	$2.1230	$2.0466	$1.9787	$1.9180	$1.8633
	$246,453	$2.5656	$2.4324	**$2.3619**	$2.3182	$2.1327	$2.0563	$1.9884	$1.9276	$1.8730
	+5%	$2.5753	$2.4421	$2.3715	$2.3279	$2.1424	$2.0660	$1.9981	$1.9373	$1.8826
	+10%	$2.5849	$2.4517	$2.3812	$2.3376	$2.1520	$2.0756	$2.0077	$1.9470	$1.8923
	+20%	$2.6043	$2.4711	$2.4006	$2.3569	$2.1714	$2.0950	$2.0271	$1.9663	$1.9116

Table 15a. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/ac-ft), by Variations in Capital Replacement Costs for RO Membranes and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (ac-ft) – ($ per acre-foot, per year)								
		5,041	5,461	**5,713**	5,881	6,721	7,141	7,561	7,981	8,401
Capital Replacement Costs for RO Membranes ($/occurrence)	($100,000)	$831.90	$788.81	$766.00	$751.88	$691.86	$667.15	$645.18	$625.53	$607.84
	($75,000)	$832.92	$789.76	$766.90	$752.76	$692.63	$667.87	$645.87	$626.18	$608.46
	($50,000)	$833.95	$790.70	$767.81	$753.64	$693.40	$668.60	$646.55	$626.82	$609.07
	$700,000	$836.00	$792.60	**$769.62**	$755.40	$694.94	$670.05	$647.92	$628.12	$610.30
	$50,000	$838.06	$794.49	$771.43	$757.16	$696.48	$671.50	$649.29	$629.42	$611.53
	$75,000	$839.08	$795.44	$772.34	$758.03	$697.25	$672.22	$649.97	$630.07	$612.15
	$100,000	$840.11	$796.39	$773.24	$758.91	$698.02	$672.94	$650.66	$630.71	$612.77

Table 15b. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/1,000 gallons), by Variations in Capital Replacement Costs for RO Membranes and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (1,000 gal) – ($ per 1,000-gallons, per year)								
		1,642,500	1,779,375	**1,861,500**	1,916,250	2,190,000	2,326,875	2,463,750	2,600,625	2,737,500
Capital Replacement Costs for RO Membranes ($/occurrence)	($100,000)	$2.5530	$2.4208	$2.3508	$2.3074	$2.1232	$2.0474	$1.9800	$1.9197	$1.8654
	($75,000)	$2.5561	$2.4237	$2.3535	$2.3101	$2.1256	$2.0496	$1.9821	$1.9217	$1.8673
	($50,000)	$2.5593	$2.4266	$2.3563	$2.3128	$2.1280	$2.0519	$1.9842	$1.9237	$1.8692
	$700,000	$2.5656	$2.4324	**$2.3619**	$2.3182	$2.1327	$2.0563	$1.9884	$1.9276	$1.8730
	$50,000	$2.5719	$2.4382	$2.3674	$2.3236	$2.1374	$2.0607	$1.9926	$1.9316	$1.8767
	$75,000	$2.5750	$2.4411	$2.3702	$2.3263	$2.1398	$2.0630	$1.9947	$1.9336	$1.8786
	$100,000	$2.5782	$2.4440	$2.3730	$2.3290	$2.1421	$2.0652	$1.9968	$1.9356	$1.8805

Table 16a. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/ac-ft), by Variations in Replacement Period for RO Membranes and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (ac-ft) – ($ per acre-foot, per year)								
		5,041	5,461	**5,713**	5,881	6,721	7,141	7,561	7,981	8,401
Replacement Period for RO Membranes (No. of years)	-3	$868.33	$822.44	$798.14	$783.10	$719.18	$692.86	$669.47	$648.54	$629.70
	-2	$852.15	$807.51	$783.87	$769.24	$707.05	$681.45	$658.69	$638.32	$619.99
	-1	$842.93	$799.00	$775.74	$761.34	$700.14	$674.94	$652.54	$632.50	$614.46
	6	$836.00	$792.60	**$769.62**	$755.40	$694.94	$670.05	$647.92	$628.12	$610.30
	+1	$831.57	$788.50	$765.71	$751.59	$691.61	$666.91	$644.96	$625.32	$607.64
	+2	$827.95	$785.17	$762.52	$748.50	$688.90	$664.36	$642.55	$623.04	$605.47
	+3	$824.87	$782.33	$759.80	$745.86	$686.59	$662.19	$640.50	$621.09	$603.63

Table 16b. Sensitivity Analysis of Annual Costs-of-Producing Water at the Southmost Desalination Facility ($/1,000 gallons), by Variations in Replacement Period for RO Membranes and Production Efficiency Rate, in 2006 Dollars.

		Annual Production Efficiency Rate (% of current maximum design)								
		60%	65%	**68%**	70%	80%	85%	90%	95%	100%
		Annual Water Production (1,000 gal) – ($ per 1,000-gallons, per year)								
		1,642,500	1,779,375	**1,861,500**	1,916,250	2,190,000	2,326,875	2,463,750	2,600,625	2,737,500
Replacement Period for RO Membranes (No. of years)	-3	$2.6648	$2.5240	$2.4494	$2.4033	$2.2071	$2.1263	$2.0545	$1.9903	$1.9325
	-2	$2.6152	$2.4781	$2.4056	$2.3607	$2.1699	$2.0913	$2.0214	$1.9589	$1.9027
	-1	$2.5869	$2.4520	$2.3806	$2.3365	$2.1486	$2.0713	$2.0026	$1.9411	$1.8857
	6	$2.5656	$2.4324	**$2.3619**	$2.3182	$2.1327	$2.0563	$1.9884	$1.9276	$1.8730
	+1	$2.5520	$2.4198	$2.3499	$2.3066	$2.1225	$2.0467	$1.9793	$1.9190	$1.8648
	+2	$2.5409	$2.4096	$2.3401	$2.2970	$2.1142	$2.0389	$1.9719	$1.9120	$1.8581
	+3	$2.5314	$2.4009	$2.3317	$2.2889	$2.1071	$2.0322	$1.9656	$1.9061	$1.8525

Discussion

Desalination of seawater and brackish groundwater has historically been considered an expensive source for municipal and industrial (M&I) users, and prohibitively expensive for traditional agricultural users. Though beyond the scope of this report, such costs are purportedly decreasing (Graves and Choffel 2004). As analyzed with DESAL ECONOMICS© and reported herein, the 'costs' of a desalination facility can be segregated into several facility segments (or 'cost centers'), as well as dissected into different types, categories, and items. This capability offers additional information which can provide further insight and added value in post-construction case studies, and during the planning and design stage of future facilities.

Research and development efforts to reduce costs with improved RO membranes are key industry topics/goals. As exemplified herein, however, several cost items (e.g., concrete, energy, chemicals, membranes, administrative overhead, labor, etc.), over many years, are involved in comprising the final total life-cycle costs (i.e., NPV of cost stream) of groundwater desalination. As energy accounts for the single largest cost item (26% as per **Table 9c**), it is likely the most significant impact associated with new RO membranes may be their ability to permeate with reduced energy and less maintenance. That is, direct initial and replacement costs of RO membranes amount to a limited portion of the life-cycle NPV cost stream and should be recognized as such with regards to their relative impact upon total life-cycle costs.

Other cost-reduction activities, such as the design and 'fast track' procurement and construction management philosophy as implemented by NRS Consulting Engineers for the Southmost facility (Norris n.d.; Norris 2004) are very effective at reducing *Initial Construction* costs and the associated life-cycle NPV cost stream. As displayed in **Table 9c**, the Southmost facility has 40% of its life-cycle cost deriving from *Initial Construction* costs, and a combined 60% from *Continued* and *Capital Replacement* costs. Thus, *ceteris paribus,*[39] efforts to significantly reduce initial and/or future costs can be expected to lower life-cycle cost.

Putting it all into context, brackish groundwater desalination <u>might</u> be a more expensive alternative for communities in the Texas Lower Rio Grande Valley, but if so, it does offer a regional supply alternative which is dependable <u>and</u> provides a measure of defense against potential security-related threats.[40] There is anticipation that desalination costs will decline in future years as a result of technology development. Any future cost reductions provided by marginal membrane-technology advancements and/or engineering-related procurement and construction-management techniques may be countered, however, with higher prices for inputs such as cement, chemicals, and energy (which is observed in today's current global economic environment). That is, in absolute nominal terms, the life-cycle cost ($/ac-ft/year) of RO-desalinated water in South Texas may not decrease much, or any, in the future. What is important to measure, however, is the <u>costs</u> of RO-desalinated water <u>relative to</u> the <u>costs</u> of conventionally-treated surface water from the Rio Grande.[41]

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[39] An economic term (Latin) meaning "other (relevant) factors being equal" (Wooldridge 2006, p. 13).

[40] The modal verb "might" is used because analyses of conventional surface-water treatment costs have not yet been finalized with comparable methodology by the authors.

[41] Note the 'costs' of conventionally-treated surface water from the Rio Grande may not necessarily equal (and could be less than) the 'charges' for such water.

Finally, at the time of the decision to build the Southmost desalination facility, the northern area of Brownsville, TX (a) was experiencing rapid urban growth and drought conditions, (b) realized its geographical position as last among diverters along the Rio Grande, and (c) was faced with having to increase M&I water supplies. The principal options identified included building another surface-water treatment facility or constructing a desalination facility. The latter option was selected. The point being, if a community's water supply is limited or considered in jeopardy because of its geographic location and/or proximity to other sources, drought, etc., having potentially expensive RO-desalinated water may be better than having no water at all. If such conditions exist, the 'premium' (above that for conventionally-treated surface water) for desalinated water could be considered a 'societal insurance premium.'[42]

Comparing Economic and Financial Results with Accounting-Based Results

These life-cycle cost results are financial and economic in nature, and will likely differ with accounting-based results.[43] Remember, both the baseline and modified results (discussed in the appendix) are put on 'annuity equivalent' (AE) measures. That is, they are adjusted for both time and inflation, and are presented on a 2006 calendar-year basis. Typical accounting approaches to calculating the annual costs of producing water involve the periodic escalation, albeit implicit, of nominal-based dollars for the various inputs. This incremental increasing of costs-of-producing happens slowly over time and can account for inflation in a non-explicit sense. That is, input costs tend to increase over time, thereby causing a ratcheting-up of the final per-unit production costs (**Figure 5**).[44]

With these AE-based results, however, inflation and other time effects are incorporated into a single value (i.e., cost), which does not need to be periodically inflated on an incremental basis to account for increasing input costs. In the case of the baseline results (i.e., life-cycle of \$769.62/ac-ft/yr, or \$2.3619/1,000 gallons/yr) (**Table 7**), the AE value can be thought of as being a constant, average amount (basis 2006 dollars) which will allow for all costs (i.e., construction, continuing, and capital replacement) to be covered (denoted by the solid, horizontal, red line in **Figure 5**). Thus, an assessment of \$769.62 (basis 2006) for each ac-ft produced, for every year of the facility's useful life, will cover the specified treatment costs, and result in a net zero-dollar profit, or a "break-even" situation.

Also differing from accounting-based results are the total dollars spent on the facility over the course of its productive life. From an accounting perspective, a total of \$195,914,480,

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[42] In this context, a societal insurance premium is the amount local stakeholders are willing to pay to insure local water supply.

[43] The *baseline* results are applicable to the 7.5 mgd Southmost facility, with the described characteristics, costs, etc., and are useful in understanding the true long-term economic and financial costs of the facility. The *modified* results (discussed in the appendix), however, have had specific input data adjusted to allow this facility's results to be compared to others'; i.e., the *modified* results are not appropriate for use in analyzing a single facility. For example, facilities operate at different production efficiency rates, thus leveling specific input data allows for fair and useful side-by-side comparisons.

[44] The *Likely Accounting Costs* depicted in **Figure 5** in the green-dashed line are based on Southmost's initial construction costs (amortized over 30 years at 5% interest) and Southmost's annual Continued Costs (inflated at a level slightly over 2%).

in nominal dollars (**Table 7**), will be spent constructing and operating the Southmost facility (i.e., from time of commencement of construction to completion of facility decommissioning). A graph representing such accounting (i.e., nominal) costs are represented by the blue vertical bars in **Figure 5**. The associated economic and financial value is $65,281,089, in real terms (**Table 7**). That is, a beginning cash balance of $65,281,089 in a banking account drawing 6.125% interest (see page 18) will provide the cash flow requirements for 'withdrawals' for construction costs and annual O&M costs and capital replacement costs (inflated 2.04% annually; see page 18), with a $0 balance left over at the end of the 50 years of useful life.

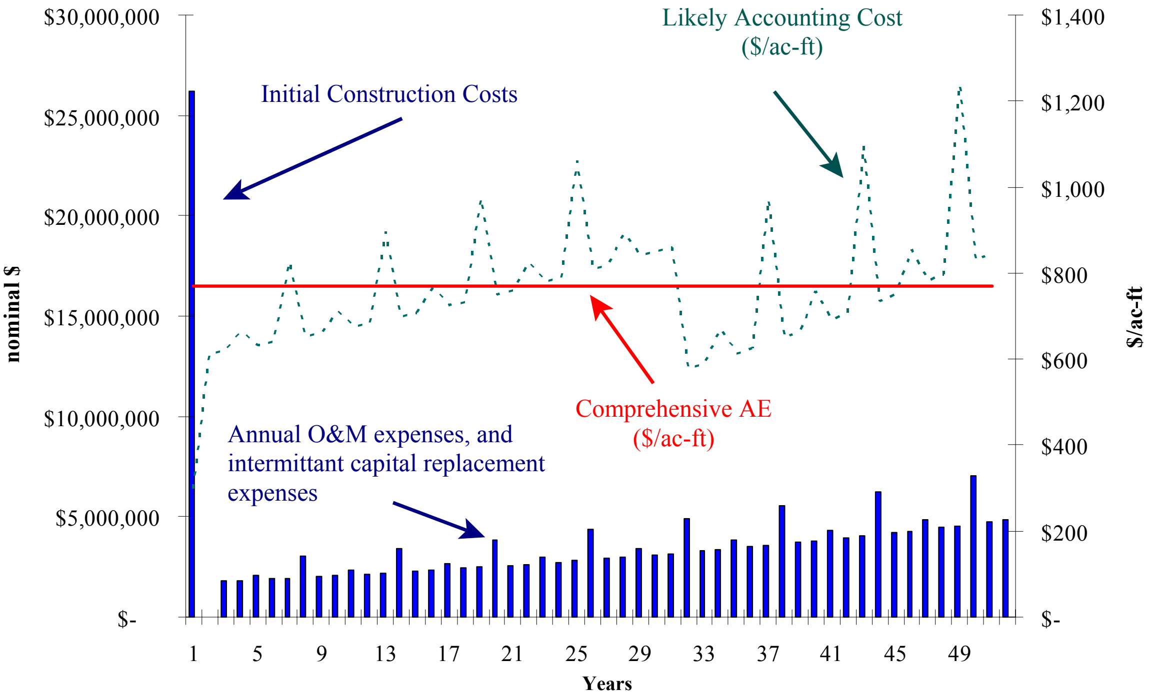

Figure 5. Depiction of Annual Cash Flow Requirements (Nominal Dollars), Likely Accounting Costs per acre-foot, and Comprehensive Annuity Equivalent (AE) Cost for the Southmost Facility Over its Useful Life.

Caveats and Limitations

Much thought and effort were put into developing the DESAL ECONOMICS© model, its comprehensive methodology, and attaining the necessary data-input for this case study. Nonetheless, a review of the usefulness of this work reveals certain caveats and limitations one should be aware of to limit any misuse and misunderstanding as to what the results represent.

- The baseline analysis/results represent a *snapshot in time* for one facility. That is to say, the results are estimates as the dynamics of costs and numerous other factors prevent the mass application of these specific life-cycle cost results of $769.62/ac-ft/yr {$2.3619/1,000 gals/yr} to other facilities. Life-cycle costs, even for the Southmost facility, change yearly, monthly, and even daily. Do not be dissuaded, however, as the results are very useful.

- The impact of location on a facility's life-cycle cost can be significant. The Southmost facility is a brackish groundwater RO facility physically close to the Gulf of Mexico. Thus, life-cycle costs incurred with disposing of the concentrate waste are very minimum for the Southmost facility (i.e., $1.62/ac-ft/yr {$0.0100/1,000 gal/yr}) and may not be representative of other facilities.

- The Southmost facility has a current maximum designed capacity of 7.5 mgd and at the data-gathering phase of the case-study had an operating production efficiency (PE) of 68%. As such, the baseline life-cycle cost results of $769.62/ac-ft/yr {$2.3619/1,000 gal/yr} may not accurately represent larger/smaller facilities, or facilities operating at higher/lower PEs. That is, this report does not report on the *economies of size* issue regarding RO desalination facilities. However, discussion and a series of sensitivity tables incorporating PEs (and other factors) differing from the baseline are provided for the Southmost facility, beginning on page 27.

- Since this study's analysis period (i.e., basis 2006) construction costs have risen about 1% per month, or about 10-12% per year (Cruz 2008). The life-cycle cost of the Southmost facility (built in 2003) has 40% of its total life-cycle cost from initial construction expenses. Thus, the 1% increase has significant implications for the life-cycle costs for any facility built after the Southmost facility.

- For the *Continued Cost*, the *Administrative* category (**Table 4**) accounts for expenses incurred at the Brownsville Public Utilities Board (BPUB) for and on behalf of the Southmost facility which are estimated as 5% of the O&M budget at the Southmost facility. This allocation amount is an approximation by management and is used in lieu of an extensive and costly accounting review/study which may, or may not, improve upon the accuracy of the *Administrative* costs used in this analysis/report.

- Oftentimes, the economic competitiveness of desalinated water is measured against conventionally-treated surface water. A caveat is warranted, however, in comparing the costs of desalination with that of charges assessed by municipalities for conventionally-treated potable water. That is, conventional-treated charges may not equate with the costs of such water. Making such an inadvertent comparison will make for an imbalanced comparison. A more appropriate comparison would involve evaluating life-cycle-derived costs for each alternative.

- The data input, and subsequently the baseline results, are deterministic. That is, they are absent stochastic elements, or risk considerations in the data input, and are based on singular, specific values for data (e.g., costs, water production, inflation, discounting, etc.). To compensate for this uncertainty about the precise exactness in the data input, several sets of sensitivity tables are included, beginning on page 27.

- The established methodology and subsequent economic and financial results significantly rely on the use of real values, which, over time, do not correlate well with accounting of nominal values. For additional discussion on this issue, please refer to the prior section entitled *Comparing Economic and Financial Results with Accounting-Based Results*.

- Nominal cost increases, specific inflation rates over relatively short periods of time, and numerous other factors can have a drastic effect on the NPV of costs. Therefore, caution is warranted in taking the baseline results of $769.62/ac-ft/yr {$2.3619/1,000 gals/yr}and making an inferential adjustment to future year values. That is, hypothetically speaking, in year 2015, it is incorrect to take these values and transform them to basis 2015 results by multiplying the baseline life-cycle cost results of $769.62/ac-ft/yr {$2.3619/1,000 gals/yr} by the then inter-temporal contemporary inflation rate.

- As discussed in the *Summary of Economic and Financial Methodology* section, the philosophy applied to baseline life-cycle cost analyses (i.e., 68% PE) is 'potable water is potable water.' That is, there are no adjustments made to a baseline analysis which accounts for differences in the quality of incoming or outgoing water at different potable-water-producing facilities. In Appendix A, this philosophy is maintained; even though certain other adjustments facilitating a more balanced comparison of dissimilar facilities and/or technologies, are discussed/made. Again, however, adjustments to account for different incoming/outgoing water qualities are not made with the modified analysis. Determining the protocol of such a process could be the subject of future research.

Implications

Though limitations exist, one should not be dissuaded from believing in the usefulness of this case study and its documentation of the initial application of the DESAL ECONOMICS© model. Though the case study provides a *look-in-time* for the Southmost facility, the DESAL ECONOMICS© model is quite capable, and really has its strength in providing information in the planning and design stages of future facilities. This holds true particularly when there are multiple alternatives amongst key facility characteristics affecting costs (e.g., location and distance from the well field and delivery point(s), process-flow designs and specific equipment used in individual segments, etc.) being considered.

As is revealed, the abridged listing of questions below points to the need for economic considerations to be an extension of engineering work in the pre-planning and design stages of a project as there are many items affecting the long-term economic/financial efficiencies. With regards to desalination facilities, answers to these questions/issues can be aided with the use of DESAL ECONOMICS©. With that said, there are several important items to be inferred and deduced from this work. Of key noteworthiness:

- Contemporary, robust data on life-cycle costs for RO desalination of brackish groundwater for South Texas is provided. Though this is a fast-growing part of the state and country, others who find themselves studying desalination for their own area or interests can benefit from the report's content, both in terms of pure information, as well as items one needs to consider (e.g., methodology, inflation, useful life, future costs beyond construction, etc.) if sound decisions are to be made regarding economically- and financially-efficient ways to increase local and/or regional water supplies;

- Awareness of the DESAL ECONOMICS© model, focused on a technology making significant inroads in today's world, provides much for water planners, investors (private or public), consulting engineers involved with project pre-planning and design, and those involved with operations management to consider. Specific insights addressed by the model's 'what-if' capabilities include:[45]

- The unique break-down of results by facility segment (see page 21) and the ability to analyze a facility (or across facilities) beyond a single, bottom-line cost value provides management the unique ability to evaluate the outsourcing of particular functions by other third parties (see footnote 38 on page 23).

- The break-down of results by cost type, category, and item (see page 24) and the implicit commitment of future years' expenses, enables stakeholders to gauge the effectiveness of different philosophies; e.g., buy lower-cost equipment up front, but spend more in chemicals, energy, repairs or replacements in subsequent years, versus spending more up front and less on future years' costs.

- Given the current escalation in construction costs of 1% per month (Cruz 2008) and the model's ability to analyze facilities by segment (see page 21), life-cycle costs of alternative facility designs and asset configurations can vary greatly. This leads to several questions, including:
    - » What are the 'overbuilds & upgrades' costing, and do we need them?
    - » Is the designed water-producing capacity right? or too low, or too high?
    - » Will the operations plan optimize use of the facility's target capacity?
    - » Within a given facility segment, is there a better, more cost-effective way?

- Given rapidly-increasing energy costs (anticipated to continue) and energy's dominance amongst cost items (see page 26), certain questions arise:
    - » Will enough energy be available at affordable rates?
    - » Is energy 'from the grid' the best? What about wind or other sources?
    - » Should the facility operate 24-7, or at off periods for the best energy rates?

- Given the potential for tougher water-quality standards, certain questions arise:
    - » Does the water-producing zone of the well field have potential problems with excess salts, arsenic, etc.?
        - redo the well-field design/depth, or compensate with more chemicals?
        - purchase land and include a back-up well-field location?
        - drill one deep well, or several shallow wells?
    - » Does the facility design and capacity take this into consideration?

○ Having a flexible design and a solid methodology in DESAL ECONOMICS© permits the analysis of any sized facility, regardless of location. As such, comparisons of different sized facilities are possible and are investigated and discussed by the authors in work by Boyer (2008) which exams the economies of size issue. Further, though beyond the scope of this report, the authors have built a related economic and financial model, CITY H_2O ECONOMICS©, on the same methodological platform and design standards as the

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[45] Note that much of the information in a DESAL ECONOMICS© model analysis is engineering related and thus necessarily requires the close collaboration with engineers and economists.

original DESAL ECONOMICS©, but designed to analyze conventional surface-water treatment facilities. Work by Rogers et al. (2009) investigates and reports on the 'Conventional' vs. 'Desalination' issue facing water planners.

Conclusions

This research has announced the development of the DESAL ECONOMICS© model and its abilities via case-study assessment of the economic and financial life-cycle cost of producing potable water, through reverse-osmosis desalination, using brackish groundwater from the Gulf Coast aquifer, at the Southmost facility in South Texas. Inferential understandings from this work can be drawn from the many engineering-, economic-, regulatory-, institutional-, and environmental-related factors encountered in this investigation. Key lessons learned include:

- Though the issue of economics and desalination are not new, this work and the related DESAL ECONOMICS© model do introduce some innovative and original approaches.

- The aggregate annual baseline life-cycle cost results herein of \$769.62/ac-ft are higher than the \$521.36 to \$586.53 per ac-ft range estimated by Norris in 2004 (i.e., prior to construction), largely due to Norris' estimate of 94% production efficiency (PE) (Norris 2007) and the DESAL ECONOMICS© analysis' use of actual data supporting a 68% PE.

- The modeled 68% PE, hampered by various operational and product-demand issues, is below the 85% level provided for the TCEQs *Rule-of-85*.[46] The difference in the life-cycle cost between the two is about \$100 per ac-ft (i.e., \$769.62/ac-ft, vs \$670.05/ac-ft).

- Consistent with other literature-review sources, energy costs are a major contributing factor in producing potable water via RO desalination. Here, energy represents 26% of total costs, or \$198.80 of the total aggregate annual life-cycle cost \$769.62/ac-ft. Given the current high-cost environment for energy, efforts to reduce the amount of energy required in desalination, and/or efforts to incorporate potentially more cost-effective alternative energy supplies (e.g., wind-powered desalination, zero-emission technology using organic wastes, etc.) will increase desalination's effectiveness and use/adoption.

- Potable water from desalination is limited in the Valley, representing only about 3% of the region's supplies. Within its immediate service area, however, the Southmost facility can provide upwards of 40% of potable water needs.

- The Southmost facility is a medium-sized reverse-osmosis (RO) desalination facility with a current maximum-designed capacity of 7.5 mgd. It is strategically located to provide

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[46] TCEQ mandate 30 TAC §291.93(30) states "A retail public utility that possesses a certificate of public convenience and necessity that has reached 85% of its capacity as compared to the most restrictive criteria of the commission's minimum capacity requirements in Chapter 290 of this title shall submit to the executive director a planning report that clearly explains how the retail public utility will provide the expected service demands to the remaining areas within the boundaries of its certificated area" (Texas Secretary of State 2008). Thus, although a facility may be operable at >85% capacity, it may necessarily be constrained (over the long term) to a lower PE rate as the public entity manages the operations of a portfolio of water supply/treatment facilities (Adams 2007).

water-supply assurances for the most downstream uses of surface water from the Rio Grande [River]. Also, its proximity to the Laguna Madre facilitates inexpensive disposal costs of the concentrate-waste discharge.

- Preferences for risk adverseness against supply shortages of downstream users of water from the Rio Grande [River] provided the impetus for building the Southmost facility. It is unlikely desalination (3% of supply) will ever overtake the dominance of Rio Grande surface water (87% of supply) in the Valley.

- Built in 2003, before a very significant escalation in costs for construction materials (about 1% per month according to Cruz 2008), the Southmost facility may have life-cycle cost advantages over similar-sized facilities built in latter, more expensive time periods (i.e., assuming future operating costs (potentially impacted by new, forthcoming technologies) are un-impacting).

Final Comments

Complete and thorough *life-cycle* cost analyses of *supply*- and/or *efficiency-oriented* capital projects which can add water to a region, including desalination, provide much useful information if they are based on methodology using NPV and annuity equivalent measures. This two-part methodology considers time and all cost types (i.e., initial construction, continuing, and capital replacement) and promotes an accurate portrayal of future years' costs ($/ac-ft/year) and productive capacity. Having the ability to objectively compare different water-supply projects and make capital investment decisions will become more important over time as populations increase, input costs rise, and water supplies become relatively scarcer. As such, sound analyses of finance and economics should be considered an extension of engineering-related tasks for capital-project alternatives involved in a region's water-resource planning.

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Appendix A: Modified Data Input and Results

Modified Data Input and Results

As advised on page 72 in Gleick et al. (2006), *"Extreme caution, even skepticism, should be used in evaluating different estimates and claims of future desalination costs. Predictions of facilities costs tend to conflict with actual costs once plants are built, and many cost estimates are based on so many fundamental differences that direct comparisons are invalid or meaningless. ... Comparison years are rarely normalized*."

To address these valid points and provide meaning to facility comparisons, in a pro-active manner, the authors provide alternative life-cycle cost results (below) which incorporate limited modifications to the Southmost facility's baseline scenario – in anticipation of their comparing its results to other facilities and/or technologies with the *DESAL ECONOMICS*© model, and its companion model *CITY H_2O ECONOMICS*© (e.g., Boyer 2008, Rogers et al. 2009). That is, the baseline results presented in the main text depict the Southmost facility in its current operating state. While the baseline results were determined using *DESAL ECONOMICS*© (previously advocated as being appropriate for making *apples-to-apples* comparisons of desalination facilities life-cycle costs), some adjustments are necessary to *level the playing field* if future comparisons are to be precisely made across other potable water facilities' (e.g., desalination, surface treatment, etc.) life-cycle costs. That is, natural variations in key data-input parameters of different facilities can distort any subsequent comparison of results. To precisely compare across individual facilities producing potable water, adjust the following data-input parameters in either the *DESAL ECONOMICS*© model, or the *CITY H_2O ECONOMICS*© model[47] (for individual facility-analysis files) so that they are the same for all facilities being analyzed:[48]

> [Author's note: text for each of the following four data-input variables discusses actions required to precisely compare other facilities to the Southmost facility (using either the *DESAL ECONOMICS*© model, or the *CITY H_2O ECONOMICS*© model). If other facilities are to be compared to one another (and not the Southmost facility), however, a common standard for each of the four variables should still be used in the analysis of each facility. That is, the specifics of those standards may need to be different than that discussed here (e.g., a commencement date different than January 1, 2006.)]

» base period of analysis – Assume the construction period commences on January 1, 2006. This insures financial calculations occur across a common time frame. For facilities constructed in different time periods, either inflating or deflating the appropriate cost values (i.e., initial construction, continuing, and capital replacement) will be necessary to accommodate this stated benchmark period.

» annual production efficiency – Assume a constant 85% production efficiency (PE) rate. This stated proportion of maximum-designed capacity is reasonable, allows for

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[47] The *CITY H_2O ECONOMICS*© model is built upon the same methodological platform and with the same design standards as *DESAL ECONOMICS*©, but targeted toward analyzing conventional surface-water treatment facilities. Documentation and implementation results using *CITY H_2O ECONOMICS*© by the authors can be found in Boyer (2008) and Rogers et al. (2009).

[48] As discussed in the *Summary of Economic and Financial Methodology* and the *Caveats and Limitations* sections, the assumption applied to baseline analyses is 'potable water is potable water.' That is, there are no adjustments made to an analysis which accounts for differences in the quality of incoming or outgoing water at different potable-water-producing facilities. That same philosophy is maintained here in Appendix A with the modified results ... even though other adjustments are made which improve the preciseness of comparing dissimilar facilities and/or technologies.

planned and unplanned downtime (e.g., maintenance, emergencies, demand interruptions, etc.), and complies with the *Rule of 85*.[49] Leveling the PE to this stated rate for each avoids potential bias associated with operating circumstances at particular facilities/sites.[50]

» overbuilds and upgrades – Ignore the *Overbuilds & Upgrades* facility segment and its impact upon the total life-cycle cost.[51] Doing so ignores the *non-essential* costs which allows levelised comparison of: (1) different technologies (e.g., desal vs. surface-water treatment) based upon only the technology itself (i.e., indifferent as to the inclusion and level of non-essentials), and (2) economies of size within (or across) a technology.

» salvage value of capital assets – Assume all capital assets (e.g., buildings, land) have an effective net salvage value of zero dollars. Doing so assumes facility decommissioning and site restoration costs equal the salvage (i.e., sale) value, and/or the investment (in buildings, land, etc.) are intended to be long term, with no expectations of ever 'salvaging' the asset(s).[52]

It is the *modified results* for individual facilities which are comparable. Making the above data-input changes to the analysis file for the Southmost facility in *DESAL ECONOMICS*© results in a modified life-cycle cost of $615.01/ac-ft/year {$1.8874/1,000 gals/year}(**Table A1**). Additional results after making the above parameter changes to the analysis file for the Southmost facility in *DESAL ECONOMICS*© are provided below. For brevity's sake, a textual discussion is not included with modified-results' tables A1, A2, A3, A4, and A5, below. Refer to the results discussion provided for baseline-results tables 7, 8, 9a, 9b, and 9c, respectively. Though the values are different, the baseline-results discussion provides direction for inferential understanding.

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[49] TCEQ mandate 30 TAC §291.93(30) states "A retail public utility that possesses a certificate of public convenience and necessity that has reached 85% of its capacity as compared to the most restrictive criteria of the commission's minimum capacity requirements in Chapter 290 of this title shall submit to the executive director a planning report that clearly explains how the retail public utility will provide the expected service demands to the remaining areas within the boundaries of its certificated area" (Texas Secretary of State 2008). Thus, although a facility may be operable at >85% capacity, it may necessarily be constrained (over the long term) to a lower PE rate as the public entity manages the operations of a portfolio of water supply/treatment facilities (Adams 2007).

[50] In reality, individual facilities operate at different PE rates, for many different reasons. In addition to the constraint induced by The Rule of 85 (see above footnote), items such as seasonal demand, source-water quality issues (e.g., abnormal arsenic, iron, etc.), and mis-matched equipment and related flow capacity across facility processes, etc. attribute to less than 100% PE.

[51] *Overbuilds & Upgrades* are the 'elbow room' allowing for future growth and 'whistles & bells' beyond baseline necessities of the process technology itself.

[52] The opportunity cost values for land, well fields, water rights, etc. associated with potable water production facilities can be argued to be net positive. Projections of such values 50+ years into the future are subject, however, to a broad range of subjective assumptions. Also, the financial discounting of such values 50+ years virtually eliminates the positive influence of such calculations in current (i.e., 2006) dollars.

Table A1. “Modified” Aggregate Results for Production and Costs for the Six Facility Segments of the Southmost Desalination Facility, in 2006 Dollars. [a]

Results	Units	Nominal Value	Real Value [b]
Initial Facility Costs	2006 dollars	$22,022,150	$22,022,150
Water Production	ac-ft (lifetime)	357,046	147,502
- annuity equivalent [c]	ac-ft/year		6,823
Water Production	1,000-gal (lifetime)	116,343,750	48,063,806
- annuity equivalent [c]	1,000-gal/year		2,223,376
NPV of Total Cost Stream [d]	2006 dollars	$209,423,179	$65,208,300
- annuity equivalent [c]	$/year		$4,196,391
Cost-of-Producing & Delivering Water [e]	$/ac-ft/year		$615.01
Cost-of-Producing & Delivering Water [e]	$/1,000-gal/year		$1.8874

[a] These modified results reflect the Southmost facility in a modified operating state (i.e., 85% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are not included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Determined using a 2.043% compound rate and a 6.125% discount factor for dollars, and a 4.000% discount factor for water.

[c] Basis 2006.

[d] These are the adjusted total net cost stream values (nominal and real) relevant to producing RO-desalinated water for the life of the facility as they include initial capital-investment costs, increased O&M and capital replacement expenses, and ignore any value (or sales revenue) of the final water product.

[e] Delivery is to a point within the municipal delivery-system infrastructure, not household delivery.

Table A2. "Modified" Costs of Producing (and Delivering) Water for the Six Facility Segments of the Southmost Desalination Facility, in 2006 Dollars.[a, b]

Facility Segment	NPV of Cost Stream[c]	Annuity Equivalents ($/yr)[d]	 ($/day)[d]	 $/ac-ft/year[e]	 $/1,000-gals/year[e]	% of Total Cost
1) Well Field	$18,598,307	$1,196,869	$3,279	$175.41	$0.5383	28.5%
2) Intake Pipeline	$2,068,143	$133,092	$365	$19.51	$0.0599	3.2%
3) Main Facility	$35,177,368	$2,263,791	$6,202	$331.77	$1.0182	53.9%
4) Concentrate Discharge	$137,325	$8,837	$24	$1.30	$0.0040	0.2%
5) Finished Water Line & Tank Storage	$2,728,024	$175,558	$481	$25.73	$0.0790	4.2%
6) Delivery Pipeline	$6,499,132	$418,243	$1,146	$61.30	$0.1881	10.0%
TOTAL	$65,208,300	$4,196,391	$11,497	$615.01	$1.8874	100.0%

[a] These modified results reflect the Southmost facility in a modified operating state (i.e., 85% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are not included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Delivery is to a point in the municipal delivery-system infrastructure, not individual household delivery.

[c] Adjusted (i.e., modified) total costs (in 2006 dollars) throughout the facility's life of producing and delivering RO-desalinated water to a point in the municipal delivery-system infrastructure.

[d] Adjusted (i.e., modified) total costs for ownership and operations, stated in 2006 dollars, and the annuity values for the first column entitled 'NPV of Cost Stream.'

[e] Adjusted (i.e., modified) total 'annualized costs' on a per ac-ft basis (or $/1,000-gals) for each segment.

Table A3. “Modified” Total NPV and Annuity Equivalent Costs, by Cost Type, Category, and Item for the Southmost Desalination Facility, in 2006 Dollars. [a]

Cost Type/Category/Item	- - - - NPV of Cost Streams - - - - “**Total** Life-Cycle Costs” [b]			- - - Annuity Equivalent Costs - - - “**Annual** Life-Cycle Costs” [b]		
	O&M	Continued	Total	O&M	Continued	Total
Initial Construction			$22,022,150			$1,417,205
Continued [c]			$39,729,651			$2,556,747
» Administrative		$1,891,888			$121,750	
» O&M		$37,837,763			$2,434,997	
• Energy	$21,078,014			$1,356,447		
• Chemicals	$6,363,404			$409,508		
• Labor	$7,615,483			$490,084		
• All Other	$2,780,863			$178,959		
Capital Replacement			$3,456,499			$222,438
TOTAL	$37,837,763	$39,729,651	$65,208,300	$2,434,997	$2,556,747	$4,196,391

[a] These modified results reflect the Southmost facility in a modified operating state (i.e., 85% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are not included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Basis 2006 dollars.

[c] “Administrative” costs are incurred by the Brownsville Public Utilities Board in association with the Southmost facility, while “Operations & Maintenance (O&M)” costs are incurred at the facility.

Table A4. “Modified” Life-Cycle (Annuity Equivalent) Costs – \$/ac-ft/year and \$/1,000-gal/year, by Cost Type, Category, and Item for the Southmost Desalination Facility, in 2006 Dollars. [a]

Cost Type/Category/Item	Annuity Equivalent Costs [b]					
	\$/ac-ft/year			\$/1,000-gal/year		
	O&M	Continued	Total	O&M	Continued	Total
Initial Construction			\$207.70			\$0.6374
Continued [c]			\$374.71			\$1.1499
» Administrative		\$17.84			\$0.0548	
» O&M		\$356.87			\$1.0952	
• Energy	\$198.80			\$0.6101		
• Chemicals	\$60.02			\$0.1842		
• Labor	\$71.83			\$0.1842		
• All Other	\$26.23			\$0.2204		
Capital Replacement			\$32.60			\$0.1000
TOTAL	\$356.87	\$374.71	\$615.01	\$1.0952	\$1.1499	\$1.8874

[a] These modified results reflect the Southmost facility in a modified operating state (i.e., 85% production efficiency level, basis 2006 dollars, costs for overbuilds and upgrades are not included, and a net salvage value of zero dollars is recorded for all capital assets).

[b] Basis 2006 dollars.

[c] “Administrative” costs are incurred by the Brownsville Public Utilities Board in association with the Southmost facility, while “Operational & Maintenance (O&M)” costs are incurred at the facility.

Table A5. “Modified” Percentage of Life-Cycle Costs, by Cost Type, Category, and Item for the Southmost Desalination Facility, based on 2006 Dollars.

Cost Type/Category/Item	% of Life-Cycle Costs		
	O&M	Continued	Total
Initial Construction			34 %
Continued			61 %
» Administrative		3 %	
» O&M		58 %	
• Energy	32 %		
• Chemicals	10 %		
• Labor	12 %		
• All Other	4 %		
Capital Replacement			5 %
TOTAL	58 %	61 %	100 %

Notes

APPENDIX B

Cost of Brackish Groundwater Desalination in Texas

12-06
September 2012

Jorge Arroyo and Saqib Shirazi
Innovative Water Technologies
Texas Water Development Board

Purpose of paper

To provide sample water production costs of brackish groundwater desalination in Texas.

Summary of Results

The capital cost of desalination plants is site specific. Factors such as depth, location and quality of the source water, and concentrate disposal method have the potential to substantially impact the capital cost of a project. Operation and maintenance will also vary from plant to plant in response to factors such as source water quality, power costs, age of the plant, and personnel allocated to the plant. Nevertheless, the cost of completed plants is a useful reference to estimate the cost of future projects with similar characteristics.

In collaboration with various utilities and consultants, we examined six brackish groundwater desalination plants completed in the last decade and arrived at the following conclusions:

- Capital cost range from \$2.03 to \$3.91 per gallon of installed capacity;
- Operation and maintenance costs range from \$0.53 to \$1.16 per 1,000 gallons of water produced; and
- Total production cost of water ranges from \$1.09 to \$2.40 per thousand gallons or \$357 to \$782 per acre-foot.

Background

In 1961 one of the first seawater desalination demonstration plants to be built in the United States was located at the Dow Chemical Complex in Freeport, Texas (The Dow Chemical Company, 1960; The Dow Chemical Company, 1961; Lomax, 2008). The first community desalting plant in Texas, designed to provide a public water supply, was installed at Port Mansfield in 1965. The plant had a design capacity of 250,000 gallons per day and used electrodialysis as the primary method of desalination (U.S. Department of Interior, 1966). Currently, there are 44 municipal brackish water desalination facilities in Texas, with a design capacity of about 120 million gallons per day or about 134,400 acre-feet per year.

In spite of this history and current status, desalination is relatively new when compared to other better-known water management strategies in Texas, and this lack of familiarity prompts questions about its costs. Desalination costs vary considerably by location based on a number of issues including feed water source, feed water quality, plant size, process type and design, intake type, pre- and post-treatment processes, concentrate disposal method, regulatory issues, land costs, and conveyance of water to and from the plant.

There are cost estimating tools that incorporate some of these variables. One such tool is the U.S. Bureau of Reclamation planning level estimating procedures for seawater and surface water brackish desalination facilities. Estimating procedures include nomographs to calculate the impact of selected variables, such as the cost of power, in the cost of desalination projects (U.S. Bureau of Reclamation, 2003). Another of Reclamation's products is WTCost©, a database and computer program with cost algorithms for different types of desalination pre-treatment and treatment technologies.

This paper provides a cost reference for brackish groundwater desalination in Texas on the basis of recently completed projects and projects currently under construction.

Cost Factors

The total production cost of desalinated water includes the cost of capital or debt service and operation and maintenance costs. Debt service costs are a function of the total capital cost of the project, the interest on the capital, and the loan payback period. The operation and maintenance costs are a function of chemical, power, equipment replacement, and labor costs. There are several approaches to calculate and report the cost of water. One approach assigns the debt service to the actual production volume (Wilf, 2007). Another alternative is to calculate the debt service load on the basis of a life-cycle analysis and use an efficiency factor [also known as plant operating factor] to estimate actual production volume instead of the design production capacity (Sturdivant and others, 2009). In this paper, the unit production cost (UPC) of desalinated water is calculated as follows:

Equation 1 - Unit Production Cost

$$UPC = \frac{Annual\ Debt\ Service}{Plant\ Design\ Capacity \times Plant\ Operating\ factor} + \frac{Operation\ and\ Maintenance}{Production\ Volume}$$

Many factors affect the capital and operational costs of desalination facilities (Graves & Choeffel, 2004; Younos, 2005). Below is an illustration of commonly recognized cost factors for desalination systems (Figure 1).

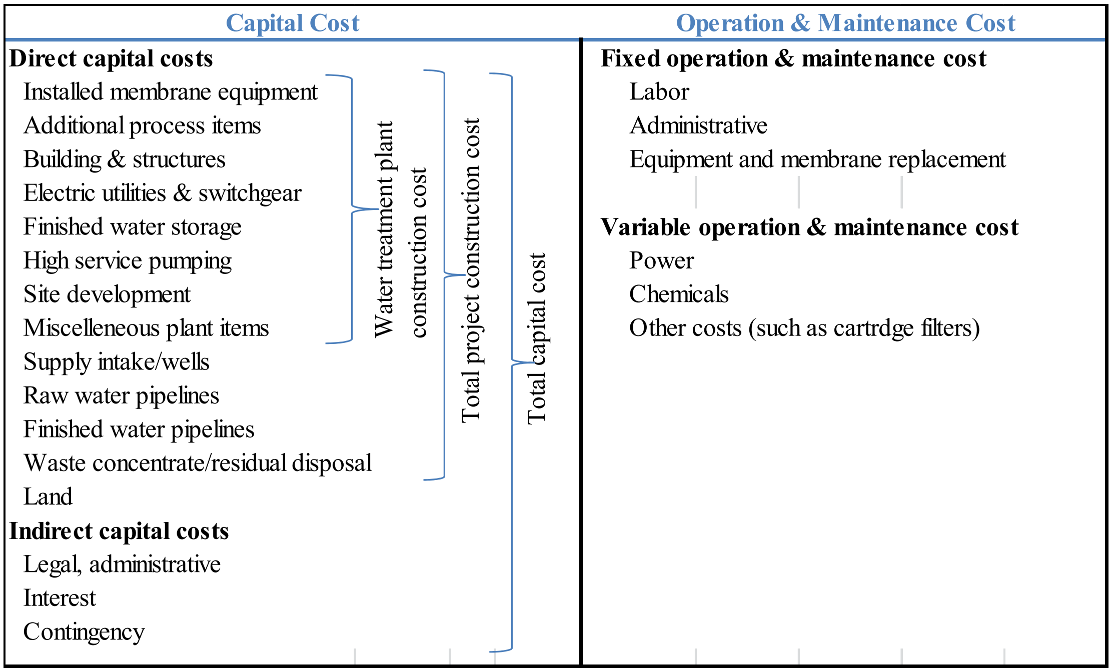

Figure 1 - Key factors for capital and operation and maintenance costs of a desalination facility (Bergman, 2012).

Projects Samples and Costs Analysis

Project Samples

Our review of brackish groundwater desalination costs considered two sets of samples. In the first set, we collected data from a sample of recently completed brackish groundwater desalination plants in Texas. In the second set, we collected data from a sample of brackish groundwater desalination projects that are currently under construction in Texas.

The sample of recently completed brackish groundwater desalination projects consists of six facilities (year of installation noted in brackets):

- North Alamo Water Supply Corporation, three facilities:
  - Lasara, Willacy County (2005)
  - Owassa, Hidalgo County (2008)
  - Doolittle, Hidalgo County (2008)
- North Cameron Regional Water Supply Corporation, Cameron County (2007)
- Southmost Regional Water Authority, Cameron County (2004)
- El Paso Water Utilities’ Kay Bailey Hutchison Brackish Groundwater Desalination Plant. El Paso County (2007)

The sample of projects currently under construction consists of three projects:

- North Alamo Water Supply Corporation- Donna, Hidalgo County
- City of Roscoe, Nolan County

- Fort Hancock Water Conservation Improvement District, Hudspeth County

Costs Analysis

Our estimates of production cost do not include any infrastructure to connect the facility to the distribution system. The cost, thus, should reflect extracting and delivering the source water to the treatment plant, treating and conditioning the water for delivery, and discharging the concentrate for disposal. We worked with representatives from the respective utilities and used TWDB records to obtain relevant capital and operation and maintenance cost information.

The completed projects have different plant start dates. To facilitate the comparison of capital costs, we normalized the capital costs for all projects to 2011 dollar equivalents. We used the Engineering News Record (ENR) construction average annual indices to estimate the trended capital costs for each project.

Equation 2 – Capital Costs Trending Formula

$$Capital\ Cost_{\$2011} = Capital\ Cost_{\$installation\ year} \times \frac{ENR\ Index_{2011}}{ENR\ Index_{installation\ year}}$$

The [trended] annual debt service was calculated by amortizing the trended capital cost over a 20-year period (n) and a 5.5 percent interest rate (i), as follows:

Equation 3 - Annual Debt Service

$$Annual\ Debt\ Service = Capital\ Cost \times \left(\frac{i}{1-(1+i)^{-n}}\right)$$

Where,

i= annual interest rate for capital borrowing

n= number of year to repay the debt

Results

Table 1 reports the unit production cost of desalinated brackish groundwater for the sample of recently completed projects. These costs are estimates of what the production cost of water would be if the plants had been built in the year 2011 and if the unit operation and maintenance costs observed on the basis of actual operation to-date were maintained. Unit production cost of desalinated brackish groundwater ranges from $357 per acre-foot (North Alamo Water Supply Corporation plant at Doolittle) to $782 per acre-foot (North Cameron Regional Water Supply Corporation).

Table 1 - Trended water production costs of a sample of existing brackish groundwater desalination facilities.

Brackish Groundwater Desalination Plant	Desalination Design Capacity (MGD)[3]	Water Treatment Construction cost ($)		Capital Cost $\$_{2011}$/gal	Capital Cost $\$_{2011}$/AF	Power cost (¢/Kw-hr)	Production cost ($) per 1,000 Gallons			Water Production Cost ($ per Acre-Foot)
[Source water salinity; start-up year]	[Reverse osmosis treatment capacity; raw water blending capacity]	Original Cost	Trended Cost 2011				O&M	Debt	Total cost	
Lasara [2,500-3,000 mg/l; 2005]	1.2 [1; 0.2]	2,000,000	2,436,180	2.03	661.53	7.2	1.13	0.46	1.59	518
Doolittle [2,500-3,000 mg/l; 2008]	3.5 [3; 0.5]	8,000,000	8,731,736	2.49	812.93	6.9	0.53	0.56	1.09	357
Owassa [2,500-3,000 mg/l; 2008][1]	2 [1.5; 0.5]	5,850,000	6,385,082	3.19	1,040.29	5.9	0.6	0.72	1.32	431
North Cameron Regional WSC [3,500 mg/l; 2007][2]	1.25 [1; 0.25]	7,033,554	8,008,327	6.41	2,087.62	8	0.95	1.45	2.40	782
	2.5 [2; 0.5]	8,033,554	9,146,916	3.66	1,192.21	8	0.95	0.83	1.78	579
Southmost Regional Water Authority [3,500 mg/l; 2004]	7.5 [6; 1.5]	23,000,000	29,319,404	3.91	1,273.84	7.49	1.16	0.88	2.04	666
Kay Bailey Hutchison El Paso-Ft. Bliss [4,365 mg/l; 2007]	27.5 [15; 12.5]	91,000,000	103,611,599	3.77	1,227.71	8.35	0.65	0.85	1.50	489

Notes:

[1] Current production capacity of the plant is only 2 MGD. The plant will be capable of producing 3.5 MGD with the addition of a well. The capital cost includes expansion capabilities.

[2] The plant currently operates with only one well and produces as much as 1.25 MGD of product water. The plant will produce as much as 2.5 MGD with the addition of a well. The plant's capital cost includes expansion capabilities for up to 5 MGD of product water.

[3] The cost analysis used "1" as the plant operating factor.

AF = acre-foot, Kw-hr = kilowatt-hour, mg/l = milligrams per liter, MGD = millions of gallons per day, O&M = operation and maintenance, TDS = total dissolved solids, WSC = water supply corporation.

The capital cost in 2011 dollar equivalents of the sample of completed facilities ranges from $2.03 (North Alamo Water Supply Corporation Lasara) to $3.91 (Southmost Regional Water Authority) per gallon of installed capacity (Figure 2).

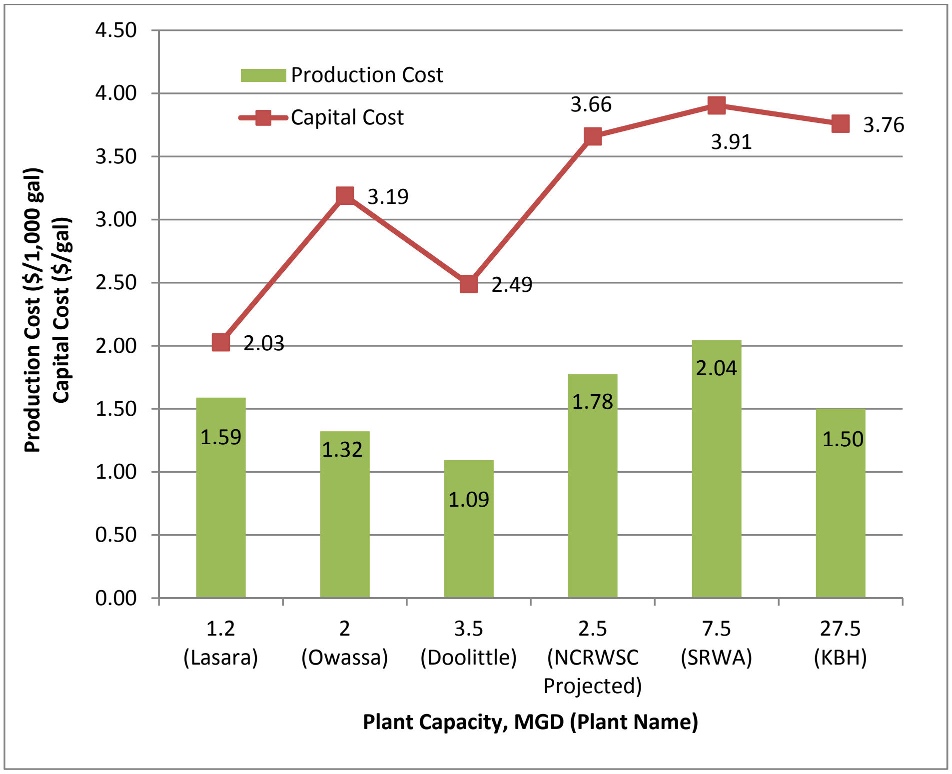

Figure 2 - Capital and Operational Costs (2011 dollar equivalents) of sample completed facilities

The projected total production cost of desalinated brackish water for a sample of projects that are currently under construction in Texas ranges from $280 per acre-foot to $1,064 per acre-foot (Table 2). The capital costs for the plants under construction were amortized on a 20-year 5.5 percent interest basis. Because these plants have not begun operation yet, the unit operation and maintenance costs were estimated on the basis of engineering analysis of the projects.

Although the desalination design capacities for the City of Roscoe and Forth Hancock Water Control and Improvement District (WCID) are almost same, the unit capital cost as well as the total production cost for these facilities is significantly different (Table 2). One of the primary reasons for such a significant difference in cost is that Forth Hancock WCID installs evaporation ponds to dispose the concentrate, while the City of Roscoe disposes the concentrate by surface water discharge. Construction cost of evaporation ponds increases the unit capital cost and the total production cost of desalinated water for Fort Hancock WCID.

Table 2 - Estimated water production cost of brackish groundwater desalination facilities under construction.

			Unit Capital Cost			Cost ($) per 1,000 Gallons			
Brackish Groundwater Desalination Plant [Source water salinity]	**Desalination Design Capacity (MGD)[1]**	**Water Treatment Plant's Capital Cost ($)**	**$\$_{2011}$/gal**	**$\$_{2011}$/AF**	**Power Cost (¢/Kw-hr)**	**O&M[2]**	**Debt**	**Total Production Cost**	**Water Production Cost ($ per Acre-Foot)**
Fort Hancock WCID [1,600-2,400 mg/l]	0.4	3,375,000	8.44	2,749	8.2	1.36	1.91	3.27	1,064
City of Roscoe [3,800 mg/l]	0.5	974,000	2.25	735	7	0.42	0.44	0.86	280
North Alamo WSC Donna [3,800 mg/l]	2.5	6,700,000	2.68	873	7	0.8	0.61	1.41	458

Notes:

[1] The cost analysis used "1" as the plant operating factor.

[2] O&M costs for these projects are estimated.

AF = acre-foot, Kw-hr = kilowatt-hour, mg/l = milligrams per liter, MGD = millions of gallons per day, O&M = operation and maintenance, TDS = total dissolved solids, WSC = water supply corporation.

Additional Considerations

Several methodologies researched for this paper provide a valuable reference for a systematic planning-level water production cost estimating for desalination facilities (U.S. Bureau of Reclamation, 2003; Wilf, 2007; Sturdivant and others, 2009). TWDB and Reclamation are in the process of applying Reclamation's WaterCost (WTCost©) estimating software to a larger sample of facilities completed in the state since 2000. This application will account for cost factors such as source water chemistry and location, recovery rate, blending ratio, energy recovery, power tariff, concentrate management strategy, and projected plant availability. A deliverable of this effort will be a set of cost curves to guide cost estimating of brackish groundwater desalination facilities in Texas.

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APPENDIX E

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April 19, 2012

TO: **Peggy Kurtz, Rockland Water Coalition**
FROM: **Ed MacMullan**
SUBJECT: **REVIEW OF COST INFORMATION IN THE *HAVERSTRAW WATER SUPPLY PROJECT DRAFT ENVIRONMENTAL IMPACT STATEMENT***

Introduction

In this memo I describe the results of my review of the cost information in the *Haverstraw Water Supply Project Draft Environmental Impact Statement*[1] ("DEIS"). My review focused on the extent to which the authors of the DEIS described cost information as it pertained to their comparison of alternatives. Specifically, I reviewed the DEIS for the following cost information: data and the sources of data, analytical methods, assumptions made as part of the analysis, and the comparison of cost information and results across alternatives. My comments address the following topics:

- *The almost complete lack of transparency and documentation regarding the data, assumptions, and analytical methods used to generate the cost results.* By excluding such basic details, the authors of the cost sections of the DEIS report results that lack credibility as a source of information for decision makers and stakeholders.

- *The DEIS authors do not use consistent measures of cost effectiveness across all alternatives.* Measuring the cost of the preferred alternative using the method applied to the wastewater reuse alternative shows that the proposed project is not necessarily the most cost effective option.

- *The cost analysis as described in the DEIS does not conform to commonly-accepted standards for measuring and describing cost-effective comparisons among competing alternatives.* The National Research Council and other industry experts provide detailed guidelines for conducting the types of cost-effective analyses at issue in the DEIS. Had the authors of the cost sections of the DEIS following these guidelines they could have produced cost results that decision makers and stakeholders could have confidence in as they deliberate the competing alternatives. Instead, the DEIS cost analysis is analytically deficient.

In the remainder of this memo I describe these topics in more detail.

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[1] AKRF, Inc., et al. 2012. *Haverstraw Water Supply Project Draft Environmental Impact Statement*. For the NY State Department of Environmental Conservation, Division of Environmental Permits, Albany, NY. January 13. http://www.haverstrawwatersupplyproject.com "DEIS."

Lack of Transparency and Documentation

The cost information reported in the DEIS suffers from an almost complete lack of transparency and documentation regarding the data, methods, assumptions and results for the major components of the analysis including:

- The construction costs and operations and maintenance costs of the proposed project.
- The construction costs and operations and maintenance costs of the alternatives to the proposed projects.
- The impacts of the costs of the proposed project or alternatives on ratepayers.

By excluding such basic details, the authors of the cost sections of the DEIS report results that lack credibility as a source of information for decision makers and stakeholders.

As described in the Executive Summary and elsewhere in the document, one of the primary purposes of the DEIS is documenting the cost effectiveness of the proposed project relative to competing alternatives. Given this goal, a reasonable expectation of the document would be details on the data, analytical methods, assumptions, etc. of the cost comparisons across alternatives. Instead, the document contains only a brief summary of cost results. For example, the entire subsection on capital costs of the proposed project (Section 2.8.4.1.) reads as follows:

> "The Proposed Project is anticipated to begin construction by May 2013, and Phase 1 is expected to be in service by December 31, 2015. The estimated range of anticipated costs associated with constructing and equipping the Project is sown in Table 2-10, below. The Project is expected to cost between approximately $139.2 million and $189.3 million at completion (Phase 3). The final cost of the Project depends on final design and permits and site plan approvals."
>
> "The capital costs presented in Table 2-10 were developed on the basis of the baseline design described above. The cost estimates were prepared based on the baseline design described in this chapter and using generally accepted scientific and engineering practices."[2]

Table 2-10 reports the capital costs, estimated annual operating costs, average daily cost per account and average daily cost per single-family household.

The list of relevant analytical details not included in the two-paragraph summary of project capital costs includes:

- Phase 3 of the project would not happen until after 2030, 18 years in the future. What inflation rate did the analysts use to account for increases in construction costs?
- Likewise, what discount rate did the analysts apply to future costs to calculate the present value of future costs?
- What are the individual line items, or categories, in the cost calculation?
- What are the contingency and design costs?
- Does the analysis include all the relevant costs of new or upgraded infrastructure upon which the operation of the proposed project would rely?

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[2] DEIS, page 2-42.

- At what capacity did the analysts assume the plant would operate?
- What analytical assumptions or data account for the low and high cost estimates?
- What data sources and other analytical assumptions does the analysis rely on?
- What are the major risks and uncertainties associated with the cost calculation and how do they affect the results?

Acknowledging the impact of uncertainties on results is especially important when estimating future construction costs. For example, United Water's own estimates of the construction costs have increased significantly over the previous five years. In early 2007, United Water estimated the cost of the proposed plant at $98 million.[3] By 2012, as reported in the DEIS, the cost increased to $139 to $189 million—a 43 to 93 percent increase in five years, well above the rate of inflation during this time. Should costs continue escalating over the 18 years of the project, total project costs will greatly exceed today's estimate, even allowing for discounting future costs to present dollars. Because the DEIS lacks details on the cost calculation, the reader has no way of knowing how or if the analysts accounted for future increases in construction costs.

Likewise, the cost analysis reported in DEIS has no information on how the uncertainty of the operating capacity of the proposed project could affect operating costs, and resulting costs on ratepayers. A recent report by the Congressional Research Service documented how not taking capacity uncertainty into account increased operating costs for a desalination plant in Tampa, Florida.[4] The Tampa project, like the proposed project, relies on brackish water. According to the CRS report,

> "Application of desalination to estuarine water is *uncommon*, with the facility in Tampa being the largest of its kind in the United States."[5] [emphasis added]
>
> "… [T]he Tampa plant, a facility to desalinate heavily brackish estuarine water, encountered technical and economic problems (e.g., less freshwater produced than anticipated, fouling of reverse osmosis membranes, financing issues) during construction and start-up, driving up the cost of the freshwater produced."[6]

In part because of the uncertainties associated with desalination plants in general, and in part because of the experience with the Tampa plant, the author of the CRS report concluded that large-scale desalination projects require "careful investigation."[7] Due to the lack of transparency and documentation noted above and in the remainder of this memo, the authors of the DEIS provide no evidence that they conducted a "careful investigation" of the costs of the proposed project and how these costs would affect ratepayers.

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[3] United Water. 2007. *United Water New York Long Term Water Supply Project*. Page 8. January 15.

[4] Carter, Nicole. 2011. *Desalination: Technologies, Use, and Congressional Issues*. Congressional Research Service. 7-5700, R40477, www.crs.gov. August 15.

[5] Carter, 2011, page 5.

[6] Carter, 2011, page 3.

[7] Carter, 2011, page 3.

The lack of transparency and documentation combined with the relatively large spread between the estimated low and high construction costs for the proposed project raises questions regarding the source of the cost results. Specifically, readers are left to wonder as to the data, assumptions, and analytical methods that the DEIS authors used to generate a cost estimate that varies by $50 million dollars, or by 36 percent relative to the low-cost estimate.

The DEIS description of operating costs of the proposed project is similarly meager. The entire subsection on operating costs (Section 2.4.4.2.) reads as follows:

> "Upon completion, the Proposed Project would incur life-cycle costs during the course of its operations. These operating costs arise from the Project's need to consume electricity, gas, and process materials. In addition, the Project would require ongoing maintenance and periodic equipment repairs and replacement. The estimated annual life-cycle cost of operating the Proposed Project, excluding depreciation, personnel and property tax expenses, would be approximately $2.2 million per year during Phase 1, increasing to $4.0 million during Phase 2, and $5.6 million per year at completion. The cost estimates were prepared based on the baseline design described in this chapter and using generally accepted scientific and engineering practices."[8]

Much of the criticism above regarding the lack of transparence and documentation in the analysis of capital costs applies to the analysis of operating or life-cycle costs for the proposed project. This is especially true for three operating costs that industry experts report as being particularly important: energy costs, the costs of managing salt concentrate, and the costs of membrane replacement.[9] Specific to electricity costs, the CRS report states, "Uncertainty in electricity prices … creates significant uncertainty in the operating costs of desalination facilities, which influences the technology's attractiveness as a water supply." A full accounting of operating costs for the proposed project would include not only the current and future costs of electricity to operate the facility, but also the cost of electricity to pump water upslope from the water source to the plant. A related cost is the cost of carbon emissions associated with the energy demand and other aspects of operating the proposed project. [10] Specific to the costs of concentrate management, a report on desalination by the National Research Council states, "… when low-cost concentrate management methods are not available, brackish groundwater desalination costs can reach or exceed seawater desalination costs."[11] On this topic the author of the CRS report concluded, "For inland brackish desalination, significant constraints on adoption are the uncertainties and the cost of the waste concentrate disposal."[12] Specific to the costs of membrane replacement, another industry expert states, "The major maintenance cost [of a desalination plant] pertains to the frequency of membrane replacement, which is affected by the

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[8] DEIS, page 2-43.

[9] Carter, 2011; Committee on Advancing Desalination Technology, National Research Council. 2008. *Desalination: A National Perspective*. The National Academies Press. ISBN: 0-309-11924-3, http://www.nap.edu/catalog/12184.html. (NRC, 2008); Younos, Tamim. 2005. "The Economics of Desalination," *Journal of Contemporary Water Research & Education*, 132: 39-45. University Council on Water Resources. December.

[10] Carter, 2011, page 4.

[11] NRC, 2008, page 153.

[12] Carter, 2011, page 5.

feedwater quality."[13] The authors of the cost sections of the DEIS provide no information on if or how they accounted for these and other uncertainties that can affect the operating costs of the proposed project, and the resulting costs to ratepayers.

The analysis of the cost of alternatives to the proposed project exhibits the same analytical deficiencies we describe above. The DEIS includes major costs of alternatives without documenting data sources, analytical assumptions, or methods. For example, the section of DEIS Appendix 18A.2 on wastewater reuse alternatives provides some details on the potential demand for wastewater reuse, but little to no information on the cost calculations for these alternatives. In a specific example, the DEIS authors assume without explanation a contingency factor for construction costs of 50 percent.[14] A reader is left to wonder how the authors concluded that the wastewater reuse alternatives warrant such a high contingency factor. Because of the almost total lack of information on the costs analysis, decision makers and stakeholders will not know the extent to which assumptions about the contingency factor and other costs overstate the true cost of a wastewater alternative. For comparison we note that the DEIS section on the cost of the proposed project has no information on a contingency factor. Relevant analytical questions include: did the analysis of the proposed project include a contingency factor? If so, what percent?

The analytical deficiencies described above render the cost sections of the DEIS almost useless for those interested in understanding or independently verifying the analysis that produced the cost results reported in the DEIS. But perhaps the most significant omission from the cost analysis is the lack of transparency and documentation regarding how the construction and operations and maintenance costs of the proposed project would impact ratepayers. The DEIS authors report their conclusions as to the costs to ratepayers, but—similar to their other cost results—provide no details as to the data, methods, or assumptions they used to generate their results.

For example, the note under DEIS Table 2-10 states that the estimated cost impacts on ratepayers excludes the costs of "Allowance for Funds Used During Construction (AFUDC)," without explanation.[15] To the extent that ratepayers will eventually pay the AFUDC charges, the cost estimates in Table 2-10 underestimate the true costs of the project on ratepayers. According to rebuttal testimony of Michael Pointing, assuming the low estimate of construction costs, and depending on when ratepayers begin paying the AFUDC charge, it can increase or decrease the charge—and impacts on ratepayers—by over $6 million.[16] Presumably, the effect would be larger for the high estimate of construction costs.

A related point is that the authors of the cost sections of the DEIS express the impact of the project's costs on ratepayers as a daily cost. Given that most ratepayers pay a monthly bill, or have an annual income, a more-useful or informative description of cost impacts on ratepayers

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[13] Younos, 2005, page 40.

[14] DEIS Appendix 18A.2, Table TM # WSP-1-3, page 8.

[15] DEIS, page 2-43.

[16] Pointing, Michael J. (no date) *Rebuttal Testimony in the Matter of a Proceeding On Motion of the Commission as to the Rates, Charges, Rules and Regulations of the United Water New York Inc. for Water Services*. P.S.C. Case No. 09-W-0731. State of New York Public Service Commission (Pointing, no date), page 36-38.

would include monthly or annual costs to ratepayers. According to Pointing's testimony, the annual impact could range from $270 to $300 per customer per year.[17] Others estimate the annual cost higher, at $485 per customer per year.[18] Another useful but missing piece of information regarding the impacts on ratepayers is the total or cumulative impact, taking into account current costs that ratepayers pay. For example, to the extent that the project's costs would be additive to other water-related costs, a more informative description of project costs would describe the additive impact on ratepayers of the proposed project, as well as the resulting total cost on ratepayers.

Finally, a transparent cost analysis would describe the project's return on investment and the annual impact of this cost on ratepayers.

Inconsistent Measure of Cost Effectiveness

The DEIS authors conclude that the proposed project is the most cost effective of the alternatives considered. They reached this conclusion in part based on their analysis of the capital costs of developing wastewater reuse capabilities. As we illustrate below, however, subjecting the proposed project to the same type of cost analysis applied to the wastewater reuse alternative, yields results that do not support the authors' conclusion as to the cost effectiveness of the proposed project.

DEIS Appendix 18A.2 Wastewater and Stormwater Reuse, includes information on the cost analysis of the wastewater alternative. As described in this appendix, analysts calculated the capital costs for four wastewater reuse projects, the total gallons of water produced per day, and the cost per gallon. We reproduce these costs calculations in Table 1 below.

Based on this analysis, the DEIS authors concluded that, "… water reuse does not appear to be economically feasible without additional water supply or regulatory drivers."[19]

We compared the results reported in the DEIS for the wastewater reuse alternatives, and summarized in Table 1 below, with the costs of the proposed project calculated using the method the DEIS authors applied to the reuse alternatives.[20] We report the results of this calculation in Table 2 below.

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[17] Pointing, no date, page 37.

[18] Dillon, Bob. 2010. *United Water's Proposed Hudson River Desalination Plant – The Estimated Annual Cost to Customers*. September 26.

[19] DEIS, Appendix 18A.2, page 17.

[20] We note that the costs per gallon reported in the DEIS for the wastewater reuse alternatives grossly overstates the true cost per gallon. The authors calculate cost per gallon by dividing the total cost of the reuse alternatives by the number of gallons produced *in a single day.* A more accurate calculation would divide the capital cost by the total number of gallons produced over the life of the reuse plant.

Table 1: Costs of Wastewater Reuse Alternatives

Reuse Project	
Stony Point	
Total Cost	$1,217,000
Gallons of Water per day	207,000
Cost per Gallon	$5.88
Pearl River	
Total Cost	$5,356,000
Gallons of Water per day	275,000
Cost per Gallon	$19.48
Orangeburg	
Total Cost	$5,449,000
Gallons of Water per day	413,000
Cost per Gallon	$13.19
Spring Valley	
Total Cost	$5,122,000
Gallons of Water per day	116,800
Cost per Gallon	$43.85

Source: DEIS Appendix 18A.2 Tables TM# WSP-1-3, page 8; TM# WSP-1-4, page 9; TM# WSP-1-6, page 11; and TM# WSP-1-8, page 13.

Comparing results from Table 1 with results from Table 2, we see that taken individually, some of the wastewater reuse alternatives compare favorably to the proposed alterative on a cost basis. Using the average of the low-high cost for the proposed project, all but the Spring Valley project are more cost effective. Comparing the average cost per gallon across the four wastewater reuse alternatives, as reported in DEIS Table 18A-5 as $16.94, with the results from Table 2, we see that the wastewater reuse alternatives have a lower average cost than any of the cost estimates for the proposed project.

Comparing the cost-effectiveness between the small capacity wastewater-reuse projects with the much higher capacity desalination plant also highlights the apparent lack of economic efficiency of the larger desalination plant. We would expect that a larger facility would benefit from economies of scale and produce water at a significant savings relative to a much smaller facility. The results, however, are opposite this expectation. The unit cost of the much larger desalination plant, with a capacity of 7.5 mgd, is *greater* than the unit cost of some of the wastewater-reuse plants that have a fraction of the capacity of the larger desalination plant.

Table 2: Cost of Proposed Project

	Low Estimate All Phases	High Estimate All Phases	Average Estimate
Capital Cost	$139,200,000	$189,300,000	$164,250,000
Gallons of Water per day	7,500,000	7,500,000	7,500,000
Cost per Gallon	$18.56	$25.24	$21.90

Source: DEIS Table 2-9, page 2-41; Table 2-10, page 2-43.

A more accurate cost comparison among the proposed project and competing alternatives would include all relevant costs, including operations and maintenance costs. We exclude these costs from our illustrated comparison because the DEIS authors did not include these costs in their assessment of the reuse alternatives. Given the energy-intensiveness of desalination and the potential for rising energy prices throughout the project timeframe, excluding operations and maintenance costs from the comparison constitutes a fatal flaw in the analysis.

We also note an inconsistency between the cost analysis of the proposed project and the project alternatives in that the DEIS authors express the cost of the proposed project as a range with a lower and upper bound, but express the cost of alternatives to the proposed project as a single number. The DEIS is silent on these and other fundamental questions or inconsistences regarding the cost analyses of the proposed project and alternatives.

Commonly Accepted Standards

The cost analysis reported in the DEIS does not conform to commonly accepted standards for reporting and describing cost-effectiveness comparisons among competing alternatives. The National Research Council (NRC) and other industry experts provide detailed guidelines for conducting the types of cost-effectiveness analyses at issue in the DEIS. For example, a NRC book on desalination includes a chapter on describing the costs and benefits of desalination facilities.[21] Among the cost information that the NRC reports for desalination that the DEIS does not include:

- annualized capital costs
- parts/maintenance
- chemicals
- labor
- membranes
- energy costs
- concentrate management

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[21] NRC, 2008.

The chapter also includes a detailed description of how to compare capital and operations and maintenance costs across project alternatives. The report also addresses some of the differences in costs analyses for desalination plants that use seawater versus brackish water.

In another example of industry standards, Tamim Younos, of the Virginia Polytechnic Institute and State University published an article titled, ”The Economics of Desalination,” in the *Journal of Contemporary Water Research and Education*.[22] As with the NRC book, Younos describes the major categories of capital and variable costs that analysts should include in a cost assessment of desalination plants. Younos also describes three “typical” cost models that analysts use to calculate the costs of desalination plants. Of the three models Younos describes, two of them would be appropriate for the types of comparison of alternatives described in the DEIS. The U.S. Bureau of Reclamation, I. Moch & Associates, and Boulder Research developed a model called the “WTCost” model, which can estimate costs for seven types of desalination plants, including those using brackish water. The Water Resources Associates developed the Reverse Osmosis Desalination Cost Planning Model that, as the name implies, describes the capital, operations and maintenance and other life cycle costs of desalination plants.

In contrast to the analytically-deficient cost information in the DEIS, an analysis that followed the guidelines described above, and, or, used one of the industry-accepted models—and clearly reported the relevant data, methods and assumptions—would yield cost results that decision makers and stakeholders could have more confidence in as they deliberate the competing alternatives. Given the analytical deficiencies in the DEIS, we urge regulators to consider conducting an independent review of the cost analysis reported in the DEIS, engage a consultant familiar with industry-accepted standards for cost analyses of desalination plants to revise the analysis reported in the DEIS, or both. Based on the experience of the Tampa desalination plant, the author of the CRS report recommends such oversight for proposed desalination plants. “… [T]he Tampa project illustrates some of the risks of working with private water developers and lowest-bid contracts without sufficient external review and accountability mechanisms.”[23]

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[22] Younos, 2005.

[23] Carter, 2011, page 3.

APPENDIX D

Congressional Research Service

Desalination: Technologies, Use, and Congressional Issues

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CRS Report for Congress
Prepared for Members and Committees of Congress

Summary

In the United States, desalination technologies are increasingly used for municipal and industrial water supplies and reclamation of contaminated supplies. At issue for Congress is the federal role in desalination research, demonstration and full-scale facilities, and regulatory requirements. Constraints on wider adoption include financial, environmental, regulatory issues and concerns.

Desalination processes generally treat seawater or brackish water to produce a stream of freshwater, and a separate, saltier stream of water that has to be disposed (often called waste concentrate). Its attractions include creation of a new freshwater source from otherwise unusable waters, and its independence from precipitation, runoff, storage, and recharge. Many states (most notably Florida, California, and Texas) and cities are actively researching and investigating the feasibility of large-scale desalination plants for municipal water supplies. Coastal communities are increasingly considering desalinating seawater or estuarine water, while interior communities are looking to brackish aquifers. Some communities and industries are opting to treat contaminated water supplies with desalination technologies (e.g., membrane separation) to meet disposal requirements or to reuse the water (e.g., saline waters from oil and gas development). Desalination also is used for obtaining high-quality water for industrial processes.

Desalination and its applications, however, come with risks and concerns. Although the costs of desalination dropped steadily in recent decades, making desalinated water more competitive with other supply augmentation options, the declining trend may not continue if energy costs rise. This creates a cost uncertainty for those contemplating desalination investments. Electricity expenses vary from one-third to one-half of the operating cost of many desalination facilities, and the energy intensity of desalination raises concerns about the greenhouse gas emissions emitted. Current desalination processes are already operating close to the theoretical minimum energy required. Therefore, significant improvements in facility-level energy efficiency are more likely to come from more energy efficient pretreatment of water before entering the desalination process and co-location with other facilities, such as power plants. Substantial uncertainty also remains about the technology's environmental impacts, in particular management of the saline waste concentrate and the effect of surface water intake facilities on aquatic organisms. Moreover, there are few federal health and environmental guidelines, regulations, and policies specific to desalination as a municipal water supply source. This creates uncertainty regarding the cost and time required for regulatory compliance. Research and public education may help to resolve some uncertainties, mitigate impacts, reduce the costs, and improve public understanding.

To date, the federal government has been involved primarily in desalination research and development (including for military applications), some demonstration projects, and select full-scale facilities. For the most part, local governments, sometimes with state-level involvement, are responsible for planning, testing, building, and operating desalination facilities, similar to their responsibility for freshwater treatment for municipal drinking water supplies. In the 112th Congress, H.R. 2664, Reauthorization of Water Desalination Act of 2011, would reauthorize a Department of the Interior program (expiring in 2011) carried out by the Bureau of Reclamation for desalination demonstration and outreach. Bills in the 111th Congress (e.g., H.R. 88, H.R. 469, H.R. 1145, S. 1462, S. 1731, S. 1733, and P.L. 111-11) represented a range of federal authorizations for desalination research and its coordination, demonstration and full-scale facilities, and planning and financing. While interest in desalination persists among some Members, efforts to expand federal activities and investment may face greater challenges in the near term due to the domestic fiscal climate and differing views on federal roles and priorities.

Contents

Appendixes

Contacts

Desalination Policy and Legislative Primer

Interest in desalination technologies for seawater, brackish water, and contaminated freshwater has increased in the United States as their costs have fallen and pressure to develop and reclaim new water supplies has grown. Adoption of desalination, however, remains constrained by financial, environmental, regulatory, and social factors. At issue is what role Congress establishes for the federal government in desalination research and development and in construction and operational costs of desalination demonstration projects and full-scale plants. Also at issue is the federal regulatory environment related to desalination.

Desalination processes generally treat seawater, brackish water,[1] or impaired waters to produce a stream of freshwater, and a separate, saltier stream of wastewater, often called *waste concentrate* or *brine*. The availability and regulation of disposal options for the waste concentrate can pose issues for desalination's adoption in some locations.

There are a number of desalination methods. Two processes, thermal (e.g., distillation) and membrane (e.g., reverse osmosis), are the most common, with reverse osmosis dominating in the United States. For more information on the technologies, see **Appendix A**. Desalination technology costs dropped steadily in recent decades, making it more competitive with other water supply augmentation and treatment options. A rise in electricity prices could reverse the trend. Electricity expenses vary from one-third to one-half of the cost of operating desalination facilities.[2] Costs and cost uncertainties remain among the most significant challenges to implementing large-scale desalination facilities, especially seawater desalination plants.[3]

Substantial uncertainty also remains about the environmental impacts of large-scale desalination facilities. Social acceptance and regulatory processes also affect the technologies' adoption and perceived risks. Research and additional full-scale facilities may resolve uncertainties and contribute to the development of methods to mitigate impacts and reduce costs.

Questions that may confront the 112th Congress in its consideration of the federal role in desalination include:

- What is the appropriate level and nature of federal investment in desalination research and development? How should federal desalination research be prioritized?
- Should the federal government participate in and provide incentives for the construction and/or operation of desalination facilities separately from other federal programs supporting municipal water investments? If so, under what circumstances or using what criteria should federal participation be governed?

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[1] For more information on what is brackish groundwater, see National Ground Water Association, *Brackish Groundwater*, NGWA Information brief, Westerville, OH, July 21, 2010, http://www.ngwa.org/ASSETS/00F07610473C44B7862DCBFA43A2D84D/Brackish_water_info_brief_2010.pdf.

[2] S. Chaudry, "Unit cost of desalination," California Desalination Task Force, California Energy Commission, 2003.

[3] A survey of municipal desalination facilities in Texas found the cost for brackish desalination ranged from $410 to $847 per acre-foot, and for seawater desalination ranged from $1,168 to $1,881 per acre-foot. (J. Arroyo and S. Shirazi, *Cost of Water Desalination in Texas*, Texas Water Development Board, Austin, TX, October 2009, p. 6, http://www.twdb.state.tx.us/iwt/desal/docs/Cost_of_Desalination_in_Texas.pdf.)

To date, the federal government has been involved primarily in research and development, some demonstration projects, and select full-scale facilities, often through congressionally directed spending. For the most part, local governments, sometimes with state-level involvement, have been responsible for planning, testing, building, and operating desalination facilities to augment community water supplies, similar to their responsibility for treating freshwater drinking water supplies.

In the 112th Congress, H.R. 2664, Reauthorization of Water Desalination Act of 2011, would reauthorize a Department of the Interior program (expiring in 2011) carried out by the Bureau of Reclamation for desalination demonstration and outreach. The bill would reauthorize the program for $2 million annually for FY2012 to FY2016. During recent Congresses, legislative proposals have identified a range of different potential federal roles in desalination, including creation of a water research program within the national laboratories of the Department of Energy (to include numerous desalination-related research areas); authorization of desalination demonstration, research, and full-scale facilities; and authorization of payments to offset the energy costs of desalination operations. Discussions on the use of tax credit bonds, infrastructure banks, and innovative infrastructure financing techniques at times have also included desalination investments. Examples of the variety of desalination legislation proposed during the 111th Congress are available in **Appendix B**.

Desalination Adoption in the United States

Desalination technology is increasingly investigated and used as an option for meeting municipal and industrial water supply and water treatment demands. Globally, seawater desalination represents 60% of the installed desalination capacity.[4] In the United States, however, only 7% of the existing capacity uses seawater as its source. More than half of the water desalinated in the United States is brackish water. Another 25% is river water treated by desalination technologies for use in industrial facilities, power plants, and some commercial applications.

Desalination's attractions are that it can create a new source of freshwater from otherwise unusable waters, and that this source may be more dependable than freshwater sources that rely on annual or multi-year precipitation, runoff, and recharge rates. Many states—most notably Florida, California, and Texas—and cities are actively researching and investigating the feasibility of large-scale desalination plants for municipal water supplies. Desalination and its different applications, however, come with their own sets of risks and concerns. The growing use of desalination technologies in the United States and related concerns are discussed below.

Adoption Growing in States Searching for Municipal Water Supplies

The nation's installed desalination capacity has increased in recent years. As of 2005, approximately 2,000 desalination plants larger than 0.3 million gallons per day (MGD) were operating in the United States, with a total capacity of 1,600 MGD (less than 0.4% of total U.S.

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[4] Data in this paragraph is from H. Cooley et al., *Desalination, With a Grain of Salt: A California Perspective*, Pacific Institute (June 2006).

water use).[5] Florida, California, Texas, and Arizona have the greatest installed desalination capacity. Florida dominates the U.S. capacity, with the facility in Tampa being a prime example (see box); however, Texas and California are bringing plants online or are in advanced planning stages. Several other efforts also are preliminarily investigating desalination for particular communities, such as Albuquerque. Two-thirds of the U.S. desalination capacity is used for municipal water supply; industry uses about 18% of the total capacity.[6]

While interest in obtaining municipal water from desalination is rising in the United States, desalination is expanding most rapidly in other world regions, often in places where other supply augmentation options are limited by geopolitical as well as natural conditions. The Middle East, Algeria, Spain, and Australia are leading in the installation of new desalination capacity.[7]

Tampa's Desalination Experience and Lessons

Tampa's planning of the first large-scale (25 MGD) desalination plant in the late 1990s ignited interest in large-scale desalination as a municipal water supply source elsewhere in the United States. The facility was thought of as a signal of desalination becoming a cost-effective supply option, However, the Tampa plant, a facility to desalinate heavily brackish estuarine water, encountered technical and economic problems (e.g., less freshwater produced than anticipated, fouling of reverse osmosis membranes, financing issues) during construction and start-up, driving up the cost of the freshwater produced. For some observers, a lesson from the Tampa plant experience is one of caution; before proceeding to full-scale implementation, large-scale desalination requires careful investigation. In the view of industry observers, the lessons to be learned from Tampa are that (1) good design suited to the local conditions and (2) a thorough pilot-study are critical for a desalination facility to function properly. For other observers, the Tampa project illustrates some of the risks of working with private water developers and lowest-bid contracts without sufficient external review and accountability mechanisms. Private developers, however, remain attractive for some communities because of their role in financing the capital cost of constructing a large-scale desalination facility.

Energy Intensity Creates Cost Uncertainties

The cost of desalination remains a barrier to adoption. Like nearly all new freshwater sources, desalinated water comes at substantially higher costs than existing sources. Much of the cost for seawater desalination is for the energy required for operation of the desalination technologies; in particular, the competitiveness of reverse osmosis seawater desalination is highly dependent on the price of electricity. Additionally, the electricity consumed in desalination has greenhouse and other emissions associated with it. Price and emissions have driven many desalination proponents to investigate renewable energy supplies and co-location with power plants.[8] As electricity becomes more expensive, less electricity-intensive options (such as conservation, water purchases, and changes in water pricing) increase in competitiveness relative to desalination.

Reverse osmosis pushes water through a membrane to separate the freshwater from the salts; this requires considerable energy input. Currently the typical energy intensity for seawater desalination with energy recovery devices is 3-7 kilowatt-hours of electricity per cubic meter of

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[5] Ibid.

[6] Ibid.

[7] J. Hughes, "Seawater Desalination Leads Response to Global Water Crisis," *AWWA Streamlines*, November 10, 2009.

[8] A major benefit of co-location is using the cooling water from the power plant for desalination; this water has been warmed by the power plant which reduces the energy requirements for desalinating it. Also, the desalination facility may avoid construction costs by sharing intake and discharge facilities.

water (kWh/m^3).[9] The typical energy intensity of brackish desalination is less than seawater desalination, at 0.5-3 kWh/m^3. This range exists and is lower than seawater requirements because the energy required for desalination is proportional to the salinity of the source water.[10] Uncertainty in electricity prices, therefore, creates significant uncertainty in the operating costs of desalination facilities, which influences the technology's attractiveness as a water supply. Reducing the technology's energy requirements would decrease its cost uncertainties. The energy used in the reserve osmosis portion of new desalination facilities is close to the theoretical minimum energy required for separation of the salts from the water.[11] Energy efficiency improvements, therefore, may be more likely to come from other components of desalination facilities, such as the pretreatment of the water before it enters reverse osmosis. Pretreatment is necessary in order to avoid fouling and harm to the reverse osmosis membranes.

Substantial further cost savings are unlikely to be achieved through incremental advances in the commonly used technologies, like reverse osmosis. The National Research Council (NRC) in a 2008 report, *Desalination: A National Perspective,* recommended that federal desalination research funding be targeted at long-term, high-risk research not likely to be attempted by the private sector that could significantly reduce desalination costs.

Health and Environmental Concerns

From a regulatory, oversight, and monitoring standpoint, desalination as a significant source of water supply is new in the United States, which means the health and environmental regulations, guidelines, and policies regarding its use are still being developed. Existing laws and policies often do not address unique issues raised by desalinated water as a drinking water supply. Similarly, the implications of integrating desalination into existing water distribution infrastructure have not been tested in a wide range of applications (e.g., corrosion of distribution facilities by desalinated water). This creates uncertainty for those considering investing millions in constructing a full-scale facility. Addressing these concerns will reduce potential risks and improve the information available for decision-making.

Evolving Drinking Water Guidelines

While the quality of desalinated water is typically very high, some health concerns remain regarding its use as a drinking water supply. For example, the source water used in desalination may introduce biological and chemical contaminants to drinking water supplies that are hazardous to human health, or desalination may remove minerals essential for human health. For example, a health concern about boron has been raised in relation to seawater desalination; this is an uncommon concern for traditional water sources. Boron is know to cause reproductive and developmental toxicity in animals and irritation of the digestive tract, and it accumulates in plants, which may be a concern for agricultural applications. There are concerns about boron in the freshwater produced from seawater desalination because the boron levels after basic reverse osmosis commonly exceed current World Health Organization health guidelines and the U.S.

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[9] National Research Council, *Desalination: A National Perspective*, 2008, pp. 74-75, and 77. Hereafter referred to as NRC *Desalination: A National Perspective*, 2008.

[10] NRC *Desalination: A National Perspective*, 2008, p. 77.

[11] M. Elimelech and W.A. Phillip, "The Future of Seawater Desalination: Energy, Technology, and the Environment," *Science*, vol. 333 (August 5, 2011), pp. 712-717.

Environmental Protection Agency (EPA) health reference level. Boron can be removed through treatment optimization, but that treatment could increase the cost of desalted seawater. Boron is one of a number of potential health concerns requiring further attention and investigation as seawater desalination is used in large-scale application for water supply; for example, microorganisms unique to seawater and algal toxins may also pass through reverse osmosis membranes and enter the water supply.

EPA sets federal standards and treatment requirements for public water supplies, and controls disposal of wastes, including concentrate disposal, which is discussed later.[12] In 2008, EPA determined that it would not develop a maximum contaminant level for boron because of its rare occurrence in most groundwater and surface water drinking water sources; EPA has encouraged affected states to issue guidance or regulations as appropriate.[13] Most states have not issued such guidance. Therefore, most U.S. utilities lack clear guidance on boron levels in drinking water suitable for protecting public health. The National Research Council recommended development of boron drinking water guidance to support desalination regulatory and operating decisions; it recommended that the guidance be based on an analysis of the human health effects of boron in drinking water and other sources of exposure.

Environmental Effects of Intake Structures and Concentrate Disposal

The environmental concerns that arise in relation to desalination facilities include the effect of intake structures and the disposal of waste concentrate, as well as the potential to open up new coastal areas to development. These concerns are often raised in the context of obtaining the permits required to site, construct, and operate the facility and dispose of the waste concentrate. According to the Pacific Institute's report *Desalination, With a Grain of Salt*, as many as 26 federal, state, and local agencies may be involved in the review or approval of a desalination plant in California. A draft environmental scoping study for a facility in Brownsville, TX, identified 26 permits, approvals, and documentation requirements for construction and operation of a seawater desalination facility.[14] Some stakeholders view these permit requirements as a barrier to adoption of desalination.

The application of desalination in the United States is also challenged by the use of estuarine water in many of the facilities being contemplated. Estuarine water, which is a brackish mixture of seawater and surface water, has the advantage of lower salinity than seawater. Application of desalination to estuarine water is uncommon, with the facility in Tampa being the largest of its kind in the United States. The presence of surface water (which tends to be more contaminated than seawater) in estuarine water may complicate compliance of desalinated estuarine water with federal drinking water standards. For inland brackish desalination, significant constraints on adoption are the uncertainties and the cost of the waste concentrate disposal.[15]

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[12] For more information on EPA's role in protecting drinking water, see CRS Report RL31243, *Safe Drinking Water Act (SDWA): A Summary of the Act and Its Major Requirements*, by Mary Tiemann.

[13] EPA, *Regulatory Determinations for Priority Contaminant s on the Second Drinking Water Contaminant Candidate List*, available at http://www.epa.gov/OGWDW/ccl/reg_determine2.html.

[14] Texas Water Development Board, *The Future of Desalination in Texas: 2010 Biennial Report*, Austin, TX, December 2010, p. 8, http://www.twdb.state.tx.us/iwt/desal/docs/2010_thefutureofdesalinationintexas.pdf. The report includes a table listing the permits, approvals, and environmental documentation compliance requirements, and estimates of the cost for obtaining each.

[15] The Texas Water Development Board undertook a study with the intent of showing that oil and gas fields can (continued...)

The National Research Council in 2008 called for further research and development on mitigating environmental impacts of desalination and reducing potential risks relative to other water supply alternatives.[16] It identified the following priority research areas to address environmental concerns:

- assess environmental impacts of desalination intake and concentrate management approaches, and synthesize results in a national assessment;
- improve intake methods at coastal facilities to minimize harm to organisms;
- develop cost-effective approaches for concentrate management that minimizes environmental impacts; and
- develop monitoring and assessment protocols for evaluating the potential ecological impacts of surface water concentrate discharge.

Federal Desalination Research

Desalination research represents less than 0.1% of the approximately $130 billion annual federal research and development investment. The optimal level of federal investment in desalination research is inherently a public policy question shaped by factors such as fiscal priorities and views on the appropriate role of federal government in research, industry development, and water supply. Increasing federal funding for desalination research raises questions, such as what should be the respective roles of federal agencies, academic institutions, and the private sector in conducting research and commercializing the results, and should federal research be focused on basic research or promoting the use of available technologies?

Desalination Research Agenda

Several reports in the last decade have aimed to inform the path forward for U.S. desalination research. The first was the *Desalination and Water Purification Technology Roadmap* produced by the Bureau of Reclamation and Sandia National Laboratories at the request of Congress. The National Research Council reviewed the roadmap in a 2004 report, *Review of the Desalination and Water Purification Technology Roadmap*, which called for a strategic national research agenda. To this end, the National Research Council convened a Committee on Advancing Desalination Technology. That NRC committee published a report in 2008, *Desalination: A National Perspective*, recommending that the strategic agenda focus on research on environmental impacts of desalination and lowering the cost of desalination. In 2010, the Water Research Foundation, WateReuse Foundation, and Sandia National Laboratories published a report on how to implement the 2003 roadmap.[17] The report identifies research agendas for a

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(...continued)

physically and chemically accept desalination waste concentrate and to recommend changes to statutes and rules to facilitate waste concentrate disposal in oil and gas fields. R. E. Mace et al., *Please Pass the Salt: Using Oil Fields for the Disposal of Concentrate from Desalination Plants*, Texas Water Development Board, Austin, TX, April 2006, http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Report366.pdf.

[16] NRC, *Desalination: A National Perspective*, 2008.

[17] Water Research Foundation, WateReuse Foundation, Sandia National Laboratories, *Implementation of the National Desalination and Water Purification Technology Roadmap*, January 2010, http://www.sandia.gov/water/docs/DesalImplementRoadmap1-26-2010_c_web.pdf.

range of topics—membrane technologies, alternative technologies, concentrate management, and institutional issues such as energy cost reduction and regulatory compliance.

Federal Desalination Funding

Most federally supported desalination spending is on research to improve existing technologies, fostering innovations in alternative technologies, and applications in the military. Much federal desalination research is managed by the Bureau of Reclamation through its Desalination and Water Purification Research & Development Program. Congress authorized the program in the Water Desalination Act of 1996 (P.L. 104-298) and has extended its authorization for appropriations of $5 million annually through FY2011.

The National Research Council in 2008 recommended a level of funding consistent with the levels in FY2005 and FY2006, roughly $25 million, but recommended that the research be targeted strategically, including being directed at the research activities described above.[18] The level of funding fell after FY2006, when the appropriations process has included less congressionally directed spending. The NRC drew the following conclusion:

> There is no integrated and strategic direction to the federal desalination research and development efforts. Continuation of a federal program of research dominated by congressional earmarks and beset by competition between funding for research and funding for construction will not serve the nation well and will require the expenditure of more funds than necessary to achieve specified goals.[19]

Although not directly addressing desalination research, H.R. 1145, the National Water Research and Development Initiative Act of 2009, would require greater coordination of federal water research and funding, which would include technologies such as desalination. Research cannot address all barriers to adoption of desalination. Efforts to overcome other constraints (e.g., public education and regulatory processes) also are often recommended as part of an overall strategy for reducing adoption barriers.

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[18] According to the 2004 NRC report, *Confronting the Nation's Water Problems: The Role of Research*, "water supply augmentation and conservation" including desalination research by federal agencies totaled $14.5 million in FY2000. In the past the federal government invested more in this area; in the late 1960s, federal research in desalination and other saline water conversion activities exceeded $100 million annually. Research alone does not represent all federal spending on and support of desalination. The EPA also may support construction of municipal desalination facilities through loans provided to these facilities through the EPA's Drinking Water State Revolving Loan Funds.

[19] NRC *Desalination: A National Perspective*, 2008, p. 228.

Appendix A. Desalination Technologies

There are a number of methods for removing salts from seawater or brackish groundwater to provide water for municipal and agricultural purposes. The two most common processes, thermal (e.g., distillation) and membrane processes (e.g., reverse osmosis), are described below; their descriptions are followed by descriptions of some of the more innovative and alternative desalination technologies. The earliest commercial plants used thermal techniques. Improvements in membrane technology have reduced costs, and membrane technology is less energy-intense than thermal desalination (although it is more energy-intense than most other water supply options). Reverse osmosis and other membrane systems account for nearly 96% of the total U.S. desalination capacity and 100% of the municipal desalination capacity.

Distillation and Reverse Osmosis

In distillation, saline water is heated, separating out dissolved minerals, and the purified vapor is condensed. Reverse osmosis forces salty water through a semipermeable membrane that traps salt on one side and lets purified water through. Reverse osmosis plants have fewer problems with corrosion and usually have lower energy requirements than thermal processes. Distillation plants, however, require less maintenance and pretreatment before the desalination process.

Innovative and Alternative Desalination Processes

Forward Osmosis

Forward osmosis is a relatively new membrane-based separation process that uses an osmotic pressure difference between a concentrated "draw" solution and the saline source water; the osmotic pressure drives the water to be treated across a semipermeable membrane into the draw solution. The level of salt removal can be competitive with reverse osmosis. A main challenge is in the selection of a draw solute; the solute needs to either be desirable in the water supply, or be easily and economically removed. Research is being conducted on whether a combination of ammonia and carbon dioxide gases can be used as the draw solution. The attractiveness of forward osmosis is that its energy costs can be significantly less than for reverse osmosis when combined with industrial or power production processes.[20]

Electrodialysis[21]

Electrodialysis depends on the ability of electrically charged ions in saline water to migrate to positive or negative poles in an electrolytic cell. Two different types of ion-selective membranes are used—one that allows passage of positive ions and one that allows negative ions to pass between the electrodes of the cell. When an electric current is applied to drive the ions, fresh water is left between the membranes. The amount of electricity required for electrodialysis, and

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[20] R. L. McGinnis, and M. Elimelech. "Energy requirements of ammonia carbon dioxide forward osmosis desalination," *Desalination* (2007) 207, pp. 370-382.

[21] The description of the remaining technologies was written by Peter Folger, Specialist in Energy and Natural Resources Policy.

therefore its cost, increase with increasing salinity of feed water. Thus, electrodialysis is less economically competitive for desalting seawater compared to less saline, brackish water.

Ion Exchange

In ion exchange, resins substitute hydrogen and hydroxide ions for salt ions. For example, cation exchange resins are commonly used in home water softeners to remove calcium and magnesium from “hard” water. A number of municipalities use ion exchange for water softening, and industries requiring extremely pure water commonly use ion exchange resins as a final treatment following reverse osmosis or electrodialysis. The primary cost associated with ion exchange is in regenerating or replacing the resins. The higher the concentration of dissolved salts in the water, the more often the resins need to be renewed. In general, ion exchange is rarely used for salt removal on a large scale.

Freezing Processes

Freezing processes involve three basic steps: (1) partial freezing of the feed water in which ice crystals of fresh water form an ice-brine slurry; (2) separating the ice crystals from the brine; and (3) melting the ice. Freezing has some inherent advantages over distillation in that less energy is required and there is a minimum of corrosion and scale formation problems because of the low temperatures involved. Freezing processes have the potential to concentrate waste streams to higher concentration than other processes, and the energy requirements are comparable to reverse osmosis. While the feasibility of freeze desalination has been demonstrated, further research and development remains before the technology will be widely available.

Appendix B. Desalination Legislation of the 111th Congress

Examples of Research Legislation from the 111th Congress

H.R. 469, the Produced Water Utilization Act of 2009, would have authorized a Department of Energy program for research, development, and demonstration of technologies (including desalination) for environmentally sustainable utilization of groundwater produced during energy development (i.e., groundwater brought to the surface as part of exploration or development of coalbed methane, oil, natural gas, or any other substance to be used as an energy source) for agricultural, irrigational, municipal, and industrial uses, or other environmentally sustainable purposes.

H.R. 1145, the National Water Research and Development Initiative Act of 2009, would have formally established a federal interagency committee to coordinate federal water research, including desalination research. The committee, with input from an advisory committee, was to develop a four-year plan for priority federal research topics and annually report on progress on the plan. Among the proposed outcomes of the plan was the promotion of technology for enhancing reliable water supply (e.g., desalination). The bill also would have established a National Water Initiative Coordination Office to function as a clearinghouse for technical and programmatic information, support the interagency committee, and disseminate the findings and recommendations of the interagency committee. A version of the committee, the Subcommittee on Water Availability and Quality (SWAQ), which was not created by statute, has been operating since 2003 within the Office of Science and Technology Policy (OSTP) as part of the National Science and Technology Council (NSTC).

S. 1462, the American Clean Energy Leadership Act of 2009, included a provision directing the Secretary of the Interior to operate, maintain, and manage the Brackish Groundwater National Desalination Research Facility.[22] The bill would have directed the facility to conduct research, development, and demonstration activities to promote brackish groundwater desalination, including the integration of desalination and renewable energy technologies, and outreach programs with public and private entities and for public education. The facility's mission also includes managing the waste concentrated from desalination, desalinating waters produced during oil and gas production, and small-scale desalination systems.

S. 1733, Clean Energy Jobs and American Power Act, included a provision requiring the U.S. Environmental Protection Agency (EPA) to establish a research program on the effects of climate change on drinking water utilities, and authorizing $25 million annually for program funding for FY2010 through FY2020. The research program would have addressed alternative water supply

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[22] The Brackish Groundwater National Desalination Research Facility is a federally constructed research facility focused on developing desalination technologies for brackish and impaired groundwater found in the inland states. It is located in Alamogordo, Otero County, NM. The facility opened in August 2007 and is integrated into Department of the Interior's existing desalination research and development program at the Bureau of Reclamation. It brings together researchers from other federal agencies, universities, the private sector, research organizations, and state and local agencies.

technology issues, including desalination, brine management, and environmental impacts of intakes for seawater desalination.

Examples of Planning, Construction, and Financing Legislation from the 111th Congress

P.L. 111-11, the Omnibus Public Land Management Act of 2009, includes provisions authorizing federal funding to be used for design, planning, and construction costs for facilities with desalination and brine disposal components—$20 million for the Rancho California Water District (CA)[23] and $46 million in the Santa Ana watershed (CA)[24]—as part of the Bureau of Reclamation's Title XVI water reuse program. The act also authorizes the Secretary of the Interior to financially assist the California Water Institute to conduct a study coordinating and integrating subregional water management plans, including desalinated water supplies, for the San Joaquin and Tulare Lake regions.

H.R. 88, the City of Oxnard Water Recycling and Desalination Act of 2009, would have authorized federal funding to be used for up to 25% of the design, planning, and construction costs ($15 million of a total $60 million) of the Groundwater Recovery Enhancement and Treatment (GREAT) project in Ventura County (CA). The bill would have authorized the project as part of the Bureau of Reclamation's Title XVI water reuse program. The project combines wastewater recycling and reuse and groundwater management and desalination to provide regional water supply solutions to the Oxnard Plain.

H.R. 4132, the Clean Renewable Water Supply Act of 2009, and S. 1731, the Clean Renewable Water Supply Bond Act of 2009, would have made facilities desalinating seawater, groundwater, or surface water among the types of projects eligible for accessing the federal bonds mechanism created by the bill.

In addition to the research provision previously described, S. 1733, the Clean Energy Jobs and American Power Act, would have included investigating, designing, or constructing desalination facilities among the eligible uses of grants provided to states as part of the bill's climate change adaptation provisions.

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[23] The project also was the subject of H.R. 371, Rancho California Water District Recycled Water Reclamation Facility Act of 2009.

[24] These activities and additional regional conveyance infrastructure for the waste brine were also the subject of H.R. 530, Santa Ana River Water Supply Enhancement Act of 2009.

APPENDIX E

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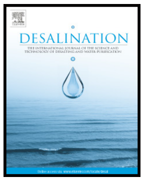

Capital cost estimation of RO plants: GCC countries versus southern Europe

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HIGHLIGHTS

- Parameters affecting the direct capital costs of BWRO and SWRO plants were assessed.
- Plants delivered through EPC contracts were considered.
- Assessment was based on cost data from 950 RO plants in the GCC and southern Europe.
- Plant capacity, type, award year, and region were found to affect RO CAPEX cost.
- A model was also developed and verified for RO CAPEX estimation.

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ABSTRACT

The installation of reverse osmosis (RO) desalination plants has been on the rise throughout the world. Thus, the estimation of their capital cost (CAPEX) is of major importance for governments, potential investors and consulting engineers of the industry. In this paper, parameters potentially affecting the direct capital costs of brackish water RO (BWRO) and seawater RO (SWRO) desalination plants, delivered through Engineering, Procurement & Construction (EPC) contracts, were assessed. The assessment was conducted based on cost data from 950 RO desalination plants contracted in the Gulf Cooperation Council (GCC) countries and in five southern European countries. The parameters assessed include plant capacity, location, award year, feed salinity, and the cumulative installed capacity within a region. Our results showed that plant capacity has the strongest correlation with the EPC cost. Plant type (SWRO or BWRO), plant award year and the region of the RO plant were also found to be statistically important. By utilizing multiple linear regression, a model was also developed to estimate the direct CAPEX (EPC cost) of RO desalination plants to be located either in the GCC countries or southern Europe, which was then verified using the *k*-fold test.

1. Introduction

In 2009, over 15,000 desalination plants were in operation worldwide with approximately half of them being reverse osmosis (RO) plants [1]. Although many countries have begun to utilize desalination to produce drinking water, no region of the world has implemented desalination as widely as the Middle East, where 50% of the world's production of desalinated water is installed [1]. Over the past 40 years, use of RO has been gradually gaining momentum in the Gulf Cooperation Council (GCC) countries, due to its lower cost, simplicity, novelties in the membrane fabrication, and the high salt rejection accomplished by RO membranes today [1–4]. It is foreseen that RO will play a key role in increasing fresh water availability globally in the future, but more so in GCC countries [1].

In a simplified manner, the cost of an RO desalination plant consists of two main elements: the capital and the annual operating costs [4–7]. The operating cost, otherwise referred to as OPEX, is not only primarily determined by the cost of energy utilized to power the desalination plant which is subject to fluctuations in energy prices [4,8,9], but also includes other costs such as manpower cost, spare parts, chemicals, membrane replacement, and insurance. The capital cost (CAPEX), on the other hand, includes indirect and direct costs. Direct capital costs comprise of the purchase cost of major equipment (e.g., high pressure pumps) and auxiliary parts, land cost, engineering cost, etc. [10]. The indirect capital costs include elements such as freight and insurance, construction, and overhead [10]. The normalized total water cost (TWC) via desalination in a specific plant is the sum of the plant's CAPEX cost, amortized over the plant's life, and the annual OPEX divided

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by the average annual production of desalinated water in that plant [4,10,11].

A desalination plant can be a large scale project of high complexity. A number of different financing and contracting packages have been successfully implemented in such projects. One family of these financing schemes is the so called 'turnkey projects' [13,14]. Financing options under "turnkey" include BOO(T) (Build–Own–Operate(–Transfer)) and Engineering–Procurement–Construction (EPC) [11,12,14]. An EPC contract is formed by a direct agreement between the client and the EPC contractor [12,14]. The EPC cost consists of all the direct capital costs (apart from land cost) of the plant and the EPC contractor's cost of services. The EPC services include: detailed design, contractor permitting, and project management costs [12]. In return, the EPC contractor must deliver the project (the desalination plant) for a fixed contract cost and by a fixed date in such a way that the plant's final performance will be the same as the one guaranteed by the contractor in terms of output quantity and quality, efficiency and reliability [15,16]. EPC contracts are commonly used for desalination projects in the GCC region.

A limited number of studies can be found in literature which model the capital cost of desalination plants [4,5,9,17,18]. In one study [9], the capital and production costs of medium-sized (100,000 m^3/day) seawater desalination plants using different technologies, including RO, were estimated. The semi-empirical method employed was originally developed in [18] and it estimated the cost of various components of the desalination plant (e.g., pre-treatment system) based on published data for other existing plants.

In another study [5], simple cost-correlations were developed between the capital cost of desalination plants and their respective capacity. The exercise was carried out for multiple stage flash distillation (MSF), multiple effect distillation (MED), SWRO and BWRO plants. The cost database that was collated by the authors contained published cost-data of more than 300 desalination plants. Ninety SWRO and 112 BWRO plants located in various regions worldwide were used in the analysis, respectively. The effect of plant location was not taken into account. Moreover, it was not always specified if the cost of land or civil works was included in the capital cost.

Apart from the mentioned empirical regression models, two packages for desalination cost modeling are also available in open literature: the Desalination Economic Evaluation Program (DEEP) [19] and the Water Treatment Cost Estimation Program (WTCost) [20]. Both are tools developed to evaluate the cost of hypothetical desalination plants. DEEP was created in 1989 by the International Atomic Energy Agency (IAEA). DEEP can perform economic analyses for different desalination technologies using energy produced by various types of fossil fuel or nuclear plants [7,8,11,21]. Water Treatment Cost Estimation Program (WTCost), on the other hand, evaluates and compares various water treatment technologies using reverse osmosis/nano-filtration (RO/NF), vapor compression (VC), ultra-filtration/micro-filtration (UF/MF), electro-dialysis (ED), MSF, MED and ion exchange [8,11].

The mentioned empirical and computerized tools for capital and water production costs have the advantage of being openly available. However, the datasets based on which the models were fitted were not always made available. Additionally, different models are based on different assumptions (e.g., interest rate or ratio of OPEX to CAPEX) and in some cases require a significant knowledge of the plant's technical details (such as the type of pre-treatment applied, intake, etc.) to conduct even a preliminary cost evaluation.

The goal of this research is to develop a model which can give a reasonably accurate estimate of the capital cost of an EPC contracted RO plant in a simple manner. This can potentially offer the desalination engineers a tool to benchmark the capital cost of an RO plant and help decision makers choose among multiple options. EPC-type contracts were specifically selected for our modeling for two reasons: 1) they are very common in the GCC region, as well as in other parts of the world and 2) EPC contracts exclude the land cost, which varies significantly by location. Land cost can later be added by the model users based on their locality, allowing more flexibility and accuracy in CAPEX estimation. The model is based on the cost analysis of a 950 RO-plant dataset, including SWRO and BWRO plants, delivered by EPC contracts between 1985 and 2013. The RO plants in the dataset were selected to be located within the GCC region and southern Europe, which also revealed interesting trends based on location.

2. Methodology

2.1. Model data

Many design parameters can affect the EPC cost of an RO plant. These include, but are not limited to, choices of pre-treatment systems, intake design, brine discharge, location parameters (water depth, geopolitical issues, etc.), product water specifications (e.g., Boron limits), ecological considerations, permitting needs, membranes selected, membrane vessel design, and many more. Cost modeling based on a large number of in-depth design details of the RO plant will lead to more accurate cost estimation. However, if the cost model was to be based on many detailed design parameters, which could be either unknown or not yet determined (as in the case of future plants), this will make the modeling tool ineffective. Therefore, our goal for this work is to provide a tool for the users to easily obtain quick estimate of an EPC cost with an acceptable level of accuracy, based on parameters that can be readily known. To achieve that, we selected easily obtainable key parameters for the model and methodologically attempted to show that these parameters were sufficient to build statistically strong correlations with the EPC cost. The EPC contract cost of a desalination plant (the *regressand* variable in this work), was initially assumed to correlate with six potential variables (the *regressor* variables), two of which were presented as dummy variables. The four numerical variables are: plant capacity (CAP), expressed in cubic meters of water produced per year, EPC contract award year (YEAR), feed water salinity (SAL) in parts per million (ppm), and the cumulative capacity of desalination plants contracted in the respective region up to the date of the award year (CUM_CAP), in cubic meters per year. The two dummy variables are the type of feed water (sea or brackish water) (variable assumes a value of "1" for SWRO, "0" for BWRO) and the region of the plant (variable assumes a value of "1" for desalination plants located in the GCC region, "0" for plants located in southern Europe). The choice of these particular regressor variables came after a comprehensive review of relevant literature on desalination costing, which suggested that the mentioned variables were among the most likely to affect the capital cost of a desalination plant, its operational cost, or both [1,5,6,8,9,11,13,17]. The rationale behind selecting these particular variables as model regressors is as follows: plant capacity reflects directly on the size of equipment, construction size, etc. Hence, it will affect the EPC cost. RO technology maturity (and that of all auxiliary processes in the plant), reflected in the award year and cumulative capacity, is also expected to affect the cost of the EPC contract. Water salinity can affect the choice of equipment or pre-treatment processes, selected membrane type (low, medium or high pressure membranes), type of pumps, pressure vessels, tubing etc. All of these can affect the EPC cost. The same applies for feed water type (SW vs. BW). It is worth mentioning here that feed water type and salinity are known to influence the operational cost of desalination plants, via energy consumption [2,4,11,13]. Finally, the location of the plant (GCC region versus southern Europe in our study) was assumed to affect the EPC cost due to a number of logistical, political and technical reasons.

In order to verify the correlations between the six mentioned variables and the EPC contract cost and to build the quantitative model for this cost, a large desalination plant dataset was used. The dataset includes 950 data points of EPC cost of desalination plants (EPC) awarded during 1985–2013, which was obtained from web-based desalination plant inventory, desaldata.com by Global Water Intelligence (GWI) [22]. The Spatial boundaries of the dataset include the GCC countries

Table 1
Sub-datasets of the desalination plants inventory used in model fitting.

	Notation	Region	Observations
Dataset 1	GCC_SWRO	GCC	138
Dataset 2	GCC_BWRO		492
Dataset 3	SE_SWRO	S. Europe	129
Dataset 4	SE_BWRO		191

(Saudi Arabia, United Arab Emirates, Oman, Qatar, Bahrain and Kuwait) and five countries of southern Europe (Italy, Greece, Spain, Malta and Cyprus). For each data point, the EPC cost, plant capacity and location, RO process type (SWRO or BWRO) and contract award year were retrieved from desaldata.com. The EPC costs of the desalination plants were reported in desaldata.com in United States Dollars (USD) at the award year. To account for inflation, these dollar values were converted to their corresponding 2013 USD values. The conversion was based on the Consumer Price Index (CPI) [23]. The capacity of each plant refers to its nominal capacity (at 100% availability). The feed water salinity for each SWRO plant was estimated based on the average salinity of the sea on which it was built. The latter was obtained from [24–26]. In cases where the desalination plant was receiving feed from a location open to more than one sea, the salinity was approximated by averaging the salinity values of the respective seas (e.g., the desalination plant of Sur in Oman). For BWRO plants, the feed salinity was available for only two plants (out of the 630 BWRO plants found) from desaldata.com, and therefore, it was initially excluded from the modeling of BWRO EPC cost, but this assumption was checked later on after the model was developed.

The dataset was divided into four sub-datasets (Table 1). The cumulative contracted capacity (CUM_CAP) for any particular plant within a subset was calculated by adding the capacities of all the plants within that subset awarded up to the plant's award year, starting with 1985 as the reference point. The cumulative capacity values for each sub-dataset are shown in Fig. 1.

In addition to the 950 data points used for cost model fitting (which had the full range of parameter values for each point), there were 1270 additional data points for desalination plants for which either the EPC cost or the type of contract were not reported. These latter data points were not used in the EPC cost model fitting; however, they were accounted for in the calculation of CUM_CAP. In Fig. 2 a depiction of the total number and capacity of both SWRO and BWRO plants in both regions is shown. It is interesting to observe that more RO plants (of both SW and BW types), both in terms of capacity and number, were contracted in the GCC region than in the five European countries. This shows a growing market for RO in the GCC region, traditionally known for dominance of thermal desalination.

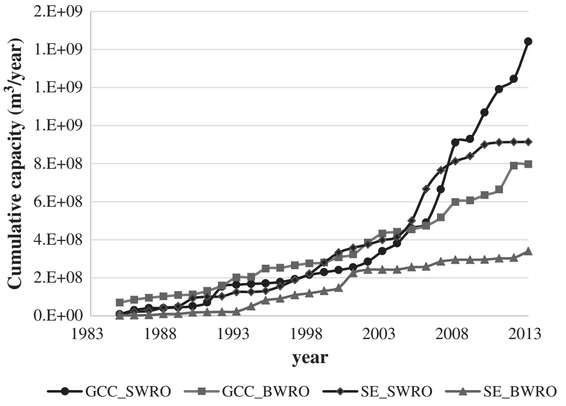

Fig. 1. Cumulative capacity of EPC contracted desalination plants in GCC countries (GCC) and five southern European countries (SE) between 1985 and 2013. Capacity of plants built in 1985 is used as baseline.

2.2. Model development

Ordinary least square (OLS) linear regression (Eq. (1)) was employed in this paper as the modeling technique to estimate the EPC cost (target or dependent variable) by using the variables of capacity, salinity, award year, etc. (training variables or regressors):

$$Y = \beta_o + \beta_1 * X_1 + \beta_2 * X_2 + \beta_3 * X_3 + \ldots \beta_n * X_n \tag{1}$$

where Y stands for the target variable (in this case, the EPC cost), X_1–X_n denote the independent variables and β_o–β_n are the regression coefficients.

For all the generated regression coefficients, their t-statistics and p-values were estimated, to decide on their statistical significance with acceptable confidence level of 0.025. That is, a p-value of a regression coefficient below 0.025 is assumed to imply that its respective regressor variable is statistically significant.

Logarithmic transformations of the target as well as of some of the training variables have been proposed by other researchers [4,5] and thus, this transformation was also attempted here. The correlation coefficients (ρ) between the EPC cost and the 4 numerical regressor variables (CAP, YEAR, SAL, and CUM_CAP) of every sub-dataset were calculated individually to determine which variables will be used in the analysis as explanatory variables. The closer the correlation coefficient value to one, the stronger the linear relationship between the two correlated variables. The correlation coefficient, ρ, between two variables v_1 and v_2 is estimated as [27]:

$$\rho = \mathrm{cov}(v_1, v_2)/\sigma_{v_1}\sigma_{v_2} \tag{2}$$

where $\sigma_{v_1}, \sigma_{v_2}$ are the standard deviations of v_1 and v_2, respectively, and $\mathrm{cov}(v_1,v_2)$ is the covariance of v_1 and v_2.

Initially, the EPC cost in each sub-dataset was regressed only with the capacity (CAP) disregarding all other variables. The variable of capacity, as will be shown later, was found to correlate strongly with the EPC for all datasets and was chosen as the primary regressor.

Award year and cumulative capacity were added separately as second regressors afterwards to investigate if they indeed improve the accuracy of the model (Eqs. (3) and (4)). As stated in [4], project award year and cumulative capacity can be considered inter-dependent parameters (both reflecting technology maturity) and thus are not used simultaneously in the same model. Salinity was then introduced as a third regressor.

$$\mathrm{EPC} = \beta_o + \beta_1 * \mathrm{CAP} + \beta_2 * \mathrm{YEAR} \tag{3}$$

$$\mathrm{EPC} = \beta_o + \beta_1 * \mathrm{CAP} + \beta_2 * \mathrm{CUM\_CAP} \tag{4}$$

The two non-numerical (dummy) variables, RO plant type (SWRO or BWRO) (TYPE) and RO plant region (REGION), were also tested as training variables to determine if they can enhance the EPC cost prediction of the model. Initially, the two variables were correlated with EPC cost separately. However, later it was found that TYPE fits better when a dataset combining data from both REGIONs was used.

In every addition of a new regressor to the model, as described above, the change in model accuracy was measured to assess the performance of the linear regression model. The correlation coefficient for the actual and the predicted values, the R-squared value (R^2), the adjusted R-squared ($\overline{R}^2$), the root-mean-square error (RMSE) and the mean absolute percentage error (MAPE) were used as statistical indicators to assess the model performance. The equations for calculating R^2

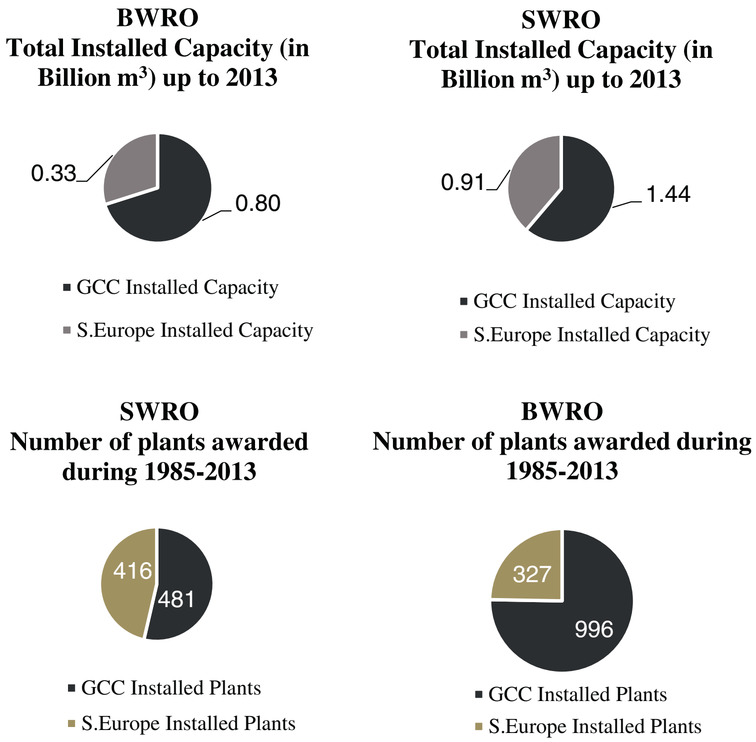

Fig. 2. Distribution of plants by size and by number of contracted plants in the GCC and southern Europe regions.

(Eqs. (5)–(7)), $\overline{R}^2$ (Eq. (8)), RMSE (Eq. (9)) and MAPE (Eq. (10)) are shown below [28]:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{5}$$

where $\mathrm{SS_{res}}$ is the residual sum of squares and $\mathrm{SS_{tot}}$ is the total sum of squares:

$$\mathrm{SS_{res}} = \sum \left(Y - \hat{Y}\right)^2 \tag{6}$$

$$\mathrm{SS_{tot}} = \sum \left((Y - \overline{Y}\right)^2. \tag{7}$$

Y stands for the actual values, $\hat{Y}$ for the predicted values and $\overline{Y}$ for the average of actual values.

$$\overline{R}^2 = 1 - \frac{\mathrm{SS_{res}}/\mathrm{df_e}}{\mathrm{SS_{tot}}/\mathrm{df_{tot}}} \tag{8}$$

where the df stands for the degrees of freedom, $\mathrm{df_e} = n - k - 1$ (where n = sample size; k = no. of variables), and $\mathrm{df_{tot}} = n - 1$.

$$\mathrm{RMSE} = \sqrt{\sum\nolimits_{i=1}^{n} \frac{1}{n}\left(Y - \hat{Y}\right)^2} \tag{9}$$

$$\mathrm{MAPE} = \sum\nolimits_{i=1}^{n} \frac{1}{n}\left|\frac{Y - \hat{Y}}{\hat{Y}}\right| \tag{10}$$

The R^2 value shows how well the data points fit the line of best fit of the model. The use of R^2 as a stand-alone diagnostic of performance could potentially be misleading. This is because as more variables are added to the model, R^2 will have at least a marginal increase. $\overline{R}^2$ is similar to R^2, but unlike the latter, it only accounts for the regressand's percentage of variance explained only by the regressors while being insensitive to additional variables that cause over-fitting (i.e., $\overline{R}^2$ will increase only if the addition of the new variable improves the model fit more than would be expected by chance) [27,28]. In cases where $\overline{R}^2$ would be significantly lower than R^2, this could indicate an over-fitting of the model caused by the addition of redundant variables. RMSE, which is used to find the error between the modeled and the observed values, is also used as another factor to assess the model's accuracy. The mean absolute percentage error (MAPE) expresses the relative deviation of the model's predicted values from the ones of the validation set.

2.3. Model validation

Once the model was developed and fitted, the robustness of the model was tested by doing a k-fold validation with $k = 2$ and $k = 4$. Cross-validation was employed as a statistical technique in order to conclude on the model's ability to explain the variance of an independent

Table 2
Correlation coefficients (ρ) of the EPC cost with each of the numerical variables of the sub-datasets.

	GCC		Southern Europe	
	SWRO	BWRO	SWRO	BWRO
CAP ($\mathrm{m^3}$/year)[a]	0.955	0.960	0.958	0.957
YEAR (1985–2013)[b]	−0.474	−0.552	−0.445	−0.420
CUM_CAP ($\mathrm{m^3}$)[a,b]	−0.486	−0.569	−0.428	−0.441
SAL (ppm)[b]	0.110	–	–	–

[a] Calculated with the logarithmic transformation of the respective variable and the EPC cost.

[b] The correlation coefficient for these variables is calculated for the normalized EPC costs (i.e. EPC cost divided by annual plant capacity).

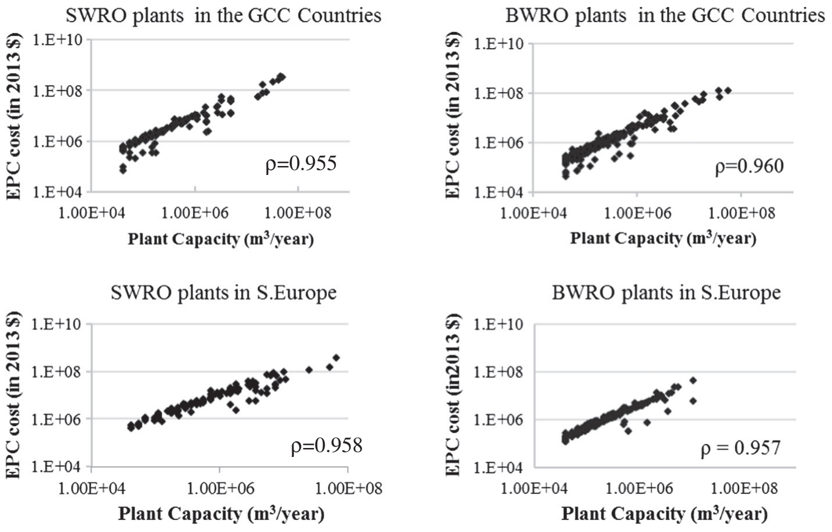

Fig. 3. EPC cost variation with RO plant capacity. Also shown are the correlation coefficients from Table 2.

dataset that was not used in the model fitting. The dataset was split randomly into 2 and 4 parts (folds) for the 2-fold and 4-fold cross validation, respectively. One fold is treated as a hold-out sample (validation dataset) and the model is generated using the remaining $k - 1$ folds. For every fold, the generated model is validated using the hold-out dataset and thus four validations were performed using R^2, $\overline{R}^2$ RMSE and MAPE. Finally, the diagnostics are averaged for all folds to give the final results of cross-validation.

3. Results & discussion

3.1. Trends and correlations of RO CAPEX cost

The correlation coefficients (ρ) of the EPC cost with each of the numerical variables individually (CAP, YEAR, SAL and CUM_CAP) were calculated for each sub-dataset as shown in Table 2. For a better fit, natural logarithmic transformation was done for CAP and CUM_CAP, while YEAR and SAL were correlated linearly. Initially, the correlation coefficient of EPC cost and CAP was calculated. Inferring from the ρ values in Table 2, it was observed that the EPC cost variance can be explained by capacity in almost 96% in all cases (for plants of both types located in the same regions). Then, for the three remaining numerical variables (YEAR, CUM_CAP and SAL), the EPC cost was normalized by dividing it by the respective plant's annual nominal capacity to rule out the CAP variable effect.

As Table 2 shows, the award year of the plants (YEAR) and the cumulative capacity (CUM_CAP) at that year present a weaker — yet significant — correlation than CAP. Also, their correlation coefficients are similar. This similarity hints the inter-dependent nature of these two variables. On the other hand, the correlation coefficient for feed water salinity

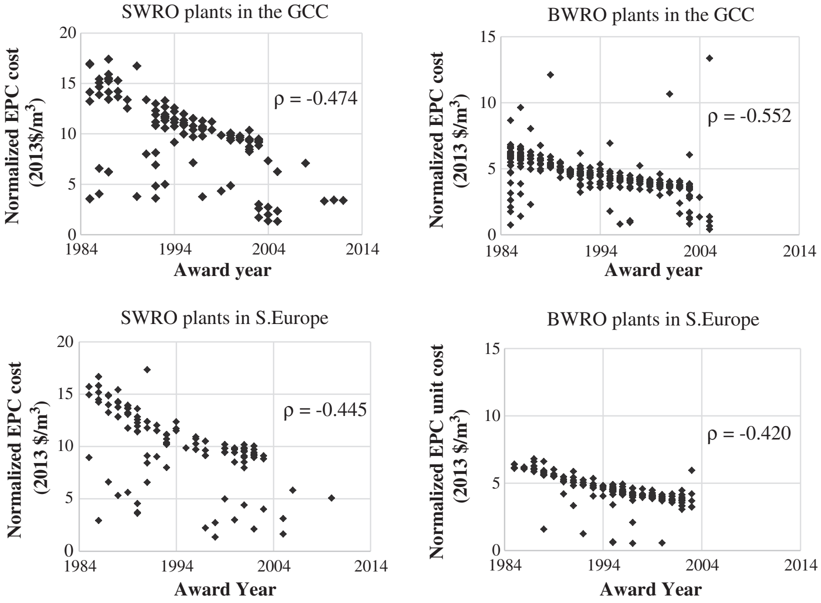

Fig. 4. EPC cost variation with RO plant award year. Also shown are the correlation coefficients from Table 2.

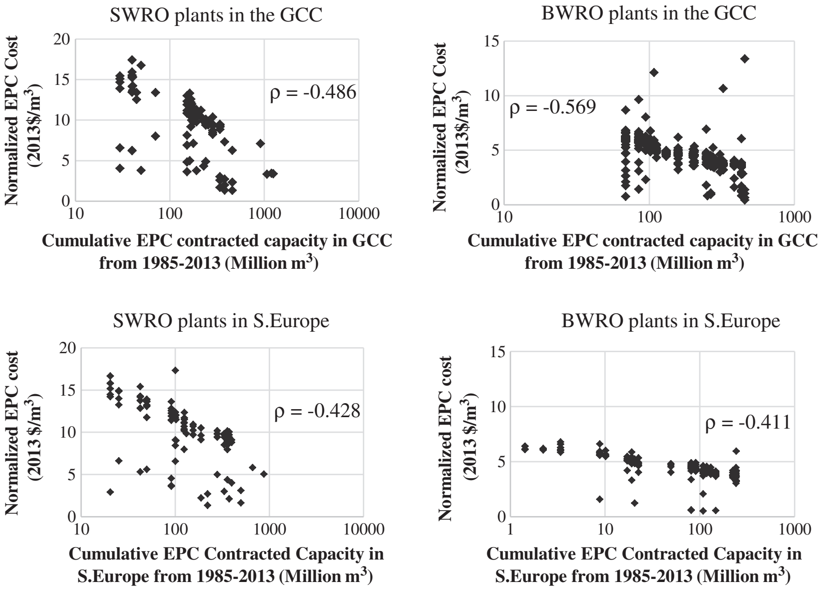

Fig. 5. RO plant EPC normalized cost variation with the cumulative EPC contracted desalination capacity in the respective region. Also shown are the correlation coefficients from Table 2. Capacity of plants awarded in 1985 is taken as the starting point.

(in ppm) indicates a weak correlation with the EPC cost as estimated for SWRO plants in the GCC (Table 2). Due to lack of salinity data in the BWRO and southern Europe datasets, the correlation coefficients for salinity and EPC cost could not be calculated for these subsets.

The EPC cost was plotted as a function of CAP, YEAR, CUM_CAP and SAL in Figs. 3, 4, 5 and 6, respectively, to better visualize the trends and the presence (or absence) of a linear relation. A strong linear relationship is evident between EPC and CAP when plotted in log scale for both types of plants (SWRO and BWRO) in the regions examined, as seen in Fig. 3 which indicates that in normal scale the two variables have a relationship of power law. The linearity shows that the capital cost of a desalination plant contracted by an EPC financing package is subject to an economy of scale. A slightly better fit is observed in the case of BWRO plants. This could be attributed to the boom in construction of similar sized small BWRO plants, mostly Saudi Arabia, which were awarded to a limited number of contractors (the dataset used show that, between 1985 and 2013, three major EPC contractors were awarded almost 70% of the BWRO plants in the GCC, mostly in Saudi Arabia). This led to less variance in the EPC cost of BWRO plants, compared to SWRO.

Figs. 4 and 5 show the change in EPC cost of SWRO and BWRO plants (normalized to their capacity), with award year (YEAR) and cumulative awarded capacity (CUM_CAP), respectively. It must be noted that there was a significant lack of data regarding the EPC cost of BWRO plants awarded since the mid of the 2000s. Both Figs. 4 and 5 indicate a reduction in EPC cost with award year and cumulative awarded capacity. The same trend is observed for both GCC and southern Europe regions. This trend reflects the accumulation of experience in desalination projects of the EPC contractors. This trend reflects RO market maturity. In every new RO plant project, the EPC contractor's engineers and consultants would already have established more knowledge of the local market and its logistics as well as more experience in choosing equipment manufacturers, leading to lower costs and avoided delays in project implementation. Similarly, over the years, the R&D departments of the EPC contracting companies introduced new and more cost-effective solutions, and so on. Another factor behind the decline of the EPC costs is the growing competition among RO EPC contractors in both regions, leading to more cost-effective deployment of new RO plants.

Time as an independent variable incorporates external and internal changes occurring in the desalination industry. An example of external changes that can affect the RO CAPEX costs is the exchange rate that could affect the import prices of raw materials and equipment [17]. Other external changes that can affect the capital cost of RO plants include regulations that allow more flexibility to the plant's manufacturers and availability of infrastructure for retrofitting existing plants (like aged power plants) into desalination plants. Internal changes that affected RO CAPEX, which are function of time, include the accumulated experience in RO plant engineering and budgeting by the EPC manufacturers as mentioned above [4].

Decrease in the TWC of desalinated water with time has been shown in [4] and [8]. However, it is apparent here that a similar dependency of CAPEX on project year and cumulative capacity also exists. It is worth mentioning here the growing concern over the ecological impacts of desalination. As a result of this concern, a growing number of governments are now imposing constraints on new RO plants and requiring elaborate and costly permitting procedures. Therefore, while the historical trend

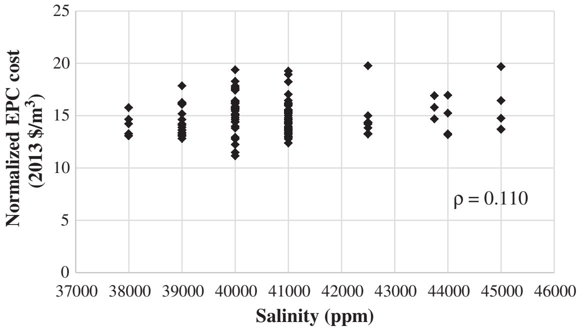

Fig. 6. RO plant EPC normalized cost variation with seawater salinity at the plant location within the GCC region (salinity data sources: Kuwait: 45 k ppm [24], Red Sea (Egypt) = 38 & Bahrain 42.5 from [25], Arabian Sea (center) = 40, Qatar = 40 & UAE = 40 from [26]). Also shown is the correlation coefficient from Table 2.

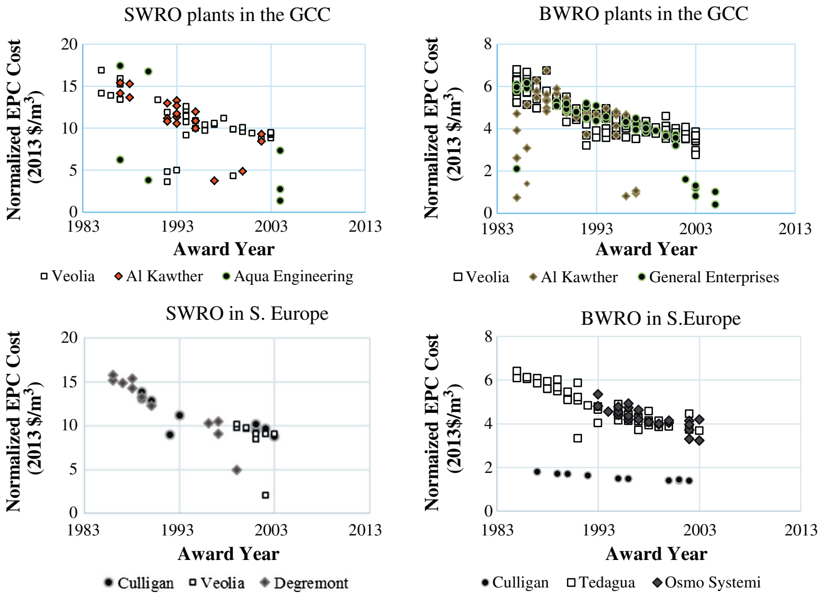

Fig. 7. Normalized EPC cost from 1985 to 2013 for three of the leading companies (in terms of number of contracts) in the respective region and for the type of RO plant shown.

from 1985 to 2013 show a reduction in normalized EPC cost with time, one may expect to see an increase in EPC cost over the coming years due to the mentioned ecological issues, which may offset or reduce the declining trend in cost.

Finally, in Figs. 4 and 5, the majority of EPC costs values form two clusters: points with close proximity to the graph's main trend line and points beneath it. This means that certain projects were contracted with a lower normalized price than most of the other projects awarded in the same year. After careful examination of those individual projects' features, it was found that most of them were large or extra-large RO plants. This confirms the importance of scaling-up as a means of reducing the normalized capital investments in EPC RO contracts [5,13,17].

Feed water salinity does not appear to be a determining factor in capital cost for SWRO. As Fig. 6 shows, no clear trend between SWRO CAPEX and feed salinity exists. This is also reflected in the low correlation coefficient between SAL and EPC cost (0.11 only, Table 2). Three reasons are speculated to stand behind this lack of correlation. First, in SWRO, specifications of high pressure pumps (a major component in SWRO equipment cost) are not likely to change much within the range of seawater salinity encountered in the GCC region (38 k–45 k ppm). On the other hand, the selection of membranes used may change based on this salinity range, but RO membranes and their vessels account for only 6–8% of the total direct capital cost, according to [17]. Finally, the design of SWRO pretreatment system (which is usually a significant part of the CAPEX cost) is independent of seawater salinity and depends more on other feed parameters (turbidity, etc.). While this is generally true for SWRO, it may not be completely true for BWRO. Brackish water salinities vary by an order of magnitude, from 2000 to 20,000 ppm. This wide variation can impact several BWRO design parameters, most notably membrane choice (low, medium or high pressure RO membranes). Unfortunately, due to the almost complete absence of salinity data on the 650 BWRO plants data set used in this study, it was not possible to verify the effect of salinity on the EPC cost of BWRO.

A potential dependency of the RO plant's CAPEX on the choice of EPC contractor was also investigated. Fig. 7 depicts the normalized EPC cost of all plants awarded from 1985 to 2013 to three of the leading EPC contractors (in terms of number of contracts awarded) in the GCC and southern Europe regions, for both SWRO and BWRO plants. Generally, it is observed that the normalized EPC costs for the contractors in Fig. 7 are following the same trend of the full dataset (Fig. 4) with data for all three companies falling closely within the main trend line. This implies that the CAPEX of an RO plant is not strongly dependent on the choice of EPC company contracted. One exception is seen in the case of BWRO plants contracted in southern Europe. Here, it appears that the choice of a certain EPC contractor (Culligan) has often led to the development of BWRO plants with normalized capital below that of the other two leading companies (Tedagoa and Osmo Systemi).

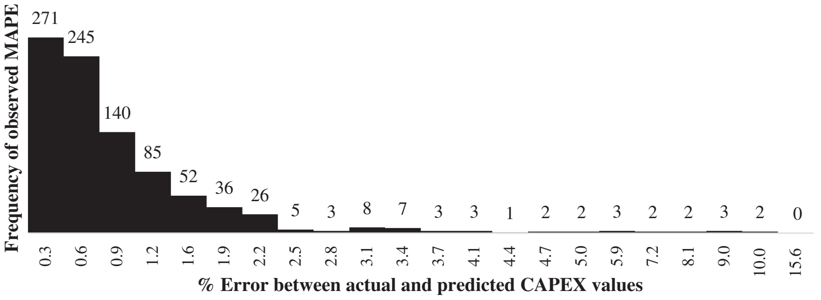

Fig. 8. The distribution of the model's mean absolute percentage errors (MAPEs).

Table 3
Final model's parameters and performance results.

Description	Intercept	CAP	YEAR	REGION dummy[a]	TYPE dummy[b]
Coefficient	58.054	0.939	−0.028	−0.074	0.830
Standard error	2.754	0.006	0.001	0.017	0.019
t-Stat	21.077	164.999	−20.180	−4.265	44.263
p-Value at 95% confidence level	$9.318 10^{-81}$	0.00	$2.99 10^{-75}$	$2 10^{-5}$	$4.81 10^{-230}$
R^2	0.976				
$\overline{R}^2$	0.976				
F-stat	9498.864				
MAPE (in log–log model)	0.929%				
MAPE (in 2013 USD)	15.32%				

[a] The REGION dummy is 1 for plants located in the GCC, 0 for plants located in southern Europe.

[b] The TYPE dummy is 1 for SWRO plants, 0 for BWRO plants.

3.2. Linear regression modeling of CAPEX

After establishing the trends of EPC cost and its correlation with each potential regressor individually, the quantitative model for EPC cost was constructed. The model construction was done by adding variables (regressors) to the model, one at a time, and checking for model accuracy improvement as a result of each regressor addition. The statistical indicators described in Section 2.1 were used to check for model accuracy, although their values for each step of new regressor addition are not shown here. To start with, CAP was the strongest regressor, so it was the first variable in the model. Then, as the feed salinity (SAL) by itself did not explain the variance of EPC and did not improve the model accuracy, it was excluded as a regressor. Following, the introduction of either YEAR or CUM_CAP as a second regressor to the base model of EPC cost and CAP led to an improvement in model accuracy. Therefore, both YEAR and CUM_CAP (which are inter-dependent variables, as described earlier) were deemed as potential regressors. Since the use of CUM_CAP as a modeling variable carries the complexity of requiring knowledge of all previously developed desalination plants capacities starting from year 1985, YEAR was chosen instead to be the second regressor due to its convenience of use. Following, the inclusion of the two dummy variables, REGION and TYPE, in the model led to further improvement of the model's fitting, so they were both included as regressors, leading to an EPC cost model with four regressor variables (CAP, YEAR, REGION, and TYPE). As mentioned earlier, the target variable (EPC cost) and the CAP regressor were correlated in their logarithmic form. Logarithmic transformations were proposed in [4] and [5] to reflect the scale-economy in estimating the TWC of desalination plants. It was confirmed in our work that logarithmic transformations of EPC cost and CAP parameters resulted in a better model fit than their linear forms. Though the common logarithm (base 10) was used in the models of [4] and [5], the natural logarithm (base e) transformation gave a slightly better R^2 in our analysis and thus was applied.

Next, the model's percentage residuals (absolute difference of predicted values and actual values of capital cost in terms of natural logarithm) were calculated and the data points that generated more than 8% absolute error in their predictions were excluded as outliers. The excluded points (29 points in total) were less than 3% of the original full dataset. More than half of these excluded data points were for BWRO plants. Since the design of BWRO can be site-specific, which can lead to a very particular CAPEX structure, it was deemed acceptable that such a small fraction of the whole data set be judged as outliers and excluded from the model fit. The distribution of the mean absolute percentage error for the full dataset is shown in Fig. 8. Based on the above and after the elimination of outliers, the final model equation was:

$$\ln(\mathrm{EPC}) = 58.054 + 0.939 * \ln(\mathrm{CAP}) - 0.028 * \mathrm{YEAR} + 0.830 * \mathrm{TYPE} - 0.074 * \mathrm{REGION}. \tag{11}$$

In Eq. (11), EPC is in USD (adjusted to 2013 dollars), CAP is nominal plant capacity in m^3 per year (not adjusted for availability), YEAR is plant commissioning date in "1234" format (example, 2010), TYPE = 1 and 0 for SWRO and BWRO, respectively, and REGION = 1 and 0 for GCC countries and southern European countries, respectively. A summary of the model's parameters and features is included in Table 3. All four variables of the model (CAP, YEAR, TYPE, and REGION) were found to be statistically significant at the 95% confidence level. Also, the $\overline{R}^2$ values showed that the R^2 was only minimally inflated (the difference between R^2 and $\overline{R}^2$ was 0.0001) which indicates very marginal over-fitting of the model. The model-predicted EPC values were plotted against the actual EPC values — both in terms of their natural logarithm values — and significantly good fit of the model to the real data was observed (Fig. 9).

The REGION coefficient (Table 3) is shown to be statistically significant which implies that the location of a RO plant can affect the capital cost of its development. It should be noted, however, that the REGION variable shows to be the least correlated variable among the model's variables as its *p*-value is the greatest. RO desalination plants of the same capacity, irrespective of whether they are SWRO or BWRO, appear to have a higher CAPEX values if they are located in the five countries of southern Europe (Spain, Greece, Italy, Malta, Cyprus) than if they were in the GCC.

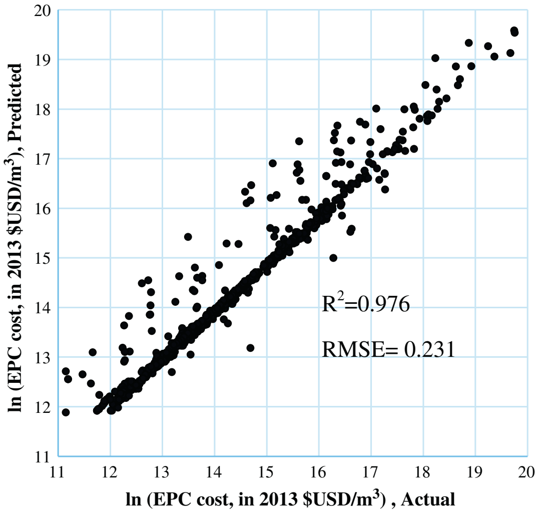

Fig. 9. Overall model fit.

Table 4
Results of 2-fold and 4-fold cross-validation calculated as an average of the validation results of all the folds.

Description	$k = 2$	$k = 4$
Correlation factor	0.989	0.989
RMSE	0.233	0.236
MAPE	0.009	0.010
R^2	0.977	0.978
	0.977	0.977

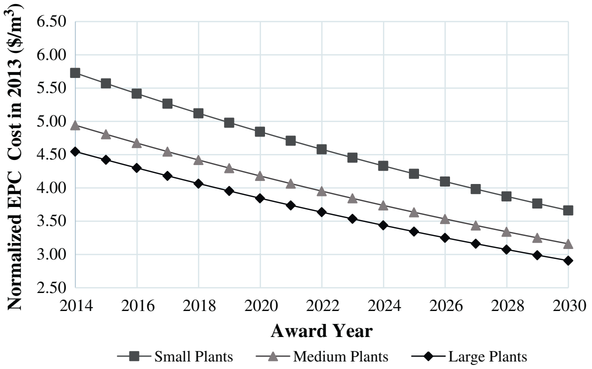

Fig. 10. Future projection of normalized EPC cost for small (500 m^3/day), medium (5000 m^3/day) and large (20,000 m^3/day) SWRO plants in the GCC region based on the model developed in this study.

The correlation coefficient of RO TYPE is the largest in absolute value after the coefficient of CAP. A SWRO plant is quite more expensive in terms of capital expenditure when compared to a BWRO plant of the same capacity. More precisely, according to our model, a SWRO and a BWRO plant of the same capacity, location and award year will have an approximate 2.3 CAPEX ratio. It was mentioned earlier that the effect of feed salinity was insignificant in SWRO. However, the feed salinities of BWRO and SWRO plants can differ by orders of magnitude while the variation in the salinity of SWRO plants examined was within 20% only (from 38,000 to 45,000 ppm). Besides the difference in feed salinity, more significant differences between SWRO and BWRO can directly influence their CAPEX. These include differences in pretreatment systems, feed intake systems, and need for second pass treatment for boron in SWRO.

The cross-validation results of the analysis are shown in Table 4. The high values of R^2 and $\overline{R}^2$, as well as the similarity in the RMSE and the MAPE values in the 2-fold and 4-fold cross-validations, validate the choice of OLS linear regression to statistically model the EPC cost data. To summarize, the modeling equation has proven to be able to estimate EPC values for plants that were not included in the analysis dataset.

Our final step was to apply our developed model to project future EPC costs of SWRO plants in the GCC region, assuming that the trends observed over our modeling period (1985–2013) will continue into the future. For this purpose, SWRO plants were categorized as small (S), medium (M), and large (L). This classification is based on [22]. An average (mean) capacity for each category was assumed to be 500 m^3, 5000 m^3 and 20,000 m^3/day for S, M and L plants respectively. Based on these capacities, our model (Eq. (11)) was used to estimate the future normalized capital costs (EPC costs per unit of product water) for the time period of 2014–2030, as shown in Fig. 10. The trend of the projected EPC costs shows that the normalized CAPEX cost will decrease with an average rate of 2.25% per year. The trends also show an economy of scale where the normalized cost decrease with plant capacity.

4. Conclusions

In this paper, capital cost values of actual commercial plants located in the regions of GCC and southern Europe were employed as input data with an aim of modeling the capital cost of RO plants that are developed via the EPC contract scheme. We found that the capacity of an SWRO or BWRO desalination plant is the most important statistical parameter influencing the EPC cost of the plant. The location of the plant (GCC versus southern Europe), though statistically significant, is potentially of less importance when estimating the EPC cost of RO desalination plants compared to capacity. The cumulative awarded capacity of RO desalination plants of the same type located in the same region shows to be correlated with the decline in the capital costs which confirms that the technology's maturity and contractors' cumulative experience within a region have both made RO more cost-effective in terms of CAPEX. The strong linearity of EPC cost and annual capacity — both fitted in their logarithmic transformation forms — confirm that the capital cost of RO plants follows the pattern of scale-economy.

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