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Economic Costs of Desalination in South Texas: A Case Study

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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 (Sturdivant et al. 2007). Since that time, opportunities for, and investigations into easing the stress from limited water supplies for municipal, industrial, and agricultural users have taken many paths, with key identified alternatives including:

1) water conservation in irrigation district water-conveyance systems,
2) on-farm and municipal water-conservation measures, and
3) desalination of brackish ground water and/or sea water.

These alternatives are capable of increasing the available local water supply, either through efficiency improvements in transport or usage, or by producing potable water from previously unavailable or contaminated water. Because of its cost, desalinated water is not considered an economically viable alternative for agricultural irrigation purposes.

When prioritizing and selecting among alternatives, a plausible query is "Assuming equivalent quality, which alternative is the most cost efficient?" An appropriate approach for resolving this question is to identify and define each project as a capital investment alternative, with each project likely differing in its initial and continued costs, quantity, and quality of output, expected useful life, and so forth. Proper implementation of accounting, finance, and economic principles and techniques (i.e., capital budgeting) and consideration of appropriate treatment cost adjustments can transform such data into comparable annual cost measures in dollars per acre-foot or per 1,000 gallons for each alternative.

This analysis addresses the economic and financial life-cycle costs of one water-supply alternative for South Texas (desalination of brackish ground water), using primary construction and continued costs for an operating desalination facility. This article provides an economic and financial analysis of the costs of producing and delivering reverse osmosis (RO) desalinated water at a specific operating facility, for a particular point in time. The estimates herein are applicable only to this facility. The method of analysis is Capital Budgeting.[1] Resulting annuity equivalent costs (or "annualized life-cycle costs") are provided on both a \$/ac-ft/year and a \$/1,000 gallons/year basis.

Target Desalination Facility

Though multiple brackish ground water 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. This facility is termed the Southmost Desalination Facility, which is owned and operated by the

Southmost Regional Water Authority (SRWA) – a consortium of six partners that 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 no date, Southmost Regional Water Authority no date).

Overview of the Southmost Desalination Facility

The Southmost facility was built to treat brackish ground water and provide an alternative water supply for the majority of the SRWA partners in the southern Cameron County region (Brownsville Public Utilities Board, no date).[2] With the completion of Phase I in the Summer of 2003, the designed 7.5 million gallons per day (mgd) total output is capable of providing more than 40 percent 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 level of 7.5 mgd (Brownsville Public Utilities Board, no date, Southmost Regional Water Authority, no date).

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 percent production efficiency rate equates the 7.5 mgd production rate to 8,401 acre-feet (ac-ft) annually. The Southmost facility utilizes brackish ground water from the Gulf Coast aquifer as its source water. This source water typically has incoming salinity levels of about 3,500 parts per million (ppm). Once the RO-processed water has been blended with source water, the finished water from the Southmost facility typically has outgoing salinity levels of 300-475 ppm, which is below the 500 ppm maximum level established by the U.S. Environmental Protection Agency for drinking water (Arroyo, no date).

Desalination Process Description for the Southmost Facility

The source brackish ground water from the Gulf Coast aquifer is obtained using 20 supply wells – 18 primary and 2 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 no date). Once the source ground water is pumped and transported via a pipeline to the main facility, the process-flow depicted in Figure 1 occurs in the Southmost facility (NRS Consulting Engineers 2006).

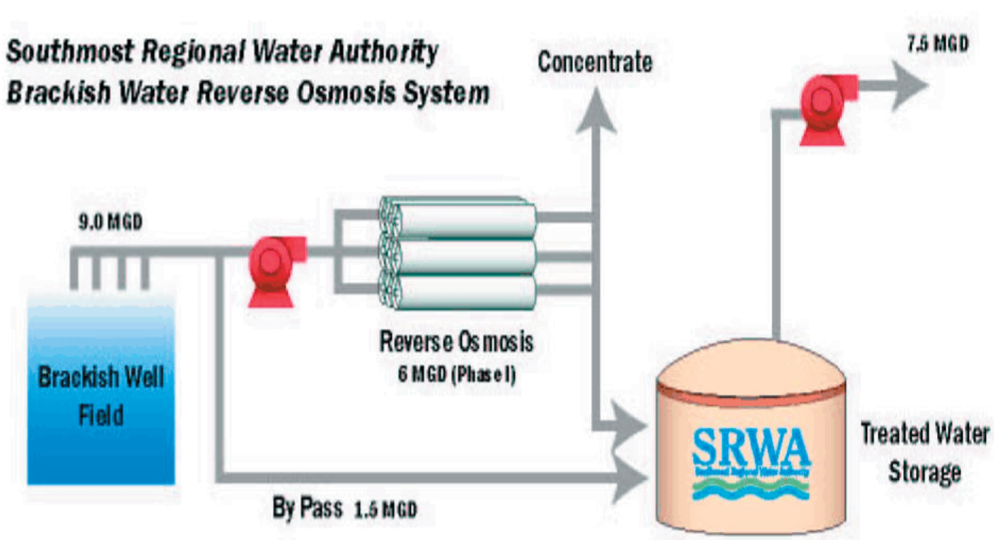

Figure 1. Graphical depiction of the process flow for the Southmost desalination facility (Southmost Regional Water Authority, no date).

Figure 2. Three banks of pressure vessels (6:11 array each) at the Southmost facility, 2007 (Sturdivant 2007).

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 a 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 2006). Prior to entering the RO system, suspended solids in the source water are removed by a series of five cartridge filters that improve the operation of the subsequent RO membranes. These filters must be replaced approximately every four months.

Reverse Osmosis (RO) Process. A series of six booster pumps move the water from the pretreatment cartridge filters to three "banks" (sometimes referred to as "trains") of pressure vessels, each configured in 6:11 arrays for a total of 198 vessels that remove total dissolved solids (Figure 2).[3] The booster pumps pressure the pretreated water against Thin Film Composite (TFC) membranes housed in each pressure vessel with approximately 180 psi, allowing only fresh water to pass through the membrane. Each pressure vessel contains seven elements (i.e., canister filters) that require replacement approximately every six years.

From a water-flow view, each bank (i.e., six columns and eleven rows) of vessels is split into two segments, each containing 33 pressure vessels. 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 2). This occurs in all three banks of pressure vessels.

Each half-bank of 33 pressure vessels (1st and 2nd stages combined) is designed to produce 1,000,000 gallons per day of permeated water. Thus, current designed capacity of permeated water for the Southmost facility is 6 mgd (i.e., three banks, multiplied by two half-banks, multiplied by 1 mgd per half-bank). The entire RO system operates at a 75 percent recovery rate, meaning three-fourths of the water entering the pressure vessels is captured as permeated (i.e., desalted) water.

Concentrate Waste Discharge. The 25 percent 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 system. The concentrate waste is discharged (Texas Commission on Environmental Quality (TCEQ) permitted) through a 16” (diameter) pipeline into an earthen drainage ditch located adjacent to the Southmost facility and extending to the Laguna Madre.[4] For other inland desalination facilities, the discharge of concentrate waste is more complex and costly.

Blend Water. After cycling through the RO pressure membranes, the permeated water, now at 40-50 ppm salinity, can be blended with nonpermeated (i.e., brackish) blend water (from after the pre-treatment process where suspended solids are removed by a sixth cartridge filter), which is about 1,800 ppm. The blended water has a salinity level of about 300-475 ppm.[5]

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) reduced amount of water 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), 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. That is, when chlorine (found in chloramines) is added to water, it forms hypochlouous acid (HOCl), an active disinfectant (Scranton Gillette Communications, Inc. 2007). Calcium chloride is added to counter extreme product-water “softness” and to assist with the pH adjusting process (NRS Consulting Engineers 2006).

Degasification and Tank Storage. After the post-RO treatments, the product water is discharged into the transfer pump station clearwell for degasification (i.e., aeration) where “air bubbles” of carbon dioxide are removed. From here, the water is pumped into a 7.5 million gallons above-ground storage tank.

Delivery of Product Water. From the storage tank, the product water is pumped via a pipeline to the municipal delivery point approximately two miles away. Plans are in place for a second delivery point to be installed in the near future. 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

For this analysis, a 1-year construction period is assumed. The various civil, electrical, and mechanical components of the Southmost facility are expected to have useful lives ranging from a low of three 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. 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 useful 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, noncapital expenses, such as electrical switches, valves, etc., are captured in annual

Table 1. Annual output and efficiency-rate measures for the Southmost desalination facility.

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

Source: (Brownsville Public Utilities Board 2007a).

a. The production rate anticipated by management and consulting engineers after operational and product-demand interruptions are completely overcome.
b. The Rule of 85 refers to a TCEQ-mandated capacity requirement level (%) which could directly impact the Southmost facility. In general/simplified terms, when a public utility (possessing a certificate of public convenience and necessity) reaches 85% of its capacity, it must submit to TCEQ a service-demand plan, including cost projections and installation dates for additional facilities.
c. As of January 2007 (Brownsville Public Utilities Board 2007b).
d. The production rate used in the baseline analysis discussed herein.
e. Annualized values account for non-productive months; this provides comparable measures across all four years; i.e., production/delivery began in April of 2004, while 2007 only includes 3 months (January - March).

operating expenses. Combined, specified capital-replacement and annual-operational expenses provide for a facility that will maintain productive capacity for 50 years.

Annual Water Production

The current maximum-designed capacity of the Southmost facility is 7.5 mgd (8,401 ac-ft annually) with a 100 percent production efficiency rate (Table 1). For this analysis, allowances are made, however, for operational and demand interruptions incurred. Imposing a less than 100 percent rate in this analysis is considered appropriate and more realistic.

The Southmost facility's actual production-efficiency rate has varied due to operational and product-demand interruptions (Table 1). Although a future higher production rate is anticipated (i.e., 94 percent), the historical data, combined with current-year-to-date values indicate a production-efficiency rate of 68 percent is representative and appropriate for use as a baseline measure in this study.[6] That is, 68 percent is used and held constant during each year of the facility's productive life in the baseline analysis.[7]

Initial Construction Cost

Initial construction costs totaled $26.2 million for the Southmost facility and are assumed to be spent immediately 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 2). As depicted in Table 2, 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, the *Pipeline* ($5,682,754) and *Building & Site Construction* ($5,630,904) items are the largest contributors to total initial construction costs.

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 percent annually herein. 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 anticipated increases in energy and chemical costs for the current fiscal year. 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 two percent or more for each successive year of useful life. For this study, continued costs total $1.7 million and are organized into two general categories (Table 3).

Administrative expenses total $80,503 and account for facility-related expenses that are not included on the Southmost desalination facility's budget, but rather are included on other owner-entity budgets (e.g., Brownsville Public Utilities Board, n.d.). Such administrative expenses are estimated as 5 percent of the Operations and Maintenance (O&M) budget for this facility. For analysis-detail and desalination-facility-comparison reasons, this category has been divided into six cost-item categories and also separated into seven individual functional areas common to desalination facilities (Table 3). The most costly area is the *Main Facility* ($46,409) (Table 3).

Annual operations and maintenance (O&M) expenses total $1,610,056 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 and also separated into seven individual functional areas common to desalination facilities (Table 3). The most costly area is the *Main Facility* ($928,172). When viewed from individual cost items, the *Electrical Power* ($800,000) item is the largest contributor to continued O&M costs. Here, many detailed cost items have been collapsed into generalized categories.

Capital Replacement Costs

Similar to continued costs, capital replacement costs facilitate perpetual desalination operations, albeit on an intermittent rather than annual basis. That is, within the facility's maximum useful life of 50 years, certain capital items wear out and must be replaced every two, five, or ten 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 percent annually in this study. Table 4 depicts the needed capital replacement items, as well as their replacement occurrence and costs that are incorporated into this study.

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 six 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 and capital budgeting. Without access to such methodological detail, however, commentary regarding the accuracy, comparability, 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 or the most-significant item in prior investigations. *Location* of a desalination facility dictates the source water type (i.e., brackish or sea water) 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 facilities around the globe and found that any given sea water RO desalination facility experienced higher per-unit costs than facilities dependent upon brackish ground water. Adams et al.'s (no date) regression results from three South Texas brackish ground water RO facilities indicate

Table 2. Initial construction costs for the Southmost desalination facility, across individual functional areas, 2006.

	Individual Functional Areas (i.e., Cost Centers) of the Southmost Desalination Facility							
INITIAL CONSTRUCTION COST ITEM	Well Field	Intake Pipeline (Well field to facility)	Main Facility	Concentrate Discharge	Treated Discharge-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	891,192		620,568				167,973	1,679,733
Electrical Service	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 Endnote 9 in the text.
b. Acronym for Supervisory Control And Data Acquisition – 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 3. Baseline annual continued costs, allocated across individual functional areas, for the southmost desalination facility, based on actual fiscal year 2004-2005 expenses.

	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	Treated Discharge Line & Tank Storage	Delivery Pipeline (to municipal line)	Overbuilds & Upgrades[a]	TOTAL COSTS
ADMINISTRATIVE								
Administrative Overhead[b]	$17,917	$200	$46,409	$181	$3,286	$8,745	$3,765	$80,503
Insurance (public officials)								0
Labor								0
Maintenance								0
Other								0
Vehicles / Rolling Stock								0
Sub-Total	$17,917	$200	$46,409	$181	$3,286	$8,745	$3,765	$80,503
OPERATIONS & MAINTENANCE								
Administrative Overhead							61,673	61,673
Chemical			241,518					241,518
Concentrate Disposal								0
Electrical Power	288,000		288,000		56,000	168,000		800,000
Insurance	8,469		31,760		2,117			42,346
Labor	36,130	3,613	307,105	3,613	7,226	3,613		361,300
Maintenance	15,525		43,469			3,105		62,099
Other							13,632	13,632
Rental (land, equip., storage)	8,287							8,287
Vehicles / Rolling Stock	1,920	384	16,320		384	192		19,200
Sub-Total	$358,331	$3,997	$928,172	$3,613	$65,727	$174,910	$75,305	$1,610,056
TOTAL	$376,248	$4,197	$974,581	$3,794	$69,013	$183,655	$79,070	$1,690,559

a. Captures the ‘whistles & bells’ beyond baseline necessities, and some ‘elbow room’ for future increased capacity – see Endnote 9 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.

Table 4. 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	20 years	$15,000	6
Membranes	6 years	$600,000	1

there is a positivelinear 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).

Energy accounts for a large portion of final product costs. Younos (2005) credits energy as the primary cost difference between desalination of sea water and brackish water. Younos' data show electric power accounts for 11 percent of total costs for brackish water-dependent facilities and 44 percent for sea water-dependent facilities. Graves and Choffel (no date) report electricity costs account for about 30 percent of the total costs for seawater-dependent facilities. Energy is a factor that is highly dependent on the location, as power costs can vary greatly from state to state and from 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 (no date). They report, for a 25 mgd sea water facility (generating 16.7 mgd of concentrate), disposal costs associated with piping concentrate one 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 that are unable to utilize the ocean for concentrate disposal, the remaining options include deep-well injections or evaporation ponds. Archuleta (no date), in a study for a potential facility in El Paso, Texas, indicates that deep-well injection would be the most economical choice. 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.[8] Several reports indicate that increasing the total capacity of the facility decreases the per-unit costs for facilities dependent upon either brackish or sea water. Arroyo (no date) estimates that production costs for brackish-ground water facilities range from $772.27 per ac-ft ($2.37 per 1,000 gallons) for a 0.10 mgd RO facility down to $231.35 per ac-ft ($0.71 per 1,000 gallons) for a 10 mgd RO facility. This theme of utilizing economies of scale to reduce per-unit costs is also noted by Norris (no date a) and Archuleta (no date) in which more than one entity collaborated (or proposed) to build one larger facility, rather than multiple, smaller facilities in South Texas and El Paso, Texas, respectively.

Pittman et al. (2004) reported sea water desalination in South Texas was not economically competitive with treated municipal water. This conclusion was based on a comparison of charges for municipal-treated water in Brownsville, Corpus Christi, and Freeport that ranged from $527.88/ac-ft to $661.48/ac-ft, with proposed sea water desalination costs ranging from a low of $1,166.55/ac-ft to a high of $1,306.66/ac-ft (Table 5). The cost to desalinate brackish ground water could be considered economically competitive, however, as Norris (no date b) states, desalinating brackish

Table 5. Charges for municipal-treated water and costs of desalinated seawater as presented in Pittman et al. (2004), and costs of brackish ground water desalination in Norris (no date a).

	Pittman et al. (2004)[a]				Norris (no date a)	
	Municipal-Treated Water Charges		Proposed Seawater Desalination Water Costs		Proposed Brackish Groundwater Desalination Water Costs	
South 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

a. Note the municipal-treated values are *charges*, which may not equate with *costs* of such water, thus making for a possible imbalanced comparison with sea water desalination costs.

ground water at the Southmost facility costs between $521.36 and $586.53 per ac-ft {$1.60 and $1.80 per 1,000 gallons} to treat and deliver (Table 5).

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. Net Present Value (NPV) analysis, in combination with the calculation of annuity equivalents, are the methodology of choice because of the capability of integrating expected life with related annual costs and outputs, as well as other financial realities, into a comprehensive $/ac-ft/year (or $/1,000 gals/year) life-cycle cost. 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 Cooperative Extension and the Texas Agricultural Experiment Station developed the Microsoft® Excel® spreadsheet model DESAL ECONOMICS©. This model analyzes and provides life-cycle costs (e.g., $/ac-ft/year) for up to eight individual functional expense areas common to desalination facilities, 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, and so forth. 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. Treated Discharge Line & Tank Storage;
6. Delivery Pipeline (to the municipal delivery point); and
7. Overbuilds & Upgrades.[9]

Results derived using DESAL ECONOMICS© allow an "apples to apples" comparison to be made across different desalination facilities or across individual expense areas of different desalination facilities. Worthy of special mention for this model is 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) that are causing the disparity. By also analyzing the individual functional cost areas, additional useful data are provided; this may highlight the need for a review assessment to see if engineering or construction changes could be made in one or more specific areas in order to reduce the composite life-cycle cost.

Also, if the same methodology and factors are used, comparisons can be made with other capital projects that augment the region's available water supply (e.g., on-farm and municipal water conservation measures, sea water desalination, rainwater harvesting, ponding and retainment, rehabilitation of water-conveyance systems).[10] Ultimately, having comparable costs for all alternatives that add water to a region's supply will provide information useful for prioritizing projects in the event of limited funding or other constraining circumstances.

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. The discount rate used for calculating 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 net present value of costs requiring 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.[11] The discount rate used in this analysis is 6.125 percent, which is consistent with and documented in Rister et al. (2002).

Discounting Water. Having different annual water output and expected useful lives across facilities encourages "normalizing" such flows by calculating the net present value of production, which requires a discount factor. Since it is inappropriate to inflate successive years' water production, there is no inflationary influence to consider in the discounting of water (Klinefelter), i.e., only the time (t) portion of the discount factor should be used. Consultations with Griffin (2002) and Klinefelter contributed to adoption of the 4 percent rate used by Griffin and Chowdhury (1993) for the social time value in this analysis.

Compounding Costs. Inflation is a financial reality with future years' ongoing operational costs. As presented in Rister et al. 2002, use of an overall discount rate of 6.125 percent, with a 4 percent social time value and no risk premium, infers a 2.04 percent annual inflation rate.

Results of Economic and Financial Analysis

Composite results for the economic and financial analysis of the aforementioned data, using the Excel® spreadsheet model DESAL ECONOMICS©, are presented here. A summary of aggregate estimated baseline results is presented first, with subsequent estimated results presented across facility segments and then by cost type. Thereafter, brief presentations of key sensitivity analyses for select parameters are provided. Herein, the phrase 'cost-of-producing water' is used. Since the costs of the Southmost facility analyzed include delivery to a point in the municipal delivery-system infrastructure, this phrase can be interpreted as the cost-of-producing-and-delivering water. This should not be confused with household delivery – it is delivery only to a point within the municipal system infrastructure.

Results – Aggregate Baseline

Initial Construction Costs. The total initial construction costs for the Southmost facility (detailed in Table 2) amount to $26,190,993 in nominal dollars (Table 6). 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 6).

Water Production. Over the 50-year expected useful life, the annual production of 5,713 ac-ft, using the modeled effective capacity of 68 will total 285,637 ac-ft on a nominal basis. This value, when adjusted for time at the 4 percent 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 6).[12]

Total Life-Cycle Costs. Summing all facility costs (i.e., initial, continued, and capital replacement) over the 50-year expected useful life result in $192,835,145 in nominal dollars. Adjusting this value for time and inflation at 6.125 percent results in a real value of $64,567,577 (Table 6). This value represents, in current 2006 dollars, the net total life-cycle costs of constructing and operating the Southmost facility. That is, at the time a commitment is made to fund the initial construction costs of $26,190,993, an additional $31,191,898 (i.e., $64,567,577 minus $26,190,993) in current 2006 dollars is also implicitly committed (Table 6).

Annual Cost Annuity. Calculating the annuity equivalent of the $64,567,577 real value results in an 'annualized cost' of $4,155,158. This real value represents, in current 2006 dollars, the net annual costs of constructing and operating the Southmost facility.[13]

Cost of Producing (and Delivering) Water (baseline). The annual *Cost-of-Producing (and Delivering) Water* value on a per ac-ft basis was derived by dividing the total cost annuity of $4,155,158 by the total water-production annuity of 5,459 ac-ft (1,778,701 1,000-gallon units). The result is a baseline annual cost of producing and delivering desalinated water at the Southmost facility of $761.21 per ac-ft ($2.3361 per 1,000-gallons) (Table 6). 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. 2002). Consistent with the methodology presented in Rister et al. 2002, 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.

Results – by Facility Segment

DESAL ECONOMICS© uniquely analyzes and provides comparable life-cycle costs (e.g., $/ac-ft/year) for up to eight individual functional expense areas, and also for the entire facility.

Table 6. Aggregate baseline results for production and costs for the seven facility segments of the Southmost desalination facility, 2006.

Results	Units	Nominal Value	Real Value[a]
Initial Facility Costs	2006 dollars	$26,190,993	$26,190,993
Water Production	ac-ft (lifetime)	285,637	118,002
annuity equivalent	ac-ft/year		5,459
Water Production	1,000-gal (lifetime)	93,075,000	38,451,045
annuity equivalent	1,000-gal/year		1,778,701
NPV of Total Cost Stream[b]	2006 dollars	$192,835,145	$64,567,577
annuity equivalent	$/year		$4,155,158
Cost-of-Producing & Delivering Water	$/ac-ft/year		$761.2100
Cost-of-Producing & Delivering Water	$/1,000-gal/year		$2.3361

a. Determined using a 6.125 percent discount factor for dollars and a 4.000 percent discount factor for water.
b. 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.

Here, the above aggregate cost-of-producing water of $761.21 (Table 6) is dissected into the seven functional expense areas detailed earlier.

Table 7 reveals the NPV of the net cost stream to range from a low of $135,724 for Concentrate Discharge, to a high of $31,836,227 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 7, the annuity equivalent values are provided for individual components, which range from $8,734/year for Concentrate Discharge to a high of $2,048,777 per year for the Main Facility. These values are interpreted as the annualized costs for each component, inclusive of all life-cycle costs and reported in 2006 dollars (Rister et al. 2002).

A further delineation of the annuity equivalents reveals the economic and financial life-cycle costs, which range from $24/day for the Concentrate Discharge segment to a high of $5,613/day for the Main Facility. The total life-cycle cost for all seven segments equates to $11,384/day. Again, these are the total daily life-cycle costs, reported in 2006 dollars (Rister et al. 2002).

Key annualized cost results presented in Table 7 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 $1.60/ac-ft/year ($0.0049/1,000-gallons/year) for Concentrate Discharge, to a high of $375.33/ac-ft/year ($1.1518/1,000-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 $761.21 per ac-ft ($2.3361 per 1,000 gallons) (Tables 6 and 7).

This analysis and presentation of segmented cost-of-producing-water results is 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©) provides benefits that can be used in both single- and multi-facility analyses:

Single-Facility Analysis. Within a single-facility

Table 7. Costs of producing (and delivering) water for the seven facility segments of the Southmost desalination facility, 2006.[a]

		- - - - - - - - - Annuity Equivalents	- - - - - - -			
Facility Segment	NPV of Cost Stream[b]	($/yr)[c]	($/day)[c]	$/ac-ft/year[d]	$/1,000 -gals/year[d]	% of Total Cost
1) Well Field	$16,846,011	$1,084,102	$2,970	$198.60	$0.6095	26.1%
2) Intake Pipeline	$2,066,371	$132,979	$364	$24.36	$0.0748	3.2%
3) Main Facility	$31,836,227	$2,048,777	$5,613	$375.33	$1.1518	49.3%
4) Concentrate Discharge	$135,724	$8,734	$24	$1.60	$0.0049	0.2%
5) Treated Discharge Line & Tank Storage	$2,389,050	$153,744	$421	$28.17	$0.0864	3.7%
6) Delivery Pipeline	$5,492,079	$353,435	$968	$64.75	$0.1987	8.5%
7) Overbuilds & Upgrades	$5,802,114	$373,387	$1,023	$68.40	$0.2099	9.0%
TOTAL	$64,567,577	$4,155,158	$11,384	$761.21	$2.3361	100.0%

a. Delivery is to a point in the municipal delivery-system infrastructure, *not* individual household delivery.
b. 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.
c. Total costs for ownership and operations, stated in 2006 dollars, and the annuity values for the first column entitled "NPV of Cost Stream."
d. These are the total "annualized costs" on a per ac-ft basis (or $/1,000-gals) for each component.

analysis, the additional segmented-cost data identifies 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.[14]

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 functional cost area(s) may be causing the disparity. By also analyzing the individual functional cost areas, the additional details provided can highlight the need for a review assessment to see if engineering or construction changes could be made in a specific area to reduce the composite life-cycle cost to a level observed at another similar facility.

Sensitivity Analyses

The baseline results are based on specific values for:

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

Having data input that lack 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 precise. Further, given the likely range in values for input parameters, a range in results is expected to exist. To further the deterministic results, two sets of sensitivity analyses are reported herein, with two parameters varied in each, leaving all others constant at the levels used in the baseline analysis.[15]

To illustrate sensitivity of the results, initial construction costs and the facility-use efficiency rate are incrementally changed. 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 facility-use efficiency rate is analyzed with variations ranging from a low of 60 percent to a high of 100 percent. Using these variation ranges, sensitivity results for these two data indicate the annual cost of producing (and delivering) desalinated water ranges from $477.54 to $929.51 per ac-ft and from $1.4655 to $2.8526 per 1,000 gallons. As expected, higher facility-use efficiency rates and lower initial construction costs contribute to the lower cost-of-producing-water estimates, and vice versa.

The sensitivity across ranges for annual energy costs and the facility-use efficiency rate are included since these factors are both subject to significant changes. Changes about the baseline annual energy costs of $800,000 are tested with 5, 10, and 20 percent variations, while the facility-use efficiency rate is analyzed with variations ranging from a low of 60 percent to a high of 100 percent. Using these variation ranges, sensitivity results for these two data indicate the annual cost of producing (and delivering) desalinated water range from $489.80 to $909.07 per ac-ft, and from $1.5031 to $2.7898 per 1,000 gallons. As expected, higher facility-use efficiency rates and lower energy costs contribute to lower cost-of-producing-water estimates, and vice versa.

Discussion

Desalination of sea water and brackish ground water has historically been considered to be an expensive source for municipal and industrial (M&I) users and prohibitively expensive for agricultural users. Though beyond the scope of this report, such desalination costs are purportedly decreasing (Graves and Choffel, no date). 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 that can provide further insight and added value in (a) post-construction case studies and (b) during the planning and design stage of future facilities.

Research and development efforts to reduce desalination costs with better and more efficient RO membranes are a key industry goal. As exemplified herein, however, several cost items (e.g., concrete, energy, chemicals, membranes, administrative overhead, labor wages, etc.), over many years are involved in the final total life-cycle costs (i.e., NPV of cost stream) of ground water desalination. As energy accounts for the single largest cost (i.e., 26 percent of the total), it is likely that the most significant impact associated with new RO membranes may be in 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 the total life-cycle cost.[16]

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, no date b), are very effective at reducing Initial Construction costs and the associated life-cycle NPV cost stream. The Southmost facility has 41 percent of its life-cycle cost deriving from Initial Construction costs, and a combined 59 percent from Continued and Capital Replacement costs. Thus, ceteris paribus, efforts to significantly reduce initial and/or future costs will likely result in a lower life-cycle cost.[17]

The economic competitiveness of desalinated water frequently is measured against municipally-treated surface water. A caveat is warranted, however, in comparing the costs of desalination with that of charges assessed by municipalities for surface water. That is, municipal-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.

Putting it all into context, desalination might 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 and provides a measure of defense against potential security-related threats. There is anticipation that desalination costs will decline in future years as a result of technology development. Any future cost reductions provided by marginal advancements in membrane technology 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 cost of RO-desalinated water relative to the cost of municipal-treated surface water from the Rio Grande.

Conclusions

Complete and thorough life-cycle cost analyses of supply- or efficiency-oriented capital projects that can add water to a region, including desalination, provide much useful information if they are based on NPV methodology 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) and productive capacity. The robust results herein are reported on a current 2006 year basis and can be used in comparisons across similarly-calculated values (e.g., Rister et al. 2006) for other alternative ways of adding water to the regional supply.[18] Sound analyses of finance and economics should be a consideration and an extension of engineering-related tasks for capital-project alternatives involved in a region's water-resource planning.

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Endnotes

1. "Capital Budgeting" is a generic phrase used to describe various financial methodologies for 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 economic and financial methodologies used in the analysis are similar to methods documented in Rister et al. 2002. 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.

2. Here, desalination is an alternative supply to treated surface water diverted from the Rio Grande, which constitutes about 87 percent of the region's supply.
3. The "6:11" notation is the membrane industry's way of describing a bank of pressure vessels that has six columns (width) and eleven rows (height). Different configurations of vessels are used in RO operations.
4. The Laguna Madre (translated: "mother lagoon") is a shallow, salty lagoon that is five miles across at its widest point and stretches for over 200 miles from southern Texas into northern Mexico. 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).
5. Such quality of blended water is comparable to conventional treatment of surface water from the Rio Grande.
6. Contributing to the lower (i.e., 68 percent) rate has been water quality issues related to arsenic and iron. These issues have forced Southmost facility management to modify operational procedures by discontinuing (temporarily) the blending of RO (i.e., permeated) and non-permeated blend water together. The subsequent reduced product-water output and associated upward adjustments in chemical usage have impacted current life-cycle costs.
7. Sensitivity analyses about this parameter are provided in the complete report (i.e., Sturdivant et al. 2007).
8. 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 all factors in fixed 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).
9. This expense area captures the "whistles & bells" included in the initial construction costs beyond baseline necessities, as well as some "elbow room" for future increased capacity. That is, the Southmost facility is considered a Type A "cornerstone" RO 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.
10. 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.
11. 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 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 (2002) and Klinefelter (2002), both Texas A&M University agricultural economists specializing in finance, a discount rate of 6.125 percent, consistent with and documented in Rister et al. 2002, was adopted for use in discounting all financial streams.
12. 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.
13. For the Water Production and NPV of Total Cost Stream results in Table 6, the real-value amounts are less than the nominal-value amounts. This occurs because the continued and capital replacement costs, and water production that occur in the latter years of the facility's life are significantly discounted (at 6.125 percent and 4.000 percent 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 that could exceed the costs; i.e., a negative NPV of total costs would infer a net profit.

14. For example, the Well Field's costs are $198.60 (Table 7) 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.
15. A more complete set of sensitivity analyses are provided in the complete report (i.e., Sturdivant et al. 2007).
16. A dedicated section in the complete report (i.e., Sturdivant et al. 2007) discusses and presents life-cycle cost results broken down into various cost types, categories, and items, with annuity equivalent measures (i.e., $/ac-ft/year, $/1,000 gal/year, and percent of total life and-cycle cost) provided for each (e.g., energy 26 percent of total, initial construction costs 41 percent of total, etc.).
17. See note 16 above.
18. Note, values provided in Rister et al. 2006 include the cost-of-saving water via rehabilitation of water-delivery infrastructure. As such, the water anticipated to be saved with that project (via reduced seepage, evaporation, etc.) is raw, untreated water, and would thus need to be treated. That is, the cost-of-saving water via rehabilitation of water-conveyance systems needs to be adjusted upwards for municipal treatment costs to par the quality of Rio Grande surface water with that of desalinated water. The authors have current, ongoing work that facilitates the upward adjustment and comparison.

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