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Desalination and Long-Haul Water Transfer as a Water Supply for Dallas, Texas: A Case Study of the Energy-Water Nexus in Texas

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Abstract: As existing water supplies become increasingly strained in some locations, water planners turn to alternative options to quench cities' thirst. Among these options for inland cities is desalination of seawater or brackish groundwater with long-haul water transfer. Desalination using reverse osmosis membranes is the most common technology in use, yet high pressures required for operation make desalination an energy-intensive water supply option. The subsequent conveyance of desalinated water through long-haul pipelines also requires large amounts of energy. To analyze desalination and long-haul transfer as a drinking water supply, Dallas, Texas, was chosen as a test-bed with two scenarios: seawater desalination near Houston and brackish groundwater desalination near Abilene, both with long-haul transfer of desalinated water to Dallas. Combining the energy requirements for long-distance pumping with the energy demands for desalination, we estimate that desalination and long-haul transfer is nine to 23 times more energy-intensive per unit of water than conventional treatment of local surface water sources, an increase of 230 to 630 MWh/d for 20 million gal (75,700 m^3). These results suggest that desalination and long-haul transfer as a water supply for Dallas is less sustainable, based on energy consumption, than use of local surface water sources or water conservation.

Keywords: desalination, long-haul transfer, energy, water

INTRODUCTION

Desalination is a water treatment technology that produces potable water from brackish groundwater or seawater. Though many desalination technologies exist, including thermal processes such as multieffect distillation and multistage flash, the most popular is reverse osmosis (Van der Bruggen and Vandecasteele 2002). Most reverse osmosis treatment operations use a staged or cascade layout like that shown in Fig. 1 to improve recovery—the ratio of permeate (product water) to feed water.

Historically, commercial desalination plants operated using thermal processes in locations where energy was plentiful or inexpensive and freshwater was scarce. For example, desalination provides substantial volumes of drinking water in areas of the Middle East with abundant energy resources. Emerging reverse osmosis technology has enabled the construction of new and larger desalination plants, yet estimated worldwide capacity totals only 15.8 billion gal/d (59.9 million m^3/d), or 0.5% of global freshwater use (Desalination & Water Reuse 2009). Public resistance to desalination plants in the United States stems from both environmental and energy sustainability issues. Seawater intake structures can harm marine wildlife and excessive brackish groundwater withdrawal can contribute to land subsidence (Galloway et al.1999; Lattemann and Hopner 2008). Furthermore, the large energy requirement for desalination—more than 10 times the traditional surface water treatment—contributes to greenhouse gas emissions when using fossil fuel-generated electricity (CEC 2005; EPRI 2002b). As an alternative, wind-generated electricity can be used to power a desalination plant, as has been demonstrated in Perth, Australia, which switched from coal to wind power after protests, and produces 36 million gal/d (mgd) (136,000 m^3/d) of potable water without emissions (Barta 2008). Sydney Water, the water utility of Sydney, Australia, has also laid plans for wind-powered desalination (Tadros and Robins 2008).

Since desalination makes use of water normally considered

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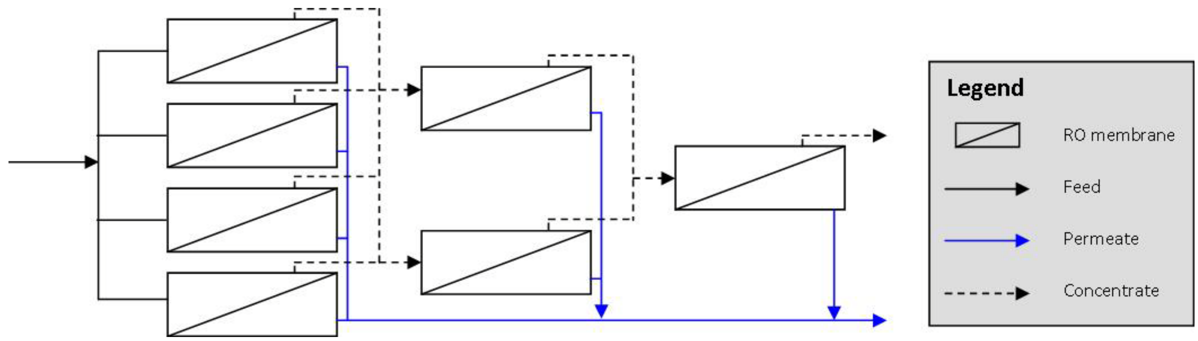

Fig. 1. Typical reverse osmosis units are configured in a cascade layout to improve water recovery, which typically ranges from 35% to 50% for seawater and 60% to 85% for brackish groundwater (Lawler and Benjamin 2008; Zander et al. 2008).

unusable, many turn to desalination as an alternative water resource when existing supplies become strained. Due to the abundance of saline ocean water and brackish groundwater, desalination—and the subsequent transfer of treated water—can provide a reliable water supply that is generally plentiful and resistant to droughts. This reliability comes with a price; desalination is an energy-intensive water treatment technology. Despite that price, historical trends show a near-exponential increase in installed desalination capacity in the United States (Gleick et al. 2006).

DALLAS, TEXAS, AS A CASE STUDY

Strained water supplies and growing populations often cause cities to pursue alternative water sources. Dallas, Texas, is no exception. In 2003, the Dallas-Fort Worth metropolitan statistical area population totaled 5.6 million people, which has increased annually by 2%, on average. Per capita water use, as reported by the Texas Water Development Board (TWDB) from Water Use Survey data, for Dallas and Fort Worth is 238 and 177 gal/person/ (0.90 and 0.67 m^3/person/d), respectively (Ward et al. 2007). This large water use in the Dallas area—the third largest in Texas based on TWDB estimates—and others throughout the state has led water resource planners to pursue alternative water supplies for the future, with desalination among those options (Herring et al. 2008; Office of Governor [cited 2009]; Texas Comptroller of Public Accounts [cited 2009]).

One drought-resistant water supply option is seawater desalination. For example, Corpus Christi, Texas, is currently evaluating three desalination opportunities for incremental water supply; additional water supply was added in 1998 via a 101-mi (163-km) long-haul transfer pipeline from Lake Texana (City of Corpus Christi 2009). For inland cities, desalination must be coupled with long-haul transfer to become a usable water supply. This analysis considers such a scenario for Dallas. In the situation modeled here, seawater from the Gulf of Mexico is desalinated near Houston, transferred via pipeline to a central distribution point in Dallas, and then distributed to water users, as necessary. As an alternative comparison, a brackish groundwater source was analyzed for desalination near Abilene and long-haul transfer to Dallas. Dallas was selected for this case study as an inland population center with potentially increasing water needs. While a project such as this would likely be both capital- and energy-intensive and is not currently being considered, this analysis focuses only on the energy aspects of two possible desalination and long-haul transfer scenarios and not life-cycle economic costs. Competing options for increasing water supply to Dallas include development of new reservoirs, construction of pipelines to connect Dallas to Lake Palestine, fostering relationships with Oklahoma Water, and conservation coupled with direct and indirect water reuse (Dallas Water Utilities Department 2009).

DATA AND ASSUMPTIONS

Analysis of this desalination and long-haul water transfer scenario was completed by integrating a variety of geographic, water, and energy datasets with models for energy consumption (for pumping, treatment, and conveyance). ArcGIS software from ESRI was used for the spatial analysis and standard fluid mechanics equations were used for the pipeline analysis. To simulate the desalination and long-haul transfer scenario, certain data and assumptions were necessary. Our analysis relied on a variety of datasets for the simulation, including the following:

- Global 30 Arc-Second Elevation Dataset (USGS [mod 2009]) – This 1-km digital elevation model (DEM) was used to determine elevation changes between the desalination plants near Houston and Abilene and the cen-

Fig. 2. Major Texas roads and highways were used to determine the right-of-way long-haul pipeline routes such that the routes follow existing easements. The brackish groundwater pipeline is shown traveling west to east and the seawater pipeline is shown traveling southeast to northwest.

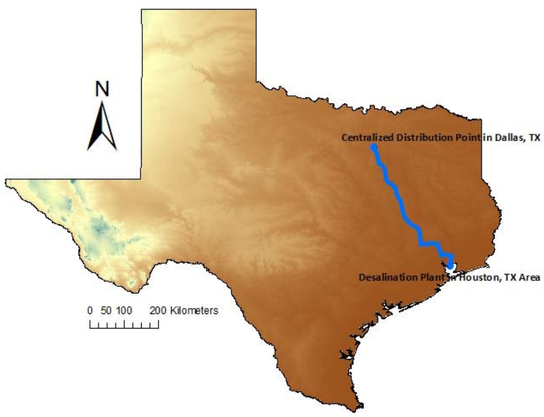

Fig. 3. A map of the right-of-way water pipeline for long-haul transfer illustrates a more practical pipeline route from a property rights perspective.

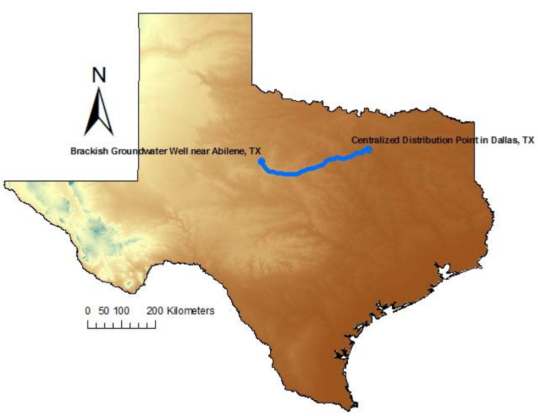

Fig. 4. An alternative desalination and long-haul transfer water supply for Dallas analyzed here is brackish groundwater desalination near Abilene with a long-haul pipeline following existing road right-of-ways.

tralized distribution point in Dallas. The 1-km DEM was appropriate for this analysis to represent topographic variability at sufficient scale.

- Roads/Highways of Texas (Texas GLO [cited 2008]) – This U.S. Department of Transportation dataset showing major roads and highways in Texas was used to determine state-owned right-of-ways as a possible water pipeline route.
- Major Texas River Basins (TWDB [cited 2008]) – This dataset from the TWDB was used to analyze which river basins were crossed by the long-haul pipeline.
- Google Earth Latitude and Longitude – Google Earth was used to estimate latitude and longitude of the potential desalination plants and centralized distribution point.
- Existing Brackish Groundwater Wells (TWDB 2009) – This dataset from the TWDB was used to determine locations and water quality of existing brackish groundwater wells near Abilene.
- Energy for Desalination (CEC 2005) – Reported ranges of energy for desalination of seawater and brackish groundwater were used to determine energy consumption for water treatment.

The following assumptions provide the basis for scenario evaluation:

- Desalination capacity of 20 mgd (75,700 m^3/d) – This treatment capacity is sufficient for 100,000 people at a mid-range current water use of 200 gal/person/d (0.76 m^3/person/d). This mid-range estimate is based on current per capita water use of 238 and 177 gal/person/day (0.90 and 0.67 m^3/person/d) in Dallas and Fort Worth, respectively, as calculated by the TWDB (Ward et al. 2007).
- Real estate available for desalination – Though demand for coastal property is high, this simulation assumes land is available for the seawater desalination facility.

While the data described above were generally reported in consistent formats, energy analysis is not a built-in function of the elevation capabilities of ArcGIS. As a result, raw elevation data exported to a spreadsheet were used for the pipeline simulation.

METHODOLOGY

DEM and facility locations

To begin the desalination with long-haul transfer to Dallas simulation, a 1-km DEM was used to represent elevation changes along the water pipeline route. The DEM and all other ArcGIS layers were projected using the North American

Datum 1983 Texas Statewide Mapping System projection. This DEM for the state of Texas was extracted from the U.S. Geological Survey 30 arc-second DEM using the raster calculator function in ArcGIS 9.3.

Pipeline routing

To simulate the long-haul water pipeline in ArcGIS, routes were drawn between the two facility points. A shortest-distance, straight-line approach was initially considered due to the possibility that is would be the lowest energy consumption option, but such a pipeline is impractical from a property rights perspective; thus a straight-line pipeline was excluded from the final analysis. If a long-haul project such as this were to be implemented, the pipeline would likely follow existing right-of-ways. Possible routes for the seawater and brackish groundwater long-haul pipelines might follow existing right-of-ways of major state roads, shown in Fig. 2, where easements could be used as pipeline routes. Adding the seawater right-of-way pipeline route shown in Fig. 2 to the DEM creates the pipeline route illustrated in Fig. 3. The brackish groundwater right-of-way pipeline, combined with the DEM, is shown in Fig. 4.

As additional analysis, a layer for major river basins in Texas was added to the DEM and simulated pipelines. Illustrated in Fig. 5, the seawater right-of-way pipeline begins in the Trinity-San Jacinto River Basin at the desalination plant, then passes into the Trinity and San Jacinto basins, returns to the Trinity basin, and then passes briefly into the Brazos River Basin before returning to the Trinity basin at the distribution point. The brackish groundwater right-of-way pipeline, shown in Fig. 6, begins in the Brazos basin and then passes into the Colorado River Basin before returning to the Brazos basin and ending in the Trinity basin.

While this case study considers two possible pipeline routes, many routes are possible between the desalination plants and distribution point.

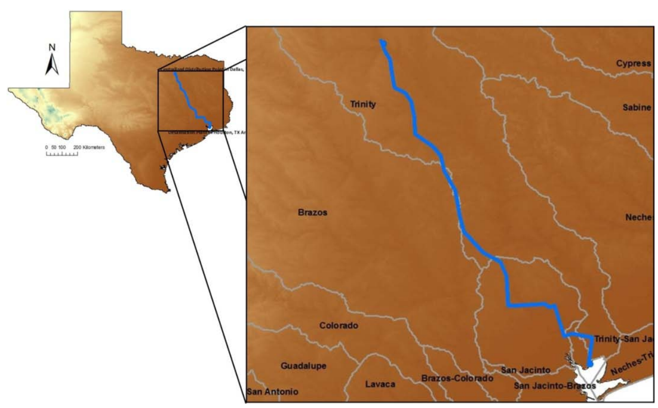

Fig. 5. The seawater right-of-way long-haul transfer pipeline passes back and forth between major river basins: Trinity-San Jacinto, Trinity, San Jacinto, and Brazos, before ending in the Trinity basin.

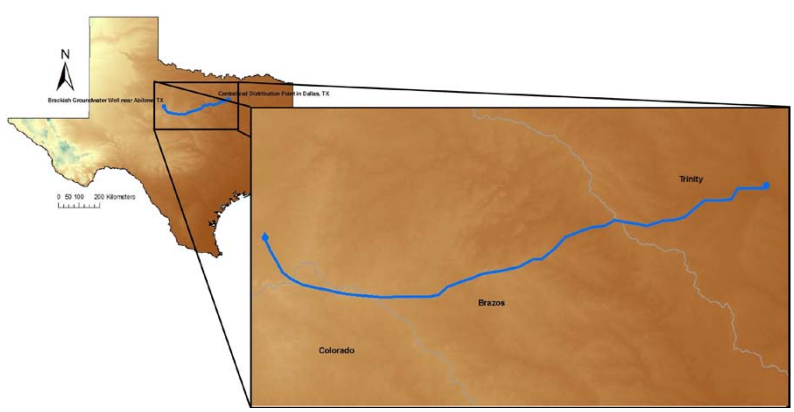

Fig. 6. The brackish groundwater right-of-way long-haul transfer pipeline begins in the Brazos basin and moves into the Colorado, before returning to the Brazos and ending in the Trinity basin.

Table 1. Pipeline length and cumulative elevation change for the long-haul pipeline routes were used to determine total energy consumed for long-haul transfer.

	Net Elevation Change (m)	Pipeline Length (km)	Cumulative Elevation Change (m)
Seawater Right-of-Way Pipeline	125	434	939
Brackish Groundwater Right-of-Way Pipeline	-385	325	1,010

Elevation change using 3D analyst

To determine the elevation change over the route of the right-of-way long-haul water pipelines, the 3D Analyst capabilities of ArcGIS were used to measure elevation changes along the route. Following the pipeline routes, the profile graph shown in Fig. 7 was generated, providing a snapshot of the elevation cross section for the seawater and brackish groundwater pipelines, respectively.

The net elevation change between the proposed seawater desalination plant in the Houston area and Dallas was measured as 125 m. Since the elevation decreases between the proposed brackish groundwater desalination plant in Abilene and the distribution point in Dallas, the net elevation change is negative at -385 m. Additionally, the cumulative elevation was measured as the summation of elevation increases measured in the direction of flow. While it is possible to generate energy during downward flows (similar to what is done in California, where water from the Owens Valley generates electricity with in-line turbines on its way downhill to Los Angeles) elevation decreases in the direction of flow are ignored to provide a high estimate of energy consumption. This high energy-consumption estimate represents a worst-case scenario, which could be used to determine whether in-line turbines or other energy-recovery devices are necessary. Complete energy recovery on downhill runs—that is, using only the net elevation change between the desalination plant and the distribution point—was used as a low estimate of energy consumption. The net elevation change, cumulative elevation change, and pipeline distance from Fig. 7 are provided in the data shown in Table 1. These data were then used to calculate energy needed for long-haul water transfer.

Table 2. Estimated and measured parameters for calculations in the long-haul transfer pipeline were used to determine energy consumption of water transfer.

Parameter	Value	Units
Acceleration due to gravity, g	9.81	m/s^2
Density, ρ	997.08	kg/m^3
Flow rate, Q	20 (0.8763)	mgd (m^3/s)
Friction factor, f (Bertin 1987)	0.0115	unitless
Height, Δh	See Table 1	m
Length, ΔL	See Table 1	m
Pipe diameter, D	3.66	m
Velocity, v	0.305	m/s
Viscosity, μ	8.94E-04	kg/m·s

RESULTS

To calculate the energy required by the desalination and long-haul transfer scenarios discussed above, the desalination treatment and long-haul transfer were considered separately. Seawater desalination requires 9,780 to 16,500 kWh/10^6 gal, while brackish groundwater requires 3,900 to 9,750 kWh/10^6 gal (CEC 2005). For treatment of 20 mgd (75,700 m^3/d), the energy requirements for seawater desalination using reverse osmosis total 196 to 330 MWh/d, while brackish groundwater desalination consumes 78 to 195 MWh/d.

To calculate the energy requirements for long-haul transfer, both the elevation change and pipeline distance were considered. The power for overcoming the potential energy of raising the elevation of the water is:

$$\frac{\Delta E_p}{\Delta t} = \rho Q g \Delta h \tag{1}$$

In Equation 1, $\frac{\Delta E_p}{\Delta t}$ is the change in potential energy per time, ρ is the fluid density, Q is the flow rate, g is acceleration due to gravity, and Δh is the net or cumulative change in height.

For the flow rate of 20 mgd (75,700 m^3/d), overcoming net elevation changes in the seawater pipeline (a low estimate of energy consumption for elevation changes, assuming complete energy recovery on downhill runs) requires approximately 26 MWh/d; overcoming cumulative elevation changes (a high estimate of energy consumption for elevation changes with no energy recovery on downhill runs) requires 193 MWh/d for right-of-way water transfer. Since the net elevation change of the brackish groundwater pipeline is negative, no energy is required to overcome net elevation changes; power generation might be possible, depending on sharp elevation increases along the route, but zero is used here as an approximation. For cumulative elevation changes, the brackish groundwater long-haul transfer requires 208 MWh/d. Note that although the net elevation change of the brackish groundwater scenario is negative, the cumulative elevation change of the downhill brackish groundwater pipeline is greater than that of the uphill seawater pipeline. Thus, these scenarios illustrate that a pipeline with an overall downhill route does not necessarily require less energy than an uphill route due to cumulative elevation changes along the pipeline.

Additional energy is required to overcome friction within the pipeline. For turbulent flow in the pipeline, the Darcy-Weisbach equation can be used to estimate head loss due to friction:

$$h_f = f \frac{v^2}{2g} \frac{\Delta L}{D} \qquad (2)$$

In Equation 2, h_f is the head loss due to friction, f is the friction factor, ΔL is the pipe length, v is the average fluid velocity, and D is the inside pipe diameter. The friction factor f was estimated using a Moody diagram (Bertin 1987). Using the head loss calculated from the parameters in Table 2 and Equation 2, the additional energy requirement to overcome pipe friction is 1.3 MWh/d and 1.0 MWh/d for seawater and brackish groundwater right-of-way transfer, respectively.

Factoring in high-flow pump efficiencies of 65% (CAT 2009) and additional distribution from the centralized point in Dallas to consumer homes at 1.2 MWh/10^6 gal, estimated total energy consumption is 261 to 653 MWh/d for seawater desalination and 423 to 540 MWh/d for brackish groundwater desalination, both with right-of-way transfer. Energy requirements for the two water supply options are shown in Table 3, showing energy for treatment and distribution with long-haul transfer for desalination.

Based on estimated energy consumption totals compared to conventional local surface water treatment, the total energy use of 261 to 653 MWh/d is nine to 23 times more energy-intensive than conventional water treatment from local surface sources at 28.5 MWh/d for 20 mgd (75,700 m3/d). Note that here conventional local surface water treatment is based on national average values of energy consumption for water treatment and distribution. Energy-consumption data for water collection, treatment, and distribution are not directly mea-

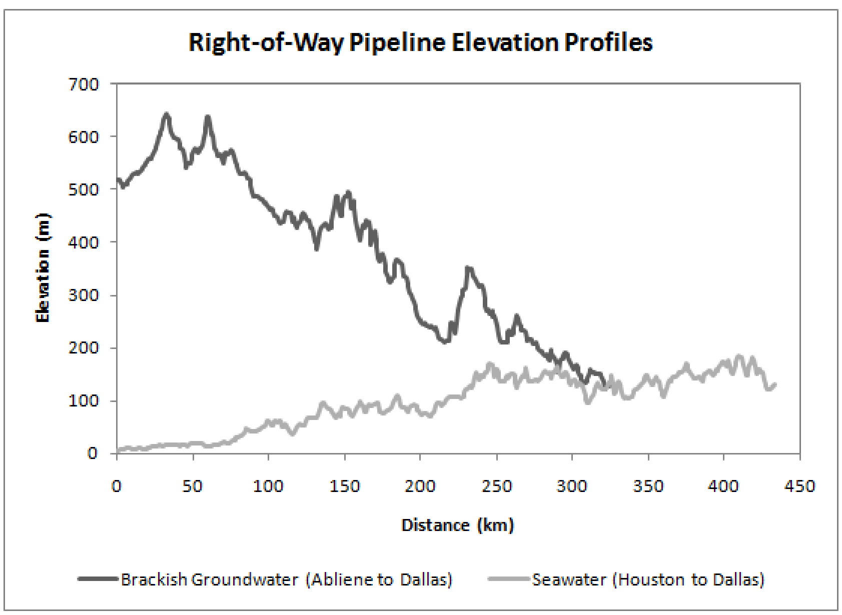

Fig. 7. Elevation profiles for the seawater and brackish groundwater pipelines show a general uphill route for seawater and downhill route for brackish groundwater. Despite these trends, elevation increases along the brackish groundwater pipeline are larger than those increases of the seawater pipeline.

sured and reported in Texas, thus this comparison to national average values of energy consumption serves as the baseline for our analysis.

IMPLICATIONS

The desalination and long-haul transfer simulation presented above represents a highly energy-intensive water supply for Dallas. For the 100,000 people served by this scenario, the energy requirements total approximately 2.61 to 6.53 kWh per person per day. On average, Texans used 39.1 kWh of electricity per person per day in 2008 (EIA 2010; U.S. Census Bureau [cited 2010]). Implementation of this desalination and long-haul transfer project causes a 7% to 17% average increase in daily energy consumption per person that uses the desalinated water.

Additional electricity generation releases additional air emissions, depending on the fuel source for power generation. For coal and natural gas, which generate much of the electricity consumed in Texas, the daily air emissions for 653 MWh, the high estimate of a desalination and long-haul transfer scenario, are shown in Table 4.

Thermoelectric power generation using coal or natural gas combined-cycle power plants also requires water for cooling. Generation of 653 MWh would withdraw 150,000 and 359,000 gal and consume 118,000 and 313,000 gal for natural gas combined-cycle and coal power generation, respectively, both using cooling towers (EPRI 2002a; Stillwell et al. 2009). While nuclear power would not directly produce air emissions like coal and natural gas, generation of 653 MWh with nuclear power would withdraw 620,000 gal and consume 470,000 gal using cooling towers (EPRI 2002a; Stillwell et al. 2009). For seawater desalination (with 50% recovery) and long-haul transfer, total water withdrawals for desalination and power generation could reach 40.6 million gal (154,000 m^3) for delivery of 20 million gal (75,700 m^3) of desalinated water. Similarly, brackish groundwater desalination (with 90% recovery) and long-haul transfer could total 22.8 million gal (86,500 m^3) of water withdrawn to deliver 20 million gal (75,700 m^3) of desalinated water. This feedback loop of alternative water supplies requiring additional energy, which requires water for power generation, might become increasingly more important

Table 3. A comparison of the energy consumption for the cases with conventional surface water treatment shows a much larger energy requirement for desalination and long-haul transfer (EPRI 2002b).

	Treatment (MWh/d)	Long-Haul Transfer (MWh/d)	Distribution (MWh/d)	Total (MWh/d)
Seawater Desalination + Long-Haul Transfer	196-330	41.4-299	24.1	261-653
Brackish Groundwater Desalination + Long-Haul Transfer	78-195	321	24.1	423-540
Conventional Surface Water	4.4	0	24.1	28.5

Table 4. Daily air emissions from electricity generation of 653 MWh using coal and natural gas show the desalination and long-haul transfer scenario to produce large quantities of greenhouse gases (CO_2) and criteria pollutants (SO_2 and NO_x) compared to conventional surface water treatment (EPA [mod 2010]).

	Desalination with Long-Haul Transfer and Distribution		Conventional Surface Water Treatment with Distribution	
	Coal	Natural Gas	Coal	Natural Gas
CO_2 (kg/d)	679,000	340,000	25,100	12,500
SO_2 (kg/d)	2,020	296	74	11
NO_x (kg/d)	1,480	8.9	55	0.3

as water managers seek the next increment of water supply.

While a desalination and long-haul transfer project would provide a plentiful source of water for Dallas, additional electricity consumption and increased air emissions are trade-offs for securing water. Notably, if nuclear, wind, or solar power were used, the emissions would be zero.

Analysis of the elevation profiles of the seawater and brackish groundwater long-haul pipelines shows that cumulative elevation changes along the route are important for energy consumption for pumping. While the brackish groundwater pipeline has a general downhill trend, the cumulative elevation changes along the route are greater than that of the uphill seawater pipeline. Thus, we cannot assume that downhill long-haul water transfer consumes less energy than uphill transfer consumes, depending on whether energy capture via in-line turbines is deployed. Elevation analysis becomes necessary to evaluate energy consumption from moving water long distances.

Additional reliability concerns might arise in response to a desalination and long-haul water transfer scenario. While reverse osmosis technology is reliable, external factors can affect the consistency of the seawater supply. The selected location of the seawater desalination plant is close to Trinity Bay as a source of seawater. Though a location near the shore minimizes raw seawater pumping distance, such a location is also susceptible to inclement weather during hurricane season. Additionally, recreational and commercial activity in Trinity Bay may degrade influent water quality by increasing suspended sediment, as was observed during pilot-scale testing for a seawater desalination plant in Brownsville, Texas (Herring et al. 2008). Discharge of seawater reverse osmosis concentrate can also harm marine life due to elevated levels of salinity (Lattemann and Hopner 2008).

Multiple factors regarding human behavior figure into such an alternative water supply option as desalination and long-haul water transfer. Quantity of water consumption is not constant and might increase or decrease over time. Additionally, lower cost options such as conservation and redistribution to high-valued water applications may replace or reduce pursuit of new water supplies (Zander et al. 2008).

Another option for providing the next increment of water supply is implementation of desalination in coastal communities in Texas, eliminating the need for long-haul water transfer. As coastal communities move to seawater or brackish water sources, holding surface water rights in these communities might no longer be necessary, opening up the possibility for inland cities to negotiate contracts for local surface water sources. While transfer of existing surface water rights would require complex legal negotiations, such a redistribution of water sources, would likely decrease energy consumption for water pumping over long distances.

CONCLUSIONS

While desalination and long-haul transfer of treated water might improve the resiliency of water supply to Dallas, this water comes with a large cost of additional energy consumption and attendant emissions. Such a water treatment and supply system is nine to 23 times more energy-intensive than conventional surface water treatment of local sources for drinking water.

Sustainability of a water supply includes all aspects of the water system: collection, treatment, disinfection, and distribution. Seawater desalination near Houston, Texas, or brackish groundwater desalination near Abilene, Texas, with subsequent long-haul water transfer to Dallas, Texas, requires additional energy over local surface water sources for both treatment and distribution. However, desalination and long-haul transfer might be appropriate as a back-up water supply during times of drought. The increased energy requirement, along with reliability concerns due to weather and influent water quality, might make desalination and long-haul transfer as a water supply scenario less sustainable than other alternatives, including conservation and end-use transfer.

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