ABSTRACT

An analysis is undertaken to evaluate the total costs of augmenting water supply through desalination of brackish water sources as compared to fresh water sources. Although membrane desalination is generally more expensive than conventional treatment, consideration should also be given to costs related to source location, regulatory compliance and supply reliability. Consideration of these additional factors has been largely unexplored in previous cost comparisons. This project involves the development of an approach which will enable communities to integrate such additional factors into their decision-making. Freshwater and brackish water sources are compared in terms of the "total cost of supply and treatment", which includes costs of acquisition, treatment to maintain regulatory compliance, and storage. The costs considered begin with the withdrawal of raw water at the source and end when the treated water enters the distribution system.

Results show that the economic viability of utilizing brackish resources increases when the total costs of supply and development are compared, especially for smaller capacity plants. Conveyance costs associated with more distant sources can quickly reduce the cost gap between membrane desalination and conventional treatment when comparing a local brackish source with a more distant fresh water source. Additionally, many conventional systems will require upgrades and/or process additions to achieve compliance with new standards (e.g. disinfection byproducts, arsenic), whereas membrane desalination processes are often able to meet new and existing standards with little modification. Therefore, the consideration of regulatory compliance can further reduce the cost gap between brackish and freshwater sources. Finally, in many water scarce areas, brackish sources may be underdeveloped relative to freshwater supplies and thus are likely to provide more reliable yields, resulting in lower capital costs through a reduction in the capacity of required storage infrastructure. A sensitivity analysis is also conducted to determine which factors have the greatest impact on the total supply and treatment costs. Through use of this approach, communities facing difficult decisions will be able to more comprehensively compare the costs of augmenting water supply through desalination with those of alternative supplies.

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CHAPTER 1

INTRODUCTION

An increasing number of communities are facing water resource planning challenges as a result of population growth, economic development, and limited freshwater supplies. Many existing sources of water are being stretched thin by a combination of consumptive demands and increasing instream-flow requirements to meet environmental needs (USGS 2002; NRC 2001). These challenges have recently been highlighted by the severe drought that has affected many areas of the country since 1995 and resulted in serious economic, social, and environmental impacts (Wilhite 2003).

One alternative for meeting growing supply challenges is through desalination of brackish water sources. Desalination has considerable potential for meeting future water demands as it often involves tapping previously unused water sources (USBR 2003). In the past, brackish water sources have often been dismissed due to the cost gap between desalination and conventional treatment, but this simple comparison neglects other important costs that should be considered when making water supply development choices. While standard conventional treatment (i.e. flocculation-sedimentation-filtration) is generally less expensive than desalination, water resource decisions are based on the achievement of several objectives, with treatment technology playing a significant, but by no means singular, role in determining overall development costs. The costs of supplying potable water include not only those associated with treating water to meet regulatory requirements, but also the costs of raw water acquisition and the expense associated with ensuring a high level of supply reliability.

Acquisition costs include those for the infrastructure to acquire the raw water (e.g. groundwater wells), as well as those associated with conveyance from source to treatment facility. Acquisition infrastructure often involves high capital and operating costs. In many regions, water scarcity has forced communities to look farther afield to find freshwater sources. Already, many cities draw water from distant sources at great expense (NRC 2001). As brackish sources have historically been passed over due to concerns with high treatment costs, they may often be more proximate and/or less expensive to access. Consideration of acquisition costs may therefore result in a closer brackish supply being cost competitive with a more distant fresh water source.

A brackish resource may be even more economically attractive if the freshwater alternative requires more than standard conventional treatment to meet drinking water standards. Several new regulations address relatively common constituents (e.g. turbidity, organic carbon), thus many freshwater sources previously considered to have been of high quality may require more advanced treatment. For example, if a water source has elevated concentrations of organic carbon, chemical disinfection may result in the formation of excess levels of disinfection by-products (Clark et al. 2001; AWWA 1999; Singer 1994). Ancillary treatment processes may therefore need to be added to a standard conventional plant in order to meet a new regulation, thereby raising the costs of conventional treatment. By contrast, membrane desalination processes are able to consistently produce a high quality water capable of meeting most, if not all, current and pending water quality regulations (USBR 2003; Pontius 1999).

The current regulatory agenda indicates a steady stream of new rules into the foreseeable future, many of which will raise the costs of treating freshwater sources. Therefore, including consideration of regulatory factors, as well as acquisition costs, when comparing the expense associated with developing brackish and freshwater sources has the potential to substantially reduce or even eliminate any treatment cost gap. This is especially true in the case of smaller utilities for whom membranes have been shown to be quite cost effective when compared with conventional treatment (Wiesner et al. 1994; Clark 1987). In addition, brackish sources may be underdeveloped relative to freshwater supplies and may therefore provide a more reliable yield, resulting in lower storage costs through a reduction in the size of required infrastructure.

Total costs of supply and treatment are therefore compared in this study in order to more completely evaluate the costs of brackish water desalination. Costs for acquisition, treatment, and storage are considered. Distribution system and administrative costs are considered equal regardless of the raw water source chosen. While conventional and desalination treatment costs have previously been compared, consideration of these broader cost categories has not been included (USBR 2000). Either individually, or in combination, these additional factors can substantially alter the economic attractiveness of brackish water resource development. This project explores a more comprehensive method of comparing various freshwater and brackish water sources in terms of the total cost of supply and treatment. This type of comparative analysis will have increasing utility for planners and policymakers as concerns over fresh water scarcity continue to grow, both within the United States and abroad.

CHAPTER 2

BACKGROUND

2.1 Water Resource Evaluation

Selection of a water supply resource is influenced by the need to provide adequate treatment to meet regulatory standards, as well as the need to provide water at a reasonable cost (AWWA 1999). Therefore, as water resource evaluation typically includes comparison of treatment costs, lower quality waters (e.g. brackish waters) requiring more costly advanced treatment (e.g. desalination processes) have often been passed over.

An initial cost comparison of treatment alternatives often involves the use of established cost relationships. There are a number of available models for estimating conventional treatment costs. Many of these relationships utilize capacity as the independent variable (Clark et al. 1994; Clark 1987; Clark and Morand 1981), however Gumerman et al. (1979) developed generalized cost equations for 99 individual treatment processes that have since been updated (Qasim et al. 1992). As conventional treatment technology has remained relatively unchanged over the past 25 years, both Clark and Gumerman's work still act as the basis for most conventional cost estimation routines (e.g. the USBR's Water Treatment Estimation Routine or WaTER (USBR 1999).

Common technologies for desalination include membranes, (i.e. reverse osmosis, RO), electrodialysis reversal (EDR), ion exchange, and distillation. Ion exchange is generally not cost effective for brackish waters (Logsdon et al. 1990). Cost considerations also generally lead to distillation being considered only for seawater desalination (AWWA 1996). Reverse osmosis and EDR are generally the most economically practical processes available to desalinate brackish water. However, the costs of membrane desalination have declined significantly in recent years as technology has improved such that it is often less expensive than EDR. In addition, reverse osmosis offers advantages over EDR in that it also acts as an effective barrier for turbidity, pathogens (e.g. giardia lamblia and cryptosporidium), and many regulated organic compounds (Morin 1998; AWWA 1996; Ray 1992). For this reason, this work focuses only on membrane desalination of brackish water.

Cost estimating methodologies for membrane processes are also available in the literature (Sethi and Wiesner 2000a; USBR 1999; Pickering and Wiesner 1993; Ray 1992; Clark and Morand 1981). Early work by Clark and Morand (1981) related reverse osmosis costs to plant capacity alone. More sophisticated relationships were developed that related costs for low pressure membrane filtration (microfiltration, ultrafiltration, and nanofiltration) to membrane area (Pickering and Wiesner 1993); these relationships have been updated and expanded (Sethi and Wiesner 2000a; Sethi and Wiesner 2000b; Sethi 1997).

Traditionally, comparisons of desalination and conventional treatment costs have implicitly assumed that standard conventional treatment would be sufficient to meet regulatory standards. However, the growing number of new and pending drinking water regulations may force many conventional plants to implement ancillary treatment processes in order to maintain compliance (Pontius 1999; Lykins and Clark 1994). Use of membranes for treatment of low quality waters, both fresh and brackish, has increased as membrane treatment costs have decreased and as membranes have demonstrated advantages over conventional treatment in meeting many new regulatory requirements (Morin 1994; Wiesner et al. 1994; Taylor et al. 1989).

While straight comparisons of treatment costs have been undertaken, the impacts of acquisition, conveyance, and storage costs have largely been neglected in these comparisons. Wiesner et al. (1994) compared the costs of ultrafiltration (UF) and nanofiltration (NF) processes with those of conventional processes when treating freshwater. Cost estimates were made both with and without the addition of granular activated carbon (GAC) filtration and ozonation to the conventional treatment train. The main goal was to evaluate NF and UF cost effectiveness for particle removal and DBP control in freshwaters. The study found that for small facilities, less than 5 MGD, both UF and NF were cost effective options for treating surface water, particularly when there are concerns over meeting DBP standards.

A direct cost comparison between membrane desalination and conventional treatment was recently undertaken by the U.S. Bureau of Reclamation (USBR) for the direct delivery of Central Arizona Project water with TDS concentrations around 700 mg/L (USBR 2000). USBR found that although RO treatment costs were more expensive than alternative technologies (conventional treatment, slow sand filtration), this comparison neglected other important factors including final water quality, environmental impacts, environmental enhancement potential, and recreational opportunities. As only one source water was under consideration, differences in acquisition costs were not an issue.

The Texas Water Development Board investigated the use of desalination as a water supply alternative (HDR 2000). The objective of the report was to provide a resource for communities considering desalination. Although preliminary cost estimates for membrane desalination were prepared and discussed, they were not compared to conventional treatment costs.

This work seeks to more fully evaluate the cost effectiveness of brackish water sources in comparison to freshwater alternatives as most cost comparisons have not included consideration of additional cost components such as acquisition or storage, and none have compared the total cost of supply and treatment. Acquisition costs have risen for many communities as untapped fresh water supplies become more scarce, and more distant sources are utilized. Raw water acquisition requires surface water intakes or groundwater wells, and cost relationships are available that relate capital costs to the design capacity of these structures (Hinomoto 1977), as well as a number of other parameters (Walski et al. 1984). Pipelines are commonly used for conveyance of water, and well established relationships based on the length, diameter, grade (i.e. uphill/downhill) and flow rate, are available in the literature (Linaweaver Jr. and Clark 1964). Storage costs are largely dependent on the required capacity, and are highly site-specific in their design, nonetheless, some simple cost relationships have been developed (Spiegler and Laird 1980). Consideration of these costs when comparing brackish and freshwater sources can be important in many cases and may significantly impact what this work refers to as the total cost of supply and treatment.

CHAPTER 3

METHODS

The primary goal of this work is to create a tool that will enable communities to more comprehensively compare costs of developing brackish and freshwater supplies. The metric used in this comparison is the "total cost of supply and treatment". This includes three components: raw water acquisition (including conveyance), treatment, and storage. The costs of distributing treated water to consumers is considered to be equal, regardless of the original source or treatment technology employed, as are the administrative costs borne by the utility.

With respect to compliance, initially both conventional and membrane systems are assumed to meet drinking water standards. Later scenarios consider source waters with elevated total organic carbon (TOC) concentrations and evaluate the cost of conventional treatment process additions intended to control formation of disinfection by-products. More specifically, process additions are included to meet the Total Trihalomethane (TTHM) maximum contaminant level (MCL) as set in the pending Stage 2 Disinfection/Disinfection By-Products (D/DBP) Rule (EPA 2003). Costs for each component are estimated for a given source water based on its type (i.e. groundwater or surface water) and quality, and are summed to determine the total cost of supply and treatment for that source. A similar analysis could be conducted for a number of current or pending regulations (e.g. Arsenic).

Preliminary planning data typically available in a water supply evaluation is required as input data, including raw water quality (e.g. pH, temperature, TOC), source location relative to treatment plant (in X, Y, and Z directions), and plant capacity. While data inputs are site-specific for each evaluation, the methods described are general in nature and are widely applicable.

3.1 Raw Water Acquisition Costs

Costs for raw water acquisition include those for withdrawal of raw water from the source, as well as costs for conveyance from the source to the treatment plant. All costs are updated to 2003$ using Engineering News Record (ENR) construction cost indices (Clark and Morand 1981) with O&M costs updated using the Producer Price Index for finished goods (Clark and Dorsey 1982; Clark and Morand 1981).

3.1.1 Surface Water Intake Structures

Use of a surface water source requires construction of an intake structure. Surface water intake systems can generally be divided into two categories: exposed intakes and submerged intakes (AWWA and ASCE 1998). Walski et al. (1984) developed cost models for both types. Capital costs are divided into five components: intake structure, pipeline, bridge, pump station and mechanical and electrical pump equipment. Conveyance costs from the source to the treatment plant are considered elsewhere so the pipeline portion of this relationship is omitted. Also, the costs of a bridge are quite site-specific and even unnecessary in many cases, so this element is likewise omitted. Thus, the total cost of the intake includes costs for the intake structure, pump station, and mechanical and electrical equipment.

Capital cost relationships were developed for the two types of intake structures. The submerged crib is typically used for flows between 0.01 and 100 MGD, while the exposed tower is for larger flows between 10-100 MGD.

Submerged Crib: $C_{CAP}^{SC}\ (\$) = 3905\, {Q_{max}}^{0.337}$ [1]

Exposed Tower: $C_{CAP}^{ET}\ (\$) = 1451\, {Q_{max}}^{0.46}\, H^{0.92}$ [2]

Where: Q_{max} = Maximum flow (MGD);
H = Tower height (ft).

The construction cost for the exposed tower also includes costs for the cofferdam, calculated as:

$$C_{CAP}^{COF}\ (\$) = 10{,}000\ {Q_{max}}^{0.24} HC^{0.6} \qquad [3]$$

Where: Q_{max} = Maximum flow (MGD);
H_C = Cofferdam Height (ft) (default = 0.75H).

Capital cost for the onshore pump station includes excavation and dewatering, as well as the cost for construction of the pump station.

Excavation and Dewatering: $C_{CAP}^{EX}(\$) = 324\, {Q_{max}}^{0.76}$ [4]

Pump Station Structure: $C_{CAP}^{PS}(\$) = 1451\, {Q_{max}}^{0.46}\, {D_{WW}}^{0.92}$ [5]

Where: Q_{max} = Maximum flow (MGD);
D_{WW} = Depth of wet well (ft).

Capital costs for pump mechanical and electrical equipment are estimated using the following equation:

$$C_{CAP}^{ME}(\$) = 965\, H_{max}\, 0.4\, Q_{max}{}^{0.935} \qquad [6]$$

Where: H_{max} = Maximum head (ft);
Q_{max} = Maximum flow (MGD).

Operation and maintenance costs for both types of intake structures include those associated with equipment replacement, labor, and energy, and is estimated by:

$$C_{O\&M}^{INT}\ (\$ / \text{year}) = \frac{114{,}000\, Q_{ave}\, (H_{ave})\, C_E}{P_E} + 208\, Q_{ave}{}^{0.32} L_R + E_{RC} \qquad [7]$$

Where: Q_{ave} = Average flow (MGD);
H_{ave} = Average head (ft);
C_E = Unit price of energy ($/kW-hr);
P_E = Pump efficiency (percent);
L_R = Standard labor rate ($/hr);
E_{RC} = Equipment replacement costs ($/year).

Equipment replacement costs are estimated at 5% of the capital cost per year.

3.1.2 Groundwater Well Construction

Capital costs for groundwater wells are taken from Mickley (2001), such that:

$$C_{CAP}^{WELL}\ (\$1000) = -\,288 + 145.9 * (D_{tube}) + 0.754 * (H) \qquad [8]$$

Where: D_{tube} = Diameter of well (inches);
H = Depth of well (ft).

The model is valid for tubing diameters of 5-24 inches, and depths up to 10,000 feet.

Operating and Maintenance expenses are based on energy costs required to pump water out of the well, such that:

$$C_{O\&M}^{WELLS}\ (\$/\text{year/well}) = \frac{Q_{DES}(mg(h + h_L)\, C_E * 384}{P_E} \qquad [9]$$

Where: Q_{DES} = Design capacity (MGD);
m = mass of water to be pumped $=\rho V$ (kg);
g = gravitational constant, 9.81 (m/s^2);
h = height of well (m);
h_L = head loss (m);
C_E = Unit cost of energy ($/kWh);
P_E = Pump efficiency (percent).

3.1.3 Conveyance Costs

The most common means of transporting water is through pipelines. Conveyance costs can be substantial, particularly when pumping uphill, and make the location of a water source a critical consideration when estimating resource development costs. Linaweaver and Clark (1964) developed well established relationships for calculating the capital and O&M costs of water transmission that continue to be updated and commonly used. These relationships have recently been verified using empirical cost data gathered as part of a research project in North Carolina (Kirsch 2004) and costs are updated to 2003$ using ENR cost indices. Capital costs ($/miles) are described as a function of pipe diameter (D), which is calculated on the basis of treatment plant design capacity as follows:

$$D\ \text{(inches)} = 24\left(\frac{Q_{OP}}{v\pi}\right)^{0.5} \qquad [10]$$

Where: v = average velocity (ft/sec);
Q_{OP} = Operating Capacity (75% of design flow) (ft^3/sec).

Capital costs are calculated in using the calculated diameter (D) as follows:

$$C_{CAP}^{PIPE}\ (\$/\text{mile}) = 1.097D^{1.3983} * 5280 \qquad [11]$$

Where: D = Diameter of pipe (inches).

Capital costs are annualized over 50 years at 8% in order to arrive at annual cost ($/mile/year).

Operation and maintenance costs consist of pumping (energy) costs and are calculated as follows:

$$C_{O\&M}^{PIPE}\ (\$/\text{kgal/mile}) = \frac{\left\lfloor 1.66 * 10^{-2}(0.75S_l + 0.667S_f)C_E \right\rfloor}{P_E} \qquad [12]$$

Where: S_l = Average line slope (ft/1000ft);
S_f = Friction Loss obtained from Hazen-Williams expression (ft/1000ft);
C_E = Energy Cost ($/kWh);
P_E = Pump efficiency (percent).

Total costs for conveyance are then calculated, with an additional 8% for other O&M costs, such that:

$$C_{T}^{PIPE}\ (\$/\text{mile/year}) = C_{CAP}^{PIPE} + 1.08C_{O\&M}^{PIPE} \quad [13]$$

Conveyance costs are estimated for a range of plant capacities and line slopes of -5 to +5ft/1000ft.

Specific parameters values for acquisition cost estimates used in this analysis are presented below (Table 3.1). These values were selected from the literature, or through personal communication with a professional engineer. When more than one value is shown, the values correspond to increasing plant capacities (i.e. 1 MGD/10 MGD/30 MGD). For groundwater wells, both pumping rates and pipe diameters are determined using an upflow velocity of 3 ft/sec.

Table 3.1 Acquisition Cost Parameters

Input Parameters	**Units**	**Value**
Acquisition Costs		
Submerged Crib Surface Water Intake (0.01 – 100 MGD)[1]		
Depth of wet well	ft	10
Maximum Head	ft	250
Unit price of energy	$/kWhr	0.07
Standard Labor Rate	$/hr	20
Pump efficiency	percent	0.8
Exposed Tower Surface Water Intake (10-100 MGD)[1]		
Tower Height	ft	45
Depth of wet well	ft	10
Maximum Head	ft	150
Unit price of energy	$/kWhr	0.07
Standard Labor Rate	$/hr	20
Pump efficiency	decimal	0.8
Groundwater Wells		
Pumping Rate	gal/min	1000/1500/2000
Diameter	inches	12/14/16
Depth of well	feet	300
Conveyance Costs[2]		
Hazen-Williams Coeff.	(steel)	120
Efficiency Factor		0.92

Notes:

[1] Parameter values are from Walski et al. (1984)

[2] Parameter values are from Linaweaver and Clark (1964)

3.2 Treatment Costs

Capital and O&M expenses for both conventional treatment and brackish water desalination are considered. Residuals disposal is also included in treatment costs for both conventional and membrane processes. In each case, the relationships used are valid over design capacities ranging from 1-30 million gallons per day (MGD). A full evaluation of available cost models for both conventional and desalination, including sensitivity analyses, can be found in Appendix 6.1. Estimates from the available cost models were verified with available empirical data from existing treatment plants (HDR 2000; Morin 1999).

Brackish sources considered in this analysis have concentrations of total dissolved solids (TDS) in the range of 1,000 to 5,000 mg/L. Unless otherwise noted, capital costs are annualized over 20 years at 8% in keeping with similar cost estimation studies (Sethi and Wiesner 2000a; Clark and Dorsey 1982; Clark and Morand 1981) and updated to 2003$ using Engineering News Record (ENR) construction cost indices (Clark and Morand 1981). Total treatment costs are the sum of annualized capital and O&M costs in $/year, divided by the annual operating capacity (Q_{OP}) of the treatment facility (70% of design capacity, Q_{DES}). O&M costs are updated using the Producer Price Index for finished goods (Clark and Dorsey 1982; Clark and Morand 1981).

3.2.1 Conventional Treatment

Baseline treatment costs for surface waters are based on a standard conventional treatment train, including pre-disinfection (chlorine), chemical feed, rapid mix, flocculation, sedimentation, filtration, post-disinfection (chlorine) and clearwell storage (Figure 3.1). Groundwater treatment costs involve only disinfection (AWWA 1999). Ancillary conventional processes (e.g. GAC filtration, alternative disinfectants) can be added if water quality analysis indicates the likelihood that drinking water standards will be violated.

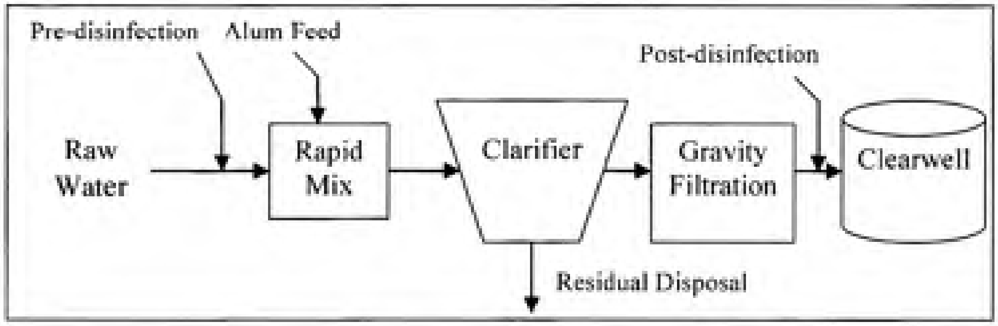

Figure 3.1 Conventional Treatment Train Schematic

For comparative purposes, three separate cost models (USBR 1999; Clark 1987; Clark and Morand 1981) are selected to estimate conventional treatment costs for a surface water source. Results from the Clark model (1987) are presented here while the USBR cost model and Clark and Morand (1981) model are explained and evaluated in Appendix 6.3.

3.2.1.1 Clark Model

The Clark model (Clark 1987) describes the capital costs of conventional treatment as a power function, such that:

$$C_{CAP}^{CONV}\ (\$1000) = 2464Q_{DES}^{0.67} \qquad [14]$$

Where: Q_{DES} = Design capacity (MGD).

A power function is also used to estimate O&M costs based on relationships defined in the same studies and subsequently updated on the basis of empirical data (Kirsch 2004), such that:

$$C_{O\&M}^{CONV}\ (\$1000/yr) = 449.4Q_{OP}^{0.83} \qquad [15]$$

Where: Q_{OP} = Average operating capacity (MGD).

Total treatment costs are the sum of the annualized capital and O&M costs ($/year), divided by the average operating capacity to yield a value in $/Kgal.

3.2.2 Membrane Treatment

Two separate membrane desalination cost models are used to provide estimates of capital and O&M costs (Sethi and Wiesner 2000a; USBR 1999), however results for the USBR cost model are presented in Appendix 6.3. Costs are estimated for a typical membrane desalination treatment train including pre-treatment, membrane processes, and post-treatment (Figure 3.2). The membrane process costed in this work is low-pressure reverse osmosis. Pre-treatment includes anti-scalant addition, pH adjustment, as well as treatment (e.g. UF, MF) to prevent membrane fouling. Post-treatment includes processes typical of drinking water treatment including corrosion control and disinfection (AWWA 1999). Concentrate disposal costs are also included in desalination cost estimates.

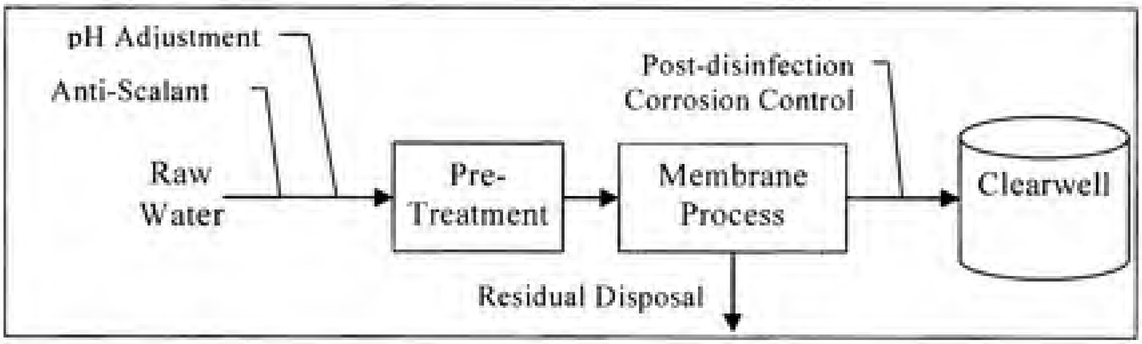

Figure 3.2 Membrane Treatment Train Schematic

Pre-treatment process options are defined based on whether the source is groundwater or surface water. Brackish groundwater sources do not usually require extensive pre-treatment, typically the raw water is sent through cartridge filters prior to reaching the membranes (Duranceau et al. 2000). However, brackish surface water generally requires more advanced pretreatment, such as UF, MF or conventional processes (Seacord 2003). Both UF and conventional processes are considered in this work.

3.2.2.1 Sethi and Wiesner Model

The model used to estimate costs for brackish water desalination is based on work by Sethi and Wiesner (2000a). The cost model was originally designed for nanofiltration (NF) cost estimates; however process configurations for NF and RO are similar, particularly for the low-pressure (~20 bar) RO systems used for brackish waters. As such, this model was used with operating parameters (e.g. permeate flux, transmembrane pressure) modified to represent typical low-pressure RO.

Two broad categories of capital costs are considered: membranes and all non-membrane equipment and facilities (Sethi and Wiesner 2000a). Membrane costs are a function of the membrane area required to produce a given design flow, calculated using:

$$A_{mem}\,(m^2) = \frac{Q_{DES}\,t_{tot}}{Jt_o - J_{bf}\,t_{bf}} \qquad [16]$$

Where:
Q_{DES} = Design flow (m^3/hr);
t_{tot} = time for one operating and flux enhancement cycle (s);
J = Time average permeate flux (cm/s);
t_o = operating time between flux enhancement cycles (s);
J_{bf} = Permeation rate of clean water through membrane during backflush (cm/s);
t_{bf} = time required for one backflush in a flux enhancement cycle (s).

Within the calculations, the design flow (Q_{DES}) is converted to MGD, in order to keep the units consistent with other models. The capital costs of membranes are then calculated as:

$$C_{CAP}^{MEM}\,(\$) = C_{mem}^{*} * A_{mem} \qquad [17]$$

Where: C^{*}_{mem} = Unit cost per unit area (\$/m^2).

The capital costs for the non-membrane equipment components (e.g. pumps, pipes and valves, instruments and controls, tanks and frames, and miscellaneous) are based on total membrane area:

$$C_{CAP}^{NM}\,(\$) = k\,(A_{mem})^n \qquad [18]$$

Where:
k = constant (specific to cost component);
A_{mem} = Membrane Area (m^2);
n = economy of scale factor (specific to cost component).

Operation and maintenance costs include energy, chemicals, membrane replacement and concentrate disposal. These costs are expressed as a function of membrane area using a cost model developed by Pickering and Wiesner (1993). Energy costs are the sum of the energy requirements for pumping the feedwater, recycling, backflushing and fastflushing, such that:

$$C_{O\&M}^{MEM/EN}(\$/\text{year}) = \frac{\left(\left(\frac{P_F * Q_F}{P_{EF}}\right) + \left(\frac{P_R * Q_R}{P_{ER}}\right) + \left(\frac{P_F * Q_{FF}}{P_{EF}}\right) * \frac{t_{ff}}{t_{tot}} + \left(\frac{P_{BF} * Q_{BF}}{P_{EBF}}\right) * \frac{t_{bf}}{t_{tot}}\right) * C_E}{Q_{des}} \qquad [19]$$

Where:
P_F = Feed pressure (kPa);
Q_F = Feed flow (m^3/hr);
P_{EF} = Feed pump efficiency;

P_R = Recycle pressure (kPa);
Q_R = Recycle flow (m^3/hr);
P_{ER} = Recycle pump efficiency;
P_F = Feed pressure (kPa);
Q_{FF} = Fastflush flow (m^3/hr);
P_{EF} = Feed pump efficiency;
t_{ff} = fastflush duration (s);
t_{tot} = time for one operating and flux enhancement cycle (s);
P_{BF} = Backflush Feed pressure (kPa);
Q_{BF} = Backflush Feed flow (m^3/hr);
P_{EBF} = Backflush pump efficiency;
t_{bf} = time required for one backflush in a flux enhancement cycle (s);
C_E = Unit cost of energy ($/kWh);
Q_{DES} = Design flow (m^3/hr).

Chemical costs are calculated on the basis of the chemical dosage and bulk cost:

$$C_{O\&M}^{MEM/CH}(\$/\text{year})=\frac{Q_F CH_d CH_c}{Q_{des}} \qquad [20]$$

Where:
Q_F = Feed flow (m^3/hr);
CH_d = Chemical dosage;
CH_c = Chemical cost;
Q_{des} = Design flow (m^3/hr).

Membrane replacement costs are annualized over their life expectancy and are expressed as:

$$C_{O\&M}^{MEM/R}(\$/\text{year})=\frac{c_{mod}N_{mod}\left(\dfrac{i_f}{(i_f+1)^{ML}-1}\right)}{Q_{des}} \qquad [21]$$

Where:
c_{mod} = Cost of one membrane module ($);
N_{mod} = Number of membrane modules;
i_f = Discount rate;
ML = Design life of membrane (yrs);
Q_{DES} = Design flow (m^3/hr).

The estimate for concentrate disposal costs considers only the resources "lost", that is the cost of the energy and chemicals invested in the water (Sethi and Wiesner 2000a), but does not account for the costs associated with disposal (e.g. deep well injection).

$$C_{O\&M}^{MEM/DIS}(\$/year) = \frac{\left(C_E * \frac{P_F * Q_C}{P_{EF}}\right) + (CH_d CH_c Q_C)}{Q_{des}} \qquad [22]$$

Where:
P_F = Feed pressure (kPa);
Q_C = Concentrate flow (m^3/hr);
P_{EF} = Feed pump efficiency;
C_E = Unit cost of energy (\$/kWh);
CH_d = Chemical dosage;
CH_c = Chemical cost;
Q_{DES} = Design flow (m^3/hr).

Representative parameter values were selected from the literature, and Table 3.2 outlines the major parameters used in the model for brackish water desalination.

Table 3.2 Desalination Treatment Cost Parameters

Input Parameters	**Units**	**Value**
Desalination Treatment		
TDS	mg/L	2000
Membrane Diameter	cm	20.32[1]
Membrane Cost (C^{*}_{mem})	\$/m^2	100[1]
Feed Pressure (P_F)	kPa	2757[2]
Membrane Life (ML)	Years	5[1]
Unit Cost of Energy (C_E)	\$/kWh	0.07
Permeate Flux	cm/sec	$5.64x10^{-4}$ [1]
Design Life of Plant	Years	20[1]

Notes:
[1] Sethi and Wiesner (2000a)
[2] Ray (1992)

3.2.3 Residuals Disposal

3.2.3.1 Sludge Disposal Costs

Conventional treatment produces residuals (i.e. sludge) consisting of suspended solids and chemical precipitates. Disposal of these wastes can include removal from the treatment plant through discharge to a waterway, sewer system, permanent lagoon, landfill, or land application (AWWA and ASCE 1998; James M. Montgomery 1985). Sludge treatment prior to disposal is generally used to reduce the volume of material to be disposed. Sludge thickening and dewatering processes include gravity thickeners, belt filter presses, and sludge dewatering lagoons. Costs associated with these processes are determined through relationships defined by Qasim et al. (1992).

Both capital and O&M costs for gravity thickeners are related to tank diameter such that:

$$C_{CAP}^{GT}\,(\$) = 15530 * D^{0.6523} e^{0.0101D} \qquad [23]$$

$$C_{O\&M}^{GT}\,(\$/\text{year}) = 21.3 * D^{1.4736} + 1200 \qquad [24]$$

Where: D = Thickener Diameter (m).

The cost relationships for the sludge dewatering lagoons are based on the effective storage volume:

$$C_{CAP}^{DL}\,(\$) = 29.5 * V^{0.793} + 2200 \qquad [25]$$

$$C_{O\&M}^{DL}\,(\$/\text{year}) = 6.473 * V^{0.9124} - 45 \qquad [26]$$

Where: V = Effective Storage Volume (m^3).

The capital and O&M cost models for a belt filter press are a function of the installed machine capacity, such that:

$$C_{CAP}^{BFP}\,(\$) = 170640 + 15196 M_C \qquad [27]$$

$$C_{O\&M}^{BFP}\,(\$/\text{year}) = 584735.8 * e^{0.001522 M_C} - 568030 \qquad [28]$$

Where: M_C = Installed Machine Capacity (m^3/hr).

3.2.3.2 Concentrate Disposal Costs

Concentrate disposal costs can be an important factor as disposal is subject to both state and federal regulations and can add significantly to the total cost of desalination (Morin 1999). Available options for concentrate disposal can include surface or ocean discharge, land application, sewer discharge, evaporation pond, or deep well injection. Most coastal desalination systems discharge concentrate to the sea (Chapman Wilbert et al. 1998). Sewer discharge is often an option for very small plants, whereas deep well injection is primarily used for larger plants (Mickley 2001; AWWA 1996). Disposal via evaporation pond and land application are used primarily with smaller plants (< 1 mgd), particularly in locations with high evaporation rates and relatively inexpensive land (Chapman Wilbert et al. 1998).

Deep well injection and evaporation ponds are the major strategies for brackish water desalination plants not located near the ocean (Glater and Cohen 2003). Cost estimates are available from Mickley (2001). The major factors influencing deep injection well costs are the depth of the well and the diameter of the well tubing. For wells with diameters of 5-24 inches, and depths of 0-10,000 feet, the following empirical relationship for capital costs has been developed:

$$C_{CAP}^{DW}(\$1000) = -288 + 145.9 * (D_{tube}) + 0.754 * (H) \qquad [29]$$

Where: D_{tube} = Diameter of well (inches);
H = Depth of well (ft).

The operating costs for disposal wells are often low for deeper wells as pressure head from the water column generally encourages reasonable disposal rates. Operating and maintenance costs for pumping (energy) costs are calculated as follows:

$$C_{O\&M}^{DW}(\$ / \text{well} / \text{year}) = \frac{Q_{CONC} * (mgh) * C_E * 384}{PE} \qquad [30]$$

Where: Q_{CONC} = Concentrate Flow (MGD);
m = mass of water to be pumped $=\rho V$ (kg);
g = gravitational constant, 9.81 (m/s^2);
h = height of well (m);
C_E = Unit cost of energy (\$/kWh);
P_E = Pump efficiency (percent).

Evaporation ponds for membrane concentrate disposal are most appropriate for smaller volume flows (<1MGD). The major capital cost element is usually the liner material. The total area necessary for the pond is based on a relationship using evaporative rate (inches/year) and the amount of concentrate stream produced (Glater and Cohen 2003; Mickley 2001).

$$A = 13440 \frac{Q_{CONC}}{E_{ave} + F} \qquad [31]$$

Where: A = Evaporative Area (acres);

Q_{CONC} = Concentrate Stream (MGD);
E_{ave} = Evaporation Rate (inches/year);
F = Freeboard (0.2 E_{ave}).

Total capital costs for an evaporative pond are thus:

$$C_{CAP}^{EP}(\$) = 5406 + 465 * T_L + 1.07 * C_L + 0.931 * C_{LC} + 217.5 * H * 1.2 * A * \frac{1 + 0.155 * H}{\sqrt{A}} \quad [32]$$

Where:
T_L = Liner Thickness (mils);
C_L = Land Cost ($/acre);
C_{LC} = Land Clearing Cost ($/acre);
A = Evaporative Area (acres);
H = Dike Height (ft).

This model is valid from 10 to 100 acres of total pond area. A contingency factor (F) of 20 percent is included in the evaporation surface required. Annual operating costs are estimated as 0.5 percent of the total capital costs.

Representative values were selected from the literature in order to calculate cost estimates for this analysis (Table 3.3).

Table 3.3 Residuals Management Parameters

Input Parameters	Units	Value
Residuals Management		
Sludge Handling[1]		
Suspended Solids	mg/L	1
Surface Loading Rate	gpm/ft2	1.0
Dry Alum Dose	mg/L	46
Iron Dose	mg/L	0
Additional Chemicals	mg/L	0.5
Evaporative Rate	inches/year	70
Deep Well Injection[2]		
Recovery	% as decimal	0.85
Diameter	inches	10
Depth of well	feet	3000
Pumping Rate	gal/min	Calculated
Unit price of energy	$/kWhr	0.07
Pump efficiency	percent	0.75
Evaporation Pond[2]		
Dike Height	ft	8
Liner Thickness	mils	60
Land Cost	$/acre	2,000

Land Clearing Cost	$/acre	2,000

Notes:
[1] Parameter values from AWWA and ASCE 1998; James M. Montgomery 1985
[2] Parameter values from Mickley (2001)

3.3 Maintaining Regulatory Compliance

Consideration of the total supply and treatment costs of any water source requires an evaluation of the treatment train's ability to meet drinking water quality standards. While systems may face a wide range of different compliance issues, we have chosen to focus on DBPs as a result of their ubiquity throughout the Unites States. Disinfection byproducts form through reactions of natural organic matter (NOM) with chemical disinfectants, especially chlorine, in the treatment process. Trihalomethanes (THMs) were the first class of halogenated DBPs identified in finished water, and have been regulated in drinking water since 1979 (Singer 2004; Singer 1994). Specifically, this work focuses on a method for utilities to evaluate compliance with the Total Trihalomethane (TTHM) maximum contaminant level (MCL) of 80 ug/L. The Stage 2 Regulations eliminates the averaging of four samples across the distribution system, and requires compliance at each sampling location (Singer 2004; Wilkes 2003)

3.3.1 TTHM Formation During Treatment

A number of studies have been conducted to develop models of DBP formation in drinking water, particularly THMs. Empirical models have been developed using regression equations to link water quality parameters and operational parameters with TTHM formation in drinking water. Models are available based on both water quality data from utilities (raw and treated water) (Milot et al. 2000; Rodriguez et al. 2000; Singer et al. 1995) as well as raw water samples that are subject to chlorine concentrations in a bench-scale application (Amy et al. 1998; Rathbun 1996). Kinetic-based models have also been developed for predicting TTHM formation (Westerhoff et al. 2002; Clark et al. 2001; Clark and Sivaganesan 1998). These models estimate DBP formation through consideration of formation mechanisms and compound stability (USEPA 2002). Additionally, the USEPA developed the Water Treatment Plant (WTP) model that utilizes empirical correlations to estimate NOM removal, DBP formation, and water quality at various points in the treatment process (Solarik et al.

2000). A complete evaluation of available TTHM formation models is presented in Appendix 6.2.

In order to more accurately predict TTHM formation in finished drinking water after conventional treatment, models using treated water will be utilized in this work. As formation of TTHMs is directly affected by the NOM concentration, these treated water quality models take NOM removal during the treatment process into account. Therefore, this involves not only the prediction of TTHM concentration, but also the estimation of NOM removal, using total organic carbon (TOC) and ultraviolet absorbance at 254nm (UVA) as surrogates for NOM concentration.

Relationships describing TTHM formation are taken from the EPA Water Treatment Plant (WTP) model as described by Solarik et al. (2000). Total trihalomethane formation is calculated for three different process configurations involving disinfection at different points in the treatment plant: (i) pre-disinfection, (ii) post- disinfection, and (iii) pre-and post-disinfection. Each configuration is outlined in Table 3.4 (with equation numbers), and a full description is given below. In all initial scenarios, disinfection is accomplished via chlorination, with subsequent scenarios involving alternative disinfectants.

Table 3.4 TTHM Formation Scenarios

Chlorination Scenario	Models Used
Pre-Chlorination	TTHM = Raw Water Model [33]*Pre-chlorination Factor [34] + Treated Water Model [35]
Post-Chlorination	TTHM = Treated Water Model [35]
Pre- and Post-Chlorination	TTHM = Raw Water Model [33]*Pre-chlorination Factor [34] + Treated Water Model [35]

In the case of pre-disinfection, two models are used to account for formation prior to and after sedimentation. For initial formation, a raw water TTHM model is used [33] (Amy et al. 1998), and an empirical pre-chlorination factor [34] is applied to account for the decrease in formation that occurs when chlorine is added before the rapid mix process (Solarik et al. 2000).

$$TTHM_{RAW} = 0.0412(TOC_{raw})^{1.098}(Cl_2)^{0.152}(Br -_{raw})^{0.068}(T)^{0.609}(pH)^{1.601}(t)^{0.263} \qquad [33]$$

Where: $TTHM_{RAW}$ = raw water TTHM (ug/L);
TOC_{raw} = raw water TOC (mg/L);

Cl_2 = applied chlorine (mg/L);
Br^-_{raw} = concentration of Bromide (ug/L);
T = temperature (°C);
pH = raw water pH;
t = reaction time (hours).

The empirical pre-chlorination factor is based on work done by Summers et al. (1998):

$$\text{Decrease in TTHM Formation (\%)} = 0.853\ (\text{\% TOC Removal}) \qquad [34]$$

Formation that occurs after sedimentation is calculated using a treated water model [35] based on settled water quality, chlorine residual, and the amount of time between sedimentation and finished water. Water quality is evaluated as a function of TOC and UVA concentration and is designed to account for both NOM removal and reactivity.

$$TTHM_{TREAT} = 23.9(TOC * UVA)^{0.403}(Cl2)^{0.225}(Br-)^{0.141}(1.027)^{(T-20)}(1.156)^{(pH-7.5)}(t)^{0.264} \qquad [35]$$

Where: $TTHM_{TREAT}$ = treated water TTHM (ug/L);
TOC = treated water TOC (mg/L);
UVA = treated water UVA (1/cm);
Cl_2 = applied chlorine (mg/L);
Br^- = concentration of Bromide (ug/L);
pH = treated water pH;
T = temperature (°C);
t = reaction time (hours).

Post-chlorination TTHM levels are predicted using the treated water model as described above [35]. For the scenario involving both pre- and post-chlorination, a combination of the raw and treated models is again used (Solarik et al. 2000). Initial formation is modeled using the raw water model with the prechlorination factor applied in order to account for the initial chlorination. To account for formation after sedimentation the treated water model is then used with settled water quality, a reaction time of 0 hours, and a treated UVA concentration that is further decreased by prechlorination [36].

UVA decreases through prechlorination are calculated as:

$$UVA_{pre\text{-}Cl2} = 0.7437(UVA_{removed}) + 0.0042 \qquad [36]$$

Where: $UVA_{pre\text{-}Cl2}$ = settled UVA after pre-chlorination (1/cm);
$UVA_{removed}$ = settled UVA without prechlorination (1/cm).

UVA removal via coagulation is predicted using:

$$UVA_{removed} = 5.716\,(UVA_{raw})^{1.0894}(Dose_{coag})^{0.305}(pH_{coag})^{-0.9513} \qquad [37]$$

Where:
$UVA_{removed}$ = UVA removed by coagulation (1/cm);
UVA_{raw} = raw water UVA (1/cm);
$Dose_{coag}$ = applied coagulant dose (meq/L);
pH_{coag} = pH of coagulation.

TOC removal is predicted using the semi-empirical sorption model developed by Edwards (1997). The model divides TOC into fractions that are sorbable and nonsorbable by the coagulant, with the nonsorbable fraction unable to be removed via coagulation. The concentration of TOC removed by the coagulant is modeled using:

$$\frac{x}{M} = \frac{[ab[Ceq]]}{1 + b[Ceq]} \qquad [38]$$

Where:
x = concentration of TOC removed (mg/L);
M = Coagulant added (mMoles/L);
a = maximum TOC sorption/mM coagulant (mg DOC/mM Al);
b = sorption constant for sorbable DOC to hydroxide surface;
[Ceq] = sorbable TOC (mg/L).

The equations used to predict pH changes are based on raw water alkalinity, coagulant dose, and carbonate chemistry and the assumption of a closed system. Iterative approaches are used to calculate pH changes associated with chemical additions as described by Solarik et al. (2000).

3.3.2 TTHM Formation in the Distribution System

The concentration of DBPs may continue to increase after treated water leaves the plant and enters the distribution system (Sohn et al. 2001; Garcia-Villanova et al. 1997). Sohn et al. (2001) found increases of TTHM levels in the distribution system of ~150% to greater than 300% of in-plant TTHM concentrations. Previous models of the water treatment process do not specify separate equations for TTHM formation in the distribution system. These models effectively consider the distribution system to be an extension of the plant, and TTHM formation is assumed to follow the same formation kinetics. Estimating DBP formation in the distribution system has become increasingly critical in recent years, as compliance with the Stage 2 D/DBP regulations will be assessed on the basis of measurements made at different points in the system.

The Information Collection Rule (ICR) was promulgated by the US EPA in 1996 to collect data in support of the development of drinking water standards. The ICR database includes treatment plant water quality data from multiple sample locations throughout the treatment process and distribution system. The data were collected from 296 public water systems (PWS) each serving at least 100,000 people, from July 1997 to December 1998. As part of this work, ICR data are used to develop a predictive model for TTHM concentrations in the distribution system based on finished water TTHM concentration, final chlorine dose, residence time, and finished water quality including pH, temperature, TOC, and UV-254. The database includes TTHM concentrations measured at 6 locations in distribution systems (n=127) at increasing distance from the finished water.

Formation relationships were developed using step-wise multiple regression analysis. Significant parameters ($p<0.15$) in the prediction of TTHM concentration in the distribution system ($TTHM_{DS}^{Cl}$, after post-disinfection with chlorine) were: finished water TTHM concentration, TOC, residence time, UV-254, and temperature (Table 3.2). The resulting model shows a relatively strong correlation ($R^2 = 0.82$), such that:

$$TTHM_{DS}^{Cl}\,(ug/L) = 0.08\,(Time) + 1.05\,(TTHM_{FW}) + 0.57(T) + 5.12(TOC) - 277(UV) \qquad [39]$$

Where:
Time = Contact time (hours);
$TTHM_{FW}$ = Finished water TTHM concentration (ug/L);
T = Finished Water Temperature;
TOC = Finished Water TOC (mg/L as C);
UV = Finished Water UV-254 (1/cm).

Table 3.5 Statistical Parameters for Post-Chlorine TTHM Formation in the Distribution System

Parameter	F-value	p-value
$TTHM_{FW}$	466.78	<0.001
TOC	8.52	0.0042
Time	5.87	0.0169
UV	4.15	0.0439
Temp	2.81	0.0964

It should also be noted that consideration of $TTHM_{FW}$ and time alone yield an R^2 value of 0.80.

The ICR database was also used to develop a predictive model for TTHM concentration in the distribution system for conventional plants that utilize chloramines for post-disinfection (n=54). Finished water TTHM concentration, pH, temp, TOC, UV-254 and distribution system residence time are considered as parameters. Step-wise multiple regression analysis was again performed, but finished water TTHM concentration is the only significant parameter ($p<0.15$) in the prediction of TTHM levels in the distribution system (Figure 3.3). The following model also shows a very strong correlation ($R^2 = 0.89$) but describes a much more limited increase in TTHM formation when chloramines are used for post-disinfection:

$$\mathrm{TTHM}_{DS}^{ClN}\ (\mathrm{ug/L}) = 1.107 * (\mathrm{TTHM}_{FW}) \tag{40}$$

Where: TTHM_{FW} = Finished water TTHM concentration (ug/L).

Table 3.6 Statistical Parameters for Post-Chloramines TTHM Formation in the Distribution System

Parameter	F-value	P-value
TTHM_{FW}	399	<0.001

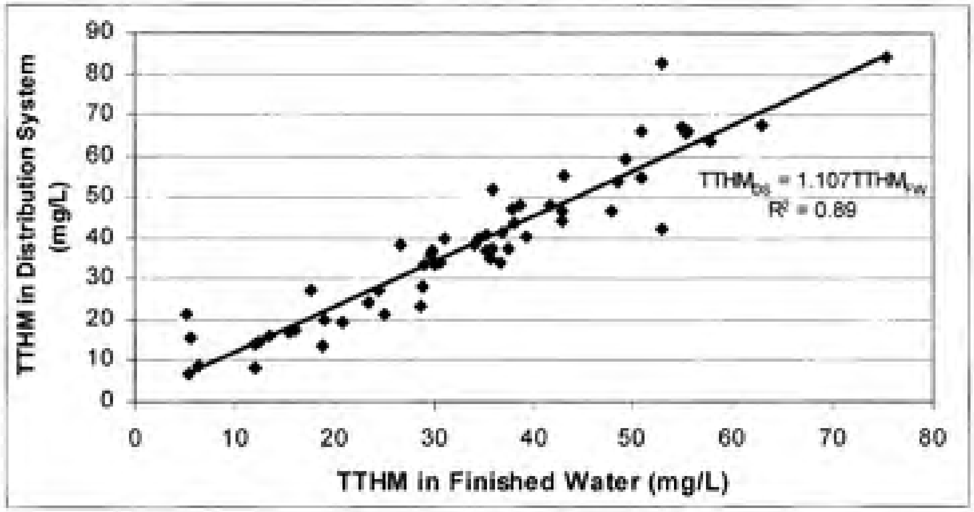

Figure 3.3 Post-Chloramines TTHM Formation in Distribution System

3.3.3 TOC Removal Costs

Costs for ancillary treatment processes for maintaining regulatory compliance were estimated and included in the overall cost estimates if the models predict TTHM concentrations above the MCL. In this work, three processes are considered for reducing TTHM formation: enhanced coagulation, alternative disinfectants, and granular activated carbon (GAC) filtration. Replacement of chlorine with alternate disinfectants can be a relatively inexpensive means of reducing TTHM formation (Clark et al. 1998; Clark et al. 1994). Available alternative disinfectants include ozone, chloramines, UV, and chlorine dioxide (AWWA 1999). The use of chloramines as a post-disinfectant has proven successful in reducing TTHM formation in distribution systems (Singer 2004). The use of ozone as a primary disinfectant can also lower TTHM concentrations in finished water (Clark et al. 1998; Singer 1994). However, research has shown that these alternative disinfectants may also form by-products (e.g. bromate) which are not considered in this work (Clark et al. 1994; Singer 1994).

Enhanced coagulation and clarification can be very effective if a utility is only slightly above the MCL (Clark et al. 1994). GAC can also be a very effective method of removing DBP precursor material, however the costs of media regeneration often make it more costly when treating raw waters with high DBP precursor levels (TOC > 6 mg/L) (Hooper and Allgeier 2001). Costs for these ancillary processes are taken from both cost models as well as estimates available in the literature (USBR 1999; Clark et al. 1994).

Further analysis of the ability of each ancillary process to bring the system into compliance is part of the final tool. In this work, these processes are used to illustrate the additional costs that may be necessary to maintain compliance with the Stage 2 D/DBP Regulations.

3.4 Storage Costs

Storage costs are an important factor to be considered in the total costs of supply and treatment. Different water sources often vary in terms of their ability to reliably meet water demand. As such, it is important that the costs of building the storage infrastructure required to ensure equal levels of supply reliability are included in any comparative analysis. General relationships exist to estimate costs for storage options, however the reader is cautioned that these relationships are much more dependent on site specific characteristics (e.g. soil, topography) than those describing acquisition and treatment costs. Storage cost estimates should therefore be viewed as illustrative. Three types of storage options are available: tanks, small impoundments, and reservoirs. Impoundments can be formed in-stream by constructing dams, or off stream by lining natural or artificial depressions with liners (UNEP, 2003). Tanks may also be built to store water for periods of low flows.

Calculations of actual storage capacity require a considerable amount of source specific data, so for the purposes of this work, three storage sizes for reservoirs are considered: 3 months, 6 months, and 12 months. Reservoir costs are calculated using median unit costs for reservoirs found in Principles of Desalination (1980). Costs are presented for both capital and O&M expenses. These costs are compared to work done by Dawes & Wathne (1968), where reservoir costs are calculated as follows:

$$C_{CAP}^{RES}\,(\$) = 9161S^{0.54} + 0.49S^{0.87}k \qquad [41]$$

Where:
S = Reservoir Storage Capacity (AF);
k = Land Cost (\$/acre).

Costs are comparable from the 2 models, and the final costing model for storage uses the available unit costs (Spiegler and Laird 1980).

CHAPTER 4

RESULTS

Costs are calculated for plant capacities of 1, 10, and 30 MGD. While the total cost of supply and treatment includes acquisition, treatment, and storage, treatment costs are presented first. This is followed by comparative analyses that include the addition of acquisition costs, regulatory compliance costs, and storage costs, in respective order. Four types of source waters are considered in the analyses, both fresh groundwater and surface water sources are compared to brackish groundwater and surface water sources. Later scenarios will focus on brackish groundwater and a fresh surface water with high values of TOC. A sensitivity analysis of the components of total supply and treatment costs is also presented. When there are multiple options available, processes are included according to Table 4.1.

Table 4.1 Selected Processes

Process	1 MGD	10 MGD	30 MGD
Surface water Intakes	Submerged Crib	Submerged Crib	Exposed Tower
Residuals Management			
Conventional Treatment: Sludge Handling	Sludge Dewatering Lagoon	Gravity Thickener/ Lagoon	Belt Press/Lagoon
Desalination: Concentrate Disposal	Evaporation Pond	Deep Well Injection	Deep Well Injection

4.1 Treatment Cost Comparison

Treatment costs (including residuals disposal) are evaluated for conventional and membrane desalination for both surface water and groundwater sources. The pre-treatment option included for desalination of brackish surface water is conventional treatment.

Figure 4.1 describes the treatment costs for each of the four source waters. Treatment of fresh groundwater is limited to disinfection (AWWA 1999) and treatment costs are commensurately low. Standard conventional treatment costs are less than brackish water desalination for all capacities considered for surface waters. However for smaller capacities (less than 10 MGD), the cost gap between brackish groundwater and fresh surface water is less pronounced. As brackish sources are often groundwater sources requiring minimal pretreatment prior to desalination, these comparisons hold particular importance, especially as communities find themselves without adequate fresh water sources.

The inclusion of the additional costs for residuals disposal is important; concentrate disposal costs are greater than those for sludge handling, and therefore increase the gap between conventional treatment and desalination. This difference is further illustrated later in Table 4.5.

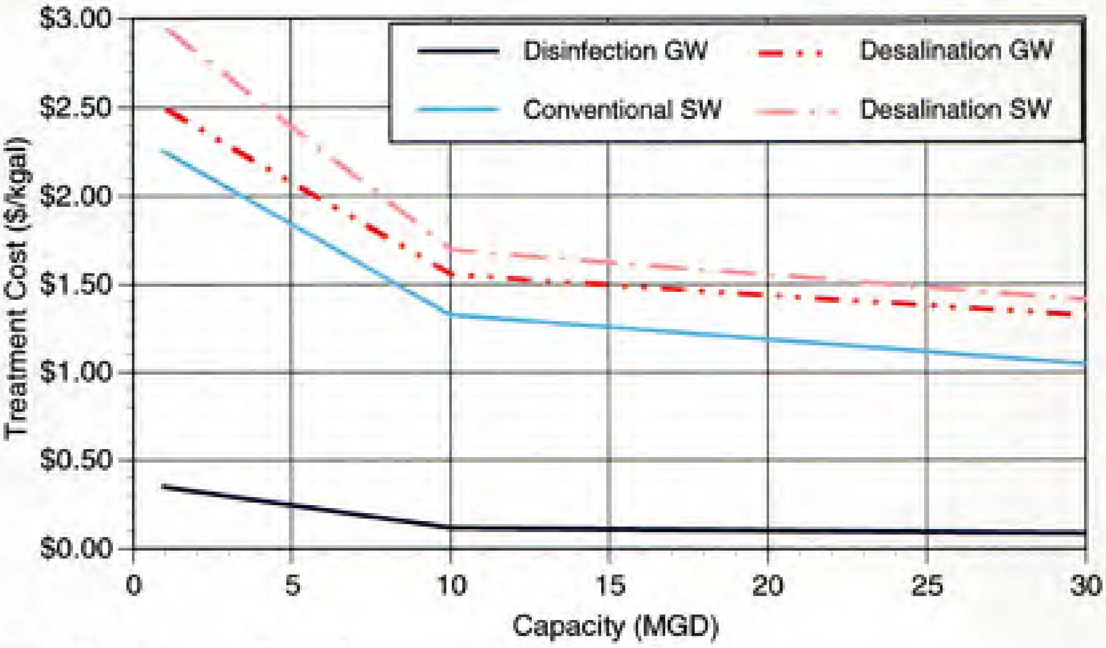

Figure 4.1 Treatment Cost Comparison

4.2 Addition of Acquisition Costs

Acquisition costs are added to the treatment costs for each source water considered. Four scenarios are evaluated to investigate the cost effectiveness of brackish water desalination in terms of distance (miles) and land surface grade (ft/1000ft) between the source and treatment plant. Land surface grade is an important consideration as costs for conveyance will be significantly higher for pumping uphill (positive grade) as compared to gravity feed (negative grade). Therefore, as communities need to travel further for a fresh water source, costs for acquisition will rise and begin to decrease the cost gap between conventional and desalination treatment seen in Figure 4.1. Therefore, local brackish sources (<1 mile from the plant location) are compared to distant fresh surface and groundwater sources (Table 4.2).

Table 4.2 Scenario Outline

Fresh Water Sources:	Brackish Water Sources: Local Brackish GW	 Local Brackish SW
Distant Fresh SW	1A	2A
Distant Fresh GW	1B	2B

In all of the following figures, the solid lines represent lines of equivalent cost (iso-cost) for the plant capacities shown (i.e., the costs of treatment plus acquisition for the fresh water at a specific distance and grade is equal to the costs of treatment plus acquisition for the local brackish water located 1 mile from the plant at a grade of 5 ft/1000ft). Therefore, if the distance to the fresh source is greater than the distance at the iso-cost line (i.e. to the right of the cost line), the costs of developing the brackish source are less than those of the fresh water source, making the brackish source a more cost effective option (indicated by arrows on the plots). Similarly, if the fresh water source is located at a distance to the left of the cost line for a specific grade, the costs for treatment and acquisition are less expensive for the fresh water source compared to the local brackish source. For example in Figure 4.2 for a 10 MGD facility, if the brackish water source is located 1 mile from the plant, the costs (treatment plus acquisition) for the brackish source are equal to that of the fresh surface water located approximately 23 miles from the treatment plant at a grade of 0 ft/1000ft. Therefore, a fresh surface water located more than 23 miles from the plant would be more expensive to develop than the local brackish groundwater.

In all scenarios, membrane desalination is more economically attractive for smaller capacity plants as communities with greater demands (10 and 30 MGD) are willing to travel farther for fresh sources. These results are consistent with previous comparisons of membrane and conventional treatment costs (Wiesner et al. 1994). In the comparison of groundwaters (Figures 4.3 and 4.5), the brackish source is much less cost-competitive than when compared to a fresh surface water (Figures 4.2 and 4.4), due to the decreased costs of treating the freshwater via disinfection alone. Also, although pre-treatment increases the treatment costs for desalination of a brackish surface water source relative to those of brackish groundwater, overall costs are similar due to the differences in acquisition costs. This is clear on Figures 4.4 and 4.5, as the distance a community would go to develop a fresh water source compared to a local brackish surface water is less (Figure 4.4) than when compared to the local brackish groundwater (Figure 4.5).

Also important to note is that conventional treatment is selected as the pre-treatment option for surface water sources considered in these analyses. Therefore, if greater pre-treatment (i.e. ultrafiltration) is required prior to the membrane treatment, these costs will be greater, and the iso-cost lines will be at even greater distances.

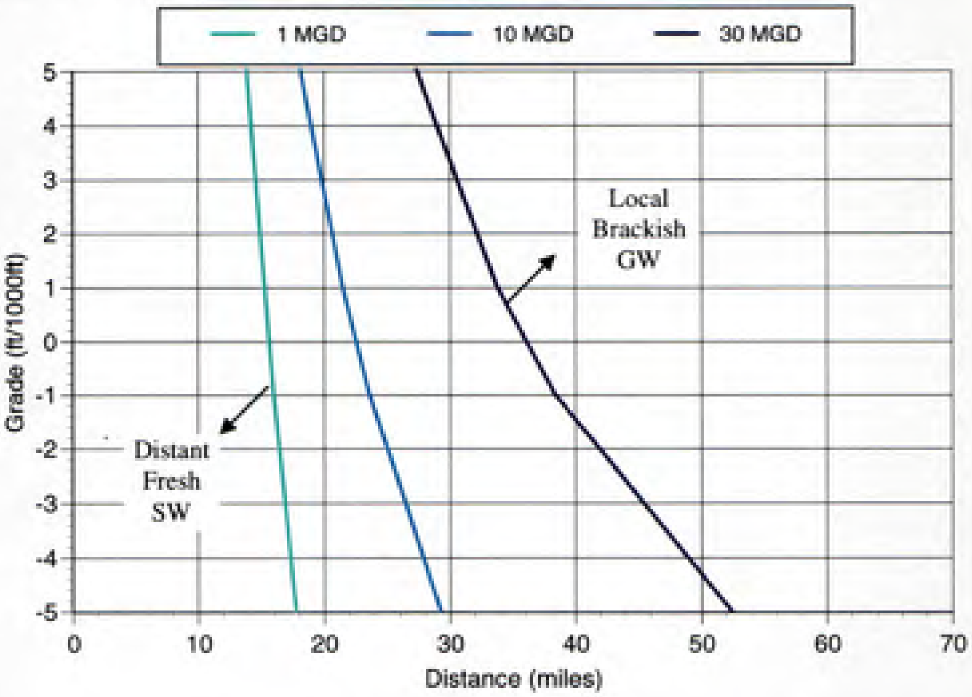

Figure 4.2 Local Brackish GW vs. Distant Fresh SW (1A)

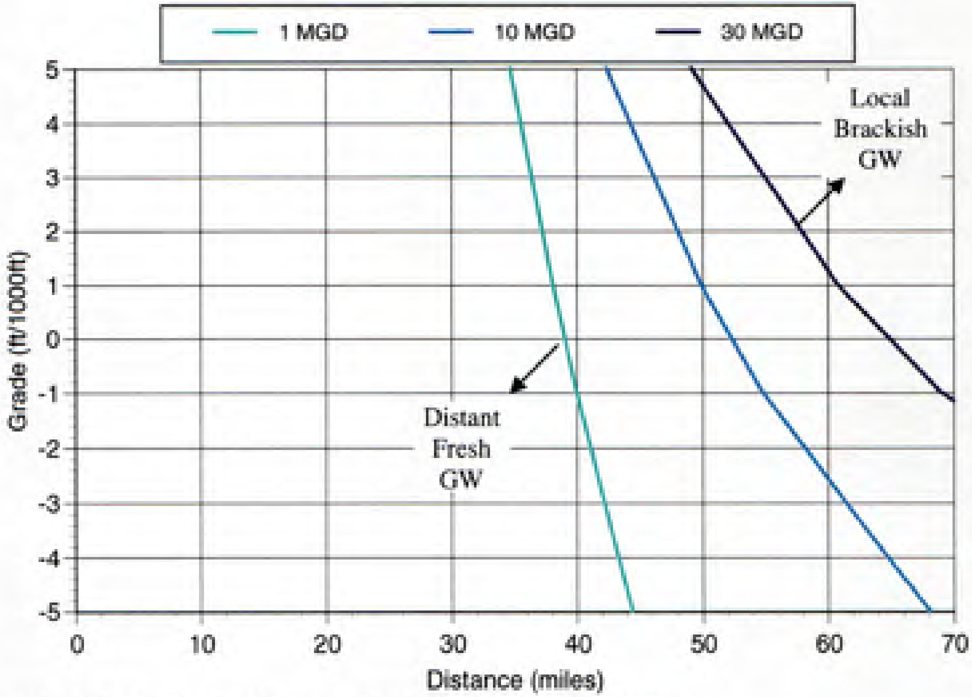

Figure 4.3 Local Brackish GW vs. Distant Fresh GW (1B)

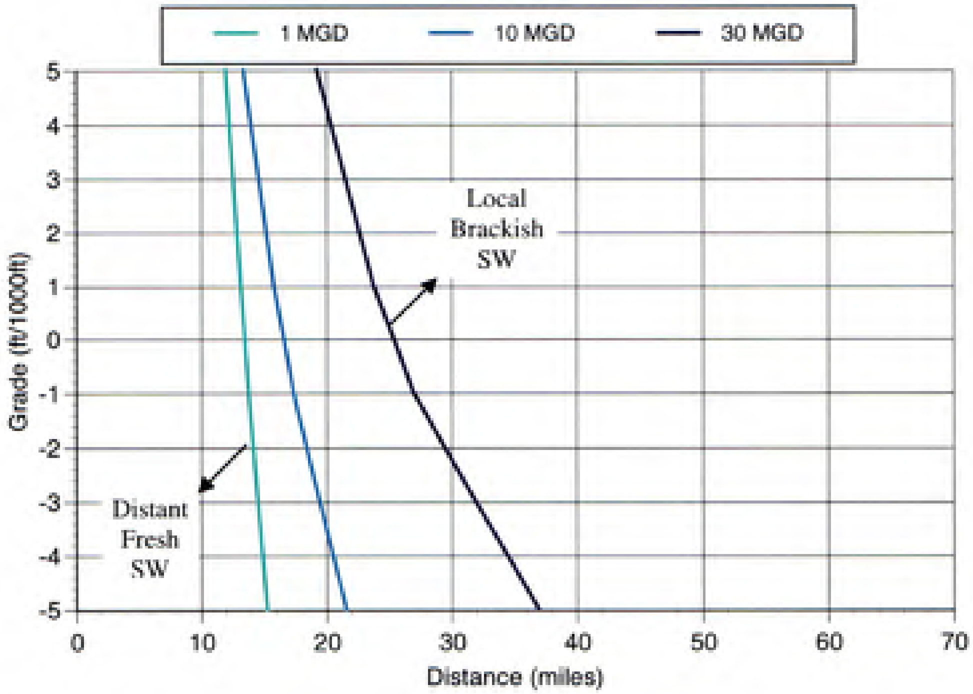

Figure 4.4 Local Brackish SW vs. Distant Fresh SW (2A)

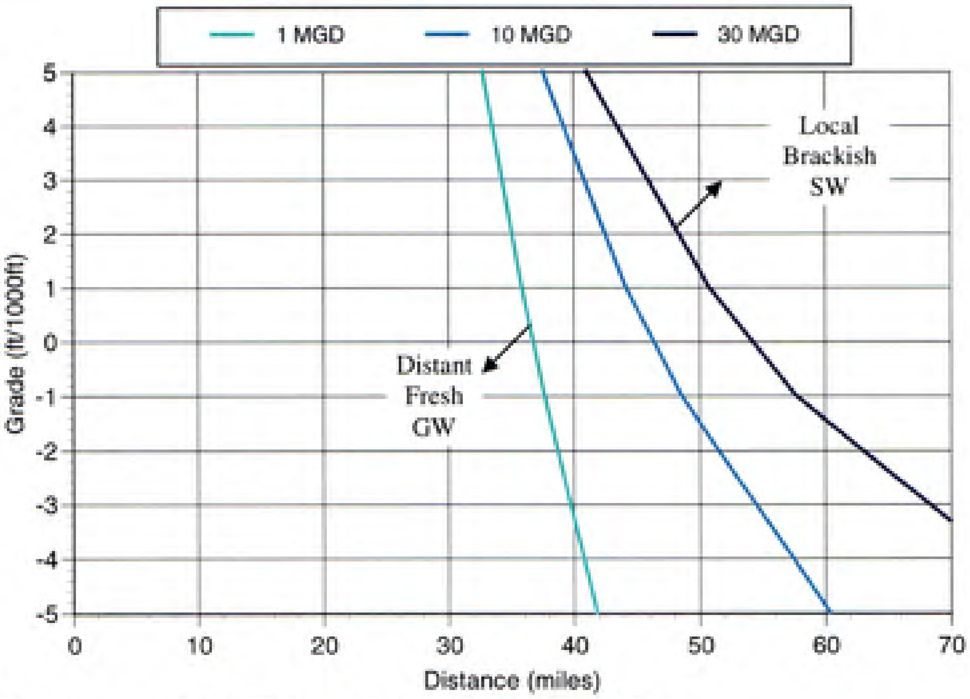

Figure 4.5 Local Brackish SW vs. Distant Fresh GW (2B)

4.3 Addition of Compliance Costs

Continuing the process of building toward the total cost of supply and development, the costs for maintaining regulatory compliance are added to the costs already considered.

Fresh waters with elevated levels of TTHM are considered in these comparisons versus local (<1 mile at a grade of 5ft/1000ft) brackish sources. In order to maintain compliance with the TTHM MCL, ancillary processes to reduce formation are added to the treatment costs. As membrane desalination processes are able to effectively remove TOC (AWWA 1996; Clark et al. 1994), these processes are assumed to maintain regulatory compliance without any additions. Therefore, results from two scenarios (Table 4.3) considering only fresh surface water are presented.

Table 4.3 Scenarios for Regulatory Compliance

	Brackish Water Sources:	
Fresh Water Sources:	Local Brackish GW	Local Brackish SW
Distant Fresh SW with ancillary processes for TTHM Reduction	1C	2C

Within each scenario, four ancillary processes for TTHM reduction are evaluated in terms of their cost for the fresh water source:

- Enhanced Coagulation
- Alternative Disinfectants
    - Ozone as Pre-Disinfectant
    - Chloramines as Post-Disinfectant
- Granular Activated Carbon Filtration

These processes are added to illustrate the additional costs that may be necessary to maintain compliance, they have not been evaluated for their ability to reduce TTHM formation and meet Stage 2 Regulations.

In all of the figures below, the solid lines are iso-cost lines from Figures 4.2 – 4.5 that include consideration of treatment and acquisition costs. The dashed lines indicate the iso-cost lines modified by the addition of ancillary processes to maintain compliance. The addition of these compliance costs increases the cost-competitiveness of the brackish sources for all scenarios, as the distance a community would go to develop a fresh water source decreases.

As the addition of chloramines and enhanced coagulation are relatively inexpensive, the shift in the iso-cost lines is not as prominent (Figures 4.6, 4.7, 4.10, 4.11) although it does decrease the distance a community would go for a fresh water source. For example, a 10 MGD facility would initially travel 23 miles (at a grade of 0 ft/1000ft) for a fresh source compared to a local brackish source, yet with the addition of chloramines, this community would only consider a source less than 21 miles away. However, if the utility requires GAC filtration to achieve compliance, the attractiveness of the brackish sources is greatly increased (Figures 4.9 and 4.13), such that distance to the fresh water source is no longer a factor. A local fresh source water (<1 miles away) that requires the addition of GAC has similar total costs for supply and treatment as a local brackish source, therefore a community would not be willing to travel greater than 1 mile for the fresh water source if a local brackish source was available. Although GAC is a very effective means for TTHM reduction, it can be an expensive option. Membranes, however, are able to remove precursors, and have the added advantage of removing additional contaminants and producing a consistent high quality water (Pontius 1999; Clark et al. 1994; Singer 1994).

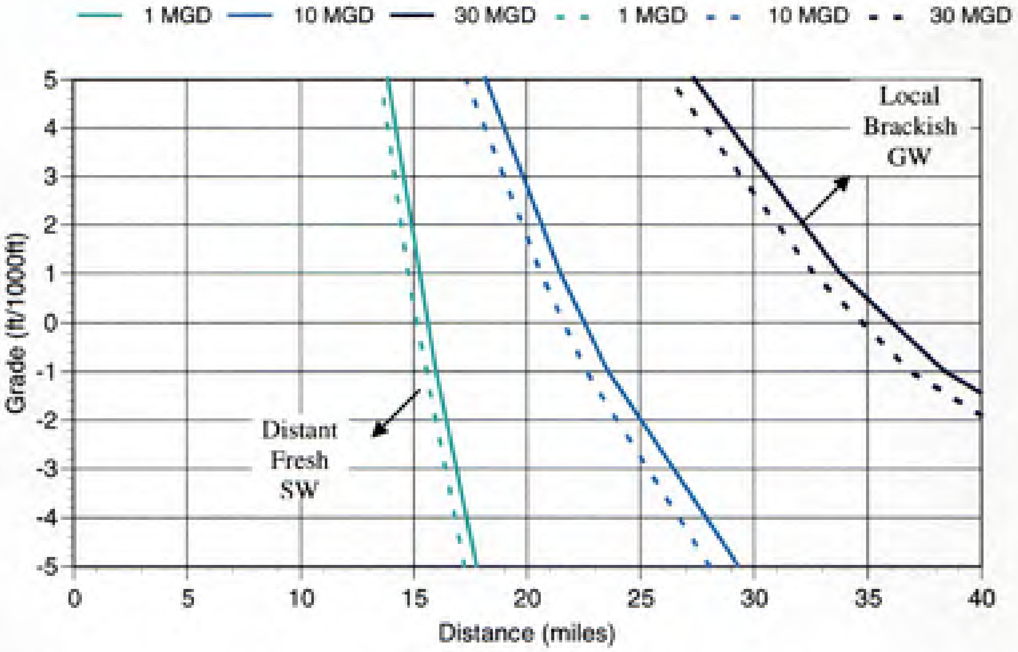

Figure 4.6 Distant Fresh Surface Water with Enhanced Coagulation vs. Local Brackish Groundwater (1C)

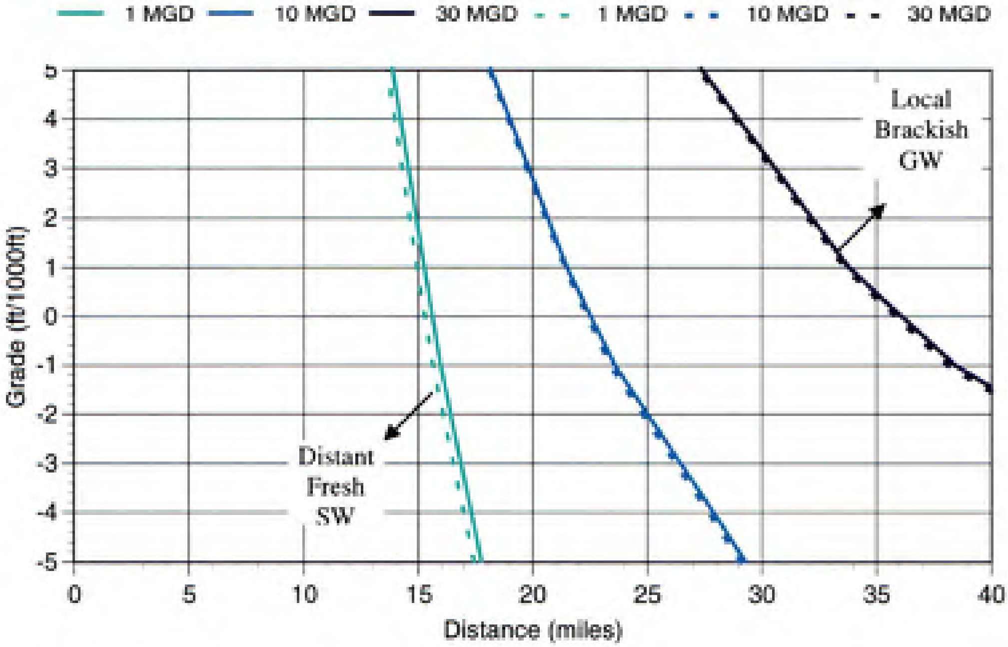

Figure 4.7 Distant Fresh Surface Water with Chloramines as Post-Disinfectant vs. Local Brackish Groundwater (1C)

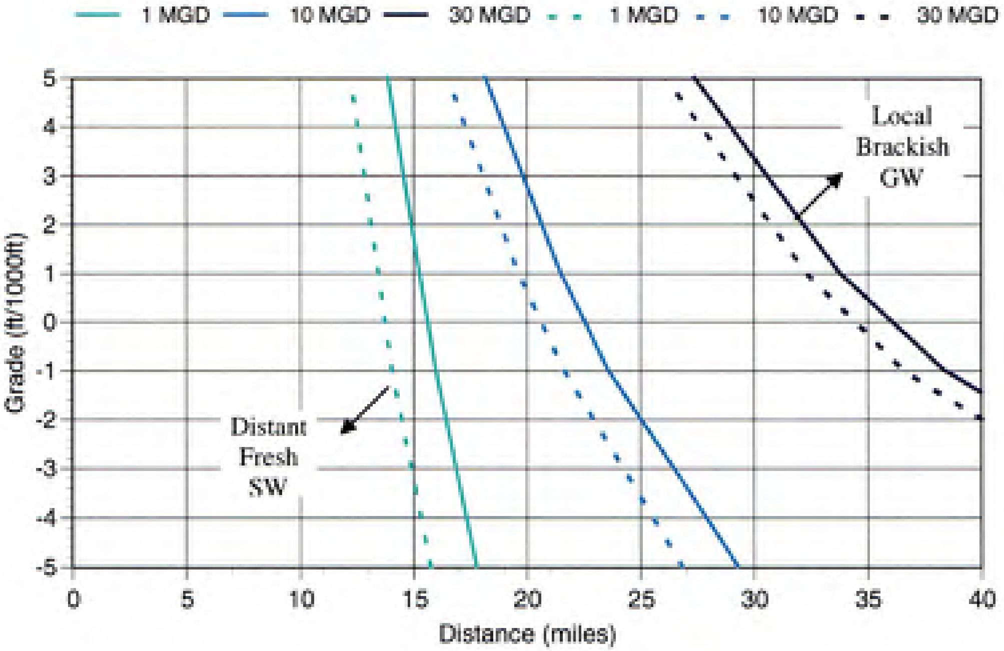

Figure 4.8 Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant vs. Local Brackish Groundwater (1C)

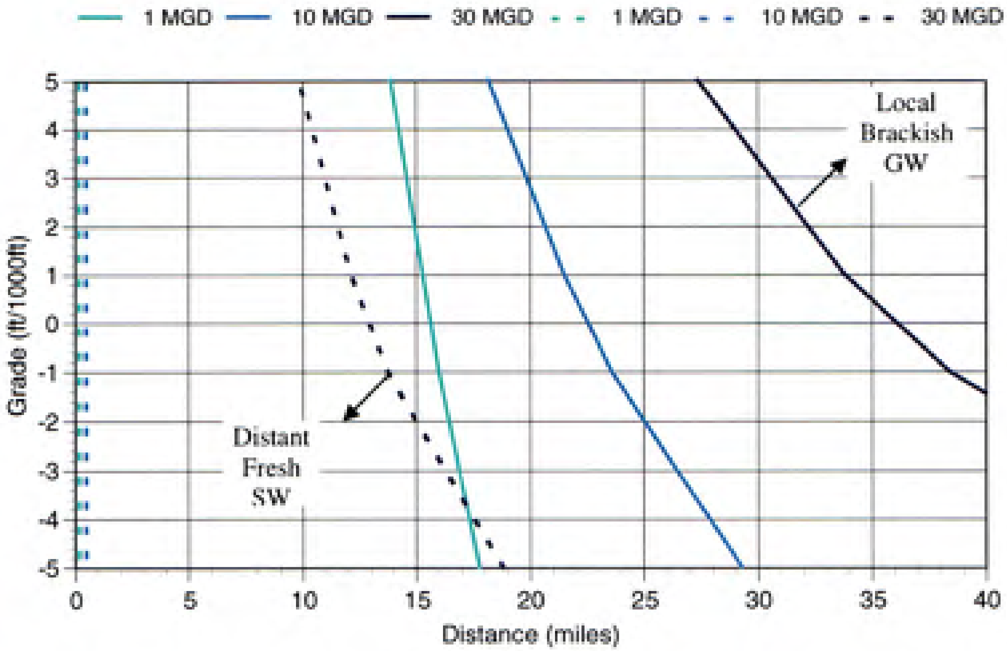

Figure 4.9 Distant Fresh Surface Water with GAC Filtration vs. Local Brackish Groundwater (1C)

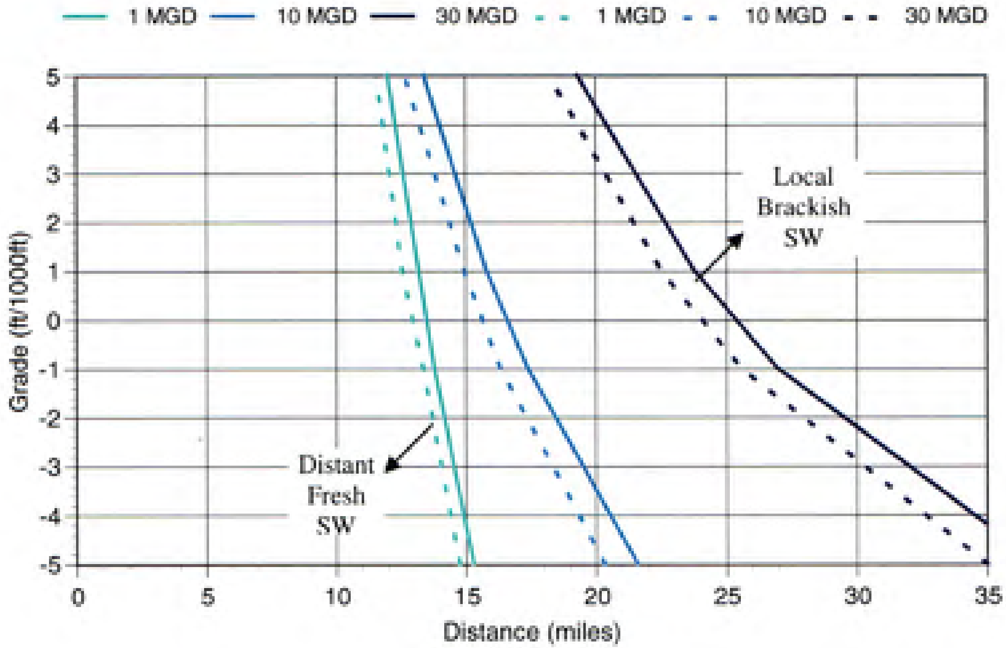

Figure 4.10 Distant Fresh Surface Water with Enhanced Coagulation vs. Local Brackish Surface Water (2C)

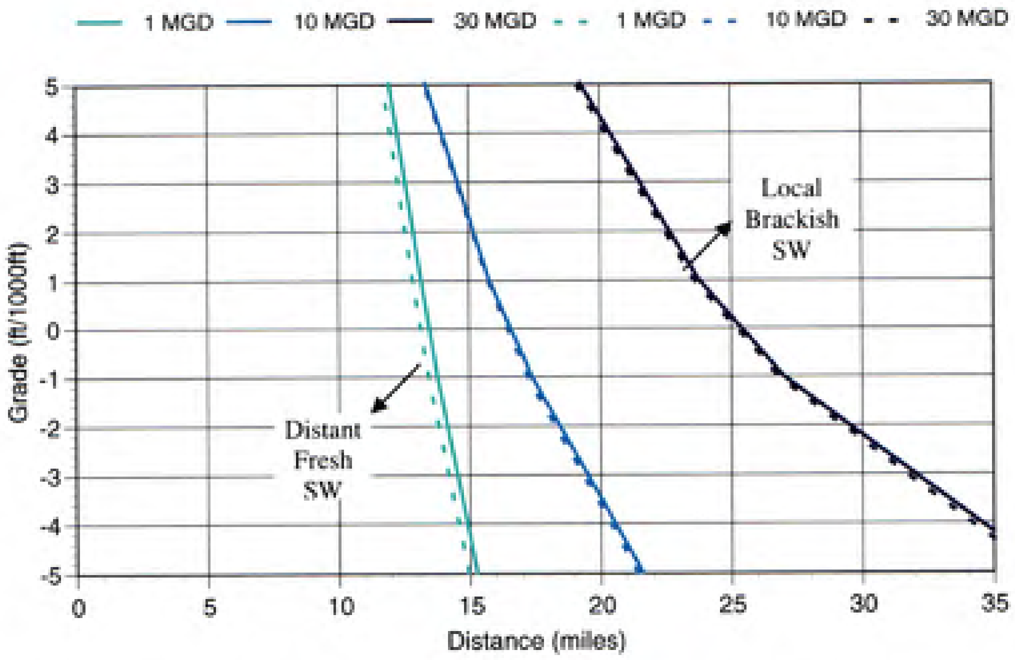

Figure 4.11 Distant Fresh Surface Water with Chloramines as Post-Disinfectant vs. Local Brackish Surface Water (2C)

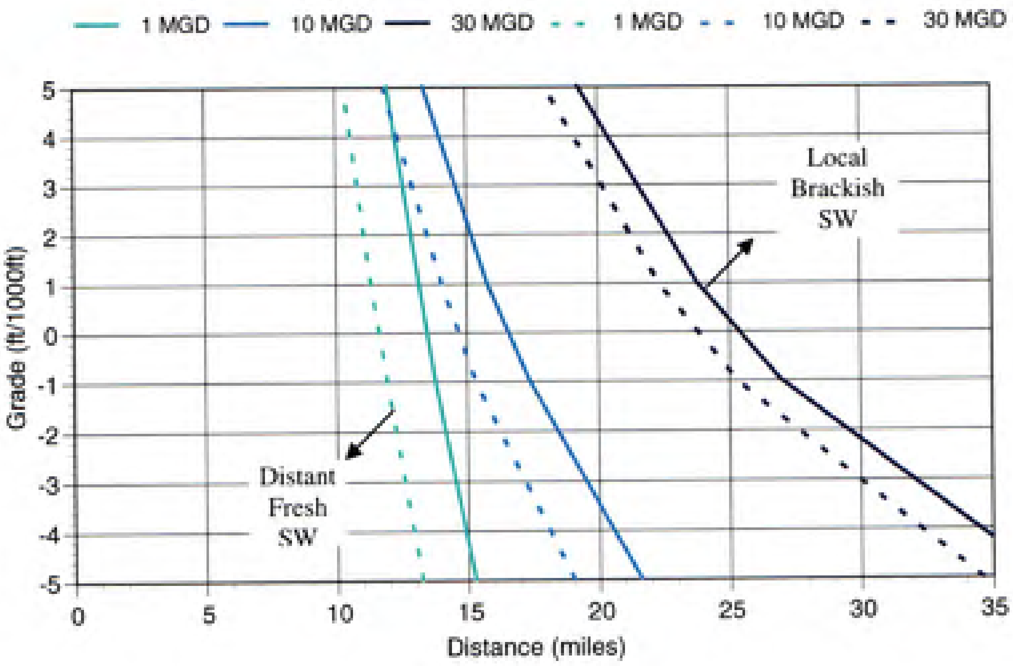

Figure 4.12 Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant vs. Local Brackish Surface Water (2C)

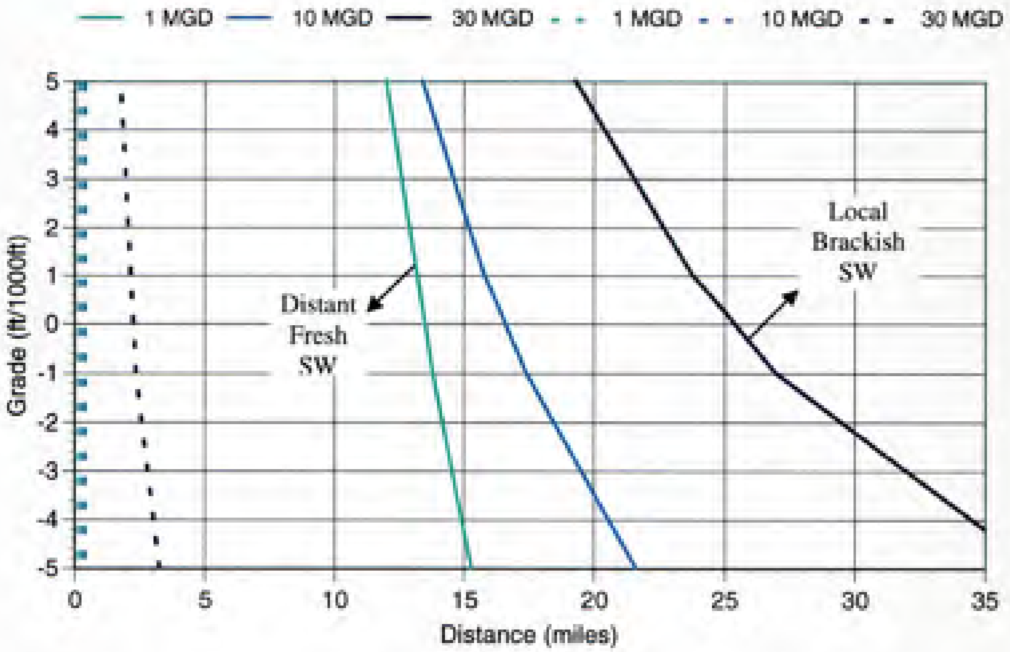

Figure 4.13 Distant Fresh Surface Water with GAC Filtration vs. Local Brackish Surface Water (2C)

4.4 Addition of Storage Costs

Storage costs are the final component of the total supply and treatment costs. In many areas, it is likely that brackish sources are relatively underdeveloped compared to fresh water sources and therefore require less, or no, storage to provide a reliable yield. For that reason, storage capacities for brackish resources are not considered a necessary component in the total cost of supply and development and are added to the fresh water sources only. Costs for storage reservoirs with capacities corresponding to 3 months, 6 months, and 12 months of average daily flow (Q_{OP}) are estimated and added to the total supply and treatment costs for fresh water sources. In these scenarios, freshwater treatment includes the use of chloramines as a post-disinfectant for Stage 2 D/DBP Compliance (Table 4.4).

Table 4.4 Scenarios for Storage

Fresh Water Sources:	Brackish Water Sources:
	Local Brackish GW
Distant Fresh SW with chloramines as post-disinfectant	1D

In all of the figures below, the solid lines are iso-cost lines from Figures 4.2 – 4.5 that include consideration of standard conventional treatment and acquisition costs. The dashed lines indicate the iso-cost lines modified by the addition of ancillary processes to maintain compliance (chloramines) as well as those for storage.

The inclusion of storage in the estimates of total supply and treatment costs also increases the attractiveness of brackish sources. As storage requirements increase, the distance to the iso-cost lines for fresh water sources decreases. For a 1 MGD plant, the need for 3 months of storage reduces the distance a community would go to develop a fresh water source to approximately 7 miles (Figure 4.14). Under these conditions, many communities would find a local brackish resource quite attractive. With the greater storage capacities of 6 and 12 months, the attractiveness of the local brackish resource greatly increases, and distance is negligible for small capacity plants (Figure 4.15 and 4.16). Costs for all components of the total supply and treatment metric are presented as well, in order to highlight the breakdown of costs for all source waters considered (Table 4.5). These cost estimates presented are for a fresh surface water source requiring 3 months storage and the use of chloramines to maintain compliance. These estimates were calculated using the parameters outlined in Chapter 3 for each cost component.

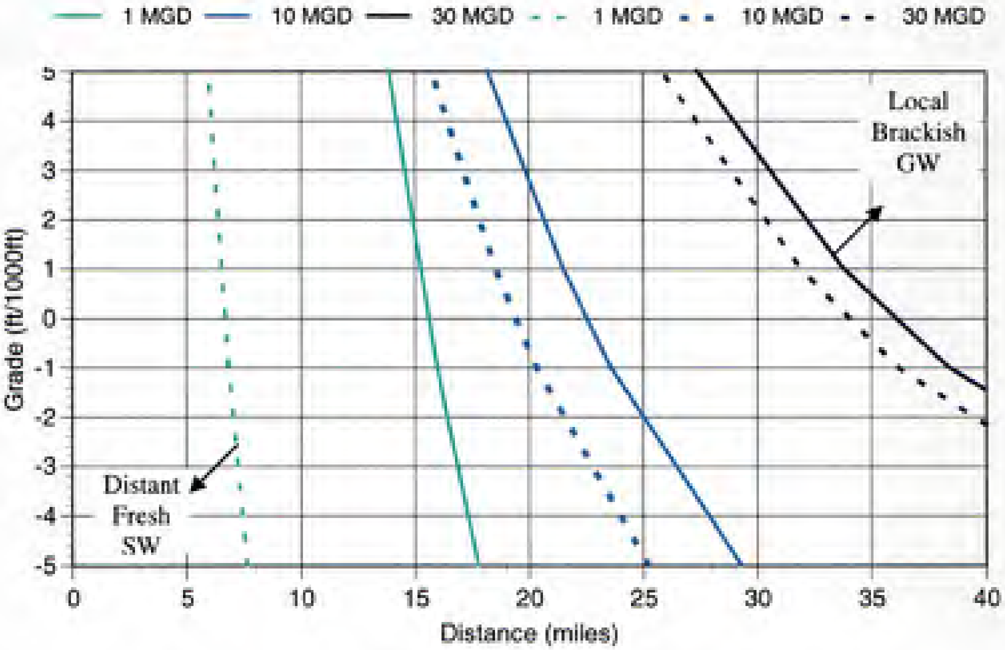

Figure 4.14 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 3 Month Storage vs. Local Brackish Groundwater (1D)

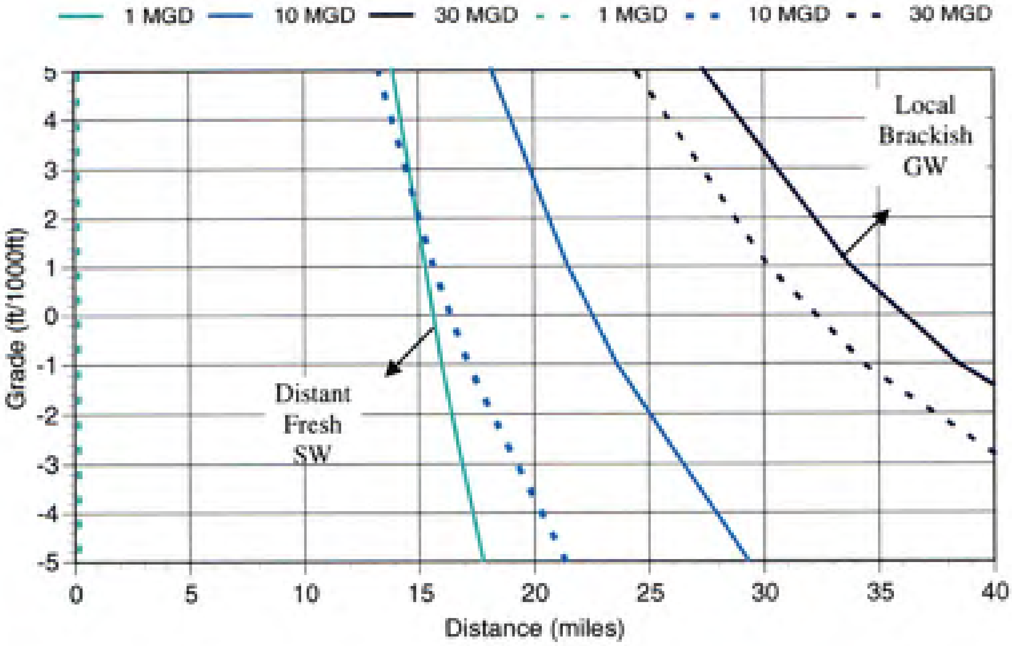

Figure 4.15 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 6 Month Storage vs. Local Brackish Groundwater (1D)

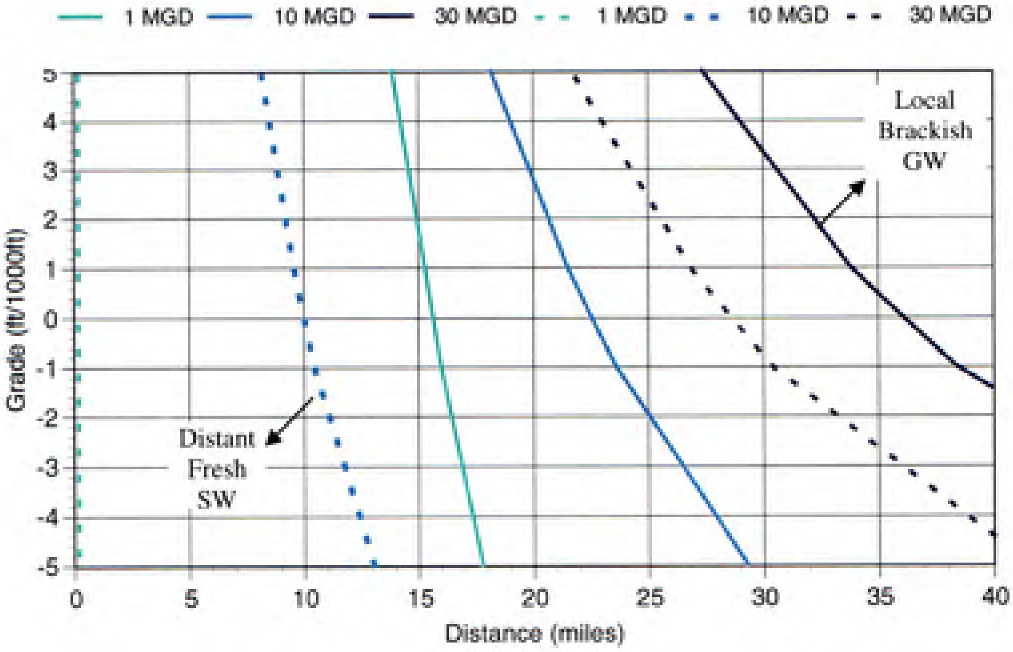

Figure 4.16 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 12 Month Storage vs. Local Brackish Groundwater (1D)

Table 4.5 Total Supply and Treatment Costs for Source Waters with 3 Month Storage

Source	Treatment Costs	Residuals Cost	Acquisition Costs	Storage Costs	Chloramine Costs	Total Cost
1.0 MGD						
Fresh SW	$2.24	$0.01	$0.24	$0.49	$0.02	$3.00
Fresh GW	$0.33	$0.01	$0.82	$0.49	$0.02	$1.67
Brackish SW	$2.22	$0.73	$0.24	NA	NA	$3.19
Brackish GW	$1.77	$0.73	$0.82	NA	NA	$3.32
10 MGD						
Fresh SW	$1.31	$0.01	$0.21	$0.09	$0.00	$1.62
Fresh GW	$0.10	$0.01	$0.53	$0.09	$0.00	$0.74
Brackish SW	$1.41	$0.37	$0.21	NA	NA	$1.99
Brackish GW	$1.26	$0.37	$0.53	NA	NA	$2.16
30 MGD						
Fresh SW	$1.03	$0.01	$0.14	$0.04	$0.01	$1.22
Fresh GW	$0.07	$0.01	$0.47	$0.04	$0.01	$0.59
Brackish SW	$1.24	$0.32	$0.14	NA	NA	$1.70
Brackish GW	$1.15	$0.32	$0.47	NA	NA	$1.94

4.5 Sensitivity Analysis

The impact of changes in inputs is evaluated for the total cost of supply and treatment for brackish groundwater and fresh surface water (Table 4.6). This specific comparison of source waters was selected as it poses what may be the most common scenario encountered by communities interested in exploring the development of brackish resources. Cost estimates presented are developed using the specific parameter values outlined in Chapter 3. Results are presented in terms of the impact on the specific component cost, the total costs of supply and treatment, as well as the distance to the iso-cost line for the surface water source. Land surface grade between the source and treatment plant is maintained at 1ft/1000 ft for all scenarios.

Treatment costs, specifically the operating and maintenance expenses, affect the total cost of supply and treatment for fresh surface water sources, and ultimately the distance, and required acquisition costs, necessary to equate costs. A relatively small change in the O&M costs can affect the distance greatly. For brackish water sources, the costs of treatment, as well as residual disposal, have the greatest impact on the total costs of supply and development. These costs can be variable depending on site-specific conditions, and may continue to decrease as technology improves (Pontius 1999; AWWA 1996). Any decrease in membrane treatment cost would lead to a decrease in the distance to the surface water source for equal costs. For example, the transmembrane pressure for brackish water desalination can operate at a range of values, from 860 to 4,140 for brackish water RO treatment (AWWA ASCE 1998), and may be greater than the 25% difference shown in this table. Disposal of concentrate is also very site-specific and site conditions greatly influence the relative ease of disposal options. Systems for brine minimization are available that can reduce the amount of concentrate stream, and therefore the costs associated with disposal (Glater and Cohen 2003). As expected, overall costs are impacted the most for the smaller facilities, and these facilities are the most cost effective for brackish alternatives.

Additional tables are presented that rank the most significant parameters for both the fresh water total supply and treatment costs (Table 4.7) and the brackish water total supply and treatment costs (Table 4.8). The parameters are ordered from high impact to low.

Table 4.6 Sensitivity Analysis

Parameter	Change in Parameter (%)	1 MGD					10 MGD					30 MGD				
		Change in Cost ($/kgal)	Change in Total Cost* ($/kgal)		Change in Distance to Iso-Cost (miles)		Change in Cost ($/kgal)	Change in Total Cost* ($/kgal)		Change in Distance to Iso-Cost (miles)		Change in Cost ($/kgal)	Change in Total Cost* ($/kgal)		Change in Distance to Iso-Cost (miles)	
Total Supply and Treatment Costs (Base Case)			**$3.00**		**6.5**			**$1.62**		**18.3**			**$1.22**		**31.9**	
Conventional Treatment		*$2.24*	%	$	%	*miles*	*$1.31*	%	$	%	*miles*	*$1.03*	%	$	%	*miles*
Conventional Capital Costs	+/-20	+/-9%	+/-7%	$0.21	-/+53%	3.4	+/-7%	+/-6%	$0.10	-/+15%	9.7	+/-6%	+/-5%	$0.06	-/+8%	2.6
Conventional O&M Costs	+/-20	+/-11%	+/-8%	$0.24	-/+65%	4.2	+/-13%	+/-10%	$0.16	-/+27%	11.9	+/-14%	+/-12%	$0.15	-/+19%	6.1
Residuals Management		*$0.01*					*$0.01*					*$0.01*				
Suspended Solids	+/-75	+/-0%	+/-0%	$0.00	-/+0%	0.0	+/-0%	+/-0%	$0.00	-/+0%	0.0	+/-0%	+/-0%	$0.00	-/+0%	0.0
Acquisition Costs		*$0.24*					*$0.21*					*$0.14*				
Maximum Head	+/-20	+/-17%	+/-1.3%	$0.04	-/+10%	0.7	+/-19%	+/-2.5%	$0.04	-/+6%	1.8	+/-21%	+/-3%	$0.04	-/+4%	1.3
Storage Costs		*$0.49*					*$0.09*					*$0.04*				
Capacity Required	+/-25	+/-25%	+/-4%	$0.12	-/+32%	2.1	+/-24.5%	+/-1.5%	$0.02	-/+3%	5.9	+/-24.5%	+/-4%	$0.05	-/+6%	1.9
Total Supply and Treatment Costs (Base Case)			**$3.32**		**6.5**			**$2.16**		**18.3**			**$1.94**		**31.9**	
Membrane Desalination		*$1.77*	%	$	%	*miles*	*$1.26*	%	$	%	*miles*	*$1.15*	%	$	%	*miles*
Transmembrane Pressure	+/-25	+/-5%	+/-3%	$0.10	+/-28%	1.8	+/-7%	+/-4%	$0.09	+/-15%	2.7	+/-8%	+/-5%	$0.10	+/-12%	3.8
Membrane Cost	+/-25	+/-9%	+/-5%	$0.17	+/-45%	2.9	+/-12%	+/-7%	$0.15	+/-26%	4.8	+/-13%	+/-8%	$0.16	+/-20%	6.4
Residuals Management		*$0.73*					*$0.42*					*$0.30*				
Recovery	+/-5	-/+34%	-/+ 8%	$0.27	-/+ 67%	4.4	-/+24%	-/+4%	$0.09	-/+14%	2.6	-41/+44%	-/+7%	$0.14	-/+19%	6.1
Depth of Well	+/-25	NA					+/-20%	-/+3%	$0.06	-/+13%	2.4	+/-22%	-/+4%	$0.08	-/+9%	4.1
Evaporative Rate	+/-20	-/+22%	-/+5%	$0.17	-/+43%	2.8	NA					NA				
Acquisition Costs		*$0.82*					*$0.53*					*$0.47*				
Depth of Well	+/-50	+/-9%	+/-2%	$0.07	+/-20%	1.3	+/-10%	+/-3%	$0.06	+/-10%	1.8	+/-11%	+/-3%	$0.06	+/-7%	3.2

* Total Cost of Supply and Treatment

Table 4.7 Rank of Impacts from High to Low for Fresh Water Total Supply and Treatment Costs

Fresh Water Total Supply and Treatment Costs (Base Case)
Conventional O&M Costs
Conventional Capital Costs
Storage Capacity Required
Maximum Head (Acquisition)
Suspended Solids (Residuals Management)

Table 4.8 Rank of Impacts from High to Low for Brackish Water Total Supply and Treatment Costs

Brackish Water Total Supply and Treatment Costs (Base Case)		
1 MGD	**10 MGD**	**30 MGD**
Recovery (Residuals Management)	Membrane Cost (Membrane Desalination)	Membrane Cost (Membrane Desalination)
Membrane Cost (Membrane Desalination)	Recovery (Residuals Management) Transmembrane Pressure (Membrane Desalination)	Recovery (Residuals Management) Transmembrane Pressure (Membrane Desalination)
Evaporative Rate (Residuals Management) Transmembrane Pressure (Membrane Desalination)	Depth of Well (Residuals Management)	Depth of Well (Residuals Management)
Depth of Well (Acquisition)	Depth of Well (Acquisition)	Depth of Well (Acquisition)

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

An increasing number of communities are facing water supply challenges, driving the need to evaluate alternative sources. Consideration of lower quality water sources, particularly brackish waters, has increased as fewer fresh water sources are available. While membrane desalination is generally more expensive than conventional treatment, membrane treatment costs are decreasing. In addition, conventional treatment costs are potentially increasing as many fresh water sources previously considered to be of high quality may require ancillary processes to maintain compliance with several new regulations that address relatively common constituents. In many areas, especially arid regions, desalination is becoming a preferred alternative due to decreasing membrane costs as a result of technological improvements, as well as due to the regulatory advantages membranes provide. If acquisition costs are also considered in the evaluation, a closer brackish groundwater source may be less expensive to develop than a more distant fresh surface water. Inclusion of storage costs may also increase the attractiveness of brackish sources as these sources may provide a more reliable yield than available fresh water sources.

When comparing the costs of developing various sources, incorporating consideration of costs associated with acquisition, compliance, and storage can be quite important. In particular, when comparing fresh and brackish water resources, inclusion of these costs into water resource evaluation can greatly increase the cost-effectiveness of brackish sources. Using the total costs of supply and treatment as a metric, a community with a 1 MGD demand evaluating an available local brackish resource might not consider a fresh water source more than 15 miles away. As ancillary treatment processes and storage considerations are included, this distance decreases by almost 50%. A community with a larger demand (10 MGD) might not consider a fresh source further than 20 miles, whereas a 30 MGD demand might not explore fresh sources located greater than 35 miles from the treatment plant. Generally, for smaller capacity plants, the economic viability of brackish resources increases considerably when the total costs of supply and treatment are compared.

Overall, the scenarios presented are general and site specific information would lead to more meaningful results for communities, nonetheless, the results demonstrate that brackish resources become increasing economically attractive when evaluated in terms of total supply and treatment costs. As such, these results provide useful information to communities considering the use of desalination in augmenting water supply.

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CHAPTER 6

APPENDICES

6.1 Treatment Cost Model Evaluation

One of the most important cost considerations in development of water supply alternatives is the cost for treatment. These costs can be dependent on many factors, most importantly on the amount of water to be treated and the raw water quality of the chosen water supply. In choosing the methods used to estimate costs for water treatment in this work, multiple models were evaluated for both conventional treatment and membrane desalination.

6.1.1 Conventional Treatment Cost Models

There are a number of available cost models for estimating conventional treatment costs (Clark et al. 1994; Clark 1987; Clark and Morand 1981; Gumerman et al. 1979). Gumerman et al. developed generalized cost equations for 99 individual treatment processes that have since been updated (Qasim et al. 1992). In addition, cost equations are available for a set configuration of conventional treatment processes based on power functions that use capacity as the independent variable (Clark 1987; Clark and Morand 1981). The United States Bureau of Reclamation (USBR) has also developed a cost estimating tool called the Water Treatment Estimation Routine (WaTER) that is based on the cost equations for individual unit processes developed by Gumerman et al. (1979) and refined by Qasim et al. (1992). Conventional treatment cost estimates are influenced by a variety of factors including plant capacity, design criteria, treatment processes, site conditions, and land costs (Qasim et al. 1992). Water treatment costs also demonstrate economies-of-scale, therefore, for smaller utilities the unit costs associated with conventional treatment are higher than for larger utilities (Clark 1987; Clark and Morand 1981).

Cost estimates from available models are compared in Section 6.1.1.5, with all costs annualized over 20 years at an 8% discount rate in keeping with similar cost estimation studies (Sethi and Wiesner 2000a; Clark and Dorsey 1982; Clark and Morand 1981) and updated to 2003$ using Engineering News Record (ENR) construction cost indices (Clark and Morand 1981). Total treatment costs are the sum of annualized capital and O&M costs in $/year, divided by the annual operating capacity of the treatment facility (70% of design capacity).

6.1.1.1 WaTER Model

The United States Bureau of Reclamation (USBR) developed a spreadsheet model (WaTER) that estimates both capital and operating and maintenance (O&M) costs for several individual water treatment processes. Cost estimates take both raw water quality and plant size into consideration, and are based primarily on equations from Gumerman (1979) and Qasim et al. (1992).

Costs for a typical conventional treatment train were estimated using WaTER, unit processes include pre-disinfection (chlorine), alum feed, polymer feed, upflow solids contact clarifier, gravity filtration, post-disinfection (chlorine), and clearwell storage. The specific cost equations used for the individual processes are shown in Table 6.1.1.

Table 6.1.1 Cost Equations for Conventional Treatment from WaTER

Process	Capital Cost Equation	O&M Cost Equation	X	Basis
Alum Feed (liquid)	$CC = 13223.3*X^{0.285}*e^{(0.000377*X)}$	$O\&M = -6880.7*e^{(-0.000659*X)}+8700$	Alum Feed Rate	Qasim (1992)
Polymer	$CC = 11760*e^{(0.00665*X)}+8200$	$O\&M = 3000.8*e^{(0.00207*X)}$	Polymer Feed (kg/day)	Qasim (1992)
Clarifier [1]	$CC = 62801+416*X$	$O\&M = 5806.5+8.8*X$	Settling Area (m^2)	EPA (1979)
Gravity Filtration[2]	$CC = 35483.4*X^{0.591}*e^{(0.000162*X)}$	$O\&M = 359.5*X^{0.8568}+8100$	Filter Area (m^2)	Qasim (1992)
Chlorine Disinfection	$CC = 680.75*X^{0.763}+11010$	$O\&M = 47.6*X^{0.89}+6000$	Cl_2 Dose (kg/day)	Qasim (1992)
Clearwell[3]	$CC = -0.002*X^2+39.556*X+58237$	--	Storage Capcity (m^3)	EPA (1979)

Notes:

[1] Capital Cost equation shown is for settling area < $400m^2$. O&M Cost equation shown is for G Rating =110

[2] Equations shown are for gravity filter structure, backwashing pump cost equations are of the same form.

[3] Equation shown is for ground level capacity

The WaTER model was used to develop estimates of total water costs ($/kgal) for conventional treatment plants with capacities from 1 to 30 MGD, based on user inputs for capacity and raw water. WaTER calculates capital costs in $1000 and O&M costs in $/year for each individual process. Annualized capital and O&M costs for the individual processes listed above were summed, and divided by the operating capacity to get total water production cost ($/kgal).

As the WATER model estimates the costs for each individual treatment process, some general factors relating to the cost of the entire project are not included. These include costs of general contractor overhead and profit, engineering, land, legal, fiscal, administrative and interest cost during construction. In order to account for these costs, 28% of the total capital cost was added to the total capital cost as suggested by Qasim et al (1992). Default parameters used in the cost estimates are shown in the table below.

Table 6.1.2 Conventional Treatment Parameters

Input Parameters	**Units**	**Value**
	Conventional Treatment	
	Raw Water Quality	
Bicarbonate Alkalinity	mg/L	25
TSS	mg/L	5
Nitrate	mg/L	0
	Chemical Costs	
Chlorine	$/short ton	20
Alum	$/lbs	15
	Chemical Doses	
Polymer	mg/L	0.5
Disinfection Residual	mg/L	3
	Process Parameters	
Gravity Filtration		Coal and Sand
Upflow Solids Contact Clarifier		2 Clarifiers

Cost estimates for an upflow solids contact clarifier are included in place of separate coagulation, flocculation, and sedimentation processes. Upflow solids contact clarifiers combine mixing, coagulation and flocculation, liquid-solids separation, and sludge removal in a single basin, and can result in lower costs (Gumerman et al. 1979). Upflow clarifier costs from WaTER were compared to costs for separate processes of flocculation, coagulation and clarification, using relationships from Qasim et al (1992). This analysis yielded that the cost of the upflow clarifier is comparable to the combined cost of the separate treatment processes.

6.1.1.2 Sensitivity Analysis

In order to understand the influence of specific parameters in WaTER, a sensitivity analysis was performed. The sensitivity of the individual processes to the factors listed in Table 6.1.3, as well as the effects on the overall treatment costs, was analyzed. Costs for all processes are sensitive to the design capacity. Typically, the costs for the clarifier, gravity filtration and clearwell drive the capital costs, with alum feed making up the largest component of the O&M costs. In addition, changes to the O&M costs had a slightly greater influence on the treatment costs in \$/kgal, so parameters affecting these processes were looked at more closely.

Plant capacity has the greatest impact on cost, particularly at smaller capacities with the influence of other factors growing as capacity increases. Beyond capacity, conventional treatment costs are most sensitive to the costs of chemicals (specifically alum), electricity costs, and parameters influencing the upflow solids contact clarifier. The most important factor affecting the cost of the clarifier is the number to be constructed. This parameter is often site-specific, and can significantly influence the estimate for treatment costs. The cost of the alum feed is sensitive to small changes in cost of the chemical, but large changes in raw water alkalinity can create significant variations in cost as well. As alkalinity values can cover a wide range depending on the source water, it is important to incorporate site-specific information into the water analyses data. Specific results of the sensitivity analysis for a 1 MGD plant are shown in Table 6.1.4 for conventional treatment costs.

Table 6.1.3 Factors Investigated in Sensitivity Analysis

Treatment Process	Factors
Pre-disinfection (chlorine)	Residual, cost of chemical
Alum Feed	Bicarbonate Alkalinity, Cost of Alum
Polymer Feed	Dose desired, cost of polymer
Upflow Solids Contact Clarifier	Flow rate, retention time, # of clarifiers, depth
Gravity Filtration	Flow rate, TSS, media depth, media cost
Post-Disinfection (chlorine)	Metals (for residual), Residual

Clearwell	Storage capacity

As seen in the above table, there are various site-specific parameters, most importantly raw water quality, influencing the cost of a conventional treatment plant. In WaTER, there are several example waters available for use (each fully characterized in terms of water quality), including a municipal water, brackish water and seawater. These waters offer an alternative when site-specific information is not available, but as shown above, this information is important in refining the cost estimates. Other significant parameters include electricity costs and chemical costs. These costs currently have a default value, but are available as user inputs.

It is important to note that the WaTER model does not update water quality after each treatment process. Therefore, the cost for each individual treatment component is based on the raw water quality, and does not take into account any changes in quality that may occur after earlier treatment steps.

Table 6.1.4 Sensitivity Analysis for WaTER Model, Conventional Treatment at 1 MGD

Parameter	Process Affected	Parameter Value	Change in Parameter (%)	Change in Cost (%)	High Value	Change with High (%)
Conventional Treatment						
Electricity Cost ($/kwhr)	USCC	0.06	+/- 10	0.52%	0.07	0.52%
Bicarbonate Alkalinity (mg/L)	Alum Feed	25	+/- 10	0.39%	200	327.28%
Cost of Alum ($/100 lbs)	Alum Feed	15	+/- 10	1.56%	23[1]	11.17%
TSS (mg/L)	Gravity Filtration	1	+/- 10	0.14%	10	11.11%
Media Depth (m)	Gravity Filtration	1.2	+/- 10	0.20%	1.32	0.20%
Depth (m)	USCC	4.8	+/- 10	-0.54%	5.28	0.47%
Retention Time	USCC	180	+/- 10	-0.47%	198	0.47%
# of Clarifiers	USCC	2	+/- 10	12.33%	3	12.33%

Notes:

Parameter values are those available as default values in WaTER model

USCC = Upflow Solids Contact Clarifier

[1] Alum costs from Summer Design Course and costs experienced by plant in Carthage, NC

6.1.1.3 Literature Cost Estimates

A number of additional conventional cost estimating models are also available in the literature. Clark (1987) presents a power function to estimate capital costs for conventional treatment plants. This relationship was updated to 2003$ using ENR cost indices.

$$C_{CAP}^{CONV}\ (\$1000) = 2464Q_{DES}^{0.67}$$

Where: Q_{DES} = Design capacity (MGD).

A power function was also developed to estimate O&M costs based on relationships defined in the literature and recalibrated with actual cost data from treatment plants in North Carolina (Kirsch 2004), resulting in:

$$C_{O\&M}^{CONV}\ (\$1000/\text{year}) = 449.4Q_{OP}^{0.83}$$

Where: Q_{OP} = Operating capacity (MGD).

O&M costs are from 2001, and were updated to 2003 using Producer Price Index (PPI) for finished goods. These two power functions were combined to form a composite model, and total treatment costs were the sum of annualized capital and O&M costs, divided by the operating capacity to yield $/kgal. The unit processes and operating parameters considered in this composite model are outlined in Table 6.1.5.

Clark and Morand's (1981) work is based on cost relationships developed by Gumerman (1979). Essentially, the separate process equations were used to develop power functions as follows:

$$C_{CAP}^{CONV} = 192Q_{DES}^{0.7}$$

Where: C_{CAP}^{CONV} = Capital cost ($1000/year);
Q_{DES} = Design capacity (MGD).

$$C_{O\&M}^{CONV} = 46Q_{OP}^{0.80}$$

Where: $C_{O\&M}^{CONV}$ = O &M cost ($1000/year);
Q_o = Operating capacity (MGD).

Costs are from 1979, and were updated to 2003 using ENR cost indices and PPI for finished goods. The total treatment cost was then calculated by summing both capital and O&M and dividing by operating capacity to yield $/kgal.

6.1.1.4 Model Evaluation

The table below outlines the components included in the three different cost models explained above.

Table 6.1.5 Conventional Cost Components

Category	**WaTER**	**Clark (1987)***	**Clark and Morand (1981)**
Capital Costs			
Land			
Site Work			
Buildings			
Process Equipment:			
Pre-disinfection	X		
Alum Feed	X	x	x
Polymer Feed	X	x	x
Upflow Solids Contact Clarifier OR Coag/Filtration/Sedimentation	X	x	x
Filtration	X	x	x
Post-disinfection	X	x	x
Storage (Clearwell)	x	x	x
Backwash pumping			x
Wash Water Surge Basin			x
Other			
Indirect Capital Cost	x (28%)		
O&M Costs			
Labor	X	x	x
Electricity	X	x	x
Chemical costs	X	x	x
Maintenance	X	x	x
Other		**	
Service Life	20	20	20
Discount Rate	8	5	8
Raw Water Acquisition			

Notes:
* With O&M Costs estimated using Kirsch (2004).
** Additional expenses beyond those listed here may be included in these cost estimates.

6.1.1.5 Cost Comparison

Total water treatment cost estimates ($/kgal) from the available cost models are compared. Costs are broken down into capital (Figure 6.1.1) and O&M costs (Figure 6.1.2) with capital costs expressed in an annualized volumetric form ($/kgal). Conventional capital cost estimates from the WaTER model are lower than those calculated using either Clark (1987) or Clark and Morand (1981) by as much as 50%, while taking on a similar form. This is likely attributable to differences in the factors and processes considered, whereas wash water surge basins, administrative costs, laboratory expenses, maintenance buildings, and pumping costs are included in the power functions and are not included in WaTER.

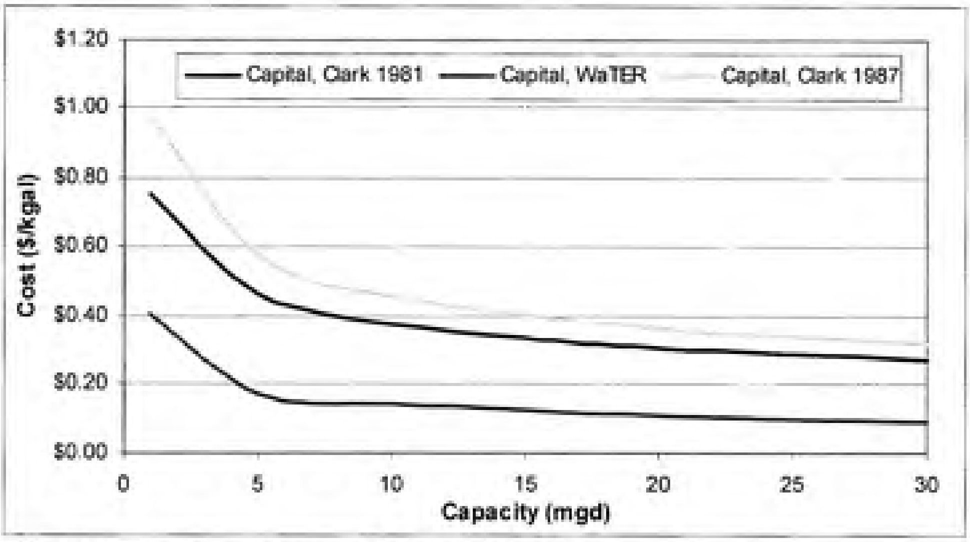

Figure 6.1.1 Conventional Capital Cost Estimates

The main difference in the treatment cost estimates lies in the O&M expenses. Operating and maintenance estimates from Kirsch (2004) were developed based on actual annual operating expenses using facility data from the State Revolving Fund in North Carolina. These costs are significantly higher than both the WaTER model and Clark (1981). Additional cost components may be included in these estimates that are not considered in either the WaTER model or Clark and Morand (1981).

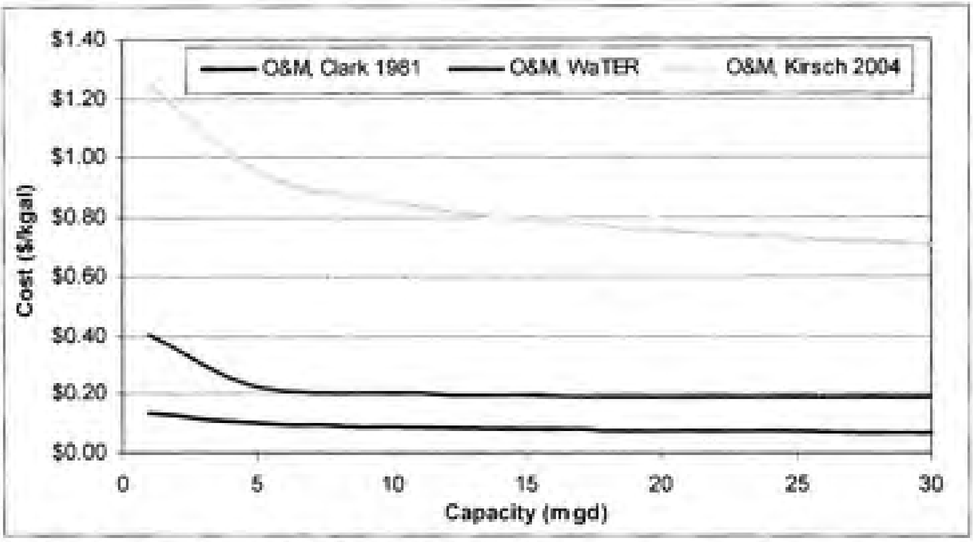

Figure 6.1.2 Conventional O&M Cost Estimates

6.1.2 Desalination Treatment Cost Models

Membrane desalination costs for brackish water can be more difficult to estimate than conventional treatment costs due to a number of factors. First, there are a limited number of existing plants in service in the United States to provide cost data. Second, the rate of change in technology is relatively rapid compared to conventional treatment, and it can be difficult to update these relationships quickly enough to keep up with falling costs. Lastly, membrane desalination cost estimates can be relatively site-specific, and are dependent on a number of factors including (Seacord 2003; Morin 1999; Pickering and Wiesner 1993): quality of raw water, type of intake system required, pre-treatment requirements, energy type and cost, labor rates, chemical costs, and land costs. Operation and maintenance costs represent the greatest expense of RO and NF treatment over the life of the plant (Seacord 2003). Permeate flux and operating pressures are other important factors in estimating the costs of brackish water desalination (Clark et al. 2001; Wiesner et al. 1994; Pickering and Wiesner 1993).

Cost estimates from the WaTER model are compared with those of other models available from the literature, as well as with empirical cost data. Membrane plants do exhibit economies of scale, particularly in the 1 MGD to 5 MGD range (AWWA 1996; Wiesner et al. 1994), although the effects are less marked than those observed in conventional plants. The Sethi and Wiesner (2000) cost model incorporates individual correlations for several major components of capital costs, allowing for different economies of scale associated with different equipment and facilities. All costs are annualized over 20 years at 8% in keeping with similar cost estimation studies (Sethi and Wiesner 2000a; Clark and Dorsey 1982; Clark and Morand 1981) and updated to 2003$ using Engineering News Record (ENR) construction cost indices (Clark and Morand 1981). Total treatment costs are the sum of annualized capital and O&M costs in $/year, divided by the annual operating capacity of the treatment facility (70% of design capacity). O&M costs are updated using the Producer Price Index for finished goods (Clark and Dorsey 1982; Clark and Morand 1981).

6.1.2.1 WaTER Model

A typical desalination treatment train is defined as: pre-treatment, membrane processes, and post-treatment. Pre-treatment includes anti-scalant addition, pH adjustment, as well as treatment to prevent membrane fouling. Post-treatment includes processes typical of drinking water treatment including corrosion control and disinfection (AWWA 1999).

The pre-treatment processes considered for desalination estimates include either micro-filtration (MF) or conventional treatment. The membrane process chosen for brackish water desalination is low-pressure reverse osmosis (RO). The most widely used membrane technology for brackish water treatment in the United States is reverse osmosis (RO) (Morin 1994). Reverse osmosis is effective for removing salts from brackish or saline water sources, but it is also acts as an effective barrier to pathogens (e.g. giardia lamblia and cryptosporidium) and many organic compounds (AWWA 1996; Ray 1992).

The cost equations for RO in the WaTER model are based mainly on desired product flow rate, raw water quality, and plant capacity. Annualized capital and O&M costs for the individual processes included are summed, and total costs for desalination of brackish water from the WaTER model are estimated for plants from 1 to 30 MGD. Specific input parameters used for the membrane processes are shown below (Table 6.1.6).

Table 6.1.6 Desalination Treatment Cost Assumptions

Input Parameters	Units	Value
	Microfiltration	

Membrane Module equipment cost	$/module	$211,500
Cost per membrane	$/m^2	$650
No. membranes per module		90
Pump efficiency	%	80%
Design feed pressure	kPa	207 kPa
Backflush pressure	kPa	200
Backwash Flow	gpm	600
Backwash intervals	minutes	15
Backwash and backflush duration	minutes	0.1
Membrane Life	years	5
Staff Days/day		3 (1 MGD), 6 (10,30 MGD)
	Reverse Osmosis	
Raw Water TDS	mg/L	2000
Product Water TDS	mg/L	300
Recovery	%	85
Membrane Diameter	cm	20.32
Transmembrane Pressure	kPa	2757
Membrane Life	years	5

6.1.2.2 Sensitivity Analysis

A sensitivity analysis was also conducted for the membrane technologies in WaTER, as these processes drive the total cost of brackish water desalination. Total cost of water was particularly sensitive to plant capacity at 1.0 MGD, as the per unit costs for small water systems are quite high. Reverse osmosis costs were most sensitive to recovery and transmembrane pressure. Recovery for a brackish water RO membrane typically ranges from 0.70 to 0.85 (AWWA, 1998), depending on the membrane system set-up and the raw water quality. Transmembrane pressure can also range from 860 to 4,140 for brackish water RO treatment (AWWA/ASCE 1998). Three brackish water reverse osmosis plants on the coast of North Carolina have average feed pressures of 1240 kPa, 1330 kPa, and 1792 kPa. For this work, a transmembrane pressure of 2757 kPa was chosen as a conservative estimate for treatment costs.

Both MF and RO costs are also sensitive to assumptions regarding membrane life. Electricity and labor costs are also important parameters, as they constitute large portions of O&M costs, particularly for smaller treatment plants. Overall, the total cost of water for brackish water desalination was most sensitive to membrane life, transmembrane pressure and electricity costs. Results for the sensitivity analysis for desalination are presented in Table 6.1.7.

Table 6.1.7 Sensitivity Analysis for WaTER Model, Desalination at 1 MGD

Parameter	Process Affected	Base Value	Change in Parameter (%)	Change in Cost (%)	High Value	Change with High (%)
Membrane Desalination						
Electricity Cost ($/kwhr)	MF, RO	0.06	+/- 10	2.00%	0.07	3.13%
Recovery	Reverse Osmosis	0.85	+/- 10	1.63%	0.9	0.30%
Membrane Life	MF, RO	5	+/- 10	0.30%	7	1.10%
Target Product TDS (mg/L)	Reverse Osmosis	300	+/- 10	0.00%	500[1]	0.34%
Raw Water TDS (mg/L)	Reverse Osmosis	2000	+/- 10	0.21%	3000	0.95%
Transmembrane Pressure (kPa)	Reverse Osmosis	2757	+/- 10	-1.58%	5516[2]	13.12%

Notes:

Parameter values are those available as default values in WaTER model

6.1.2.4 Sethi and Wiesner Model

A membrane cost model based developed by Sethi and Wiesner (2000) was also used to estimate desalination costs. The model includes estimation of both capital and O&M costs for membrane plants. A complete description of this model is undertaken in Section 3.2.2.1.

6.1.2.5 Project and Literature Costs

Several other membrane desalination cost estimation routines were also evaluated for comparative purposes. Ray (1992) presents representative costs for capital and O&M cost components for brackish water treatment by reverse osmosis. These representative costs can be used as an estimate of costs to be expected, or can be refined to a specific application using available equations. Cost estimates were calculated for 1 - 30 MGD plants.

Water treatment alternatives were evaluated in the Southern Arizona Regional Water Management Study (SARWMS) for the Central Arizona Project (CAP) water which has high concentrations of TDS (700 mg/L) (USBR 2000). The alternatives considered included both conventional treatment and reverse osmosis with conventional treatment or MF considered for pre-treatment. Reverse osmosis costs were calculated based on the same capital cost equations used in WaTER. Costs estimated by SARWMS were for large treatment plants greater than 30 MGD, and are therefore not comparable to the brackish water treatment costs calculated with WaTER.

The Texas Water Development Board (HDR 2000) also evaluated costs of membrane desalination. The estimation method was based on costs for reverse osmosis system components, including pretreatment, feedwater pumping, membrane process system, and chemical cleaning system. Annual costs of brackish water treatment were presented for various capacities.

Brackish water reverse osmosis treatment costs were also available from Morin (1999). These cost estimates include pre- and post-treatment capital costs, membrane plant costs, as well as O&M costs. Morin (1998) also presented similar costs for brackish water RO treatment for various plant capacities. Cost components included in the cost estimates for each of the models are outlined below (Table 6.1.8).

Table 6.1.8 Brackish Water Desalination Cost Components

Category	WaTER Model	Sethi and Wiesner (2000)	Ray (1992)	USBR (2000)	HDR (2000)	Morin (1999)
Direct Capital						
Land			NO			NO
Site Work			x	x	x	
Buildings	x	x	x	x	x	x
Process Equipment	x	x	x	x	x	x
Pre-treatment equipment	x		x	x	x (minimal)	x
Post-treatment equipment	x	x (disinfection)				x
Storage	x	x				x
Instrumentation and Controls	x	x		x	x	x
High Service Pumps	x	x		x	x	x
Well Supply and Disposal	x (disposal)		x			x
Indirect Capital Cost						
Total	26%		22%	42.25%	55%	45%
Interest during construction	x (4%)			x (6.25%)		
Working Capital	x (4%)			x (3%)		
Freight and Insurance						x (15%)
Construction Overhead	x (12%)		x (12%)	x (13%)	x (10%)	x (15%)
Owner's Cost						x (10%)
Engineering, Legal, Administrative					x (20%)	
Contingency	x (6%)		x (10%)	x (20%)	x (25%)	x (10%)
Operations and Maintenance						
Labor	x		x	x	x	x
Electricity	x	x	x	x	x	x
Supplies						
Chemical costs	x	x	x	x	x	x
Maintenance						
Membrane replacement	x	x	x	x	x	x
Repair and spare parts	x		x	x	x	x
Other						
Insurance	x			x		x
Concentrate Disposal		x				
Service Life	20	20	15	20	30	25
Discount Rate	8	8	12	5.5	6	6

Notes:
If left blank, no specific mention of this factor is made.

6.1.2.6 Cost Comparison

Cost estimates from each model were updated to 2003 using ENR construction cost indices and Producer Price indices for finished goods for capital and O&M costs, respectively. Costs were compared in order to evaluate the estimates generated by the WaTER model relative to the other desalination cost models. One consideration in comparing cost estimates is the selection of pre-treatment processes. These costs can be a significant portion of the total desalination costs, ranging from a small fraction of equipment costs for clean waters to more than half of equipment costs for poor quality waters (Ray 1992). Pre-treatment options are largely dependent on the type of source water, as surface water sources typically require greater treatment (i.e. conventional treatment or MF/UF). Minimum pretreatment processes consist of antiscalant and/or acid addition and cartridge microfiltration (AWWA, 1999). These less costly approaches can often be implemented for brackish groundwaters. For example, there are 3 brackish water treatment plants located on the eastern coast of North Carolina that utilize cartridge filtration for pretreatment of the brackish groundwater prior to the reverse osmosis membranes. The costs from the Sethi and Wiesner model do not include pre-treatment costs (Table 6.1.8). Therefore, a comparison was done using WaTER cost estimates for brackish desalination (cartridge filtration costs are included). This comparison is shown in the figure below (Figure 6.1.3).

The WaTER cost estimates for brackish desalination are reasonably comparable to those from the Sethi and Wiesner (2000) model. Costs from Ray (1992) are consistently higher than other estimates, and costs from both Morin (1999) and HDR (2000) are consistently lower. The most variability is seen for the smaller capacity plants. Costs from USBR (2000) were not included in this comparison as the plant capacities evaluated in their analysis are all greater than 30 MGD.

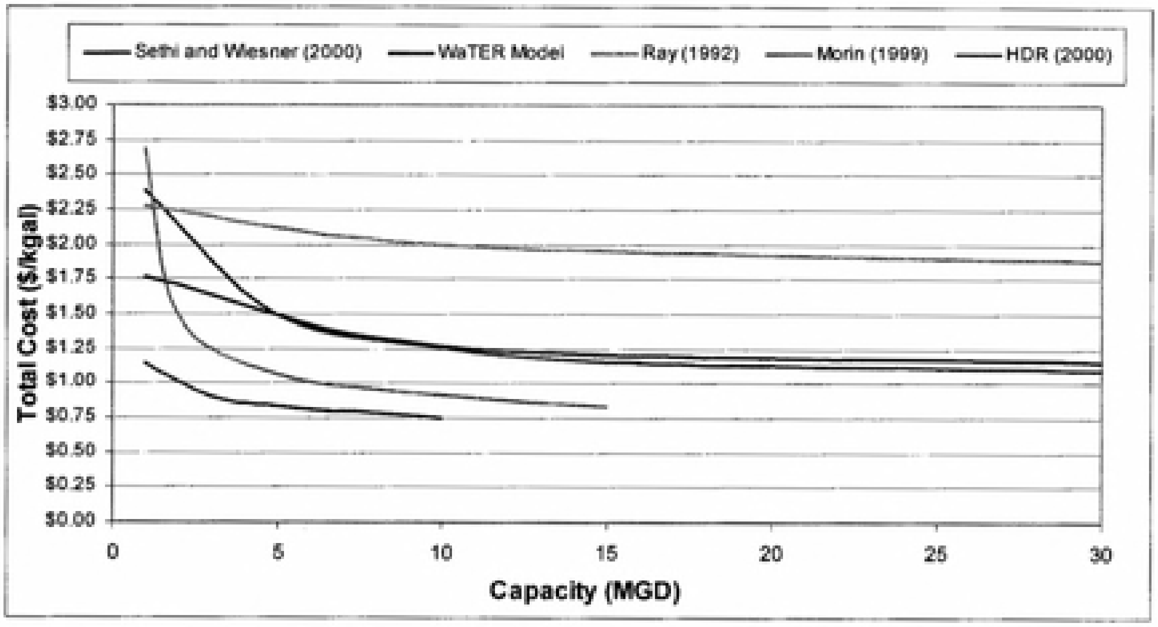

Figure 6.1.3 Reverse Osmosis Cost Comparison

6.2 Maintaining Regulatory Compliance

Consideration of any water supply requires an evaluation of the ability to meet water quality regulations through treatment. In this work, the focus is on assessing the potential cost impacts of the Stage 2 Disinfectant/Disinfection By-Products (DBPs) Regulation. More specifically, the ability of a system to meet the total trihalomethane (TTHM) maximum contaminant level (MCL) as specified in the Stage 2 D/DBR guidelines. The Stage 2 Regulations eliminates the averaging of four samples across the distribution system, and will require compliance at each sampling location (Singer 2004; Wilkes 2003). Trihalomethanes (THMs) were the first class of halogenated DBPs identified in finished water, and have been regulated by the EPA since 1979 (Clark et al. 1998; Singer 1994). Although THMs are only one class of halogenated by products produced by chlorination of drinking water, they are the focus of this work.

Chlorine is the most widely used drinking water disinfectant in the United States as a result of its effectiveness in inactivating pathogenic microbial organisms (Clark et al. 2001). Disinfection by-products (DBPs) form through reactions of natural organic matter (NOM) with chemical disinfectants, specifically chlorine, in the treatment process (Clark et al. 1998; Rathbun 1996; Singer 1994). Since the discovery of chlorination byproducts in drinking water in 1974, numerous toxicological studies have been conducted that show some DBPs to be carcinogenic and/or cause reproductive or developmental effects in laboratory animals (Clark et al. 1994), and a number of epidemiological studies have shown a positive association between consumption of chlorinated drinking water and bladder and rectal cancer in humans (Morris et al. 1992). Additionally, exposure to high levels of disinfectants over long periods of time may cause health problems, including damage to blood and kidneys (EPA 2003).

Water utilities are therefore caught between maintaining adequate disinfection and the potential adverse health impacts associated with disinfection by-products (Clark et al. 1994; Singer 1994). As a result, many utilities using standard conventional treatment will have difficulty complying with the Stage 2 Disinfectant/Disinfection By-Product Rule without ancillary treatment (Wilkes 2003).

6.2.1 TTHM Formation Models

Formation of TTHMs has been shown to be a function of a number of water quality parameters and operating conditions. The following parameters and their effects should be considered (Clark et al. 2001; Clark and Sivaganesan 1998): pH, nature and concentration of NOM, total organic carbon (TOC), water temperature and season, UV-254 absorbance, bromide level, contact time, and chlorine dose. Table 6.1 below outlines the influence of these parameters on the formation of DBPs, and specifically TTHM (Amy et al. 1998; Clark and Sivaganesan 1998; Singer 1994).

Table 6.2.1 Parameter effects on TTHM Formation

Factor	Influence
pH	Both the distribution and concentration of DBPs vary with pH. Increase in TTHM formation has been observed with increases in pH
Nature and concentration of NOM	TTHM formation is directly proportional to NOM concentration at the time of chlorination
Total organic carbon (TOC)	Used as a surrogate parameter for NOM
Dissolved organic carbon (DOC)	Used as a surrogate parameter for NOM
UV-254 absorbance	Used as a surrogate parameter for NOM
Water Temperature and Season	TTHM concentrations tend to increase and form more rapidly with increasing temperature
Bromide level	In the presence of bromide, both chlorinated and brominated species are formed
Contact time	A longer reaction or contact time generally leads to greater TTHM formation
Chlorine dose	The formation of TTHMs increases with chlorine concentration

A number of studies have been conducted in an attempt to model the formation of TTHMs in drinking water. Empirical models have been developed using regression equations to link water quality parameters and operational parameters with TTHM formation in drinking water. Models are available based on both water quality data from utilities (raw and treated water) (Milot et al. 2000; Rodriguez et al. 2000; Singer et al. 1995) as well as raw water samples that are subject to chlorine concentrations in a bench-scale application (Amy et al. 1998; Rathbun 1996). Kinetic-based models have also been developed for predicting TTHM formation (Westerhoff et al. 2002; Clark et al. 2001; Clark and Sivaganesan 1998). These models estimate the formation of TTHMs through consideration of chemical kinetic relationships and compound stability (USEPA 2002). Additionally, the USEPA developed the Water Treatment Plant (WTP) model that utilizes empirical correlations to estimate NOM removal, DBP formation, and water quality at various points in the treatment process (Solarik et al. 2000). The location in the plant where chlorination occurs can influence TTHM formation (Clark and Boutin 2001), therefore it is important to incorporate treatment process removal into TTHM formation predictions.

Total trihalomethanes may also continue to form in the distribution system due to continued reactions with chlorine (Sohn et al. 2001; Garcia-Villanova et al. 1997). This continued formation is important to evaluate as the Stage 2 Regulations will mandate compliance at each sampling location in the distribution system. A table of the models evaluated is presented below in Table 6.2.2.

Table 6.2.2 TTHM Formation Models

Model	Water	Regression Model	n	r^2
		Empirical Regression Models		
Bench-scale data	Raw/Untreated	$TTHM = 0.044(DOC)^{1.03}(t)^{0.262}(pH)^{1.149}(D)^{0.277}(T)^{0.968}$	1463	0.90
Field-scale Site 2	Direct Chlorination	$TTHM = 1.392(DOC_{raw})^{1.092}(pH_{raw})^{0.531}(T)^{0.255}$		0.34
Field-scale Site 3	Direct Chlorination	$TTHM = -132.2 + 7.5(DOC_{raw}) + 14.5(pH_{raw}) + 2.0(T) + 48.4(FC)$		0.57
Amy et al. 1987	Raw/Untreated	$TTHM = 0.00312(UV{*}TOC)^{0.440}(D)^{0.409}(t)^{0.265}(T)^{1.06}(pH-2.6)^{0.715}(Br+1)^{0.036}$	995	0.90
Rathbun 1996	Raw/Untreated	$THM = 14.6(pH-3.8)^{1.01}(Cl)^{0.206}(UV254)^{0.849}(t)^{0.306}$	669	0.98
Amy et al. 1998	Raw/Untreated	$TTHM = 0.041(DOC)^{1.098}(Cl_2)^{0.152}(Br^-)^{0.068}(T)^{0.609}(pH)^{1.601}(t)^{0.263}$	786	0.90
Amy et al. 1998	Coagulated-Water: Alum	$TTHM = 4.47(DOC)^{0.752}(Cl_2)^{0.246}(Br^-)^{0.185}(t)^{0.258}$	143	0.87
Amy et al. 1998	Coagulated-Water: Iron	$TTHM = 2.44(DOC)^{0.839}(Cl_2)^{0.287}(Br^-)^{0.259}(t)^{0.270}$	143	0.88
Amy et al. 1998	Coagulated-Water: Alum plus Iron	$TTHM = 3.30(DOC)^{0.801}(Cl_2)^{0.261}(Br^-)^{0.223}(t)^{0.264}$	287	0.87
		Kinetic Formation Model		
Clark Model		$TTHM = D(C_{Ao} - (C_{Ao}(1-K)/1-Ke^{-ut}))$		

A number of empirical models are available to estimate TTHM formation. Singer et al (1995) investigated a number of DBPs, including TTHMs, in chlorinated drinking waters from 6 utilities in North Carolina to evaluate the relationships among different by-products, as well as the effects of water quality. Regression analyses were used to explore potential relationships between TTHM formation and chlorine consumption. A correlation coefficient (r) of 0.805 was found suggesting that chlorine consumption is a reasonably good indicator of DBP formation. This approach indirectly considers reaction time as a parameter for DBP formation through the effects of reaction time on chlorine decay (Westerhoff et al. 2000).

Rodriguez (2000) investigated compliance with stricter TTHM standards for utilities in Canada that utilize a surface water source and disinfect with free chlorine. Regression models of TTHM formation in these chlorinated surface waters were developed using both bench-scale and field data studies. The models were then used in combination with the EPA-water treatment model (WTP) to evaluate the effect of three different treatment strategies for THM precursor material removal (Rodriguez et al. 2000).

The model was developed using three databases of bench-scale data. Dissolved organic carbon (DOC) concentrations between 1.0 and 8.0 mg/L were considered, resulting in 1483 observations. A multivariate regression model for TTHM formation was developed using a step-wise statistical method such that parameters are added to the model and evaluated for significance one at a time, such that:

$$\mathrm{TTHM} = 0.044(\mathrm{DOC})^{1.03}(t)^{0.262}(\mathrm{pH})^{1.149}(D)^{0.277}(T)^{0.968}$$

Where:
DOC = dissolved organic carbon (mg/L);
t = contact time (hours);
D = chlorine dose (mg/L);
T = water temperature (°C).

Additional TTHM models were developed using field data from distribution systems of Quebec. Two sites were considered, and the models are as follows:

Site 2: $\mathrm{TTHM} = 1.392(\mathrm{DOC}_{raw})^{1.092}(\mathrm{pH}_{raw})^{0.531}(T)^{0.255}$
Site 3: $\mathrm{TTHM} = -132.2 + 7.5(\mathrm{DOC}_{raw}) + 14.5(\mathrm{pH}_{raw}) + 2.0(T) + 48.4(\mathrm{FC})$

Where:
DOC_{raw} = raw water dissolved organic carbon (mg/L);
FC = free residual chlorine (mg/L).

TOC removal equations from the WTP model were used to simulate water quality changes after standard conventional treatment, conventional treatment with enhanced coagulation, and conventional treatment with GAC filtration. These equations, combined with the TTHM models, were used to evaluate the effectiveness of the process configurations in meeting the TTHM regulations based on raw water quality.

Rathbun (1996) investigated the formation of TTHMs using raw water samples from the Mississippi, Ohio, and Missouri Rivers. THM formation potential was evaluated as a function of pH, initial free-chlorine concentration and reaction time at a constant temperature of 25 °C. A parameter was incorporated for pH (3.8) to account for the pH range below which TTHMs do not form. Multiple linear regression equations were developed, with the final prediction equation for THM formation potential represented as:

$$\mathrm{THM} = 14.6(\mathrm{pH}-3.8)^{1.01}(\mathrm{Cl})^{0.206}(\mathrm{UV254})^{0.849}(\mathrm{t})^{0.306}$$

Where: Cl = initial free-chlorine concentration (mg/L);
t = contact time (hours).

Empirical models are also available for TTHM formation in waters subject to treatment for DBP precursor (NOM, represented as DOC) removal. Weight-based and molar-based models for predicting TTHM formation in raw/untreated water have also been developed (Amy et al. 1998). These models were based on data from 11 source waters and include six independent variables: DOC, chlorine dose, bromide levels, temperature, pH and reaction time. The effect of coagulation on THM formation was also investigated, and models were developed for both iron and alum treated drinking waters. Coagulation has been shown to not only remove bulk DOC, but may also preferentially remove more reactive THM precursors (Amy et al. 1998). Coagulated water models for TTHM were developed at pH=7.5, and temperature of 20, and are as follows:

ALUM : $\mathrm{TTHM} = 4.47(\mathrm{DOC})^{0.752}(\mathrm{Cl_2})^{0.246}(\mathrm{Br^-})^{0.185}(\mathrm{t})^{0.258}$
IRON : $\mathrm{TTHM} = 2.44(\mathrm{DOC})^{0.839}(\mathrm{Cl_2})^{0.287}(\mathrm{Br^-})^{0.259}(\mathrm{t})^{0.270}$
BOTH: $\mathrm{TTHM} = 3.30(\mathrm{DOC})^{0.801}(\mathrm{Cl_2})^{0.261}(\mathrm{Br^-})^{0.223}(\mathrm{t})^{0.264}$

Where: DOC = dissolved organic carbon in coagulated water (mg/L);
t = reaction time (hours);
$\mathrm{Cl_2}$ = applied chlorine (mg/L);
$\mathrm{Br^-}$ = concentration of Bromide (ug/L).

The major objective was to determine a coagulant dose that would provide a targeted DOC reduction within the range of 25 to 50%.

Clark et al. (1998) developed a kinetic model to predict chlorine residuals and the formation of TTHMs in drinking water using bench scale chlorination experiments. The variables considered included pH, temperature, initial concentration of chlorine and TOC. A separate study conducted in 2001 utilized the same kinetic model, but looked only at pH, initial concentration of chlorine, concentration of bromide ion, and time of reaction (Clark and Sivaganesan 1998). The kinetic model developed for TTHM formation in treated drinking water, based on chlorine decay, is as follows:

$$\mathrm{TTHM} = D\left[C_{Ao} * \left(\frac{C_{Ao}(1-K)}{1-Ke^{-ut}}\right)\right]$$

Where: C_{Ao} = initial chlorine residual (mg/L);
D = ratio of TTHM formed to chlorine consumed;
K = dimensionless parameter from chlorine decay equation;
u = dimensionless parameter from chlorine decay equation;
M = estimated value of TTHM at time zero;
T = reaction time (minutes).

The parameters used above (D,K) are estimated using regression models developed on the basis of water quality characteristics, including TOC, pH, temperature, and initial chlorine residual level. The following models are used to predict the parameters:

$$K = e^{0.32}(C_{Ao})^{-0.44}(\mathrm{TOC})^{0.63}(\mathrm{pH})^{-0.29}(\mathrm{temp})^{0.14}$$
$$D = e^{1.49}(C_{Ao})^{-0.48}(\mathrm{TOC})^{0.18}(\mathrm{pH})^{0.96}(\mathrm{temp})^{0.28}$$

The WTP Model simulates the formation of THMs and HAAs under conditions of full scale treatment plants through use of empirical equations. DBP formation equations used in the WTP model for treated waters are based on the work of Amy et al. (1998) using both iron and alum coagulated waters. These equations, however, are based on treated water quality parameters: TOC, UVA, pH, and Br. The TTHM equations for treated water use a combined TOC and UVA input parameter to account for the impact of treatment on NOM removal as well as NOM reactivity, such that:

$$\mathrm{TTHM} = 23.9(\mathrm{TOC}*\mathrm{UVA})^{0.403}(\mathrm{Cl}_2)^{0.225}(\mathrm{Br}^-)^{0.141}(1.027)^{(T-20)}(1.156)^{(\mathrm{pH}-7.5)}(t)^{0.264}$$

Where: TTHM = treated water TTHM (mg/L);
TOC = treated water TOC (mg/L);
UVA = treated water UVA (mg/L);
Cl_2 = applied chlorine (mg/L);
Br^- = concentration of Bromide (ug/L);
t = reaction time (hours).

The WTP model includes equations to estimate DBP precursor removal by individual process units in the process train (e.g. removal from coagulation). Additionally, the model predicts changes in pH throughout the treatment process.

6.2.2 Use of Models

There are a number of advantages to using models that were developed on the basis of bench-scale data. These include the ability to control operation parameters (i.e. dose, temperature, pH), and the ease of monitoring contact time (Rodriguez et al. 2000). In addition, development of bench scale empirical models allows for the integration of a large number of variables and suggests more widespread applicability (Milot et al. 2000).

Existing empirical models can provide accurate predictions of the formation of TTHM's in chlorinated waters as a function of reaction time, however these models have been largely based on raw/untreated waters. When these models are then applied to treated waters, it is often assumed that the form of the precursor remaining after treatment is the same as that found in the raw water (Amy et al. 1998). However, water with high levels of NOM may not produce high levels of TTHM if it is submitted to appropriate chemical and physical treatment (Milot et al. 2000). Therefore in order to more accurately predict TTHM formation after conventional treatment, models using treated water will be utilized in this work.

6.3 Additional Results

Additional results are presented for two alternative treatment cost models, the USBR WaTER model and the Clark and Morand (1981) model. The WaTER model includes cost estimation routines for both capital and O&M for both conventional treatment as well as desalination. The Clark model only provides cost estimates for conventional treatment, so the Sethi and Wiesner (2000) model is utilized for desalination cost estimates. Results are presented first as treatment costs, followed by comparative analyses that include the addition of acquisition costs, regulatory costs and storage costs in respective order.

6.3.1 Water Treatment Estimation Routine (WaTER)

6.3.1.1 Conventional Treatment

Conventional treatment cost estimates are calculated using the Water Treatment Estimation Routine (WaTER) developed by the US Bureau of Reclamation. The model estimates cost for individual water treatment processes based on a number input parameters, including raw water quality (e.g. pH, TDS, TSS, temperature), plant capacity and operating parameters (e.g. chemical dose rates). Treatment processes included in the WaTER model vary slightly from the standard conventional treatment train as an upflow-solids contact clarifier was used in place of separate coagulation, flocculation, and sedimentation basins. Raw water quality data was based on several selected surface waters and default plant operating parameters defined by USBR (1999).

The WaTER model is used to develop estimates of treatment costs ($/kgal) for conventional treatment plants over capacities ranging from 1 to 30 MGD. Capital costs are returned in $1000's and O&M costs in $/year for each individual process. Capital costs are then annualized and updated to the current year, added to O&M costs and divided by the average operating capacity to get water treatment cost in $/kgal. Cost equations for the individual treatment processes are presented in Appendix 6.1.

As the WATER model estimates the costs for each individual treatment process, some general factors relating to the cost of the entire project are not included. These include costs of general contractor overhead and profit, engineering, land, legal, fiscal, administrative and interest cost during construction. In order to account for these costs, 28% of the total capital cost was added to the total capital cost as suggested by Qasim et al (1992).

Table 6.3.1 Conventional Treatment Cost Parameters for WaTER

Input Parameters	Units	Value
Conventional Treatment		
Raw Water Quality		
Bicarbonate Alkalinity	mg/L	25
TSS	mg/L	5
Chemical Costs		
Chlorine	$/ton	20
Alum	$/lbs	15
Chemical Doses		
Polymer	mg/L	0.5
Disinfection Residual	mg/L	3
Process Parameters		
Gravity Filtration		Coal and Sand
Upflow Solids Contact Clarifier		2 Clarifiers

6.3.1.2 Membrane Desalination

Desalination cost estimates are calculated using the WaTER model (USBR 1999). The membrane process chosen for brackish water desalination is low-pressure reverse osmosis (RO). Cost estimates from WaTER are available for each individual process, and are summed to estimate costs for desalination of brackish water for plant capacities over the range of 1 to 30 MGD. Pretreatment via cartridge filters is already included in the RO cost estimates. Costs for two additional pre-treatment processes are included in the case of a surface water: microfiltration (MF) and conventional treatment. Total desalination treatment costs are the sum of annualized capital and O&M costs in $/year, divided by the annual operating capacity ($/kgal).

Table 6.3.2 Desalination Treatment Cost Parameters for WaTER

Input Parameters	Units	Value
Desalination Treatment		
TDS	mg/L	2000
Membrane Diameter	cm	20.32
Recovery	%	0.85
Transmembrane Pressure	kPa	2757
Membrane Life	years	5
Electricity Cost	$/kWh	0.07

6.3.1.3 WaTER Treatment Cost Comparison

A comparison between conventional and desalination treatment costs for both fresh and brackish surface and groundwaters is presented (Figure 6.3.1). As expected, conventional treatment costs are less than those for desalination. Treatment for fresh groundwater is limited to disinfection, and treatment costs are therefore low.

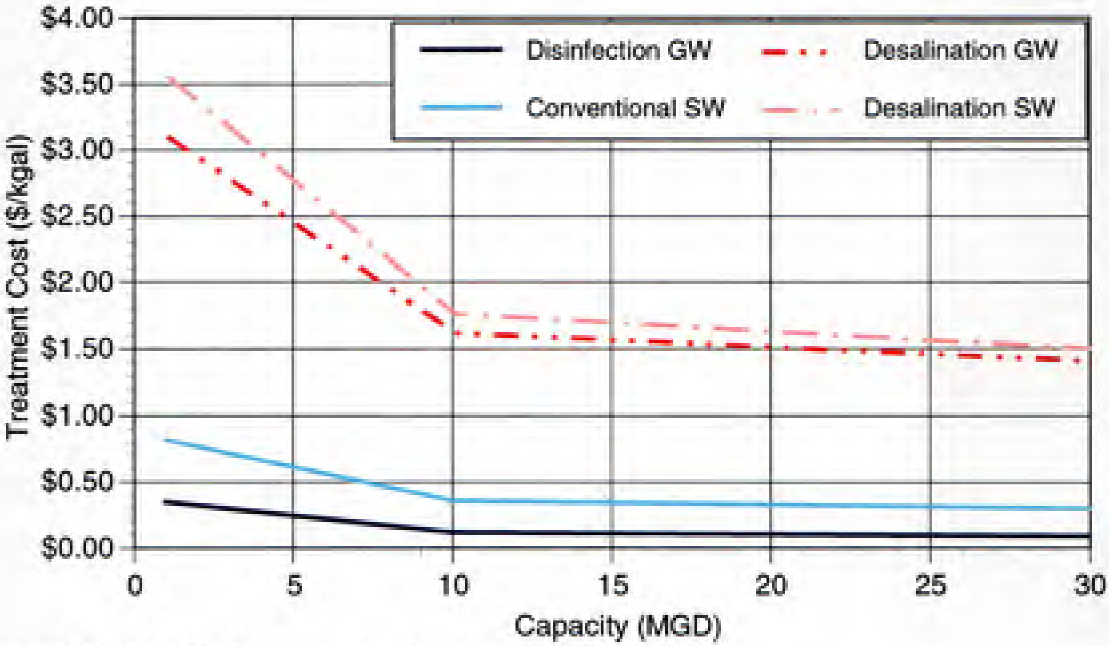

Figure 6.3.1 WaTER Treatment Cost Comparison

6.3.1.4 Addition of Acquisition Costs

Acquisition costs are added to the treatment cost estimates from WaTER for each source water. Each of the four scenarios is evaluated to investigate the cost effectiveness of brackish water desalination in terms of distance (miles) and grade (ft/1000ft) between the source and treatment plant (Table 6.3.3).

Table 6.3.3 Scenario Outline for Addition of Acquisition Costs

	Brackish Water Sources:	
Fresh Water Sources:	Local Brackish GW	Local Brackish SW
Distant Fresh SW	1A	2A
Distant Fresh GW	1B	2B

As explained in section 4.2, the results are presented in terms of iso-cost lines where the costs (treatment plus acquisition) for the fresh water source are equivalent to those of the brackish source located 1 mile from the plant at a grade of 5ft/1000ft. Similar to earlier results, membrane desalination is more economically attractive for smaller capacity plants.

It is important to note is that the addition of acquisition costs increases the attractiveness of a both brackish and fresh surface water sources compared to groundwater. Although treatment costs for surface waters are more expensive, the difference in acquisition costs is enough to make the surface water a less expensive option. This is shown in the comparison with brackish sources and a fresh surface water (Figures 6.3.2 and 6.3.4). The local brackish surface water becomes a more attractive option closer than the brackish groundwater. In addition, the crossover of the 1 and 10 MGD iso-cost lines seen in all of the comparisons is due to the steep increase in costs of treatment for brackish sources at 1 MGD as estimated using the WaTER model. This increase in costs is shown in Figure 6.3.1. Due to these higher costs for brackish water at 1 MGD, the iso-cost lines do not follow the same curve as those at 10 and 30 MGD.

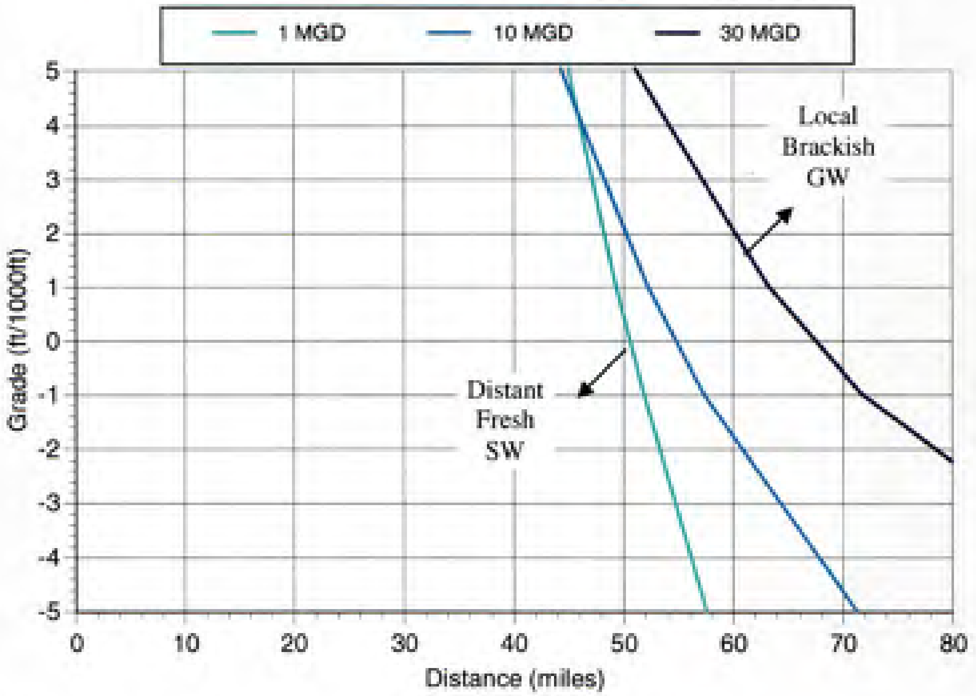

Figure 6.3.2 Local Brackish GW vs. Distant Fresh SW (1A)

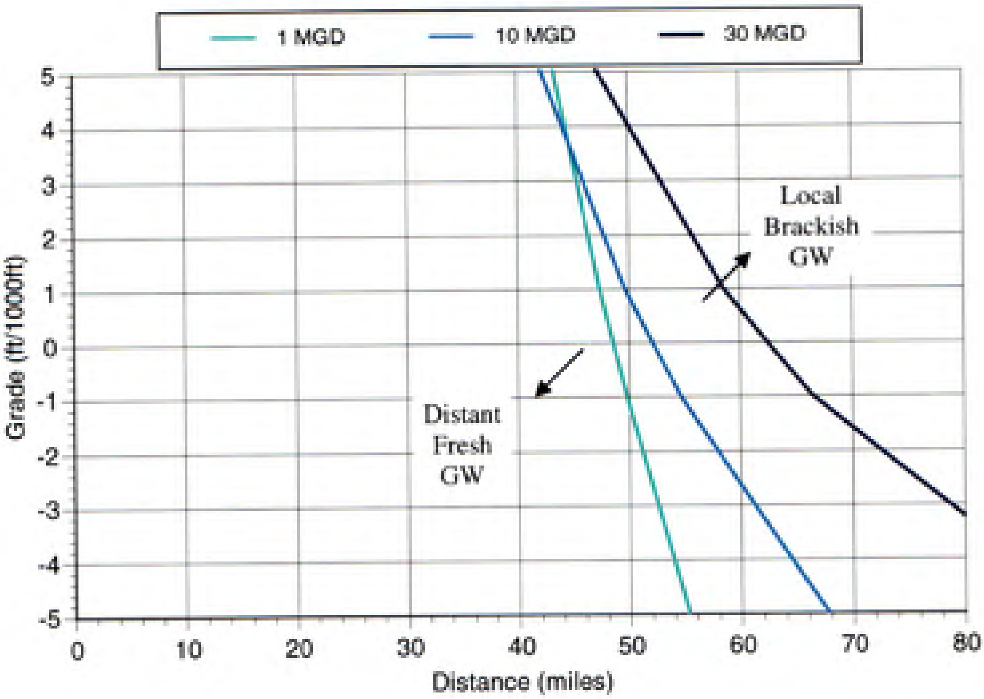

Figure 6.3.3 Local Brackish GW vs. Distant Fresh GW (1B)

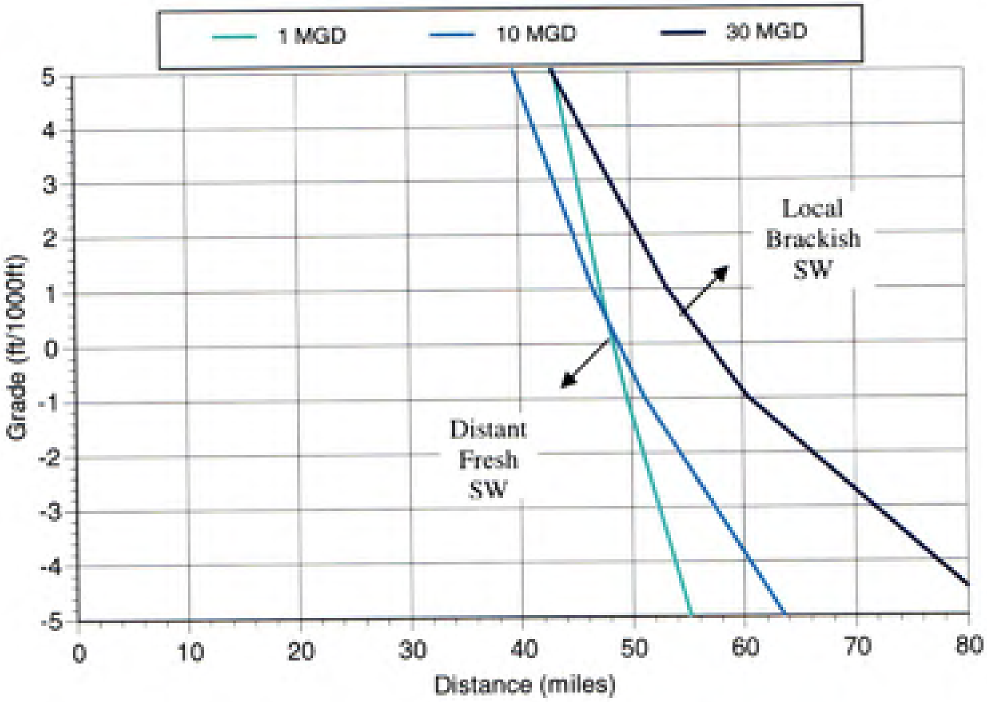

Figure 6.3.4 Local Brackish SW vs. Distant Fresh SW (2A)

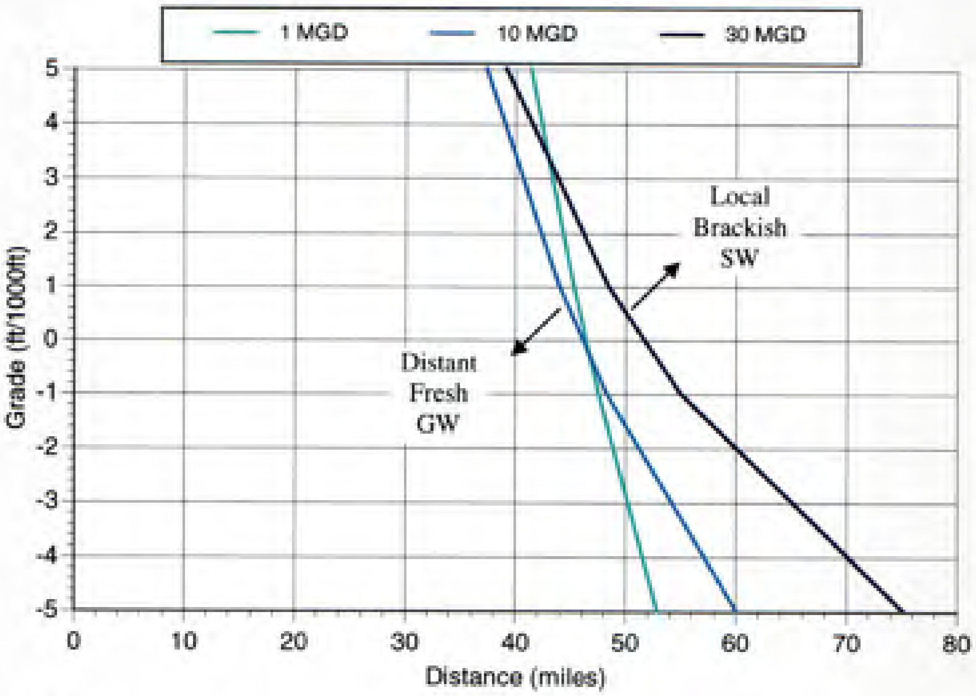

Figure 6.3.5 Local Brackish SW vs. Distant Fresh GW (2B)

6.3.1.5 Addition of Compliance Costs

Costs for maintaining regulatory compliance are added to the costs already considered. In order to maintain compliance with the TTHM MCL, ancillary processes to reduce TTHM formation are added to the treatment costs. As membrane desalination processes are able to effectively remove TOC (AWWA 1996; Clark et al. 1994), these processes are assumed to maintain regulatory compliance without any additions. Therefore, results from two scenarios (Table 6.3.4) considering only fresh surface water (with elevated levels of TOC) are presented.

Table 6.3.4 Scenarios for Regulatory Compliance

	Brackish Water Sources:	
Fresh Water Sources:	Local Brackish GW	Local Brackish SW
Distant Fresh SW with ancillary processes for TTHM reduction	1C	2C

Within each scenario, four ancillary processes for TTHM reduction are evaluated for the non-brackish water source:

- Enhanced Coagulation
- Alternative Disinfectants
    - Ozone as Pre-Disinfectant
    - Chloramine as Post-Disinfectant

- Granular Activated Carbon Filtration

In all of the figures below, the solid lines are the iso-cost lines from the previous figures that include consideration of standard conventional treatment and acquisition costs. The dashed lines indicate modified iso-cost lines including costs for ancillary processes to maintain compliance. The addition of these compliance costs increases the cost-competitiveness of the brackish sources for all scenarios. As the addition of chloramines and enhanced coagulation are relatively inexpensive, the shift in the iso-cost lines is not as prominent (Figures 6.3.6, 6.3.7, 6.3.10, 6.3.11). However, if GAC filtration is required to achieve compliance, the attractiveness of the brackish sources is greatly increased (Figures 6.3.9 and 6.3.13) and can reduce the distance a community would go for a fresh surface water by half.

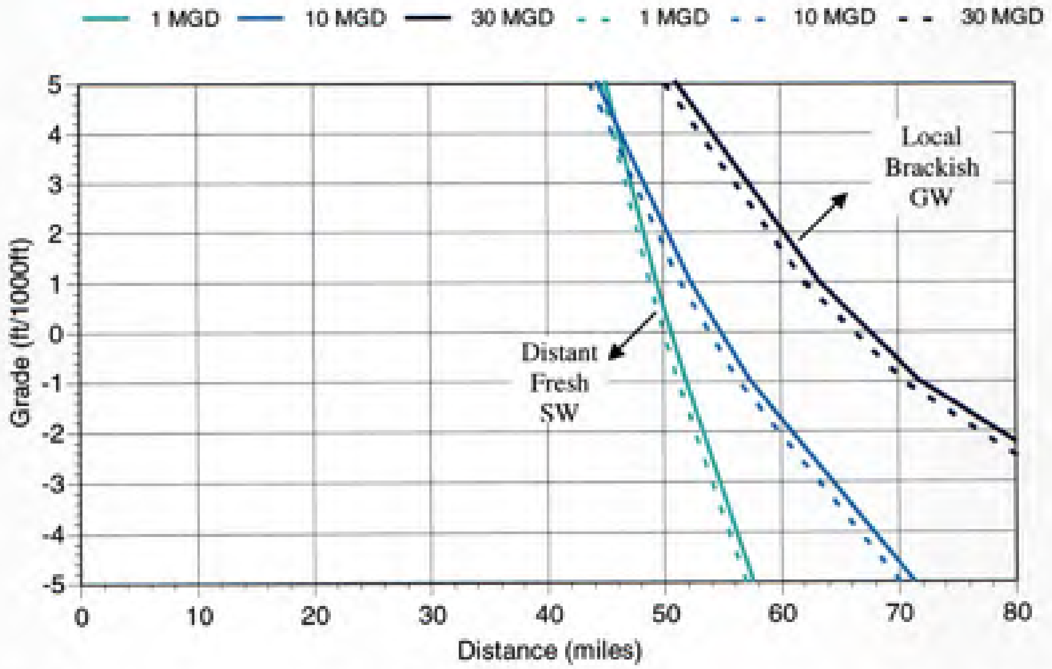

Figure 6.3.6 Distant Fresh Surface Water with Enhanced Coagulation vs. Local Brackish Groundwater (1C)

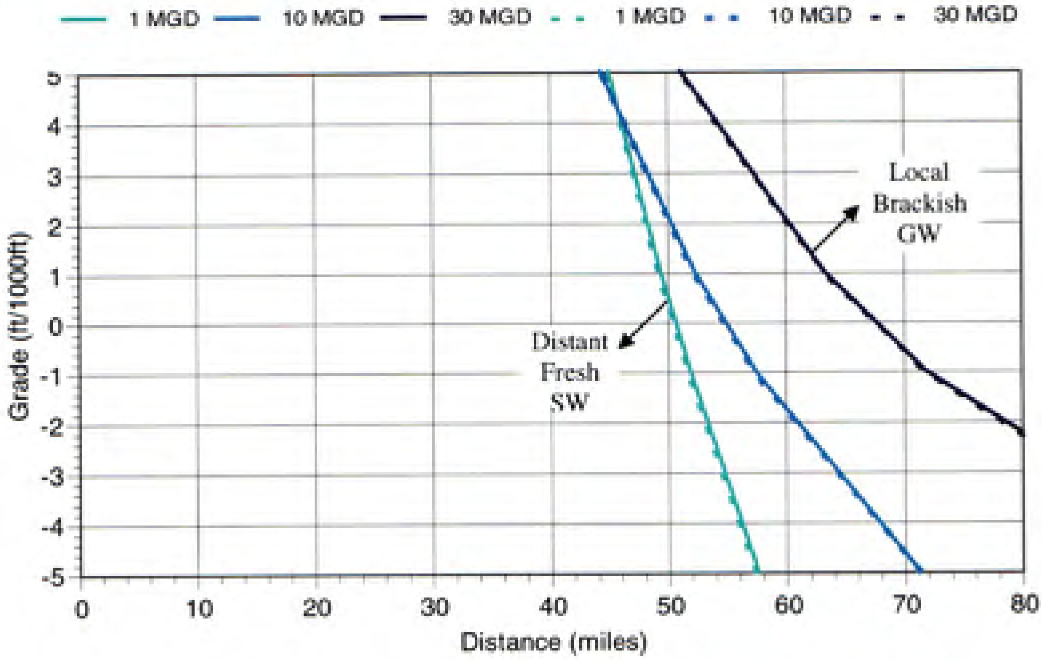

Figure 6.3.7 Distant Fresh Surface Water with Chloramines as Post-Disinfectant vs. Local Brackish Groundwater (1C)

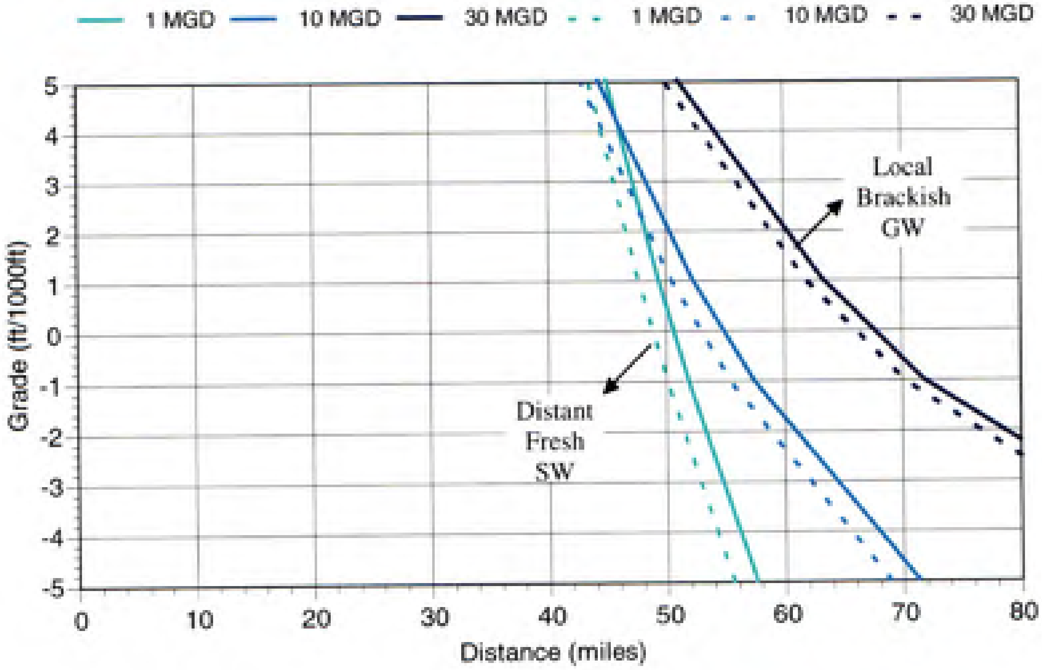

Figure 6.3.8 Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant vs. Local Brackish Groundwater (1C)

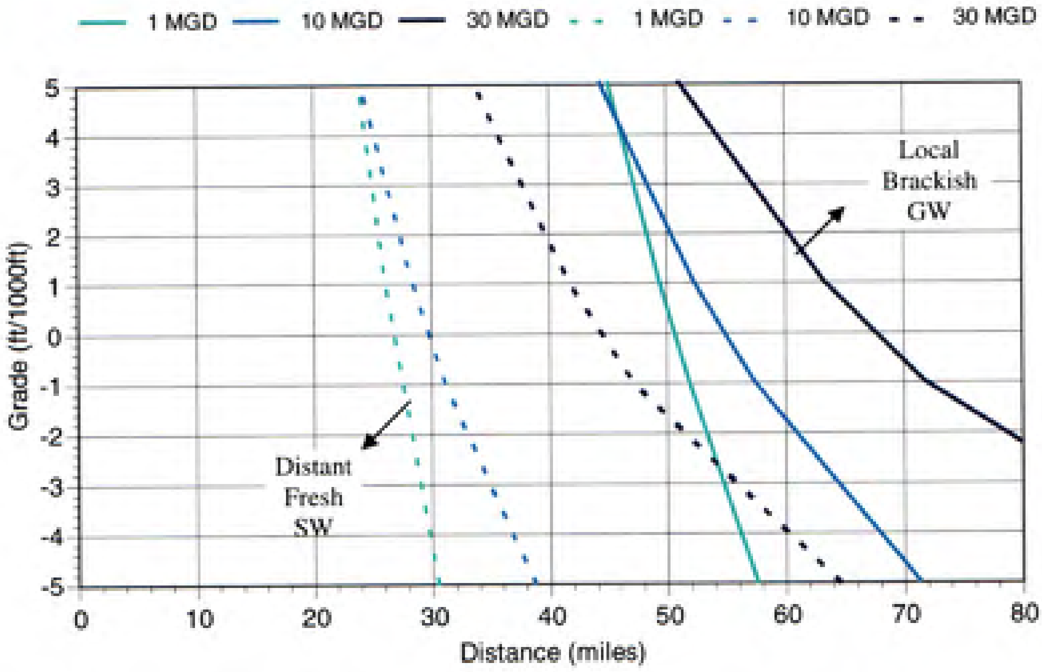

Figure 6.3.9 Distant Fresh Surface Water with GAC Filtration vs. Local Brackish Groundwater (1C)

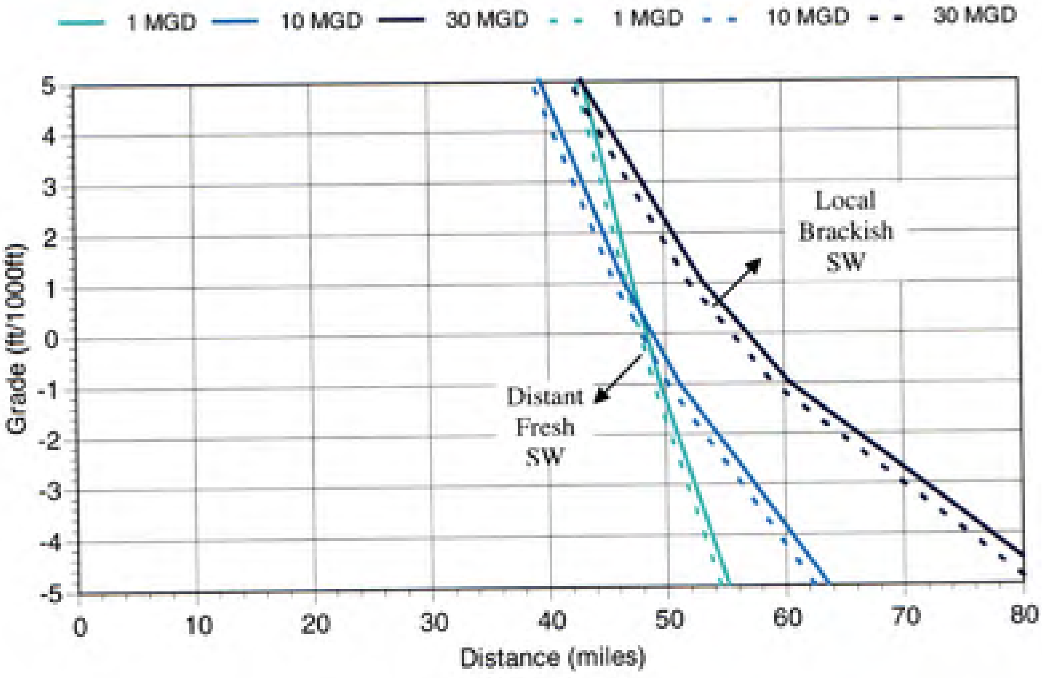

Figure 6.3.10 Distant Fresh Surface Water with Enhanced Coagulation vs. Local Brackish Surface Water (2C)

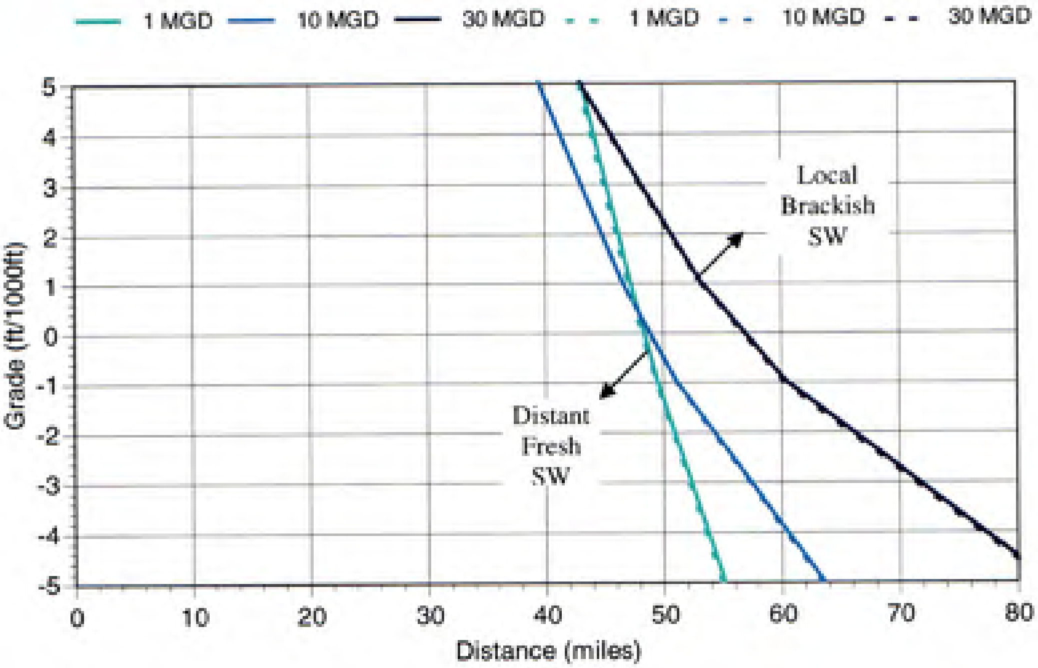

Figure 6.3.11 Distant Fresh Surface Water with Chloramines as Post-Disinfectant vs. Local Brackish Surface Water (2C)

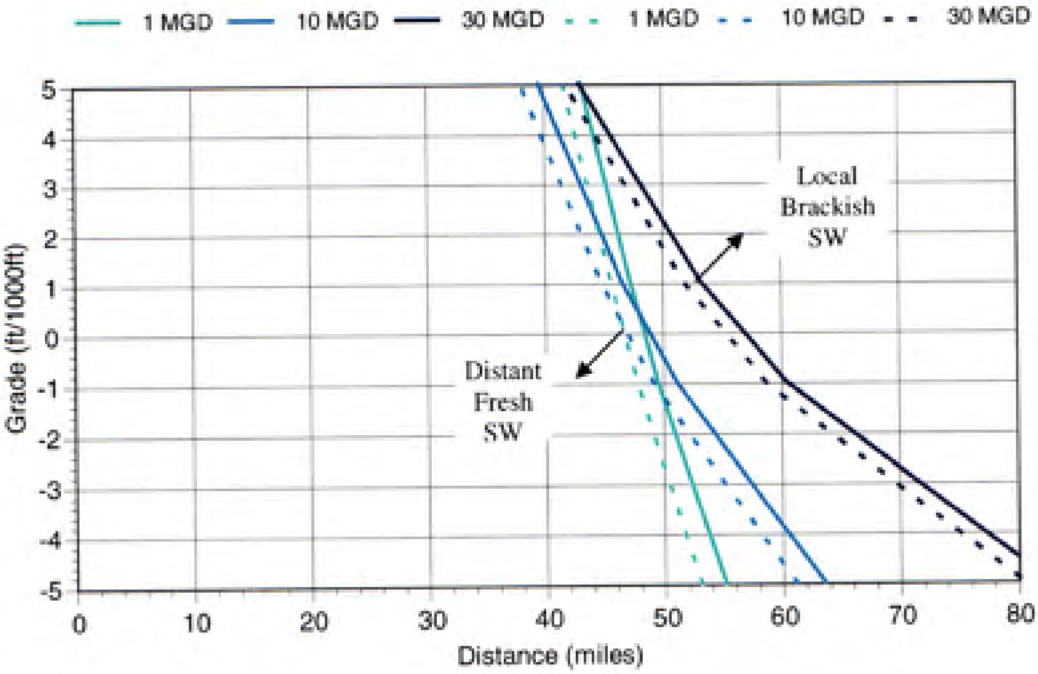

Figure 6.3.12 Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant vs. Local Brackish Surface Water (2C)

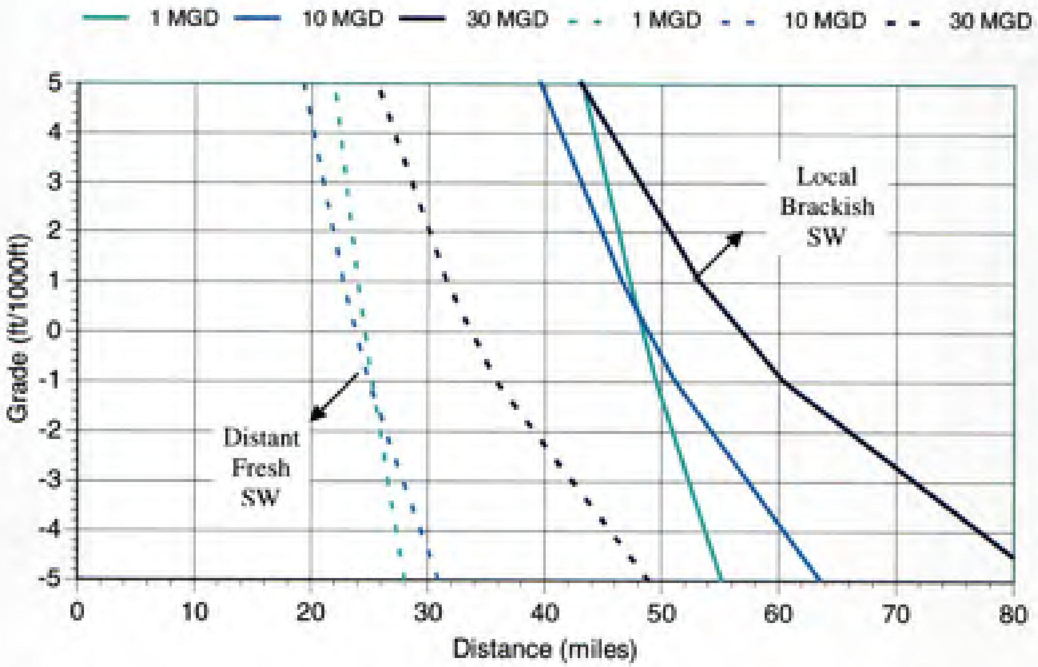

Figure 6.3.13 Distant Fresh Surface Water with GAC Filtration vs. Local Brackish Surface Water (2C)

6.3.1.6 Addition of Storage Costs

Storage costs are added to complete the total supply and treatment costs. Storage capacities for brackish resources are not considered a necessary component in the total cost of supply and treatment as these sources are relatively underdeveloped compared to fresh water sources. Therefore, costs for storage reservoirs with capacities corresponding to 3 months, 6 months, and 12 months of average daily flow (Q_{OP}) are estimated and added to the total supply and treatment costs for fresh water sources. In these scenarios, freshwater treatment includes the use of chloramines as a post-disinfectant for Stage 2 D/DBP Compliance (Table 6.3.5).

Table 6.3.5 Scenarios for Storage

	Brackish Water Sources:
Fresh Water Sources:	Local Brackish GW
Distant Fresh SW with chloramines as post-disinfectant	1D

The addition of storage costs to the total supply and treatment costs improves the attractiveness of brackish sources, especially for the smaller capacity plants. Costs for all components of the total supply and treatment metric are presented as well, in order to highlight the breakdown of costs for all source waters considered (Table 6.3.6). These cost estimates presented are for a fresh surface water source requiring 3 months storage and the use of chloramines to maintain compliance. These estimates were calculated using the parameters outlined in Chapter 3 for each cost component.

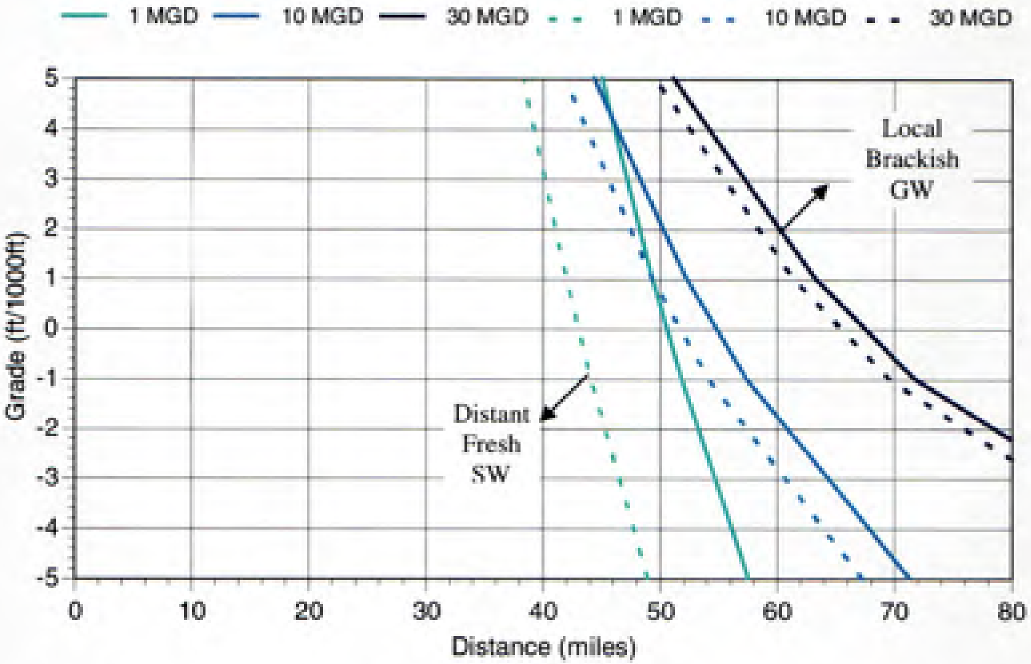

Figure 6.3.14 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 3 Month Storage vs. Local Brackish Groundwater (1D)

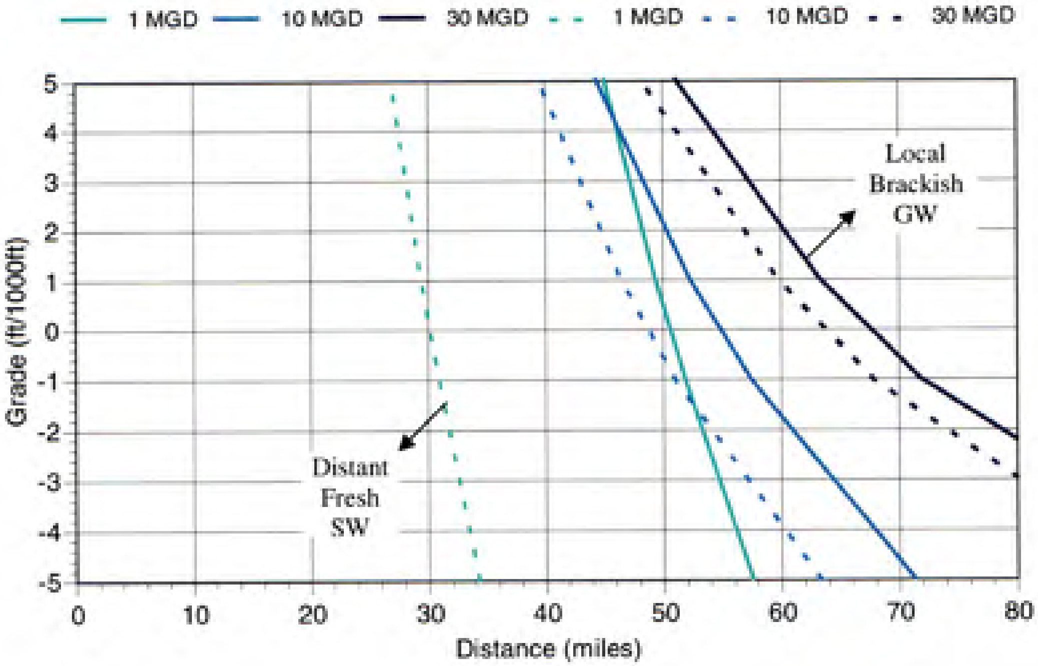

Figure 6.3.15 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 6 Month Storage vs. Local Brackish Groundwater (1D)

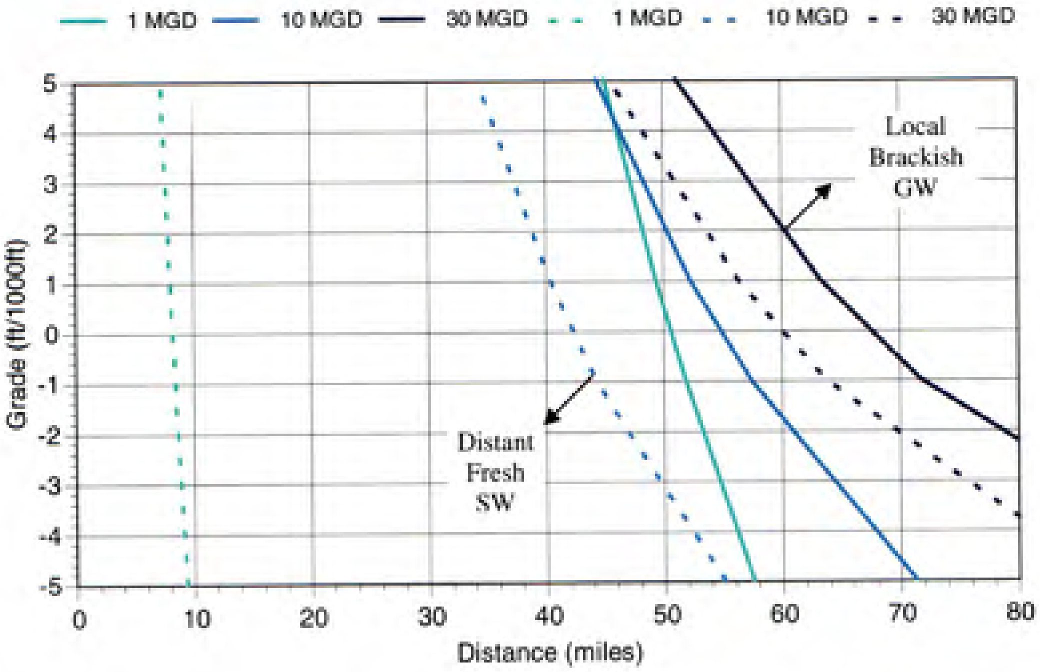

Figure 6.3.16 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 12 Month Storage vs. Local Brackish Groundwater (1D)

Table 6.3.6 Total Supply and Treatment Costs for Source Waters with 3 Month Storage

Source	Treatment Costs	Residuals Cost	Acquisition Costs	Storage Costs	Chloramine Costs	Sum
1.0 MGD						
Fresh SW	$0.80	$0.01	$0.24	$0.49	$0.02	$1.54
Fresh GW	$0.33	$0.01	$0.76	$0.49	$0.02	$1.59
Brackish SW	$2.84	$0.73	$0.24	NA	NA	$3.81
Brackish GW	$2.38	$0.73	$0.76	NA	NA	$3.87
10 MGD						
Fresh SW	$0.34	$0.01	$0.21	$0.09	$0.00	$0.65
Fresh GW	$0.10	$0.01	$0.47	$0.09	$0.00	$0.67
Brackish SW	$1.40	$0.37	$0.21	NA	NA	$1.98
Brackish GW	$1.26	$0.37	$0.47	NA	NA	$2.10
30 MGD						
Fresh SW	$0.28	$0.01	$0.14	$0.04	$0.01	$0.47
Fresh GW	$0.07	$0.01	$0.41	$0.04	$0.01	$0.53
Brackish SW	$1.19	$0.32	$0.14	NA	NA	$1.65
Brackish GW	$1.10	$0.32	$0.41	NA	NA	$1.83

6.3.2 Clark and Morand Model

This model is based on conventional cost relationships developed by Clark and Morand (1981) and desalination cost estimates from the Sethi and Wiesner (2000) model.

6.3.2.1 Conventional Treatment

Clark and Morand's (1981) work is also based on cost relationships developed by Gumerman (1979). Essentially, the separate process equations were used to develop power functions as follows:

$$C_{CAP}^{CONV} = 192Q_{DES}^{0.7}$$

Where: C_{CAP}^{CONV} = Capital cost ($1000/year);
Q_{DES} = Design capacity (MGD).

$$C_{O\&M}^{CONV} = 45.849.4Q_{OP}^{0.80}$$

Where: $C_{O\&M}^{CONV}$ = O &M cost ($1000/year);
Q_o = Operating capacity (MGD).

The total treatment cost (capital + O&M) for fresh surface water is then calculated in $/kgal.

6.3.2.2 Membrane Desalination

The model used to estimate costs for brackish water desalination is based on work by Sethi and Wiesner (2000), as explained in Section 3.2.2.1.

6.3.2.3 Clark and Morand Treatment Cost Comparison

Treatment costs are evaluated for both conventional and membrane desalination for both surface water and groundwater sources. As seen in previous results, standard conventional treatment costs for fresh waters are less than brackish water desalination for all capacities considered. Groundwater treatment consists of only disinfection, and is therefore much lower than all other treatment costs.

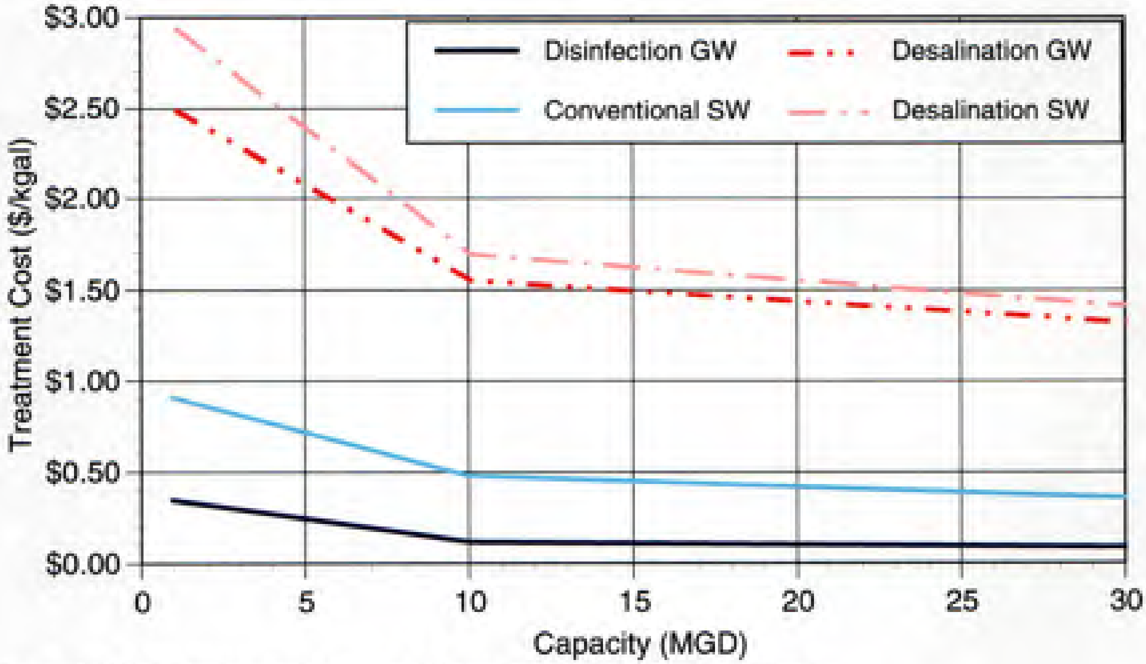

Figure 6.3.17 Clark and Morand Treatment Cost Comparison

6.3.2.4 Addition of Acquisition and Conveyance Costs

Acquisition costs are added to the treatment cost estimates from WaTER for each source water. Each of the four scenarios is evaluated to investigate the cost effectiveness of brackish water desalination in terms of distance (miles) and grade (ft/1000ft) between the source and treatment plant (Table 6.3.7).

Table 6.3.7 Scenario Outline

Fresh Water Sources:	Brackish Water Sources: Local Brackish GW	Local Brackish SW
Distant Fresh SW	1A	2A
Distant Fresh GW	1B	2B

As explained in section 4.2, the results are presented in terms of iso-cost lines where the costs (treatment plus acquisition) for the fresh water source are equivalent to those of the brackish source located 1 mile from the plant at a grade of 5ft/1000ft. Similar to earlier results, membrane desalination is more economically attractive for smaller capacity plants.

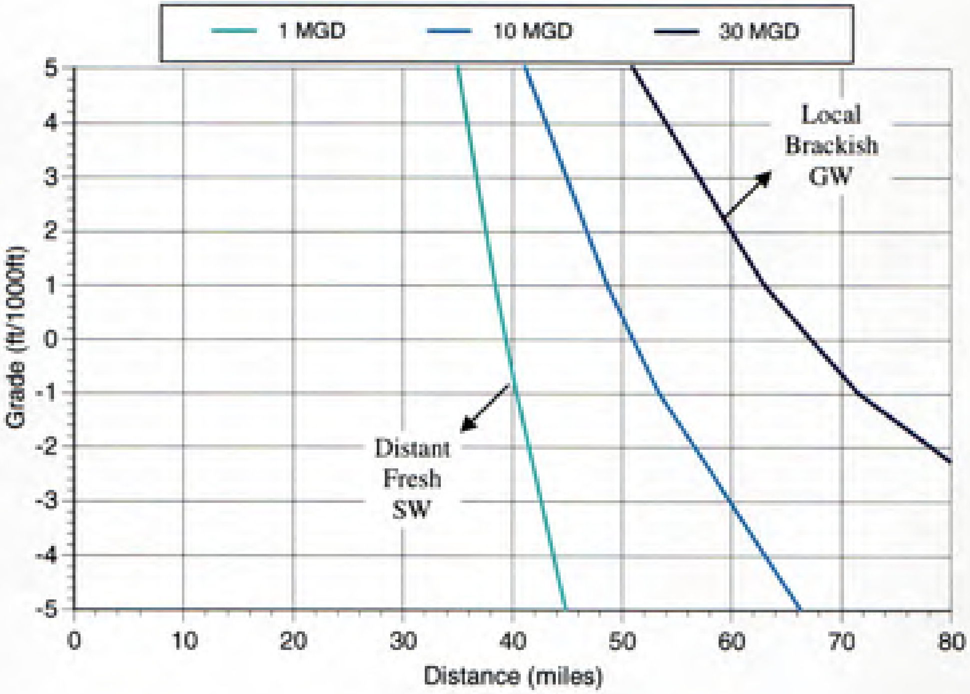

Figure 6.3.18 Local Brackish GW vs. Distant Fresh SW (1A)

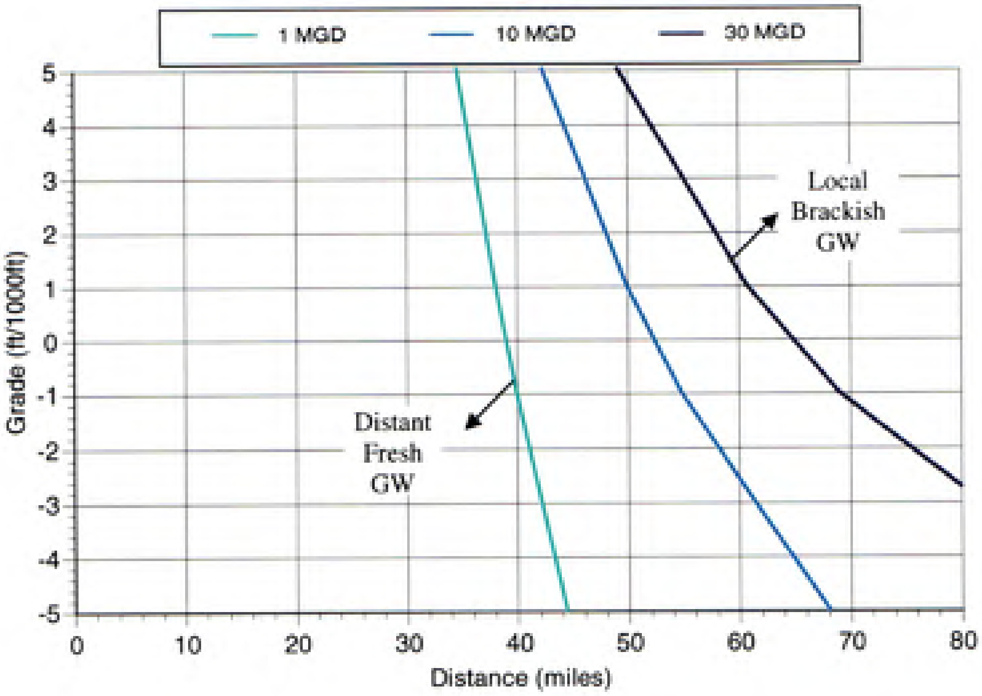

Figure 6.3.19 Local Brackish GW vs. Distant Fresh GW (1B)

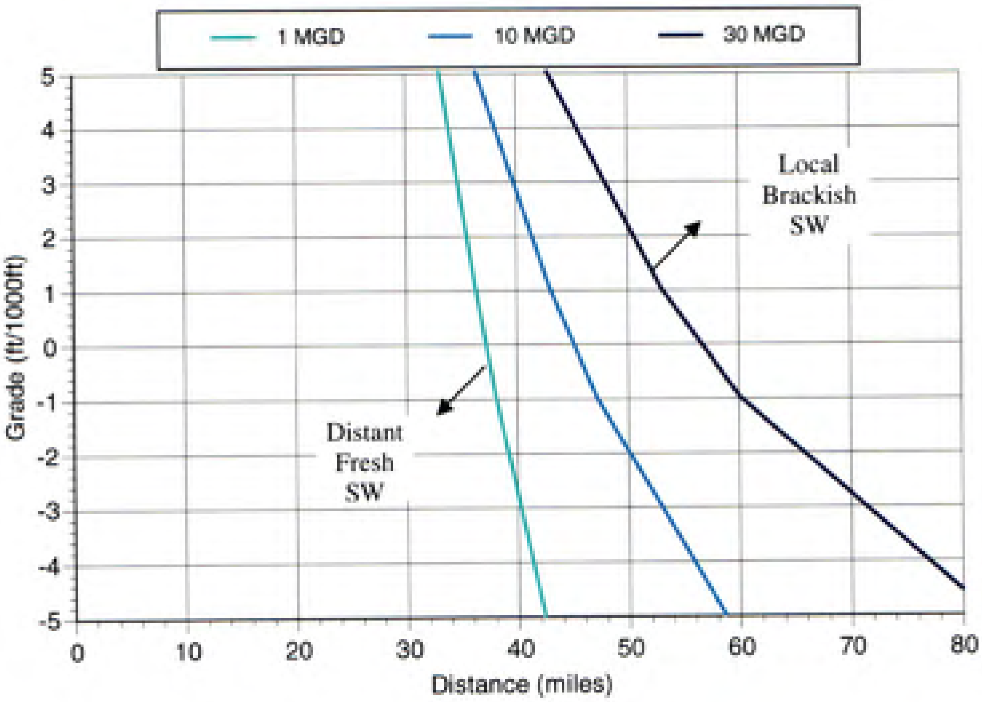

Figure 6.3.20 Local Brackish SW vs. Distant Fresh SW (2A)

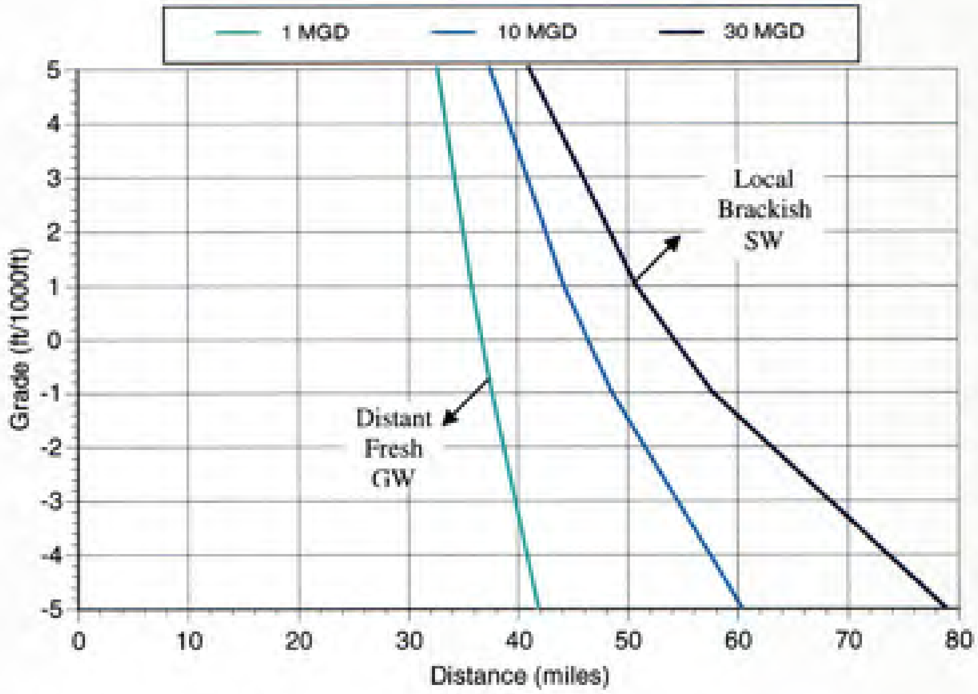

Figure 6.3.21 Local Brackish SW vs. Distant Fresh GW (2B)

6.3.2.5 Addition of Compliance Costs

Compliance costs are added to the costs already considered. Ancillary processes to reduce TTHM formation are added to the treatment costs n order to maintain compliance with the TTHM MCL. Membrane desalination processes are assumed to maintain regulatory compliance without any additions (AWWA 1996; Clark et al. 1994). Therefore, results from two scenarios (Table 6.3.8) considering only fresh surface water (with elevated levels of TOC) are presented.

Table 6.3.8 Scenarios for Regulatory Compliance

Fresh Water Sources:	Brackish Water Sources:	
	Local Brackish GW	Local Brackish SW
Distant Fresh SW with ancillary processes for TTHM reduction	1C	2C

Within each scenario, four ancillary processes for TTHM reduction were evaluated for the non-brackish water source:

- Enhanced Coagulation
- Alternative Disinfectants
    - Ozone as Pre-Disinfectant
    - Chloramine as Post-Disinfectant
- Granular Activated Carbon Filtration

In all of the figures below, the solid lines are the iso-cost lines from the previous figures (Figure 6.3.18 - 6.3.21) that include consideration of standard conventional treatment and acquisition costs. The dashed lines indicate iso-cost lines modified by the addition of ancillary processes to maintain compliance. Overall, the addition of compliance costs increases the cost-competitiveness of the brackish sources for all scenarios considered. The shift in the iso-cost lines is not as prominent for the addition of chloramines and enhanced coagulation as these are the least expensive ancillary processes considered (Figures 6.3.22, 6.3.23, 6.3.26, 6.3.27). However, with the addition of GAC filtration, the attractiveness of the brackish sources is greatly increased (Figures 6.3.25 and 6.3.29).

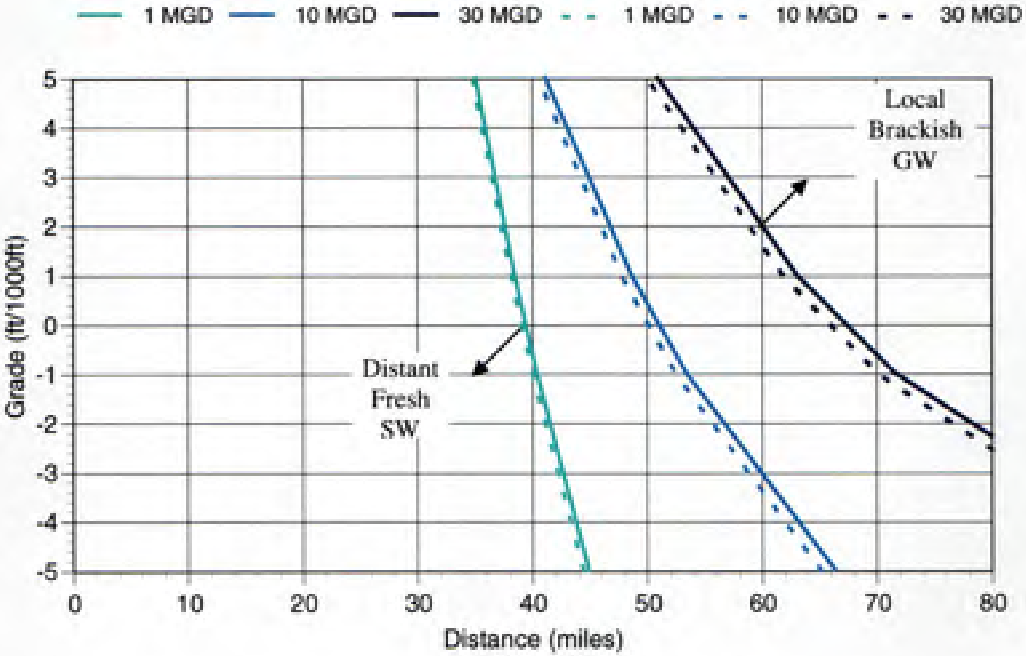

Figure 6.3.22 Distant Fresh Surface Water with Enhanced Coagulation vs. Local Brackish Groundwater (1C)

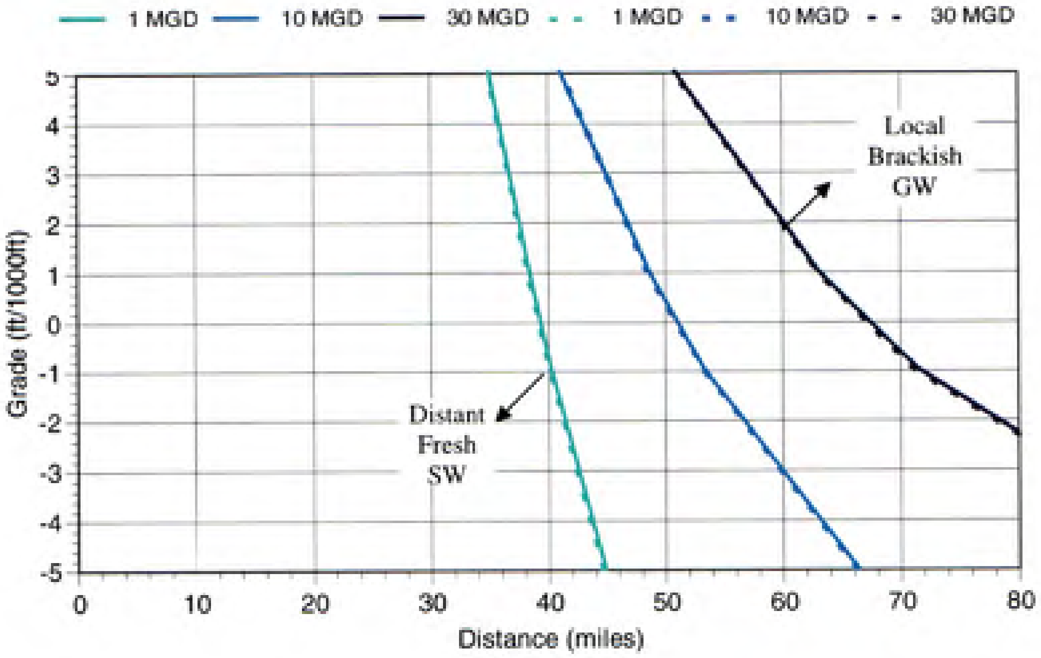

Figure 6.3.23 Distant Fresh Surface Water with Chloramines as Post-Disinfectant vs. Local Brackish Groundwater (1C)

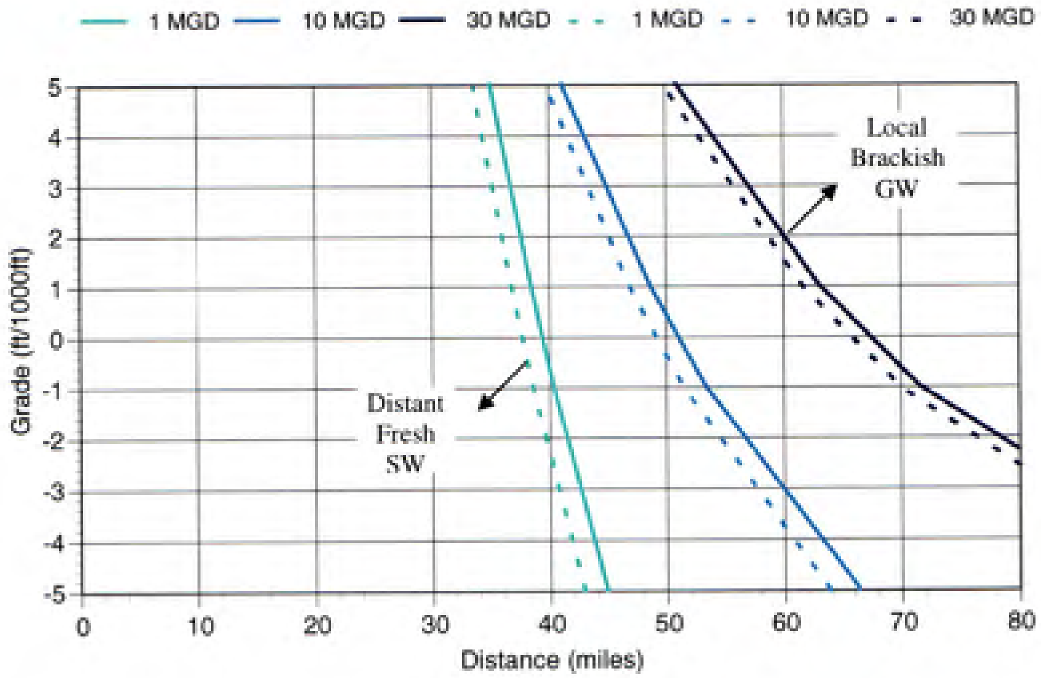

Figure 6.3.24 Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant vs. Local Brackish Groundwater (1C)

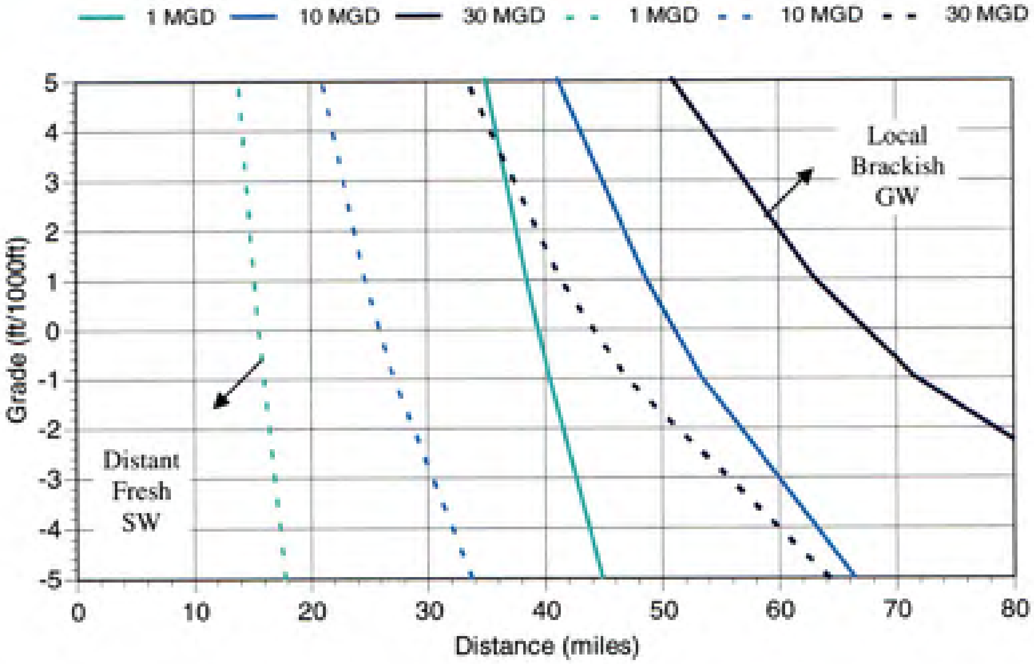

Figure 6.3.25 Distant Fresh Surface Water with GAC Filtration vs. Local Brackish Groundwater (1C)

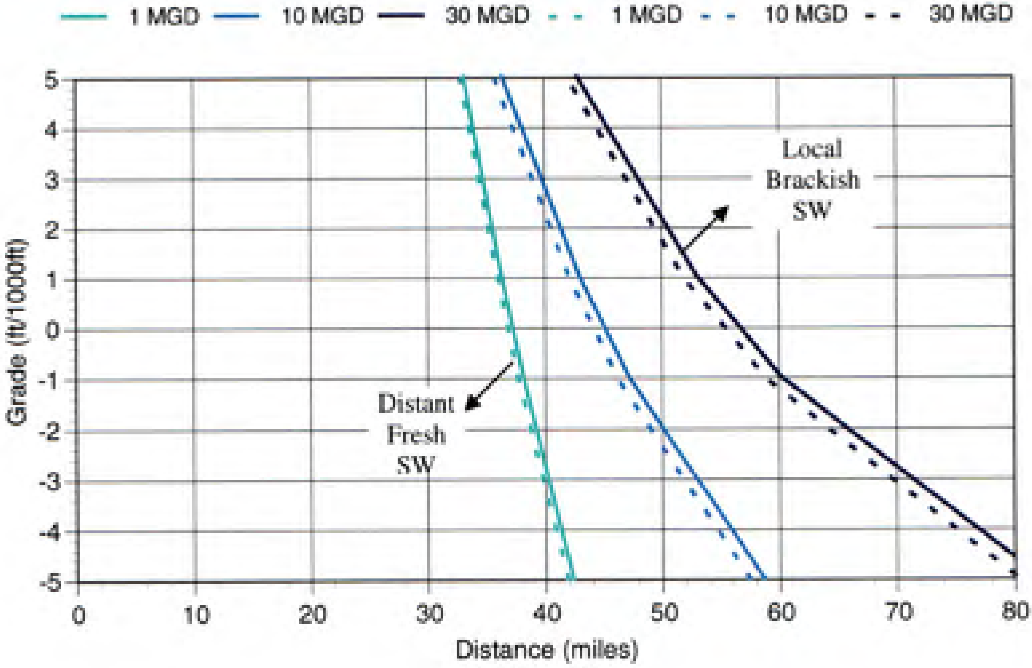

Figure 6.3.26 Distant Fresh Surface Water with Enhanced Coagulation vs. Local Brackish Surface Water (2C)

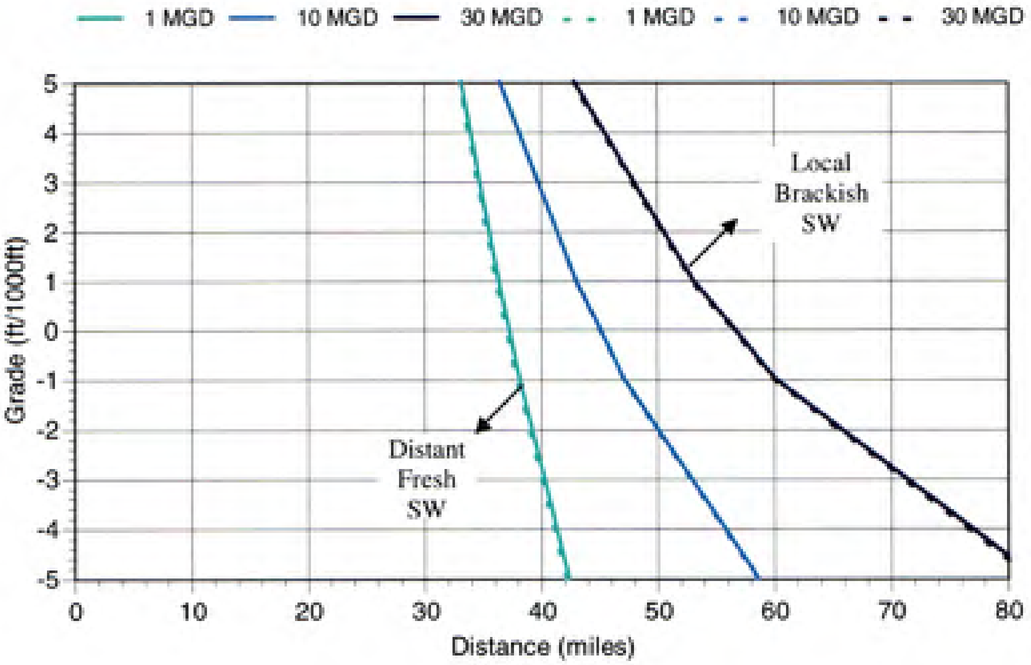

Figure 6.3.27 Distant Fresh Surface Water with Chloramines as Post-Disinfectant vs. Local Brackish Surface Water (2C)

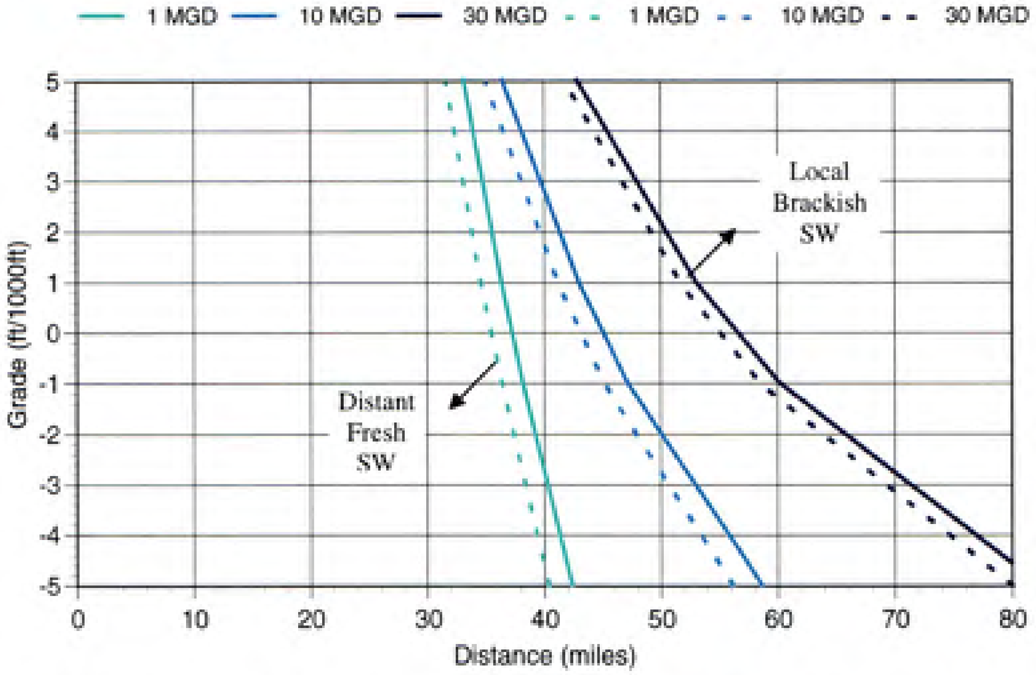

Figure 6.3.28 Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant vs. Local Brackish Surface Water (2C)

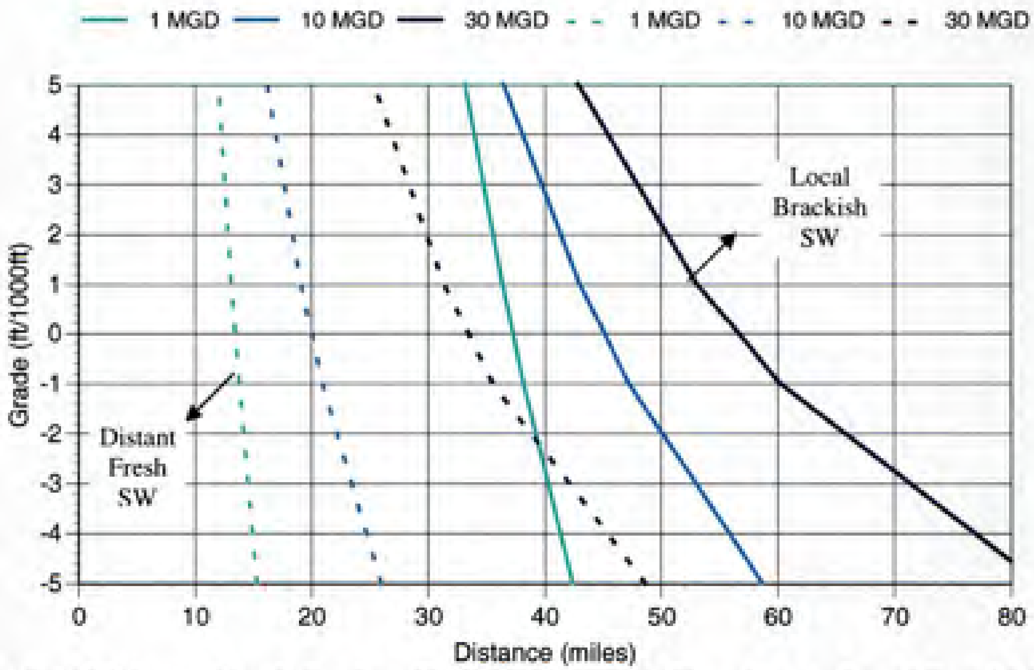

Figure 6.3.29 Distant Fresh Surface Water with GAC Filtration vs. Local Brackish Surface Water (2C)

6.3.2.6 Addition of Storage Costs

Storage costs are added to complete the total costs of supply and treatment. Storage capacities for brackish resources are not considered a necessary component in the total cost of supply and treatment and are added to the fresh water sources only. Costs for storage reservoirs with capacities corresponding to 3 months, 6 months, and 12 months of average daily flow (Q_{OP}) are estimated and added to the total supply and treatment costs for fresh water sources. In these scenarios, freshwater treatment includes the use of chloramines as a post-disinfectant for Stage 2 D/DBP Compliance (Table 6.3.9).

Table 6.3.9 Scenarios for Storage

	Brackish Water Sources:
Fresh Water Sources:	Local Brackish GW
Distant Fresh SW with chloramines as post-disinfectant	1D

The addition of storage costs to complete the total supply and development costs increases the attractiveness of brackish sources at all plant capacities, particularly for smaller demand plants (1 MGD). Costs for all components of the total supply and treatment metric are presented as well, in order to highlight the breakdown of costs for all source waters considered (Table 6.3.10). These cost estimates presented are for a fresh surface water source requiring 3 months storage and the use of chloramines to maintain compliance. These estimates were calculated using the parameters outlined in Chapter 3 for each cost component.

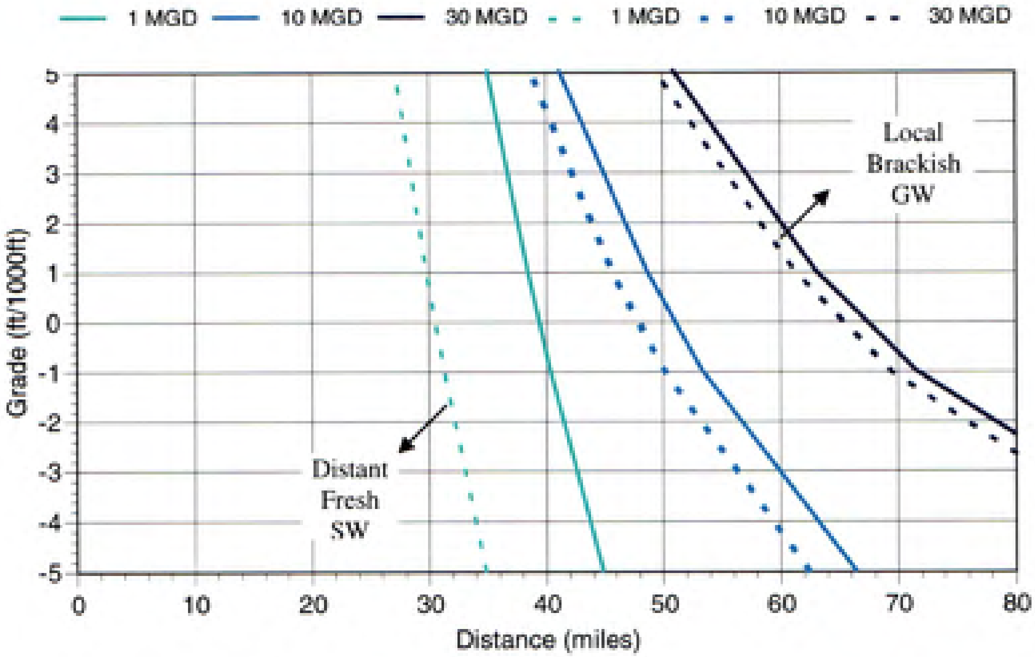

Figure 6.3.30 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 3 Month Storage vs. Local Brackish Groundwater (1D)

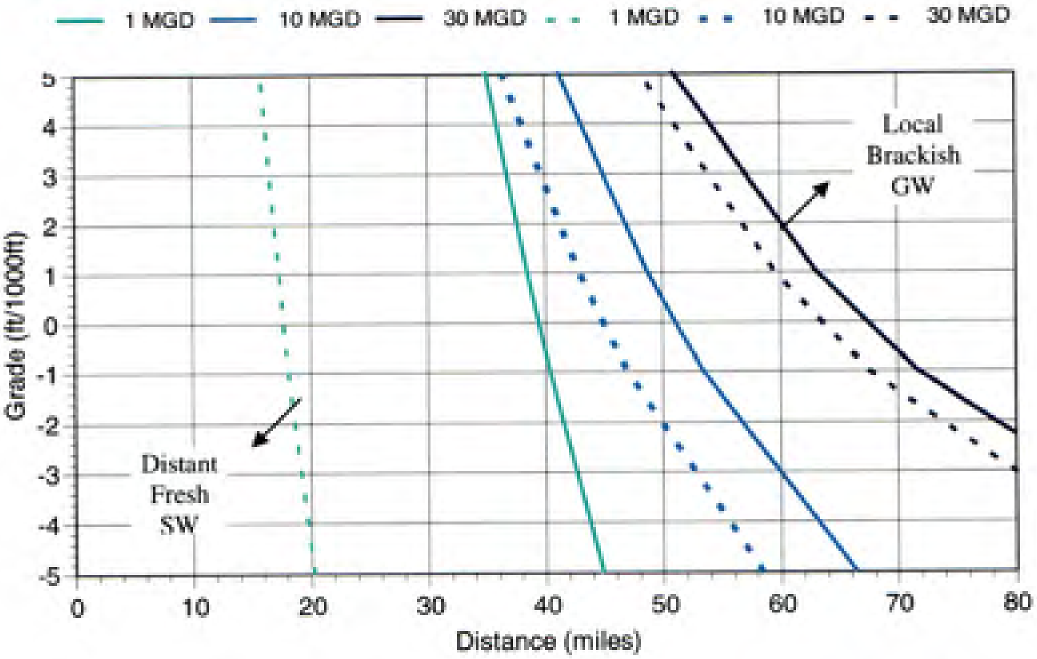

Figure 6.3.31 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 6 Month Storage vs. Local Brackish Groundwater (1D)

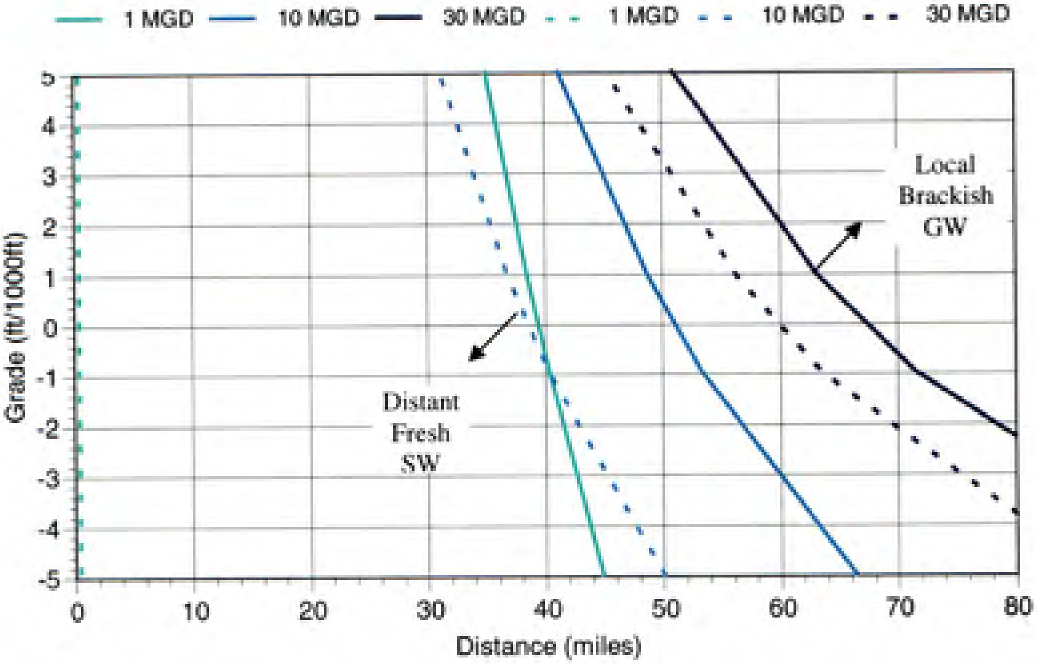

Figure 6.3.32 Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 12 Month Storage vs. Local Brackish Groundwater (1D)