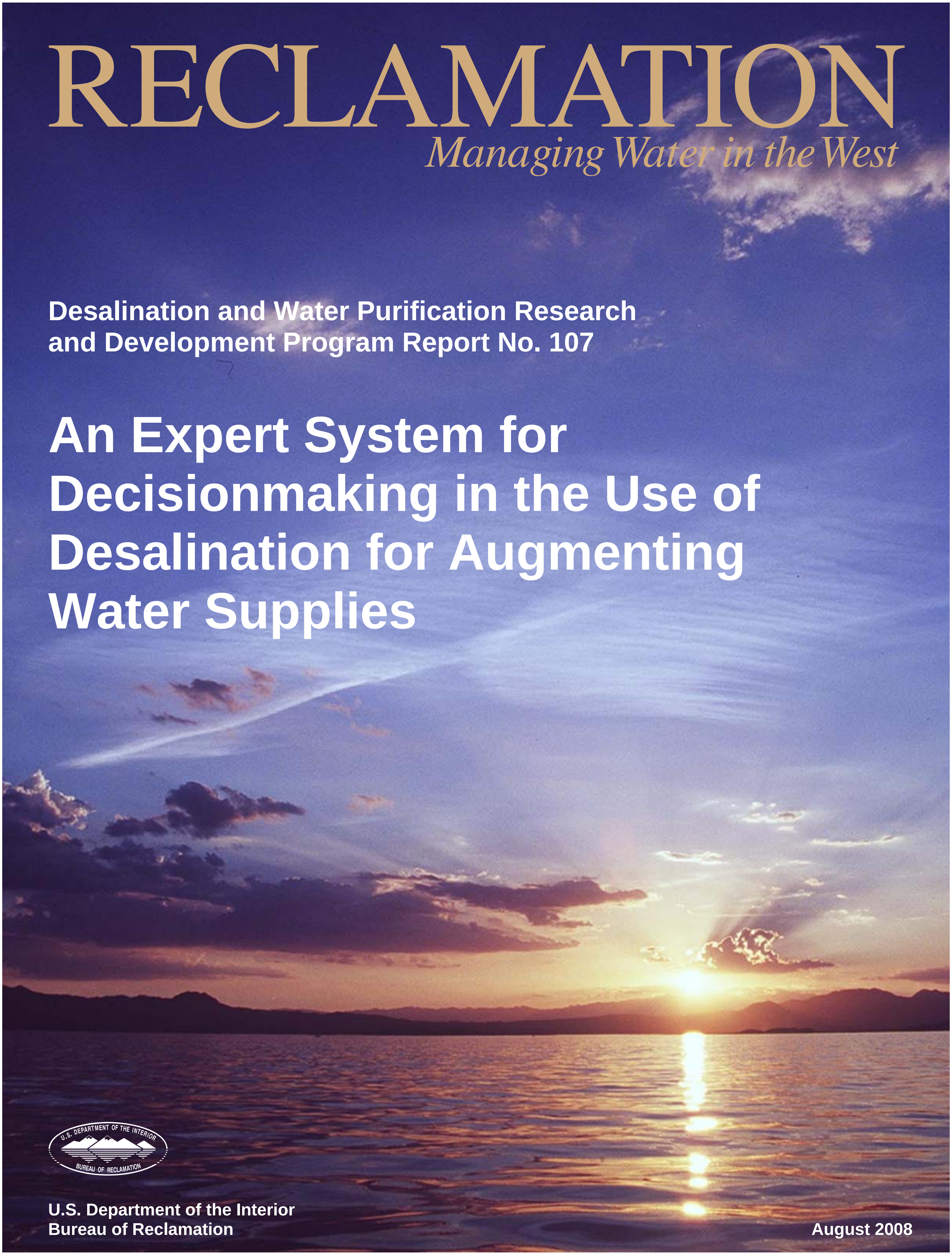

RECLAMATION
*Managing Water in the West*

Desalination and Water Purification Research
and Development Program Report No. 107

# An Expert System for Decisionmaking in the Use of Desalination for Augmenting Water Supplies

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An expert decisionmaking system was developed to incorporate consideration of acquisition, compliance, and storage expenses into cost comparisons of alternative water supply sources. The model (ACASE) is developed in Microsoft Excel format and integrated with Reclamation's Water Treatment Estimation Routine (WaTER), such that both models can provide a comprehensive estimate of the "total costs of supply and treatment," a term defined as all nonadministrative costs between the point at which raw water is acquired from the source and the point at which treated water leaves the treatment plant and enters the distribution system. The original intent of the project was to provide an improved means of equitably comparing the costs of developing brackish and freshwater resources, but the model is sufficiently general to allow for an analysis of the development costs of a wide range of water sources.

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### Desalination and Water Purification Research and Development Program Report No. 107

# An Expert System for Decisionmaking in the Use of Desalination for Augmenting Water Supplies

### Prepared for Reclamation Under Agreement No. 01-FC-81-0757

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## Disclaimer

# Preface

This project was funded to develop an expert system to complement the Bureau of Reclamation's existing water treatment cost model (WaTER) by adding considerations of costs related to raw water supply development, meeting select regulatory standards, and maintaining supply reliability. The relevance of this project derives from the fact that while WaTER provides reasonable estimates of treatment costs, treatment costs are often only a fraction of the total costs of delivering treated water to consumer taps. Therefore, this project developed an expert system that could be used in concert with a modified version of WaTER (WaTER-DBP) to provide a more comprehensive estimate of the "total costs of supply and treatment" associated with a particular water source. Estimates include all (nonadministrative) costs that accrue from the point at which raw water is removed from the source to the point at which treated water enters the distribution system. This approach allows various water sources to be compared on a more equal basis and may result in a very different cost ordering of water supply alternatives than would occur if the alternatives were compared on the basis of treatment costs alone.

The Acquisition, Conveyance, and Storage Expenses (ACASE) model described herein was originally developed with the idea of providing an improved means of comparing the costs of developing fresh and brackish water resources. Nonetheless, it is sufficiently general that (in combination with WaTER-DBP) it can be used to estimate the costs associated with almost any type of source water, fresh or brackish, surface or ground water. As with all models of this sort, the cost estimates provided are only as accurate as the input data; and even when a sufficient quantity of reliable input data is available, cost results should still be viewed as "planning level" estimates (+/-20 percent). Even so, the value in a tool that allows for a more comprehensive cost analysis of various supply alternatives is likely to have value to many regional planners and policymakers as they consider strategies for water resource development.

# Acknowledgements

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# 1. Introduction

An increasing number of communities are facing water resource planning challenges as a result of population growth, economic development, and limited fresh water availability. One alternative for meeting growing supply challenges is through the use of brackish or semibrackish water sources, many of which remain untapped (Bureau of Reclamation [Reclamation], 2003). In the past, the damages imposed on municipalities by tapping these poorer quality sources (e.g., accelerated corrosion) have often been deemed unacceptable and the costs of desalinating these waters to a suitable level were deemed too high (Characklis, 2004). Thus, 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 supply development choices. While standard conventional treatment (i.e., flocculation-sedimentation-filtration) is generally less expensive than desalination, water resource decisions are generally based on the achievement of much broader objectives. Water utilities seek to maintain regulatory compliance, meet supply reliability targets, and control the total cost of operations, which often involve much more than treatment costs alone. Alternative water sources should, therefore, be evaluated within this context, an approach that may substantially change the preferential cost ordering of alternatives relative to a “treatment only” comparison.

In many cases, the ever increasing number of regulatory standards makes it increasingly difficult to maintain compliance through standard conventional treatment alone. Therefore, many conventional facilities will need to add ancillary treatment processes (e.g., granular activated carbon [GAC] filtration) to comply with new mandates. As a result, in cases where source alternatives might include a fresh surface water (i.e., conventional treatment) and a brackish ground water (e.g., membrane desalination), a treatment cost comparison should include consideration of whether standard conventional treatment will be sufficient to maintain compliance. If not, and ancillary processes are required, the treatment cost gap between conventional treatment and desalination will shrink and may even be eliminated. Source location is another important factor, as the capital and operating costs associated with transporting water from a more distant source are often substantial. In this respect, poorer quality sources may have some advantages, as many have previously been passed over in favor of higher quality supplies. In addition, since poorer quality sources are often underutilized, they may also provide a greater degree of supply reliability than other alternatives, reducing the need for expensive storage infrastructure.

Thus, the costs of supplying potable water include not only those associated with treating water, but also the costs of raw water acquisition and the expense of ensuring a high level of supply reliability. This project has addressed these issues in two ways:

(1) Water quality and cost relationships related to regulatory compliance have been added to Reclamation’s existing Water Treatment Estimation Routine (WaTER) model to create a modified version entitled “WaTER-DBP.”

(2) A separate model, Acquisition, Conveyance, and Storage Expenses (ACASE), has been developed to estimate costs related to acquisition and storage costs, as well as those related to residuals disposal (e.g., sludge, concentrate).

Inclusion of these additional costs allows for a comparison based on the “total cost of supply and treatment.” This term is defined as all (nonadministrative) costs that occur between the point at which raw water is removed from the source and the point where treated water enters the distribution system (distribution and administrative costs are considered equal regardless of source). Using the WaTER-DBP and ACASE models in combination can provide a more comprehensive approach to comparing the costs of developing alternative water sources, particularly in cases where the sources involved are of substantially different qualities (e.g., fresh water versus brackish).

This manual provides background information and guidance for using the ACASE model. The organization of the manual largely parallels that of the model, with sections labeled to correspond to the appropriate worksheet. The ACASE model includes consideration costs in the following areas:

- Acquisition costs
  - Surface water intakes
  - Ground water wells
- Conveyance costs
  - Pipelines
  - Canals
- Residuals disposal
  - Sludge thickener
  - Dewatering lagoon
  - Belt filter press
- Concentrate Disposal
  - Deep well injection
  - Evaporation pond
- Storage (reservoir)

In addition, this manual includes a discussion of additions made to the Reclamation’s existing WaTER model which evaluates a system’s ability to achieve compliance with Stage 2 disinfectant/disinfection byproducts (DBP) standards for total trihalomethanes (TTHMs). These sections are also labeled to correspond to the appropriate worksheets and include consideration of the following areas within the WaTER-DBP model:

- Assessment of TTHM formation in finished water leaving a conventional treatment plant
  - Pre-disinfection with chlorine
  - Post-disinfection with chlorine
  - Pre- and post-disinfection with chlorine
- Assessment of TTHM formation in the distribution system
  - Pre-disinfection with chlorine
  - Post-disinfection with chlorine
  - Pre- and post-disinfection with chlorine
- Ancillary treatment processes used to achieve compliance with Stage 2 TTHM levels
  - Chloramines as post-disinfectant
  - Granular activated carbon filtration

## 1.1 Acquisition, Conveyance, and Storage Expenses Model

The model is a Microsoft Excel workbook with the filename: *ACASE.xls*. Computer software requirements are as follows:

- Windows 95 or higher with Microsoft Excel version 7
- Macintosh OS with Microsoft Excel for Macs (uses version 5 for Windows)
- Microsoft Excel Solver Add-In

To take full advantage of the ACASE model, the user must also have a copy of the WaTER-DBP model installed. After downloading both files, place each in the same folder. Open the WaTER-DBP model first, and a dialog box will appear requesting permission to enable all macros. Allow them to be enabled; then open the ACASE model. When a dialog box appears asking you if you want to link the ACASE workbook to another workbook, respond “yes.” Another dialog box will appear asking you to identify the workbook to be linked; find the WaTER-DBP model file and choose it. Both models are now ready to run.

To bring a desired worksheet of either workbook into the window, single-click on the name of the worksheet tab at the bottom of the screen. To navigate through the worksheets, simply click on the name of the worksheet tab. Remember that the worksheets are linked (both within and across workbooks) so that changes in one worksheet will be reflected in the other worksheets. The ACASE model includes the following worksheets, all of which are described in greater detail in section 2:

- ACASE Report – parameter input and final cost estimates
- Cost Index
- Surface Water Intake
- Ground Water Wells
- Pipeline
- Canals
- Sludge Disposal – includes costs for belt filter press, gravity thickener, and sludge dewatering lagoon
- Concentrate Disposal – includes costs for deep well injection and evaporation pond
- Storage

To create cost estimates, change the original parameters on the report worksheet. The applicable ranges for the input parameters are listed on the report worksheet. If the calculated values for your system are outside these ranges, the cost values may not be representative.

## 1.2 ACASE Input Requirements

Most general user inputs are entered in the "ACASE Report" worksheet in the yellow highlighted cells; these values are accessed by the other worksheets when making calculations. Cells highlighted in blue denote values that have been drawn from the linked WaTER model. Gray cells indicate values that have been calculated within the ACASE model itself. Inputs in the "ACASE Report" worksheet represent the first level of estimation. To refine cost estimates further, it is necessary to adjust process design parameters (default values) within individual activity worksheets. All final cost estimates are presented in the "ACASE Report" worksheet. Construction cost and operation and maintenance (O&M) costs are reported in each area (e.g., pipeline, surface water intakes); these values are then combined and translated into volumetric costs of dollars per thousand gallons ($/kgal).

The "Cost Index" worksheet also requires periodic modification based on changes in Engineering News Record (ENR) or Bureau of Labor Statistics (BLS) indices. It is important to note that the guidance manual describes all cost relationships derived from the literature in terms of the units and dollars (e.g., $1999) used in the original work. This facilitates a reader's ability to more readily track down these relationships in the references provided, should points of clarification be sought. While the guidance manual uses a variety of units and dollars, all are converted to uniform levels in the model itself where final results are presented in constant dollars ($2003), as well as in both English and metric units.

## 1.3 Overview of Additions to the Existing WaTER Model (WaTER-DBP)

Worksheets have been added to the latest version of Reclamation's existing WaTER model to introduce considerations of compliance with impending Stage 2 DBP standards. The resulting WaTER-DBP model includes the following worksheets:

- TTHM Input Values – water quality parameters defined
- TTHMs in Distribution System
- TTHMs in Finished Water
- Pre-Chlorination TTHM
- Post-Chlorination TTHM
- Pre- and Post-Chlorination TTHM

The last three worksheets contain intermediate calculations that are used in computing the final TTHM concentrations presented in the "TTHMs in Finished Water" and "TTHMs in Distribution System" worksheets. Details related to all of these worksheets are available in section 3.

## 1.4 Simultaneous Use of the WaTER-DBP and ACASE Model

Costs can be estimated at a very broad level with relatively few user inputs related only to water quality and flow capacity (relying largely on default values for many parameters). Alternatively, a user with more information can base cost estimates on much more detailed parameter inputs for any individual treatment process or structural asset. Both the WaTER-DBP and ACASE models return results in the form of individual costs for each process or activity. In all cases, cost estimates are expressed as capital and operating (O&M) costs and, subsequently, translated into terms of dollars per thousand gallons.

A comprehensive estimate of the "total costs of supply and treatment" is obtained by simply adding up costs related to the processes and activities that correspond to the system of interest. For example, for a brackish ground water source located 15 miles (downhill) from the community it is intended to serve, the user might input parameters related to water quality and system capacity. The user would then add the costs of ground water wells (ACASE), a pipeline (ACASE), membrane desalination (WaTER-DBP), and concentrate disposal (ACASE) to obtain an estimate of the total costs of supply and treatment. For a local surface water source, a cost estimate would include consideration of surface water intakes (ACASE), conventional treatment processes (WaTER-DBP), and sludge disposal (ACASE). Some consideration might also be given to storage costs (ACASE) and ancillary treatment costs (WaTER-DBP), depending on the surface water's reliability and quality, respectively.

Example calculations and scenarios are included (see Appendix A). These demonstrate a comparative analysis of a number of different water sources that vary with respect to type (e.g., ground, surface), location, quality, and reliability.

# 2. ACASE Model

Guidance material for the ACASE model is presented in sections that correspond to the individual worksheet names. When cost estimates from ACASE are combined with the treatment cost estimates provided by the WaTER model, a user can calculate all (nonadministrative) costs that accrue between the acquisition of raw water at the source and the point at which the treated water enters the distribution system.

## 2.1 Surface Water Intakes

Use of a surface water source requires construction of intake structures. Surface water intake systems can generally be divided into two categories: exposed intakes and submerged intakes (American Water Works Association [AWWA] and American Society of Civil Engineers [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 (e.g., pipeline) 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 million gallons per day (mgd), while the exposed tower is for larger flows between 10-100 mgd.

Submerged crib: $$C_{CAP}^{SC}\ (\$) = 3{,}905\, Q_{max}^{\ 0.337} \qquad [1]$$

Exposed tower: $$C_{CAP}^{ET}\ (\$) = 1{,}451\, Q_{max}^{\ 0.46}\ H^{0.92} \qquad [2]$$

Where: $Q_{max}$ = Maximum flow (mgd)
$H$ = Tower height (feet [ft])

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

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

Where: $H_C$ = 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: $$C_{CAP}^{EX}(\$) = 324\, Q_{max}^{\ 0.76} \qquad [4]$$

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

Where: $D_{WW}$ = 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)

O&M costs for both types of intake structures include those associated with equipment replacement, labor, and energy, and are 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 (dollars per kilowatthour [$/kWh])
$P_E$ = Pump efficiency (percent [%])
$L_R$ = Standard labor rate (dollars per hour [$/hr])
$E_{RC}$ = Equipment replacement costs (dollars per year [$/year])

Equipment replacement costs are assumed to be 5% of the capital cost per year. Default parameters values are derived from the literature and presented below (table 1).

**Table 1. Surface Water Intake Default 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 | $/kWh | 0.07 |
| Standard labor rate | $/hr | 20 |
| Pump efficiency | % | 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 |

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

## 2.2 Ground Water Wells

Capital costs for ground water wells are taken from Mickley (2001):

$$C_{CAP}^{WELL}(\$1{,}000) = -288 + 145.9\,(D_{tube}) + 0.754 * (d_w) \qquad [8]$$

Where: $D_{tube}$ = Diameter of well (inches)
$d_w$ = Depth of well (ft)

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

O&M expenses are based on energy costs required to pump water out of the well, such that:

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

Where: $Q_{DES}$ = Design capacity (mgd)
m = mass of water to be pumped =ρV (kilogram [kg])
g = gravitational constant, 9.81 (meters per second squared [$m/s^2$])
$d_L$ = depth to water level (meters [m])
$h_L$ = head loss (m)
$C_E$ = Unit cost of energy ($/kWh)
$P_E$ = Pump efficiency (%)

Default parameter values for cost estimates are presented below (table 2). These values were selected from the literature or through consultation with a practitioners. Well diameters and $Q_{DES}$ are related using an upflow velocity of 3 feet per second (ft/sec).

**Table 2. Ground Water Well Default Cost Parameters**

| Input Parameters | Units | Value |
|---|---|---|
| **Acquisition Costs** | | |
| *Ground Water Wells* | | |
| Pumping rate | gallons per minute (gal/min) | [1]1,000/1,500/2,000 |
| Diameter | inches | [1]12/14/16 |
| Depth of well | feet | 300 |

[1] Correspond to values for 1-mgd/10-mgd/30-mgd facilities.

## 2.3 Pipelines

Pipelines are a common method of transporting water, and these costs can be substantial, particularly when pumping uphill. This makes the relative location of the water source and end user 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 updated to 2003$ (ENR cost indices) and verified using empirical cost data gathered as part of a research project in North Carolina (Kirsch, 2004). 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:

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

Where: v = average flow velocity (feet per second [ft/sec])
$\mathrm{Q_{OP}}$ = Operating capacity (75% of design flow)
(cubic feet per second [$\mathrm{ft^3/sec}$])

Capital costs are calculated in using the pipe diameter (D) such that:

$$\mathrm{C_{CAP}^{PIPE}}(\$/mile) = 1.097\mathrm{D}^{1.3983} * 5{,}280 \qquad [11]$$

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

O&M costs consist of pumping (energy) costs and are calculated as follows:

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

Where: $\mathrm{S_l}$ = Average uphill/downhill slope (ft/1,000 ft)
$\mathrm{S_f}$ = Friction loss from Hazen-Williams equation (ft/1,000 ft)
$\mathrm{C_E}$ = Energy cost ($/kWh)
$\mathrm{P_E}$ = Pump efficiency (-)

Care should be taken when considering steeper downhill grades in [12], as pumping costs could be calculated as negative values (i.e., gravity flow in pipe). Total costs for conveyance include an additional 8% to account for O&M costs beyond pumping, such that:

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

Default parameters values for pipeline cost estimates are derived from the literature and presented below (table 3).

**Table 3. Pipeline Default Cost Parameters**

| Input Parameters | Units | Value |
|---|---|---|
| **Conveyance Costs[1]** | | |
| Average flow velocity | (ft/sec) | 3 |
| Hazen-Williams coefficient | (steel) | 120 |
| Efficiency factor | | 0.92 |

[1] Parameter values are from Linaweaver and Clark, 1964.

## 2.4 Canals

Cost relationships are also available for concrete lined canals (Linaweaver Jr. and Clark, 1964) such that:

$$C_{TOTAL}^{CANAL}\ (\$/\text{kgal/mile}) = \frac{[fC_T + 0.01C_T]}{365 * 10^3 Q(0.75)}$$

Where: $f$ = capital recovery factor, $= r \bullet [1+r]^t \Big/ \left([1+r]^t - 1\right)$ (-);
r = discount rate (-)
t = useful life of the canal (years)
$C_T$ = capital cost ($/mile)
Q = capacity (mgd)

## 2.5 Sludge Disposal (Conventional Treatment)

Conventional treatment produces residuals (i.e., sludge) consisting of suspended solids and chemical precipitates. Disposal of these wastes can occur via several mechanisms, including lagoons, landfills, or land application (James M. Montgomery, 1985; AWWA and ASCE, 1998). Sludge treatment, via thickening and dewatering processes, is often used as a first step to reduce the volume of material prior to final disposal in dewatering lagoons. Costs associated with these processes are determined through relationships defined by Qasim et al. (1992). Costs are estimated for each process separately. Lagoon cost estimates are also included for instances in which lagoon disposal is preceded by either a gravity thickener or a belt filter press. In both cases, the lagoon storage volume is modified based on the additional sludge reduction achieved through using a thickener or belt filter press.

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

$$C_{CAP}^{GT}\ (\$) = 15{,}530 * D^{0.6523} e^{0.0101D} \quad [14]$$

$$C_{O\&M}^{GT} (\$ / year) = 21.3 * D^{1.4736} + 1{,}200 \quad [15]$$

Where: D = Thickener diameter (m)

The capital and O&M costs of a belt filter press are expressed as a function of the installed machine capacity, such that:

$$C_{CAP}^{BFP}\ (\$) = 170{,}640 + 15{,}196\, M_C \quad [16]$$

$$C_{O\&M}^{BFP} (\$ / year) = 584{,}735.8 * e^{0.001522 M_C} - 568{,}030 \quad [17]$$

Where: $M_C$ = Installed machine capacity (cubic meters per hour [$m^3$/hr])

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

$$C_{CAP}^{DL}\ (\$) = 29.5 * V^{0.793} + 2{,}200 \qquad [18]$$

$$C_{O\&M}^{DL}\ (\$/\text{year}) = 6.473 * V^{0.9124} - 45 \qquad [19]$$

Where: V = Effective storage volume ($m^3$)

Representative default values were selected from the literature (table 4).

**Table 4. Residuals Management Default Parameters**

| Input Parameters | Units | Value |
|---|---|---|
| **Residuals Management** | | |
| *Sludge Handling1* | | |
| Suspended solids | milligrams per liter (mg/L) | 1 |
| Surface loading rate | gallons per minute per square foot (gpm/ft$^2$) | 1.0 |
| Dry alum dose | mg/L | 46 |
| Iron dose | mg/L | 0 |
| Additional chemicals | mg/L | 0.5 |
| Evaporative rate | inches/year | 70 |

[1] Parameter values are from from AWWA and ASCE, 1998; James M. Montgomery, 1985.

## 2.6 Concentrate Disposal (Desalination)

Concentrate disposal costs can be an important factor, as disposal is generally subject to stringent regulations at both the State and Federal levels. As a result, disposal costs can add significantly to the total cost of desalination (Morin, 1999). 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 to the sea (Chapman Wilbert et al., 1998). Sewer discharge is only an option for very small plants, whereas deep well injection is primarily used for larger plants (AWWA, 1996; Mickley, 2001). Evaporation ponds and land application are used primarily by smaller plants (less than [<] 1 mgd), particularly in locations with high evaporation rates and relatively inexpensive land (Chapman Wilbert, Leib et al., 1998).

Deep well injection and evaporation ponds are the major strategies for brackish desalination plants not located near the ocean (Glater and Cohen, 2003), and both approaches are considered in the ACASE model. Capital and O&M cost estimates are derived from Mickley (2001). The major determinants of injection costs are well depth and the well tubing diameter. 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:

$$C_{CAP}^{DW}(\$1{,}000) = -288 + 145.9 * (D_{tube}) + 0.754 * (d_{w}) \qquad [20]$$

Where: $D_{tube}$ = Diameter of well (inches)
$d_w$ = 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 subsurface infiltration rates. O&M costs for pumping (energy) costs are calculated as follows:

$$C_{O\&M}^{DW}(\$/well/year) = \frac{Q_{CONC} * (mgd_{L}) * C_{E} * 384}{PE} \qquad [21]$$

Where: $Q_{CONC}$ = Concentrate flow (mgd)
m = mass of water to be pumped =$\rho V$ (kg)
g = gravitational constant, 9.81 ($m/s^2$)
$d_L$ = depth to water level (m)
$C_E$ = Unit cost of energy ($/kWh)
$P_E$ = Pump efficiency (%)

Evaporation ponds are most appropriate for disposal of smaller volumes of concentrate (< 1 mgd). 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 volume of concentrate produced (Mickley, 2001; Glater and Cohen, 2003) as represented by:

$$A = 13{,}440 \frac{Q_{CONC}}{E_{ave} + F} \qquad [22]$$

Where: A = Evaporative area (acres)
$E_{ave}$ = Evaporation rate (inches/year)
F = Freeboard (= $0.2 * E_{ave}$)

Total capital costs for an evaporative pond are described as:

$$C_{CAP}^{EP}(\$) = 5{,}406 + 465 * T_{L} + 1.07 * C_{L} + 0.931 * C_{LC} + 217.5 * H * 1.2 * A \; * \frac{1 + 0.155 * H}{\sqrt{A}} \qquad [23]$$

Where: $T_L$ = Liner thickness (mils)
$C_L$ = Land cost ($/acre)
$C_{LC}$ = Land clearing cost ($/acre)
H = Dike height (ft)

This model is valid from 10 to 100 acres of total pond area. A free board factor (F) is included in the evaporation pond depth to account for variations in evaporative rates. Annual operating costs are estimated as 0.5% of capital costs.

Representative information for various parameters were selected from the literature as default values (table 5).

**Table 5. Concentrate Disposal Default Parameters**

| Input Parameters | Units | Value |
|---|---|---|
| **Concentrate Disposal** | | |
| *Deep Well Injection*[1] | | |
| Recovery | % as decimal | 0.85 |
| Diameter | inches | 10 |
| Depth of well | feet | 3,000 |
| Pumping rate | gal/min | Calculated |
| Unit price of energy | $/kWhr | 0.07 |
| Pump efficiency | % | 0.75 |
| *Evaporation Pond* | | |
| Dike height | ft | 8 |
| Liner thickness | mils | 60 |
| Land cost | $/acre | 2,000 |
| Land clearing cost | $/acre | 2,000 |

[1] Parameter values are from Mickley (2001).

## 2.7 Storage

The natural variability in different water sources can often affect their ability to reliably meet water demand. As such, it is important that the costs ensuring equal levels of supply reliability are included in any comparative analysis of different sources. While reliability analyses of individual sources is beyond the scope of this model, general relationships exist to estimate storage costs; and if information regarding reliability/ storage requirements is available, such estimates can be employed in a comparative assessment. The reader is cautioned, however, that storage costs are often more difficult to accurately estimate than acquisition/treatment costs, as site specific characteristics (e.g., soil, topography) can have a considerable impact. Storage cost estimates should, therefore, be viewed largely as illustrative. Three types of storage options are available: tanks, small impoundments, and reservoirs. Impoundments can be formed instream 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. Costs are included only for reservoirs in the model.

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* (Spiegler and Laird, 1980). Costs are presented for both capital and O&M expenses. These cost estimates are compared to work done by Dawes & Wathne (1968) where reservoir costs are calculated as follows:

$$C_{CAP}^{RES}\ (\$) = 9{,}161S^{0.54} + 0.49S^{0.87}k \qquad [24]$$

Where: S = Reservoir storage capacity (acre-feet)
k = Land cost ($/acre)

The cost estimates from the two models are comparable; and while both cost models are presented in the ACASE model, the costs presented on the ACASE Report worksheet use the available unit costs (Spiegler and Laird, 1980).

# 3. TTHM REGULATORY COMPLIANCE ROUTINES (WaTER-DBP)

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, covering all, or even most, of them would be a substantial undertaking. Therefore, in order to provide an illustrative example of the impact that considering compliance issues can have on a comparative source analysis, this work focuses solely on disinfection byproducts, an appropriate example given the ubiquity of DBP compliance challenges throughout the United States. It should be noted that DBP compliance calculations apply only to conventional treatment.

Disinfection byproducts form during the treatment process when natural organic matter (NOM) reacts with chemical disinfectants, especially chlorine. Trihalomethanes (THMs) were the first class of DBPs identified in drinking water and have been regulated since 1979 (Singer, 1994; Singer, 2004). Specifically, this work focuses on a method for evaluating compliance with the U.S. Environmental Protection Agency's (USEPA's) Stage 2 TTHM maximum contaminant level (MCL) of 80 micrograms per liter (ug/L). Compliance with this standard is measured in the distribution system; therefore, TTHM concentrations are calculated in a two step process. First, TTHM concentration in the treated water leaving the plant is calculated; this value is then input into calculations that determine TTHM concentration in the distribution system. Note: Stage 2 Regulations eliminate the practice of taking four samples from across the distribution system and using their average concentration to determine compliance. Stage 2 regulations require that concentrations at each sampling location be below the standard (Wilkes, 2003; Singer, 2004).

## 3.1 TTHM Input Values

A modified version of Reclamation's WaTER model (WaTER-DBP) has been developed to evaluate a treatment train's ability to maintain compliance with the TTHM MCL. Open WaTER-DBP before opening the ACASE model (which should be linked to WaTER-DBP), remembering to enable macros, and the Microsoft Excel Solver Add-In. Required inputs include both raw water quality parameters (total organic carbon [TOC], UV-254, temperature, pH, and bromide concentration) and plant operating parameters (table 6).

## 3.2 TTHMs in Finished Water

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

**Table 6. Description of Required TTHM Input Parameters**

| Parameter | Units | Description |
|---|---|---|
| Coagulant dose | mmoles/L | Coagulant dose added |
| Coagulant dose | milliquivalent per liter (meq/L) | Coagulant dose added |
| Applied Cl2 dose (pre) | mg/L | Pre-chlorination dose |
| Applied Cl2 dose (post) | mg/L | Post-chlorination dose |
| Reaction time, rapid mix | hours | Time for rapid mix process |
| Reaction time, flocculation | hours | Time for flocculation |
| Reaction time, sedimentation | hours | Time from plant entry through sedimentation |
| Reaction time, treated water | hours | Time from plant entry through plant exit |
| Reaction time, distribution system | hours | Time in distribution system |

TTHM formation in drinking water. Models are available based on both water quality data from utilities (raw and treated water) (Singer et al., 1995; Milot et al., 2000; Rodriguez et al., 2000) as well as models based on chlorinating raw waters at the bench-scale (Rathbun, 1996; Amy et al., 1998). Kinetic-based models have also been developed for predicting TTHM formation through consideration of formation mechanisms and compound stability relationships (Clark and Sivaganesan, 1998; Clark et al., 2001; Westerhoff et al., 2002; USEPA, 2002). Additionally, USEPA has 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). Relatively little work has directly addressed TTHM formation in distribution systems.

The formation of TTHMs occurs throughout the conventional treatment process during which water quality varies. Therefore, TTHM formation in this work is estimated using a combination of several models which take into account NOM concentrations throughout the treatment process, as well as various process configurations (e.g., pre-disinfection, post-disinfection, or both). The prediction of finished water TTHM concentration includes estimates of NOM removal, using parameters such as TOC and ultraviolet absorbance (UVA) as surrogates for NOM concentration.

Relationships describing TTHM formation are derived from the USEPA WTP model as described by Solarik et al. (2000). TTHM formation is calculated for three different process configurations involving disinfection at different points in the treatment plant: (1) pre-disinfection, (2) post- disinfection, and (3) pre-and post- disinfection. Calculations are based on a typical water treatment plant layout (figure 1) with the locations assumed for both pre- and post-chlorination. The general approach used in calculations for each configuration is outlined in table 7 (with equation numbers), and a full description is given below.

Calculations of TTHM concentration in the three scenarios described in table 7 are carried out in the “Pre-Chlorination TTHM,” “Post-Chlorination TTHM,” and “Pre- and Post-Chlorination” worksheets in the WaTER model.

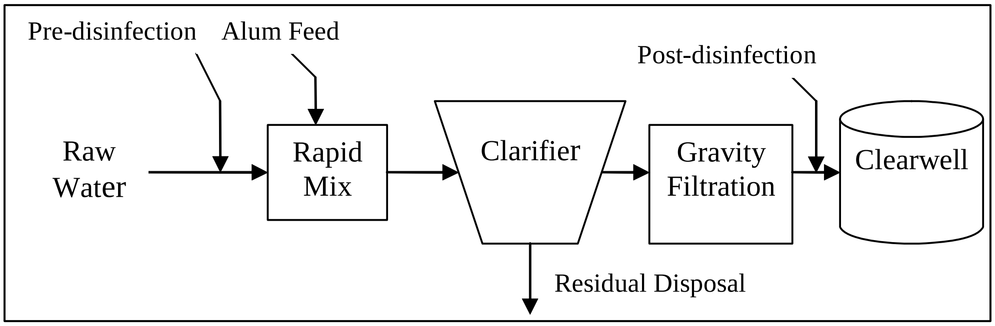

**Figure 1. Schematic of Chlorination Scenarios.**

**Table 7. TTHM Formation Scenarios**

| Chlorination Scenario | Models Used |
|---|---|
| Pre-chlorination | $TTHM_{finish}$ = Raw Water Model [25]*Pre-chlorination Factor [26] + Treated Water Model [27] |
| Post-chlorination | $TTHM_{finish}$ = Treated Water Model [27] |
| Pre- and post-chlorination | $TTHM_{finish}$ = Raw Water Model [25]*Pre-chlorination Factor [26] + Treated Water Model [27] |

### 3.2.1 Pre-Chlorination TTHM

In the case of pre-disinfection, finished water TTHM concentration is estimated using two models to account for formation prior to and after sedimentation (i.e., clarifier). Prior to the clarifier, a raw water TTHM model is used [25] (Amy, Siddiqui et al., 1998), with an empirical pre-chlorination factor [26] applied to account for the decreased formation that occurs when chlorine is added before rapid mix (Solarik et al., 2000).

$$TTHM_{RAW} = 0.0412(TOC_{raw})^{1.098}(Cl_2)^{0.152}(Br^-_{raw})^{0.068}(T)^{0.609}(pH)^{1.601}(t)^{0.263} \quad [25]$$

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 (degrees Celsius [ºC])
pH = raw water pH
t = reaction time (hours)

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

$$\text{Decrease in TTHM formation (\%)} = 0.853 \text{ (\% TOC removal)} \quad [26]$$

Formation occurring after sedimentation is calculated using a treated water model [27] is based on settled water quality, chlorine residual, and the amount of time that transpires between the clarifier and the point at which the finished water leaves the plant. Water quality is evaluated as a function of TOC and UVA concentration in a manner designed to account for both NOM removal and reactivity, such that:

$$\mathrm{TTHM}_{\mathrm{TREAT}} = 23.9(\mathrm{TOC} * \mathrm{UVA})^{0.403}(\mathrm{Cl2})^{0.225}(\mathrm{Br\text{-}})^{0.141}(1.027)^{(\mathrm{T}-20)}(1.156)^{(\mathrm{pH}-7.5)}(\mathrm{t})^{0.264} \quad [27]$$

Where: $\mathrm{TTHM}_{\mathrm{TREAT}}$ = treated water TTHM (ug/L)
TOC = treated water TOC (mg/L)
UVA = treated water UVA (1 per centimeter [/cm])
$\mathrm{Cl}_2$ = applied chlorine (mg/L)
$\mathrm{Br}^-$ = concentration of Bromide (ug/L)
PH = treated water pH
T = temperature (ºC)
t = reaction time (hours)

## 3.2.2 Post-Chlorination TTHM

Concentrations of TTHMs when only post-chlorination is used are estimated using the treated water model [27].

## 3.2.3 Pre-and Post-Chlorination TTHM

In scenarios involving both pre- and post-chlorination, a combination of the raw and treated models is again used (Solarik et al., 2000). Initial formation is estimated using the raw water model with the prechlorination factor applied [26]. Formation of TTHMs after sedimentation is then estimated using the treated water model with inputs corresponding to settled water quality, a reaction time of 0 hours, and a treated water UVA concentration that is reduced to account for prechlorination [28].

### *3.2.3.1 UVA Removal*

UVA decreases occurring as a result of prechlorination are calculated as:

$$\mathrm{UVA}_{\mathrm{pre\text{-}Cl2}} = 0.7437(\mathrm{UVA}_{\mathrm{removed}}) + 0.0042 \quad [28]$$

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

UVA removal via coagulation for the treated water model [27] is calculated as follows:

$$\mathrm{UVA}_{\mathrm{removed}} = 5.716\,(\mathrm{UVA}_{\mathrm{raw}})^{1.0894}(\mathrm{Dose}_{\mathrm{coag}})^{0.305}(\mathrm{pH}_{\mathrm{coag}})^{-0.9513} \quad [29]$$

Where: $\mathrm{UVA}_{\mathrm{removed}}$ = UVA removed by coagulation (1/cm)
$\mathrm{UVA}_{\mathrm{raw}}$ = raw water UVA (1/cm)
$\mathrm{Dose}_{\mathrm{coag}}$ = applied coagulant dose (meq/L)
$\mathrm{pH}_{\mathrm{coag}}$ = pH of coagulation

### *3.2.3.2 TOC Removal*

TOC removal is predicted using the semiempirical 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 for the treated water model [27] is modeled using:

$$\frac{x}{M} = \frac{\left[ab[Ceq]\right]}{1 + b[Ceq]} \qquad [30]$$

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

Final results describing TTHM concentration in water leaving the treatment plant are summarized in the “TTHMs in Finished Water” worksheet. Results are presented for the range of scenarios described in table 7 and with consideration of the implementation of several ancillary processes (e.g., alternative disinfectants, GAC filtration) intended to bring systems violating Stage 2 TTHM standards into compliance (see next section). The finished water TTHM concentrations described in this worksheet act as the basis for estimates of TTHM concentration in the distribution system (see “TTHM in Distribution System” worksheet).

### 3.2.4 Ancillary Processes

A number of ancillary processes can be implemented to reduce TTHM formation and bring a system into compliance. These can include enhanced coagulation, alternative disinfectants (e.g., ozone, chloramines, UV, and chlorine dioxide), membranes, and GAC filtration (AWWA, 1999; Clark et al., 1994). Alternative disinfectants are often a relatively inexpensive method of reducing TTHM formation, while GAC provides a more costly, but in some cases, more effective approach. These ancillary processes act to “bracket” the costs associated with this range of possibilities, and both are evaluated in terms of their ability to achieve compliance.

Using chloramines as a post-disinfectant, often the least expensive approach, has proven successful in reducing TTHM formation in many distribution systems (Singer, 2004). For a system only slightly out of compliance, consideration of converting to chloramines for post-disinfection may be a very practical path to meeting regulatory standards.

GAC filtration can be a very effective method to remove DBP precursor material; however, the costs of media regeneration often make it more expensive when treating raw waters with high DBP precursor levels (TOC greater than [>] 6 mg/L) (Hooper and Allgeier, 2001).

In order to estimate the ability of post-disinfection via chloramines to aid a utility in meeting compliance, the equations developed for chloramines in the distribution system [32] are used in conjunction with the TTHM formation equations for the three chlorination scenarios (table 7). Within the treatment plant, formation after chloramination is considered to be 20% of formation that occurs due to chlorine (Solarik et al., 2000).

Regulatory compliance with GAC is estimated by assuming GAC provides 20% removal of the post-sedimentation TOC concentration (Solarik et al. 2000). TTHM is calculated using the three chlorination scenarios (table 7); however, for the treated water models, TOC removal is calculated post-sedimentation [30] and then further reduced by 20% for GAC filtration.

These same ancillary processes are evaluated for the different disinfection scenarios for water in the distribution system (see “TTHMs in Distribution System”).

## 3.3 TTHMs in Distribution System

The concentration of DBPs often increases after treated/finished water leaves the plant and enters the distribution system (Garcia-Villanova et al., 1997; Sohn et al., 2001). Sohn et al. (2001) found increases of TTHM levels in the distribution system ranging from 150% to greater than 300% of in-plant TTHM concentrations. Previous models of the water treatment process do not specify separate relationships 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 TTHM 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 USEPA in 1996 to collect data in support developing 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 six locations in a number of distribution systems (n = 127) at increasing distance from the treatment plant.

Formation relationships were developed using step-wise multiple regression analysis. Parameters significant ($p < 0.15$) in the prediction of TTHM concentration in the distribution system ($\mathrm{TTHM}_{\mathrm{DS}}^{\mathrm{Cl}}$, after post-disinfection with chlorine) were: finished water TTHM concentration, TOC, residence time, UV-254, and temperature (table 8). The resulting model demonstrates relatively strong predictive power ($R^2 = 0.82$), and the following relationship was defined:

$$\mathrm{TTHM}_{\mathrm{DS}}^{\mathrm{Cl}}\ (\mathrm{ug/L}) = 0.08\,(\mathrm{Time}) + 1.05\,(\mathrm{TTHM}_{\mathrm{FW}}) + 0.57(\mathrm{T}) + 5.12(\mathrm{TOC}) - 277(\mathrm{UV}) \quad [31]$$

Where: Time = Residence time in distribution system (hours)
$\mathrm{TTHM}_{\mathrm{FW}}$ = 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 8. Statistical Parameters for Post-Chlorine TTHM Formation in Distribution System**

| Parameter | F-value | p-value |
|---|---|---|
| $\mathrm{TTHM}_{\mathrm{FW}}$ | 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 $\mathrm{TTHM}_{\mathrm{FW}}$ and time alone, exclusive of the other parameters, yields a comparable $R^2$ value of 0.80.

The ICR database was also used to develop a predictive model for TTHM concentration in the distribution system for a number of 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 following chloramines post-disinfection (figure 2). The resulting model also shows a very strong correlation ($R^2 = 0.89$) between TTHM concentration in the finished water and that in the distribution system, but describes a much more limited increase:

$$\mathrm{TTHM}_{\mathrm{DS}}^{\mathrm{CIN}}\ (\mathrm{ug/L}) = 1.107 * (\mathrm{TTHM}_{\mathrm{FW}}) \qquad [32]$$

Where: $\mathrm{TTHM}_{\mathrm{FW}}$ = Finished water TTHM concentration (ug/L).

**Table 9. Statistical Parameters for Post-Chloramines TTHM Formation in Distribution System**

| Parameter | F-value | p-value |
|---|---|---|
| $\mathrm{TTHM}_{\mathrm{FW}}$ | 399 | <0.001 |

Both relationships ([31] and [32]) are used with estimates of finished water TTHM concentration (summarized in the “TTHMs in Finished Water” worksheet) for the three disinfection scenarios (table 7), to produce values for TTHM concentration in the distribution system (see "TTHMs in Distribution System"). These results also include an assessment of the ability of the selected ancillary processes (i.e., alternative disinfectants, GAC filtration) to meet Stage 2 D-DBP regulations.

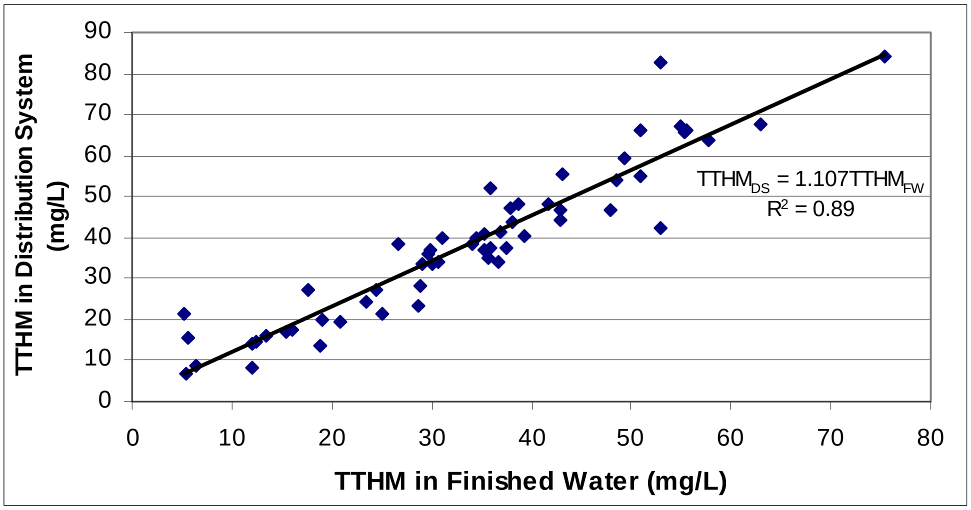

**Figure 2. Post-Chloramines TTHM Formation in Distribution System.**

# 4. REFERENCES

Amy, G., M. Siddiqui, et al., 1998. *Empirically Based Models for Predicting Chlorination and Ozonation Byproducts: Trihalomethanes, Haloacetic Acids, Chloral Hydrate, and Bromate*, USEPA Office of Water.

AWWA, 1999. *Water Quality and Treatment*. New York, McGraw-Hill, Inc.

AWWA and ASCE, 1998. *Water Treatment Plant Design*. New York, McGraw-Hill.

AWWA, 1996. *Water Treatment Membrane Processes*. New York, McGraw-Hill, Inc.

Chapman Wilbert, M.F. Leib, et al., 1998. *The Desalting and Membrane Treatment Manual: A Guide to Membranes for Municipal Water Treatment*. Denver, Colorado, U.S. Department of the Interior, Bureau of Reclamation.

Characklis, G.W., 2004. "Economic Decisionmaking in the Use of Membrane Desalination for Brackish Supplies" in *Journal of the American Water Resources Association* 40(3): 615-630.

Clark, R.M., J.Q. Adams, et al., 1994. "DBP Control in Drinking Water: Cost and Performance" in *Journal of Environmental Engineering* 120(4): 759-782.

____________, 1998. "Control of Microbial Contaminants and Disinfection Byproducts for Drinking Water in the U.S.: Cost and Performance" in *Journal of Water Supply: Research and Technology* 46(6): 255-265.

Clark, R. M. and M. Sivaganesan, 1998. "Predicting Chlorine Residuals and Formation of TTHMs in Drinking Water" in *Journal of Environmental Engineering* 124(12): 1203-1210.

Clark, R.M., R.C. Thurnau, et al., 2001. "Predicting the Formation of Chlorinated and Brominated Byproducts" in *Journal of Environmental Engineering* 127(6): 493-501.

Edwards, M. (1997). "Predicting DOC Removal During Enhanced Coagulation" in *Journal of American Water Works Association* 89(5): 78-89.

Garcia-Villanova, R.J., C. Garcia, et al., 1997. "Formation, Evolution and Modeling of Trihalomethanes in the Drinking Water of a Town: I. At the Municipal Treatment Utilities" in *Water Research* 31(6): 1299-1308.

Glater, J. and Y. Cohen, 2003. *Brine Disposal From Land Based Membrane Desalination Plants: A Critical Assessment*. Los Angeles, Polymer and Separations Research Laboratory University of California: 1-16.

Hooper, S.M. and S C. Allgeier, 2001. *GAC and Membrane Treatment Studies: Data Managment and Analysis*: 43.

Linaweaver Jr., F.P. and C.S. Clark, 1964. "Costs of Water Transmission" in *Journal of American Water Works Association*: 1549-1560.

Mickley, M.C., 2001. *Membrane Concentrate Disposal: Practices and Regulation*. Denver, Colorado, U.S. Department of the Interior, Bureau of Reclamation: 1-266.

Milot, J., M.J. Rodriguez, et al., 2000. "Modeling the susceptibility of drinking water utilities to form high concentrations of trihalomethanes" in *Journal of Environmental Management* 60(2): 155-171.

Montgomery, James M., C.E., Inc., 1985. *Water Treatment Principles and Design*. New York, John Wiley & Sons.

Morin, O.J., 1999. *Desalting Plant Cost Update*. IDA World Congress on Desalination and Water Reuse, San Diego, California.

Rathbun, R.E., 1996. "Regression Equations for Disinfection Byproducts for the Mississippi, Ohio, and Missouri Rivers" in *The Science of The Total Environment* 191(3): 235-244.

Reclamation, 1999. *Water Treatment Estimation Routine*.

____________, 2003. *Water Desalination*.

Rodriguez, M.J., J. Serodes, et al., 2000. "Estimation of Water Utility Compliance with Trihalomethane Regulations Using a Modelling Approach" in *Journal of Water Supply: Research and Technology*: 57-73.

Singer, P.C., 1994. "Control of Disinfection Byproducts in Drinking Water" in *Journal of Environmental Engineering* 120(4): 727-742.

____________, 2004. "Disinfection Byproducts in U.S. Drinking Waters: Past, Present, and Future" in *Water Science and Technology: Water Supply* 4(1): 151-157.

Singer, P.C., A. Obolensky, et al., 1995. "DBPs in Chlorinated North Carolina Drinking Water" in *Journal of American Water Works Association*: 83-92.

Sohn, J., D. Gatel, et al., 2001. "Monitoring and Modeling of Disinfection Byproducts (DBPs)" in *Environmental Monitoring and Assessment* 70: 211-222.

Solarik, G., R.S. Summers, et al., 2000. "Extensions and Verification of the Water Treatment Plant Model for Disinfection Byproduct Formation" in *Natural Organic Matter and Disinfection Byproducts, ACS Symposium Series 761*. S.E. Barrett, S.W. Krasner, and G. Amy. Washington DC, American Chemical Society.

Spiegler, K.S. and A.D.K. Laird, eds., 1980. *Principles of Desalination, Part B*. New York, Academic Press.

Westerhoff, P., D. Reckhow, et al., 2002. *Mechanistic-based Disinfectant and Disinfectant Byproduct Models*: 1-43.

Wilkes, D.R., 2003. *The New Stage 2 DBP Rules: Strategies for Evaluation and Compliance*. South Carolina Environmental Conference.

# APPENDIX A:  Example Calculations

The following results were developed using the WaTER-DBP and Acquisition, Conveyance, and Storage Expenses (ACASE) models to compare the total costs of supply and treatment of several different source waters.  Initial results describe the treatment costs only, while subsequent results demonstrate how location, compliance, and storage considerations can alter an analysis of the “total costs of supply and treatment” associated with a surface or ground water.

## Conventional Treatment Costs

Conventional treatment cost estimates are calculated using the Water Treatment Estimation Routine (WaTER) developed by the Bureau of Reclamation (Reclamation). The model estimates cost for individual water treatment processes based on a number input parameters, including raw water quality (e.g., pH, totally dissolved solids [TDS], totally suspended solids [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 Reclamation (1999) (table A-1).

**Table A-1.  Conventional Treatment Cost Parameters Used in Examples**

| Input Parameters | Units | Value |
|---|---|---|
| **Conventional Treatment** | | |
| *Raw Water Quality* | | |
| Bicarbonate alkalinity | milligrams per liter (mg/L) | 25 |
| TSS | mg/L | 5 |
| *Chemical Costs* | | |
| **Chlorine** | dollars per ton ($/ton) | 20 |
| **Alum** | dollars per pound ($/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 | | Two clarifiers |

The WaTER model is used to develop estimates of treatment costs (dollars per kilogallon [$/kgal]) for conventional treatment plants over capacities ranging from 1 to 30 million gallons per day (mgd). Capital costs are returned in $1,000s and operation and maintenance (O&M) costs in dollars per year ($/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 sections 2 and 3.

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 percent (%) of the total capital cost was added to the total capital cost as suggested by Qasim et al. (1992).

## Membrane Desalination Costs

Desalination cost estimates are calculated using the WaTER model (Reclamation, 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 pretreatment processes are included in cases where RO is used to treat a surface water: microfiltration (MF) and conventional treatment (table A-2). Total desalination treatment costs are the sum of annualized capital and O&M costs in dollars per year ($/year), then divided by the annual operating capacity top yield costs in dollars per thousand gallons ($/kgal).

**Table A-2. Desalination Treatment Cost Parameters Used in Examples**

| Input Parameters | Units | Value |
|---|---|---|
| **Desalination Treatment** | | |
| TDS | mg/L | 2,000 |
| Membrane diameter | centimeter (cm) | 20.32 |
| Recovery | % | 0.85 |
| Transmembrane pressure | kilo Pascal (kPa) | 2,757 |
| Membrane life | years | 5 |
| Electricity cost | dollars per kilowatthour ($/kWh) | 0.07 |

### Treatment Cost Comparison

A comparison between conventional and desalination treatment costs for both fresh and brackish surface and ground waters is presented (figure A-1). As expected, conventional treatment costs are less than those for desalination (desalination of surface water includes microfiltration pretreatment). Treatment for fresh ground water is limited to disinfection;

and treatment costs are, therefore, low. In these examples, all conveyance is assumed to occur via pipeline. A complete breakdown of costs and assumptions regarding raw water acquisition/residuals disposal are described in tables A-6 and A-7, later in this document.

Acquisition costs are added to the treatment cost estimates from WaTER for each source water using ACASE. Each of the four scenarios is evaluated to investigate how the costs of brackish water development compare with fresh water development as the distance (miles) and grade (feet per 1,000 feet [ft/1,000 ft]) between the source and plant varies (table A-3).

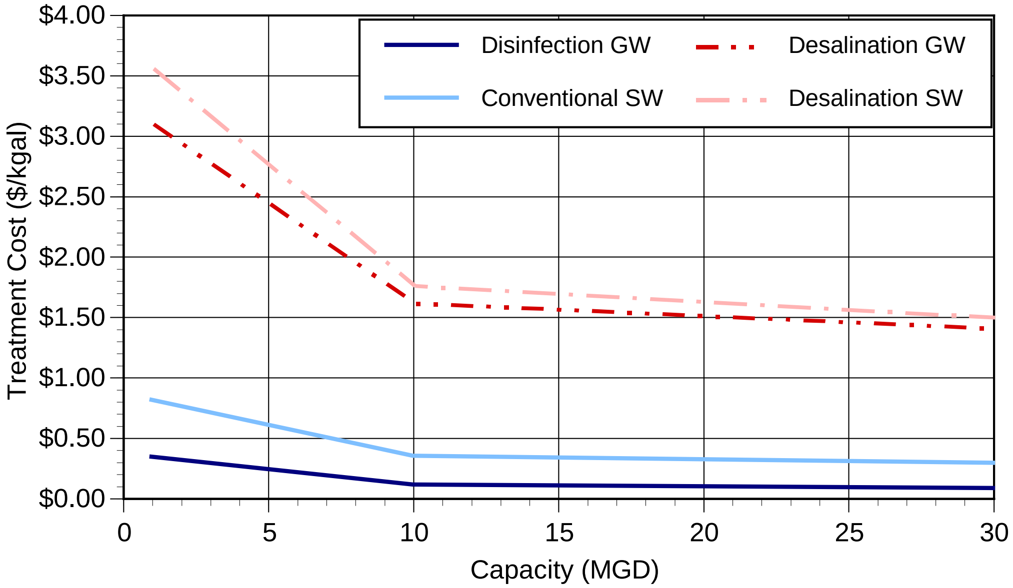

**Figure A-1. WaTER Treatment Cost Comparison Addition of Acquisition Costs.**

**Table A-3. Scenario Outline for Addition of Acquisition Costs**

| | Brackish Water Sources | |
|---|---|---|
| **Fresh Water Sources** | **Local Brackish Ground Water (GW)** | **Local Brackish Surface Water (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. That is, the total costs of supply and treatment for the fresh water at the specified distance (and grade) is equal to the total costs of supply and treatment for the “local” brackish water (local = 1 mile from plant; grade of 5 ft/1,000 ft). Therefore, if the distance to the fresh source is to the right of the iso-cost line, total costs of supply and treatment for the brackish source are less than those of the fresh water source (indicated by arrows on the plots). Similarly, if the fresh water source is located at a distance to the left of the iso-cost line, the total costs of supply and treatment are lower for the fresh water source. Although desalination costs for a brackish ground water may be higher than conventionally treated surface water, if the distance to the surface water exceeds 66 miles (grade of 0), then the brackish ground water becomes more economically attractive (figure A-2). If the surface water source is closer than 66 miles, than this source has a lower total cost of supply and treatment. Similar comparisons of different combinations of distant/local surface and ground waters are shown in figures A-3, A-4, and A-5. In these examples, surface water is acquired through exposed towers, treated via conventional processes; and sludge disposal involves lagoons and filter presses. Ground water is acquired through wells, treated via RO (conventional pretreatment); and concentrate is handled through deep well injection. All conveyance is carried out via pipeline.

Note: The crossover of the 1 and 10 mgd iso-cost lines seen in these comparisons is due to increases in uphill pumping costs for the smaller diameter pipelines which experience a higher relative level of frictional losses for the transported flow.

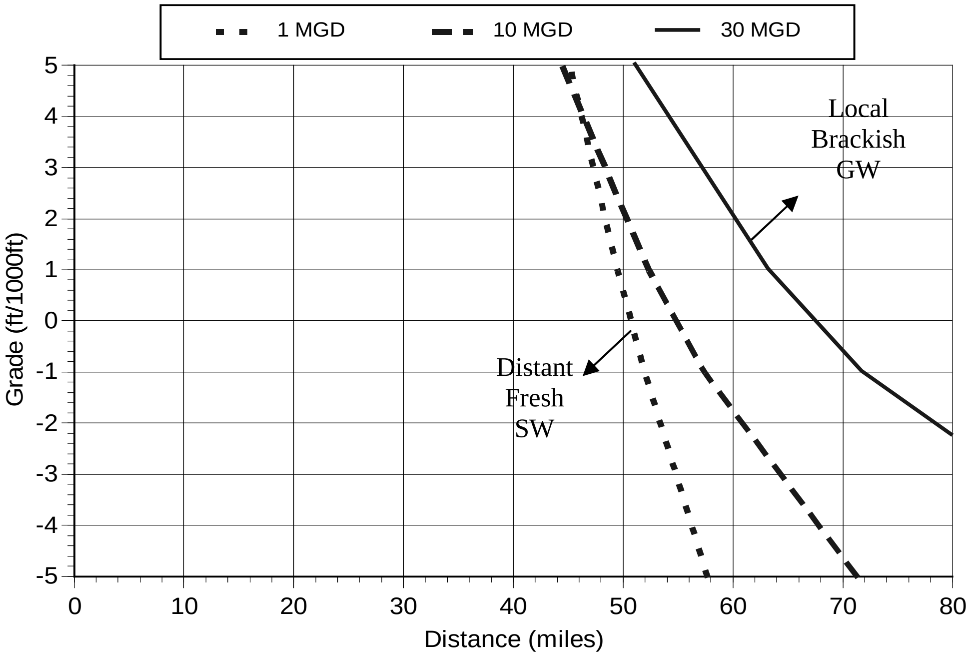

**Figure A-2. Local Brackish GW Versus Distant Fresh SW (1A).**

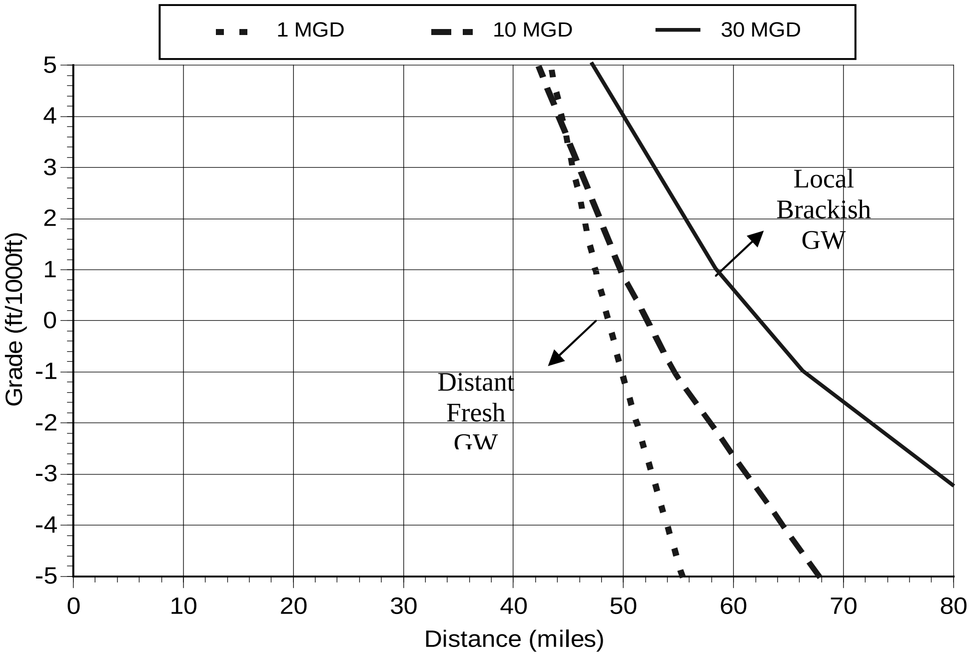

Figure A-3. Local Brackish GW Versus Distant Fresh GW (1B).

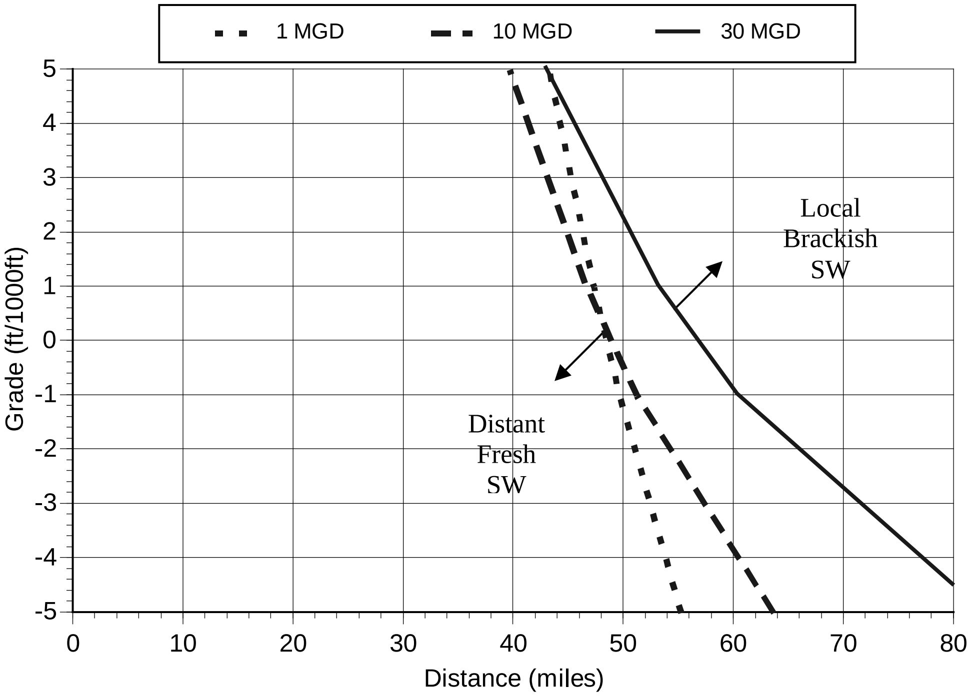

Figure A-4. Local Brackish SW Versus Distant Fresh SW (2A).

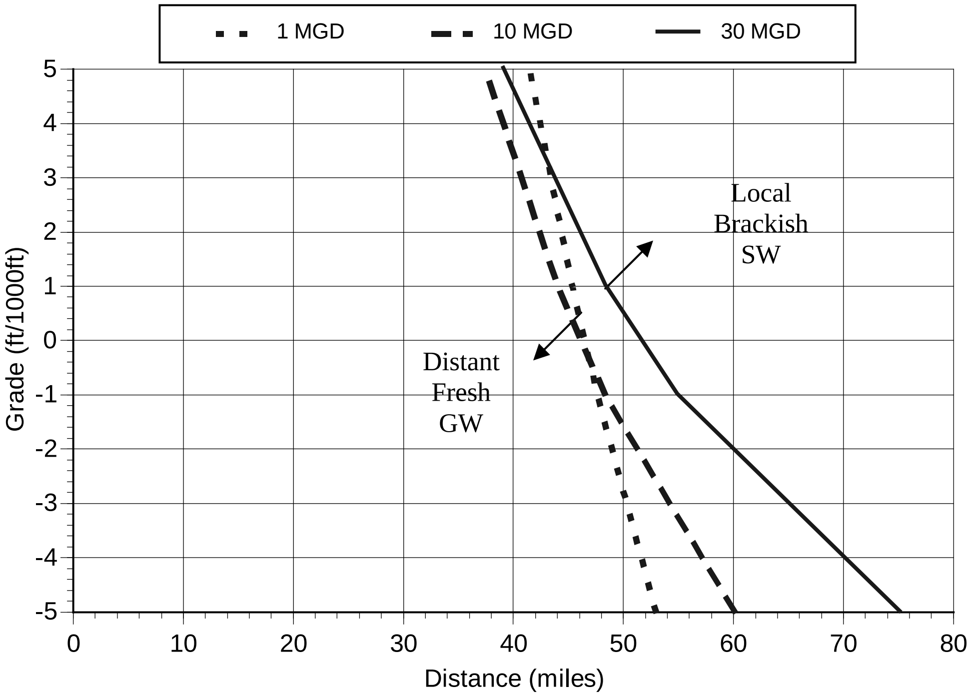

**Figure A-5. Local Brackish SW Versus Distant Fresh GW (2B).**

## Addition of Compliance Costs

Consideration is also given to waters (high total organic carbon (TOC) levels) that might violate Stage 2 D-DBP drinking water regulations. In order to maintain compliance with the total trihalomethane (TTHM) maximum contaminant level (MCL), ancillary processes are added to conventional treatment processes to reduce TTHM formation using the WaTER-DBP model. As membrane desalination processes can effectively remove TOC (Clark et al., 1994; American Water Works Association (AWWA), 1996), these processes are assumed to maintain compliance without any additions. Therefore, results from two scenarios (table A-4) considering only fresh surface water (with elevated TOC) are presented.

**Table A-4. 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 are evaluated for the fresh water source: enhanced coagulation, alternative disinfectants (ozone as pre-disinfectant and chloramines as a post-disinfectant), and granular activated carbon (GAC) filtration. (Note: Not all of these alternatives were implemented in WaTER-DBP).

In all the figures below, the “dark” iso-cost lines are the same as those in figures A-2 to A-5, respectively. The “lighter” iso-cost lines indicate modifications that include the additional costs of ancillary processes to maintain compliance (and later the costs of additional storage as well). Consideration of these additional costs increases the attractiveness 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 A-6, A-7, A-10, A-11). However, if GAC filtration is required to achieve compliance, the economic attractiveness of the brackish source is greatly increased (figures A-9 and A-13), and the distance at which the total costs of supply and treatment are equal for both sources is reduced by approximately 50%.

## Addition of Storage Costs

Storage costs are only considered in the development of fresh surface waters, as it would be rare that a brackish water requiring both desalination and additional storage would be economically attractive. Costs for reservoirs with capacities of 3, 6, and 12 months of average daily flow ($Q_{OP}$) are added to the total supply and treatment costs for fresh water sources using the ACASE model. In these scenarios, fresh water treatment includes the use of chloramines as a post-disinfectant for Stage 2 D/DBP compliance (table A-5).

The addition of storage costs improves the attractiveness of brackish sources, especially for smaller plants. Figures A-14, A-15, and A-16 describe costs for a fresh surface water source requiring 3-month storage and the use of chloramines to maintain compliance. The distribution of total supply and treatment costs are presented in table A-6.

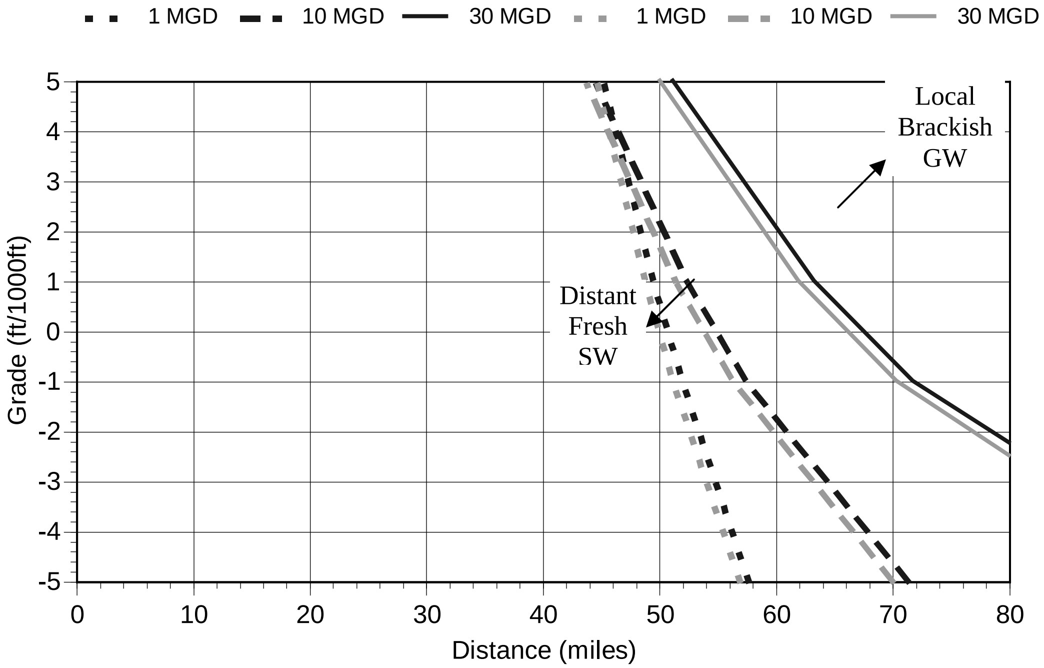

**Figure A-6. Distant Fresh Surface Water with Enhanced Coagulation Versus Local Brackish Ground Water (1C).**

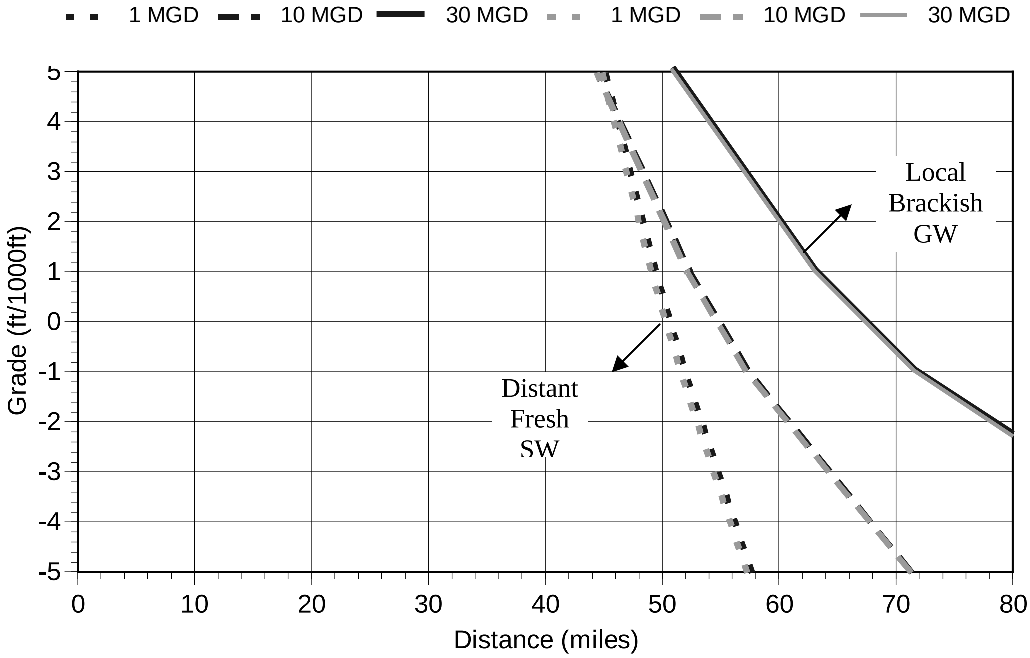

Figure A-7. Distant Fresh Surface Water with Chloramines as Post-Disinfectant Versus Local Brackish Ground Water (1C).

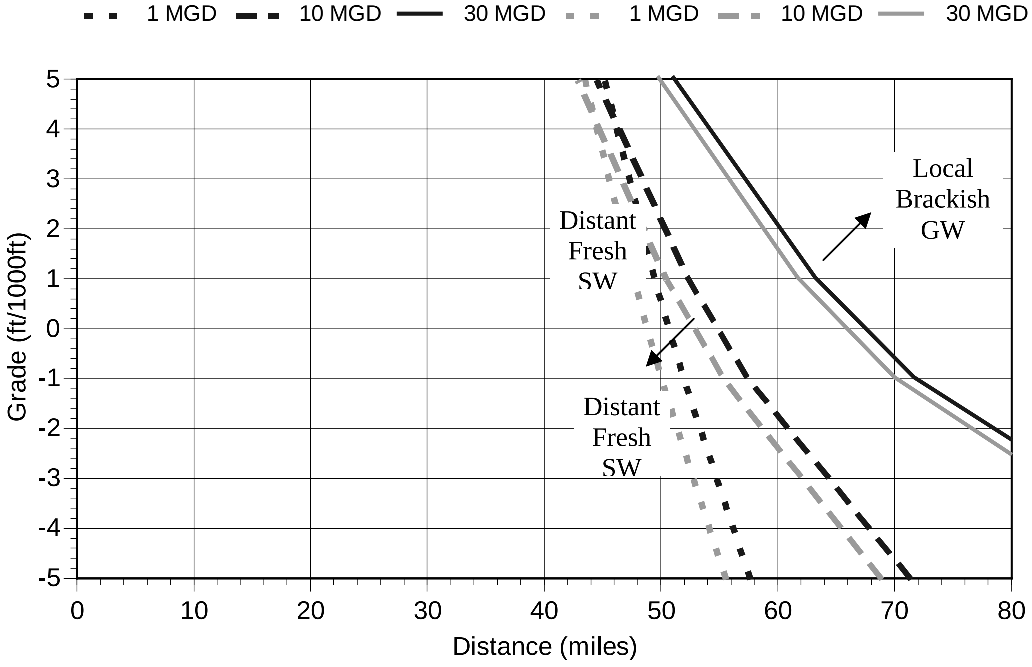

Figure A-8. Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant Versus Local Brackish Ground Water (1C).

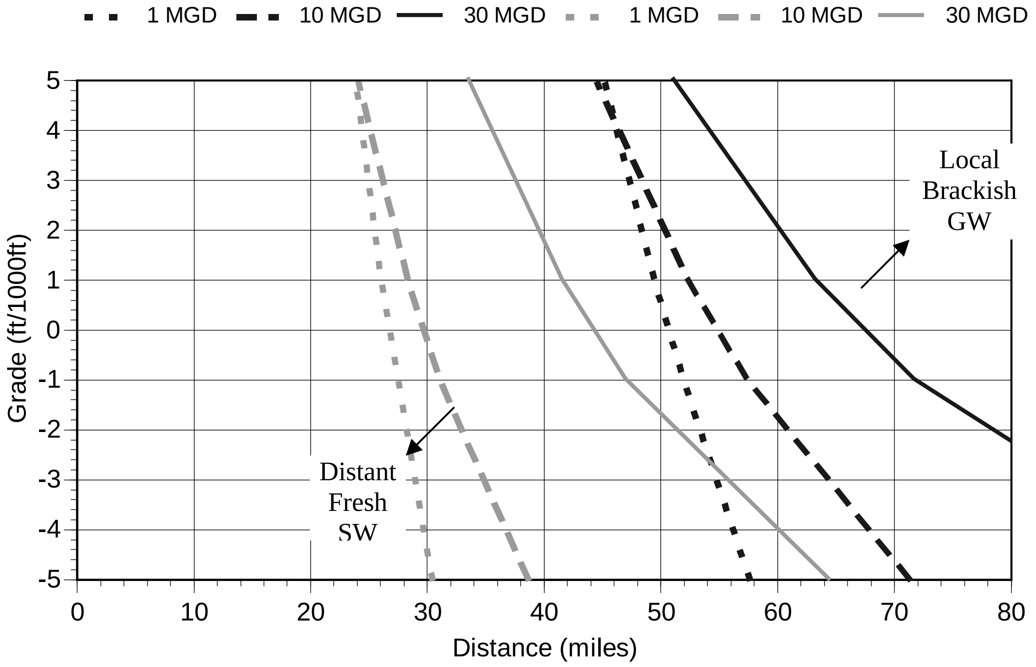

**Figure A-9. Distant Fresh Surface Water with GAC Filtration Versus Local Brackish Ground Water (1C).**

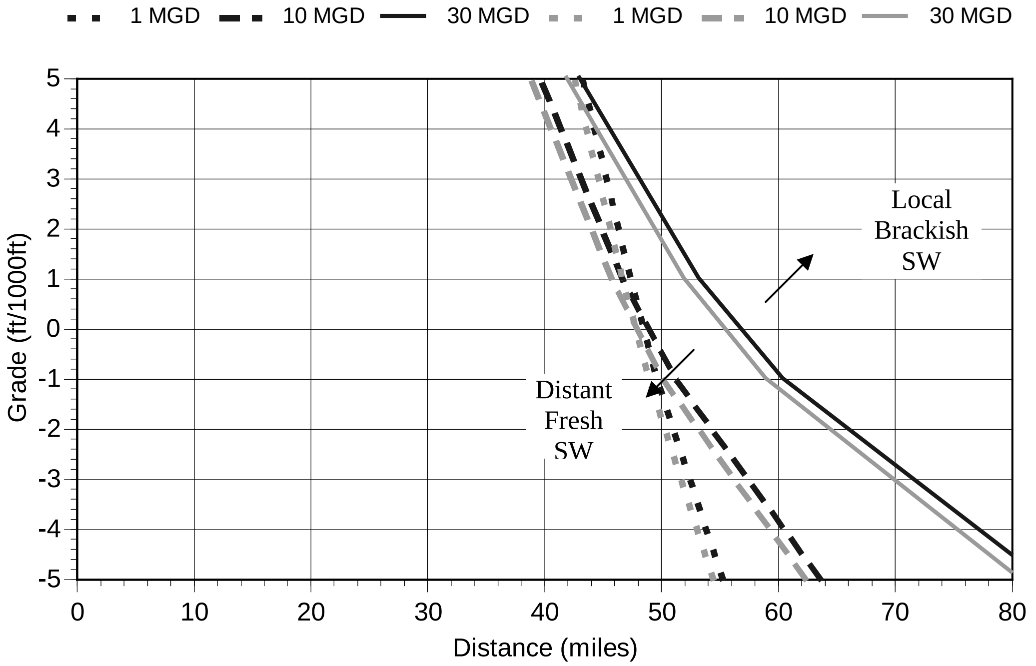

**Figure A-10. Distant Fresh Surface Water with Enhanced Coagulation Versus Local Brackish Surface Water (2C).**

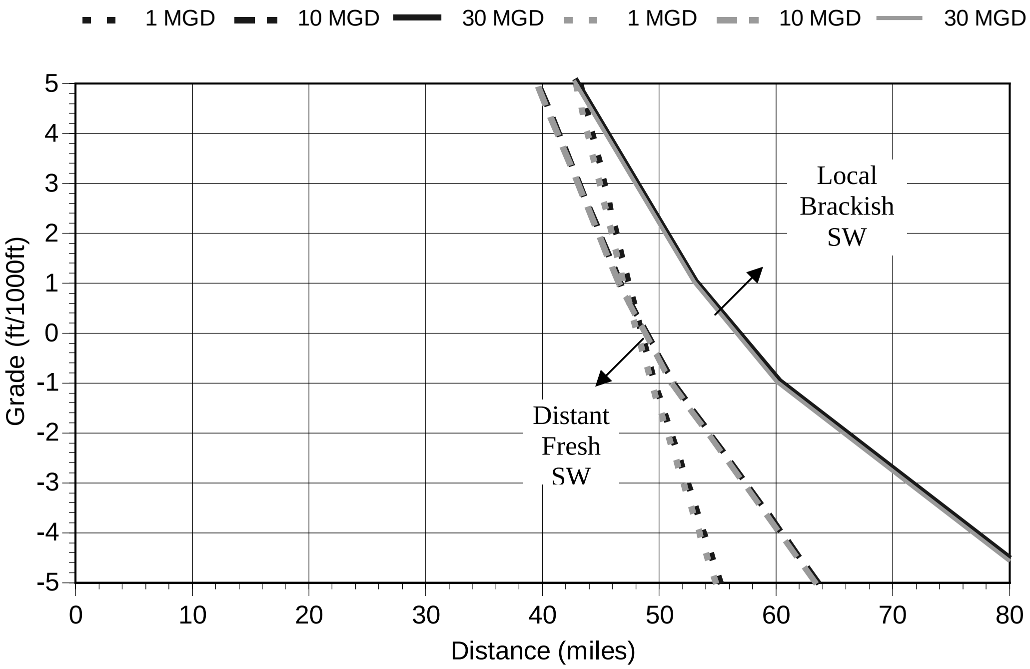

**Figure A-11 Distant Fresh Surface Water with Chloramines as Post-Disinfectant Versus Local Brackish Surface Water (2C).**

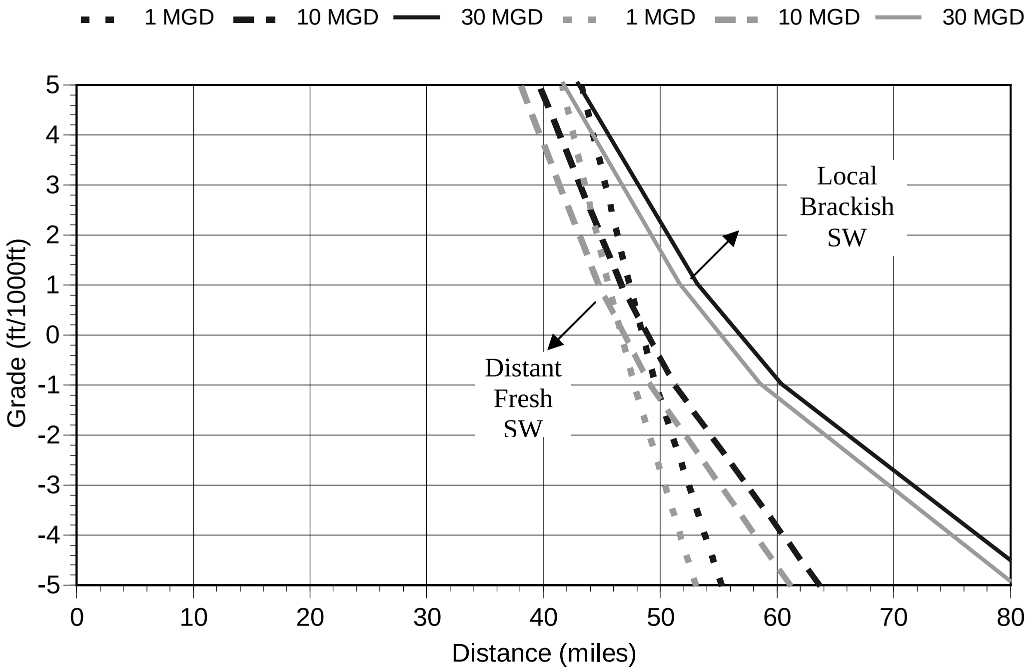

**Figure A-12. Distant Fresh Surface Water with Ozone as Pre- and Chloramines as Post-Disinfectant Versus Local Brackish Surface Water (2C).**

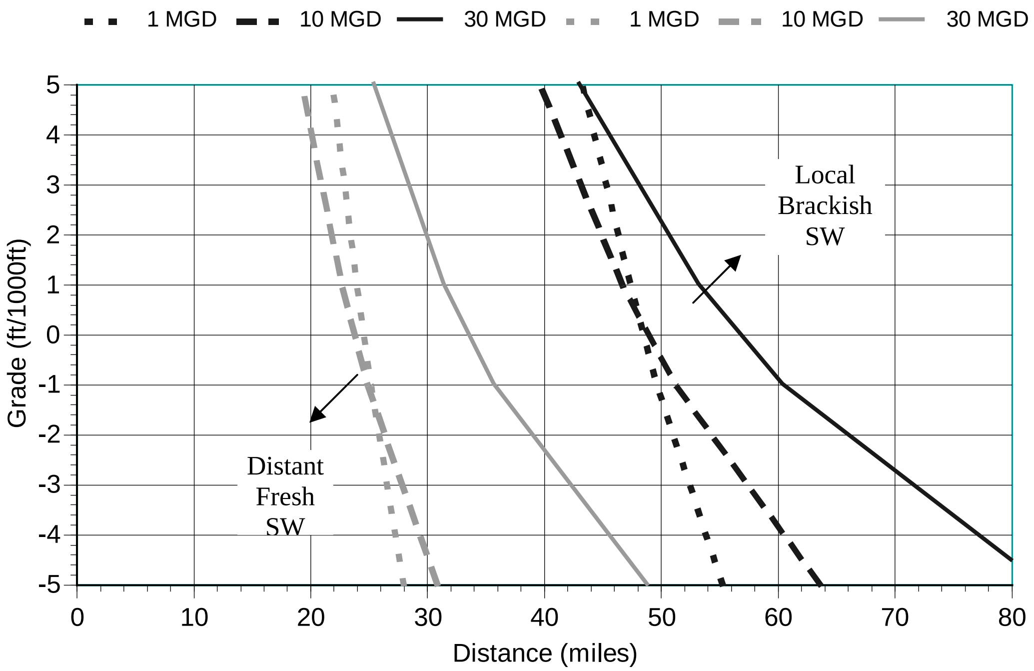

Figure A-13. Distant Fresh Surface Water with GAC Filtration Versus Local Brackish Surface Water (2C).

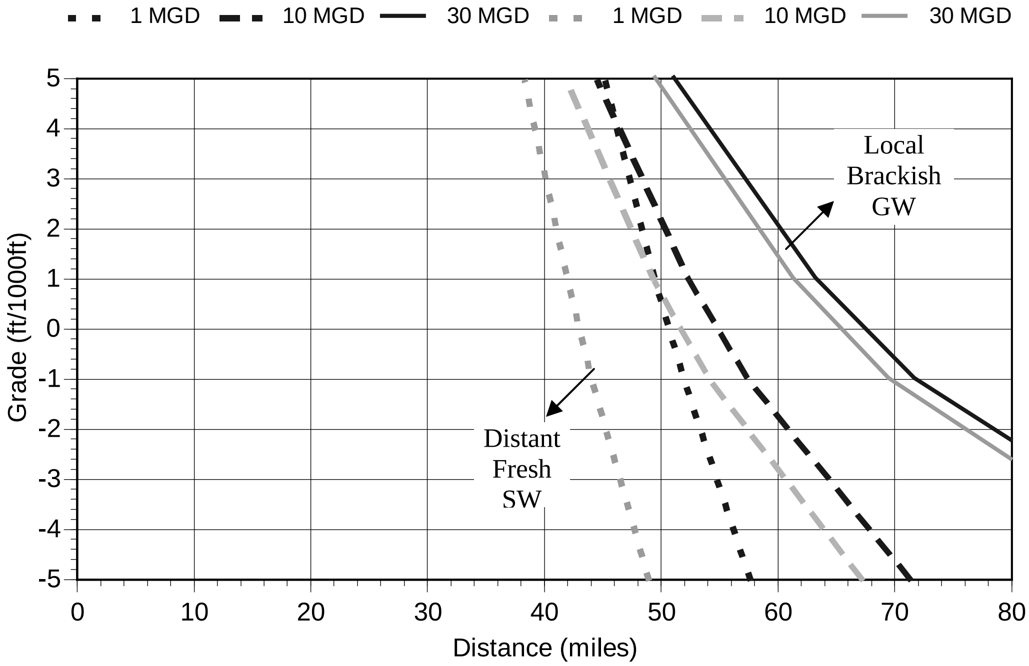

Figure A-14. Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 3-Month Storage Versus Local Brackish Ground Water (1D).

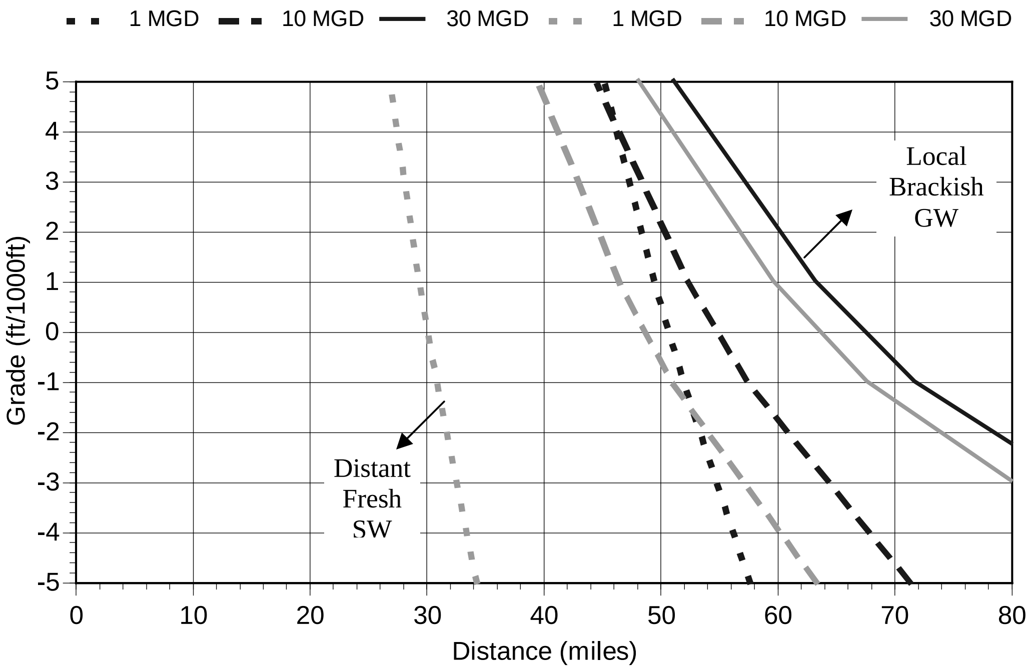

Figure A-15. Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 6 Month Storage Versus Local Brackish Ground Water (1D).

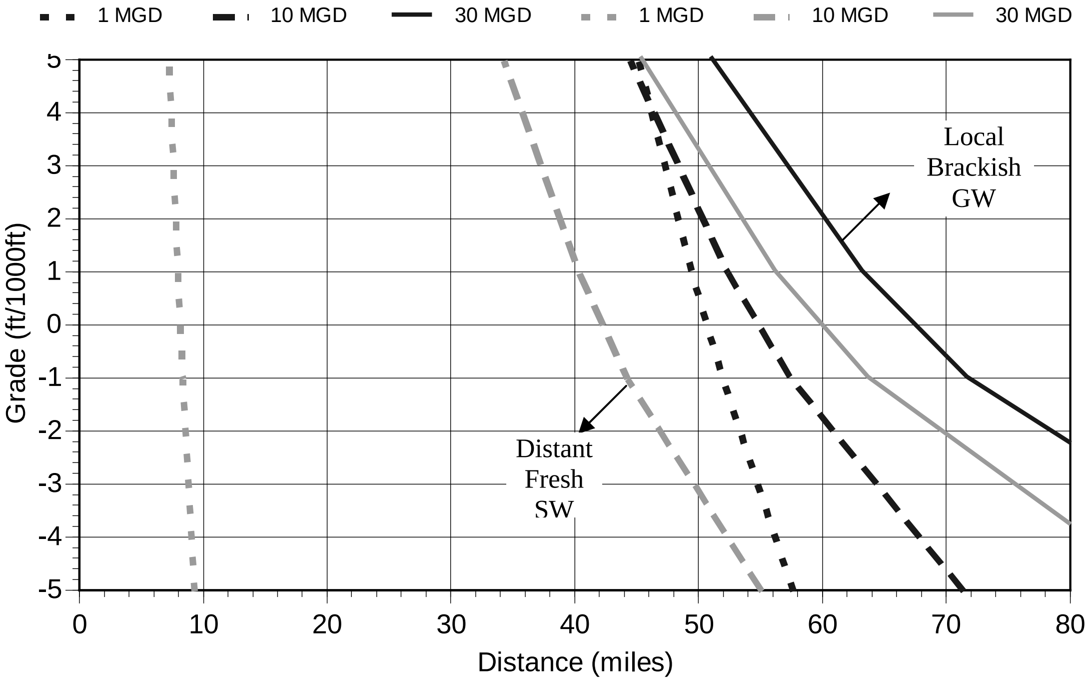

Figure A-16. Distant Fresh Surface Water with Chloramines as Post-Disinfectant and 12-Month Storage Versus Local Brackish Ground Water (1D).

**Table A-5. Scenario for Storage**

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

**Table A-6. Total Supply and Treatment Costs with 3-Month Storage**

| Source | Treatment Costs | Residuals Disposal 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 |

**Table A-7. Assumptions Used in Comparative Analyses**

| 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 |