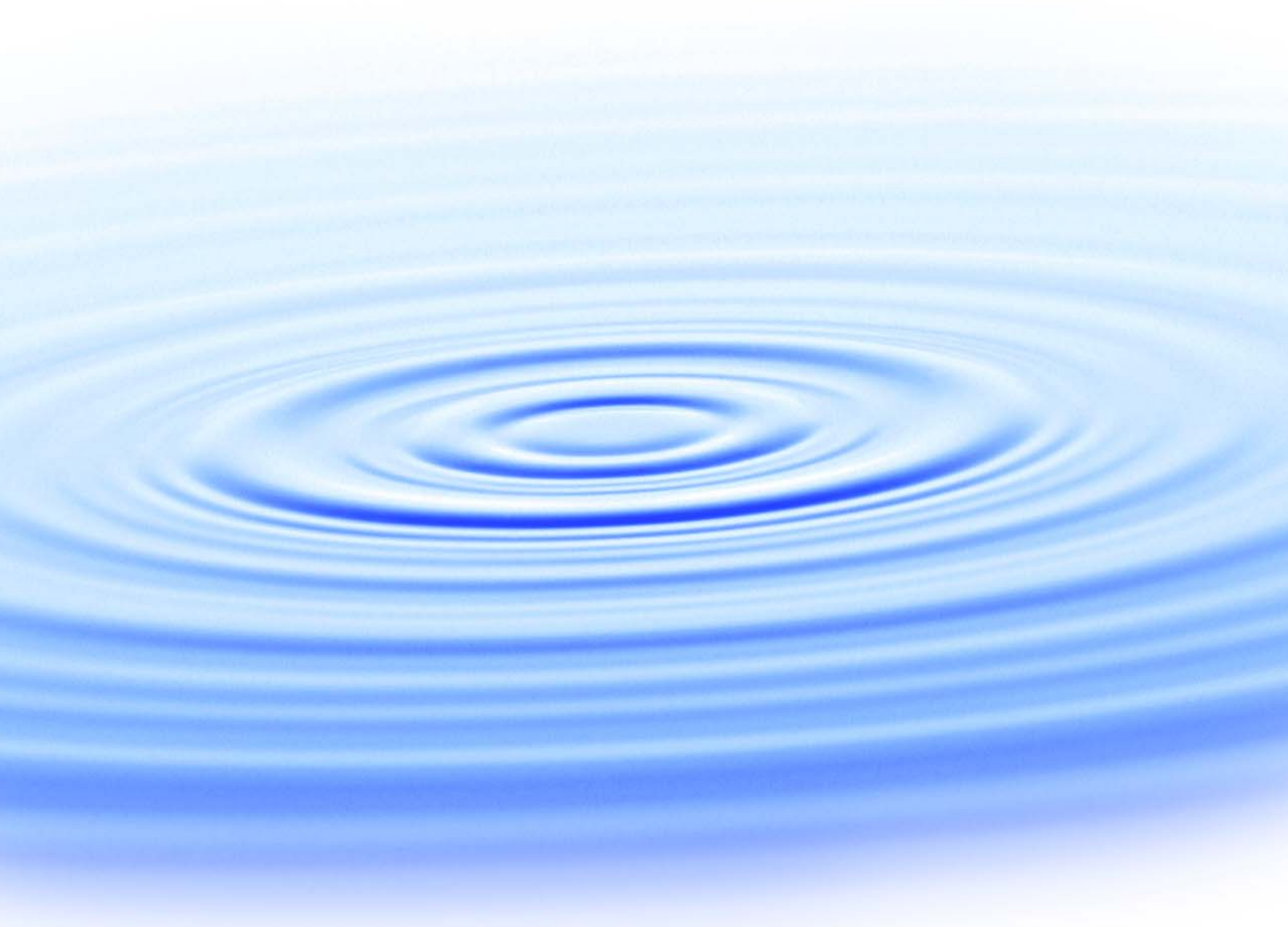
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

WATEREUSE RESEARCH

Fit for Purpose Water: The Cost of Overtreating Reclaimed Water



WateReuse Research Foundation

Fit for Purpose Water: The Cost of Overtreating Reclaimed Water

About the WateReuse Research Foundation

The mission of the WateReuse Research Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high-quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, and the California Department of Water Resources. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations.

Fit for Purpose Water: The Cost of Overtreating Reclaimed Water

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Acronyms

AHMC	Australia Health Ministers' Conference
ASR	aquifer storage recovery
BAC	biological activated carbon
BenMAP	Environmental Benefits Mapping and Analysis Program
BW	backwash water
$CBOD_5$	5-day carbonaceous biochemical oxygen demand
CDPH	California Department of Public Health
CEC	contaminants of emerging concern
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	CO_2 equivalent
COD	chemical oxygen demand
CPES	CH2M HILL’s parametric cost estimating system
DAF	dissolved air flotation
DSAYs	discounted service acre years
EC	electrical conductivity
EPA	U.S. Environmental Protection Agency
EPHC	Environmental Protection and Heritage Council
EWATRO	Evaluation of Wastewater Treatment and Reuse Options
Foundation	WateReuse Research Foundation
GAC	granular activated carbon
GHG	greenhouse gas
GMF	granular media filtration
GRI	Global Reporting Initiative
GW	groundwater
GWP	global warming potential
GWRS	Groundwater Replenishment System
HEA	habitat equivalency analysis
H_2O_2	hydrogen peroxide
IPCC	Intergovernmental Panel on Climate Change
IRWP	Incremental Recycled Water Program
LACSD	Los Angeles County Sanitation Districts
LCA	life-cycle assessment
LRVs	log reduction values
MATS	Mercury and Air Toxics Standards
MCL	maximum contaminant level

MF	microfiltration
MOVES	Motor Vehicle Emission Simulator
N_2O	nitrous oxide
NACWA	National Association of Clean Water Agencies
NDMA	N-nitrosodimethylamine
NEBA	net environmental benefit analysis
NH_3	ammonia
NO_X	nitrogen oxides
NPV	net present value
NRC	National Research Council
NRMMC	National Resource Management Ministerial Council
NTU	nephelometric turbidity unit
O_3	ozone
O&M	operation and maintenance
O.W.L.	Open Space and Water Resource Protection and Land Use
OCWD	Orange County Water District
PAC	powdered activated carbon
PFD	process flow diagram
RBF	riverbank filtration
RO	reverse osmosis
RWC	recycled water contribution
SAR	sodium adsorption ratio
SAT	soil aquifer treatment
SAYs	service acre years
SCADA	supervisory control and data acquisition
SO_x	sulfur oxides
TBL	triple bottom line
TDS	total dissolved solids
TKN	total kjeldahl nitrogen
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
UF	ultrafiltration
UOSA	Upper Occoquan Service Authority
UV	ultraviolet
UVAOP	ultraviolet advanced oxidation process
WTP	water treatment plant
WWTP	wastewater treatment plant
ZLD	zero liquid discharge

Foreword

The WateReuse Research Foundation (Foundation), a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high-quality water, protect public health, and improve the environment.

An Operating Plan guides the Foundation's research program. Under the plan, a research agenda of high-priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities including water professionals, academics, and Foundation subscribers. The Foundation's research focuses on a broad range of water reuse research topics includes the following:

- Definition of and addressing chemicals of emerging concern (CECs)
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

The Operating Plan outlines the role of the Foundation's Research Advisory Committee, Project Advisory Committees, and Foundation staff. The Research Advisory Committee sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. Project Advisory Committees are convened for each project and provide technical review and oversight. The Foundation's Research Advisory Committee and Project Advisory Committees consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the Research Advisory Committees and Project Advisory Committees and provide overall management of projects.

More communities than ever are investigating the feasibility of implementing potable and nonpotable reuse projects to increase their available yield and protect against periods of drought. The complexity of this task is compounded by the variety of reuse treatment technologies, which can differ in terms of benefit to the end user, as well as in the true cost of implementation. This research project examines the benefits and costs of various levels of treatment for potable and nonpotable reuse applications. A triple bottom line (TBL) analysis was performed that includes financial, environmental, and social elements to help ensure that the right treatment process is applied for the intended use without expending unnecessary funds, energy, greenhouse gases, and other social and environmental costs. Potable and nonpotable reuse scenarios are examined.

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Executive Summary

As populations around the world continue to grow and communities appreciate the difficulty in securing new water supplies, water reuse is expected to expand in the coming years. Other factors, such as localized drought severity and increased community and regulatory pressure may also increase the application of water reuse. The level of treatment provided in water reuse projects varies significantly throughout the world depending on numerous factors, such as regulations, water quality, end uses of the treated water, and public influence. Selecting the appropriate treatment technology and level of treatment can be a complex decision. Recent experiences within the water reuse industry have demonstrated that governmental and nongovernmental organizations and advocacy groups can influence selection of a higher or more costly level of treatment than is fit for the water purpose. This is partially because of a failure to consider the full financial, environmental, and social elements of the triple bottom line (TBL). The focus of this report was to develop and apply a TBL framework to help guide sound selection of the treatment process. The objective is to match the treatment to the intended use without expending unnecessary funds or energy or emitting excess greenhouse gas (GHG) and other air emissions, while minimizing other environmental and social costs. Although the present research addresses water reuse only, the TBL approach is equally applicable toward evaluating the full suite of water supply and demand alternatives.

Scenarios Examined

A number of treatment technologies are commercially available when implementing nonpotable and potable reuse projects. For example, California has approved 45 different filtration systems for use at nonpotable reuse treatment plants, with 19 granular media filtration types, 19 membrane systems, and 7 cloth filters (CDPH, 2009). Similarly, numerous potable reuse technologies are available including microfiltration (MF), reverse osmosis (RO), ultraviolet advanced oxidation (UVAOP), ozone (O_3), biological activated carbon (BAC), granular activated carbon (GAC), ultraviolet irradiation (UV), and soil aquifer treatment. Consequently, selection of the appropriate treatment process can be difficult and is sometimes based on the perception that more advanced treatment is better without an indepth consideration regarding numerous financial, environmental, and social factors. In some cases, a similar and use-appropriate level of water quality can be provided at substantially lower costs and with fewer environmental and social effects. Treatment trains that are perceived as “more advanced” or “higher tech” do not always provide more appropriate treatment and can result in such high TBL costs that water reuse may be prohibitively expensive.

Two water reuse scenarios (Figure ES1) were developed for detailed TBL evaluation on the basis of review of applicable regulations, ranking of reclaimed water uses, utility surveys, reuse trends, and likely situations for potential overtreatment:

- **Scenario 1** is a nonpotable reuse application for landscape irrigation that compares a granular media filtration approach to two membrane-based approaches.
- **Scenario 2** is a potable reuse scenario for reservoir augmentation comparing the RO-based approach—used extensively in California and internationally, and widely considered the “gold-standard” for potable reuse—to the GAC-based approach used in the eastern United States.

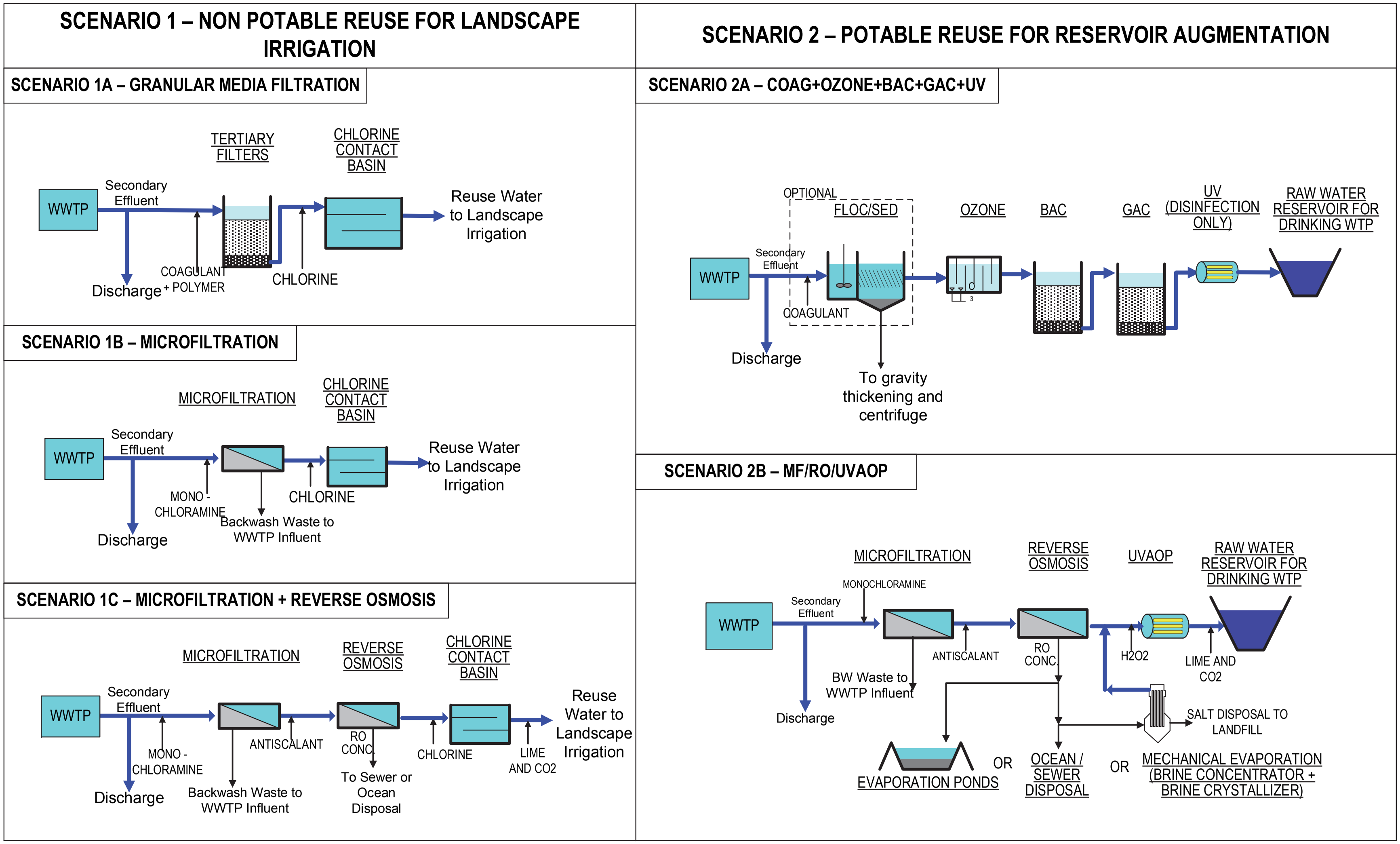

Figure ES1. Scenarios examined.

Notes: BAC = biological activated carbon filtration; BW = backwash water; Coag = coagulation; CO_2 = carbon dioxide; GAC = granular activated carbon; H_2O_2 = hydrogen peroxide; MF = microfiltration; O_3 = ozone; RO = reverse osmosis; UV = ultraviolet disinfection; UVAOP = ultraviolet advanced oxidation; WTP = water treatment plant

Both of the scenarios were examined at three plant capacities—5 mgd, 20 mgd, and 70 mgd—to determine the TBL costs for treatment plant capacities applicable to most utilities considering implementation of a water reuse project. Capital costs were determined for the plant capacities stated. Annual operating, environmental, and social costs were determined on the basis of an annual production of 60% of the plant capacity (e.g., 12 mgd for the 20 mgd plant capacity).

This research was intended to develop the TBL approach as it pertains to selecting water reuse treatment and illustrate the methodology with carefully selected treatment scenarios. The analysis of treatment did not exhaust all alternatives. For example, one alternative treatment process, soil aquifer treatment (SAT) for potable reuse was not included in this research, although it is expected to have relatively low TBL costs, especially for potable reuse projects, such as those practiced in California (e.g., Montebello Forebay groundwater recharge project).

Triple Bottom Line Accounting

This research uses an economic cost−benefit analysis approach to identify and quantify the most significant TBL factors in dollars to inform reuse water treatment selections and avoid costly overtreatment. Overtreatment is defined as spending more than is necessary or causing adverse environmental impact and social effects without providing counterbalancing benefits. To ensure a fair comparison, the treatment technologies were selected with the aim of providing comparable water quality. Any differences in water quality that remained were discussed in terms of the benefits associated with selecting one treatment technology over another. Of the comprehensive TBL effects relevant to water reuse projects identified and documented in this report, the following TBL elements were determined to be most influential in the implementation of nonpotable and potable reuse projects:

- **Direct Financial Costs—**Construction, engineering, and annual operating costs
- **Upstream Environmental and Social Factors—**GHG and other air emissions resulting from the plant's electricity use and the production and transportation of chemicals required for water treatment
- **Downstream Environmental and Social Factors—**GHG and other air emissions and land requirements resulting from the transportation and disposal of salt and chemical solids concentrated at the treatment plant site

Where possible, environmental and social factors were monetized and combined with the direct financial costs to allow a quantifiable comparison of alternative treatment trains through net present value (NPV) calculations. For example, all GHGs released at a power plant resulting from electricity use at the water reuse plant were monetized using EPA established values to reflect the effects on agricultural productivity, human health, property damage resulting from flood risk, and the value of ecosystem services because of climate change. Some downstream environmental impacts, such as salinity concentrations in groundwater, are described qualitatively, as they are highly variable depending on site-specific conditions. Situations where such qualitative factors can influence the TBL results are few but noteworthy, particularly in the case of excess salinity.

Capital and annual operating costs were determined using a parametric cost model for water and wastewater treatment plants. The parametric cost estimating program uses fundamental design criteria for treatment processes, general arrangement drawings based on actual plant designs, and an extensive water treatment cost database from constructed plants to generate detailed quantity takeoffs and reliable cost estimates. The costs are for a complete and fully operational water reuse plant (excludes wastewater treatment through secondary treatment) with the necessary site development, electrical, computer, operations and maintenance buildings, and miscellaneous support infrastructure included in a typical plant. Standard percentages for items, such as overhead and profit, contingency, engineering, and bonds and insurance, are applied to the construction cost estimate to generate a total capital cost estimate. Annual operating costs are estimated using outputs from the capital cost model that include power consumption, chemical consumption, equipment replacement requirements, labor requirements, and miscellaneous maintenance and repair. All costs are reported in 2012 U.S. dollars.

Utility Survey

A survey of utilities that operate full-scale potable and nonpotable reuse plants was conducted to collect relevant data that supported development of the TBL cost estimates. Data collected included design and operational criteria for the water treatment processes used, water quality data, annual operational costs, reclaimed water end uses, and regulatory requirements. Much of the data collected provided specific information on plant design and operation that can significantly affect costs. For example, one reuse plant may operate an RO process at 75% recovery because of specific feed water quality conditions that lead to scale formation, whereas another plant may be able to operate at 85% recovery because of different water quality characteristics. This difference in design and operation can lead to significant differences in capital and operating costs that must be accounted for and explained. Analysis of the data collected during the utility survey that is relevant to this research includes:

- Annual operation and maintenance (O&M) costs for nonpotable reuse plants ranging from $0.65/kgal to $1.55/kgal, with a median value of $1.11/kgal. However, for all but one plant, these costs included biological treatment costs in the wastewater treatment plant, which are estimated at about $1/kgal. Therefore, the annual O&M cost for nonpotable reuse treatment only is significantly lower than shown and likely less than $0.50/kgal for the plants reporting costs.
- Annual O&M costs for the potable reuse plants ranging from $0.62/kgal to $2.43/kgal. Costs for the RO-based plants ranged from $1.14/kgal to $2.43/kgal. Costs for the GAC-based plants ranged from $0.62/kgal to $2.00/kgal; however, costs for the GAC-based plant with $2.00/kgal costs included biological treatment at the wastewater treatment plant. Assuming biological treatment costs are typically near $1/kgal, the tertiary treatment annual O&M costs for the GAC-based plants shown likely range from $0.4/kgal to $1/kgal, which are lower than the RO-based plants.
- Power, labor, chemical, and maintenance and repair costs being the most significant elements of annual operating costs. Representative values for each were identified and compared to the cost estimates developed for Scenarios 1 and 2.
- Collection of construction cost data from the participating utilities proving to be very difficult, and numerous problems encountered, including incomplete cost information for the entire project scope, inadequate description and understanding of the project scope, combination of other project elements not related to treatment improvements without detailed cost breakdown, and incomplete and inaccurate construction cost data. Consequently, construction cost data from all the plants included in the utility survey were not collected.

Where feasible, calibration of the cost model was conducted using the utility survey data. For example, the construction cost estimate for Scenario 2B (MF-RO-UVAOP) was compared to the actual costs for the 70 mgd Groundwater Replenishment System (GWRS) potable reuse plant (Figure ES2). The construction cost estimate for Scenario 2B was 6% higher than the actual 2004 contracted cost and 20% less than the 2012 escalated cost. Similarly, calibration results were good for most annual operating cost categories, including costs for power, chemicals, and maintenance and repair. Labor costs were significantly different because of the higher price of labor in Southern California, and major equipment costs were significantly different because of GWRS's contingency approach to budgeting for major equipment replacement.

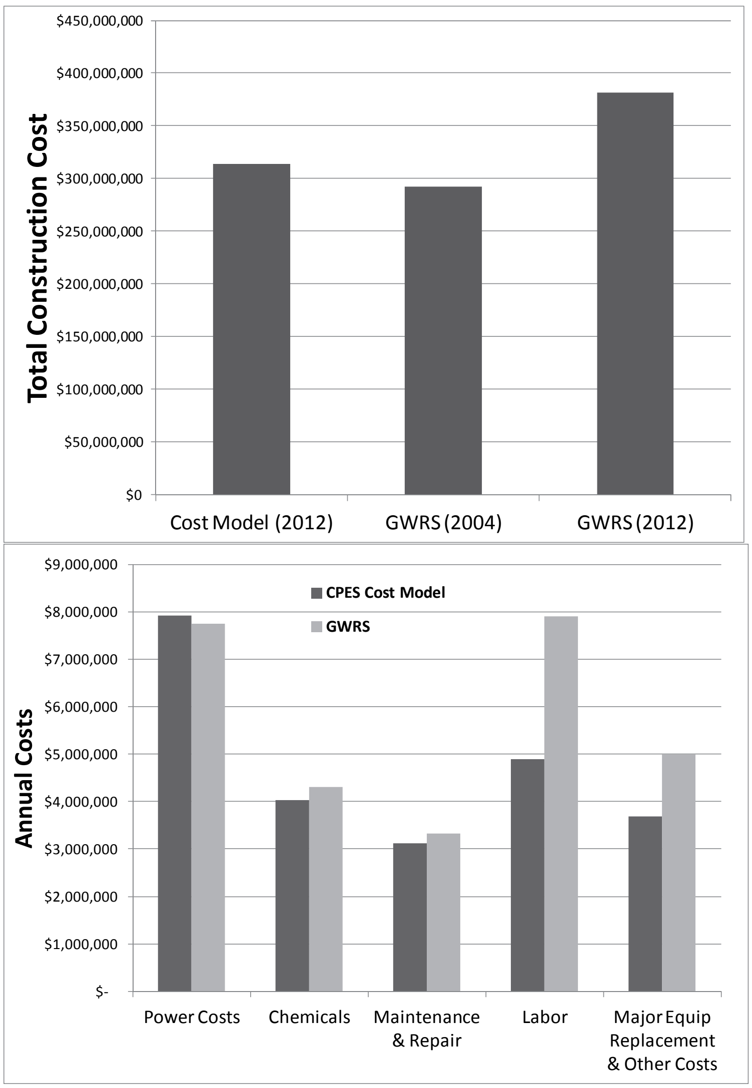

Figure ES2. Construction and annual cost comparison between cost model and 70 mgd groundwater replenishment system plant.

Triple Bottom Line Costs

Triple bottom line costs were developed for both scenarios at three flow rates using design criteria collected from participating utilities and supplemented with professional experience.

Table ES1 shows TBL results from the 20 mgd plant capacity analysis. The major conclusions are as follows:

- **Nonmembrane-based treatment trains have the lowest TBL costs for all flows analyzed.** Capital, O&M, environmental, and total TBL costs are lowest at all flows analyzed for Scenario 1A (compared with 1B and 1C) and Scenario 2A (compared to 2B).
- **Differences in costs are smallest for small plants.** Although the nonmembrane treatment trains have the lowest costs for all flows analyzed, the difference in capital, O&M, and environmental costs is smallest for the 5 mgd plant capacity. For example, at a 5 mgd plant capacity capital costs for the potable reuse Scenarios 2A (GAC-based) and 2B (RO-based with ocean disposal) are $50 million and $52 million, respectively. Annual operating costs are $1.9M and $2.4M, respectively, and annual environmental costs are $0.19M and $0.63M, respectively. Therefore, where inexpensive ocean or sewer disposal is readily available for RO concentrate disposal for plant capacities of 5 mgd or less, the RO-based membrane treatment approach is relatively cost-competitive with the GAC-based approach. The nonpotable reuse Scenarios 1A (granular media filtration) and 1B (MF) are also relatively cost-competitive at the 5 mgd flow and lower, but the addition of RO to the MF process as depicted in Scenario 1C is quite a bit more costly, even at low flows and with ocean disposal.
- **Large plants favor nonmembrane-based treatment trains.** At flow rates of 20 mgd and 70 mgd, the capital, O&M, and environmental costs for the membrane-based treatment trains are significantly higher than the nonmembrane-based treatment trains for both the potable and nonpotable reuse scenarios. For example, capital costs for Scenario 2B with ocean disposal of RO concentrate at a plant capacity of 20 mgd are $29M (32%) higher than Scenario 2A. Annual O&M and environmental costs are also significantly higher, resulting in a total NPV for Scenario 2B that is 54% higher than 2A. This difference increases substantially at a 70 mgd plant capacity. For locations where sewer or ocean disposal is not possible and concentrate handling and disposal must be incorporated, these differences increase significantly.
- **RO concentrate disposal costs can be cost prohibitive.** Where RO concentrate handling is required (e.g., inland locations), the associated capital, O&M, and environmental costs can be prohibitive. For example, measured relative to the ocean disposal case, capital costs for Scenario 2B at 20-mgd increase by $52 million and $183 million for mechanical evaporation and evaporation pond approaches, respectively. Annual O&M and environmental costs are also significantly higher, resulting in a total NPV for the mechanical evaporation and evaporation pond approaches that exceed Scenario 2B with ocean disposal by 100% and 92%, respectively. This difference increases significantly at a 70 mgd plant capacity. An RO-concentrate volume reduction approach using a brine concentrator (but without the brine crystallizer) followed by evaporation ponds was analyzed to determine if cost reduction was possible. Results showed lower costs, but the NPV was still 54% higher than Scenario 2B with ocean disposal, which suggests that a volume reduction approach to concentrate management might also be cost prohibitive.
- **Electricity requirements for RO plants are high.** Most reuse plants utilizing RO membranes operate at feed pressures in excess of 150 psi, which consumes large amounts of electricity. If mechanical evaporation technology is incorporated for RO-concentrate treatment, the electricity draw increases considerably because of the vapor compression and heating requirements associated with mechanical evaporation. To illustrate this point,

the Scenario 2B RO-based ocean disposal approach at 20 mgd uses approximately 16,000 MWh/year of electricity compared to 4,400 MWh/year used by Scenario 2A (GAC based). Utilization of mechanical evaporation increases the Scenario 2B annual consumption to 65,400 MWh/year (equivalent to 5,800 average U.S. households).

- **Electricity requirements most significantly affect environmental costs.** Electricity generation for use at the water reuse plant is the most significant contribution to the environmental costs. For all scenarios examined, electricity generation was responsible for 70 to 90% of all GHG and other air emissions costs.
- **GHG emissions dwarf other air emissions.** The production of GHGs from electricity generation far exceeds other air emissions. For example at 20 mgd plant capacity, Scenario 2A is responsible for 2,900 tons/year of GHGs compared to 11 tons/year of other air emissions (SO_x, NO_x, $PM_{2.5}$). However, the environmental unit costs for these emissions (i.e., the value of the adverse effects associated with each ton of emission) are dramatically different, resulting in lower GHG costs relative to environmental costs for other air emissions. For Scenario 2B (20 mgd plant capacity), annual environmental costs associated with GHGs are $90,000/year versus $360,000/year for other air emissions.
- **Sensitivity analyses of the discount rate and the social cost of carbon .** The base case NPV of TBL costs is calculated using a 3% discount rate. A second set of NPV results are also reported at the 7% discount rate, which resulted in lower overall NPVs but did not change the relative ranking of the treatment trains. Given the relatively high level of uncertainty about the environmental and social cost of GHG emissions, especially as it relates to the higher cost and lower probability events, a second set of values was selected from the report prepared by Interagency Working Group on the Social Cost of Carbon (2010). This parameter was increased by about a factor of three. The resulting increase in NPV ranged from 3 to 20%, primarily related to the amount of energy demanded by the treatment train.
- **Total dissolved solids removal may be required at some locations.** Although water reuse is practiced in many areas of the world without the use of salt removal technologies (e.g., RO), certain conditions may require its use. For example, in closed or semiclosed watersheds with high source water TDS, some salt removal may be necessary to prevent significant cycling up of salts caused by water reuse. Therefore, RO treatment is necessary in some situations. However, because RO has much higher capital, O&M, and environmental costs, especially when concentrate treatment is required, utilities should carefully consider its use before implementation. Alternatives, such as partial RO treatment and blending with other less saline water sources, should also be considered.

Table ES1: Major Financial and Environmental Costs and Associated Considerations for 20 mgd Plant Capacity

Scenario	Capital Cost (millions)	Annual O&M Cost (millions)	Annual Environ-mental Cost (millions)	Total TBL NPV (millions)	Power Consump-tion (MWh/year)	Chemical Consumption (dry tons/year)	Air Emissions (tons/year)	
							CO_2e	Other
Nonpotable Reuse for Landscape Irrigation								
S1A (GMF-CL2)	$32	$2.1	$0.17	$72	1,800	190	1,200	4.5
S1B (MF-Cl2)	$47	$2.8	$0.2	$101	2,200	230	1,900	5.2
S1C (MF-RO-Cl2)	$101	$5.5	$1.4	$233	13,300	1,900	11,800	34
Potable Reuse for Reservoir Augmentation								
S2A (Coag-Sed-O_3-BAC-GAC-UV)	$91	$4.2	$0.4	$173	4,400	1,770	2,900	11
S2B (MF-RO-UVAOP) with Ocean Disposal of Concentrate	$120	$5.9	$1.6	$267	16,000	1,860	13,400	30
S2B (MF-RO-UVAOP) with Mech Evaporation of Concentrate	$172	$10.9	$6.3	$533	65,400	3,020	44,200	150
S2B (MF-RO-UVAOP) with Evaporation Ponds for Concentrate	$303	$9.0	$2.2	$512	22,000	1,860	17,200	49

Chapter 1

Introduction

1.1 Project Background

The beneficial use of municipal wastewater effluent for nonpotable and potable use (water reuse) is currently practiced in various regions of the world. The level of treatment provided in water reuse projects varies significantly throughout the world depending on factors, such as regulations, water quality of the wastewater effluent, water quality goals, end uses of the treated water, and public influence. Recent experiences within the water reuse industry have demonstrated that governmental and nongovernmental organizations and other advocacy groups are influencing selection of a higher level of treatment to minimize a perceived risk to members of the public or the environment. However, selection and implementation of higher-level treatment is often done without full consideration of triple bottom line (TBL) components that include financial, environmental, and social elements.

The focus of this report is to develop and apply a TBL framework document to help ensure that the right treatment process for the intended use is selected without expending unnecessary funds, energy, and greenhouse gas (GHG) emissions or generating other social costs that waste society's resources because they fail to generate a corresponding benefit to society. Included in this report is the application of the TBL framework to pairs of water reuse treatment train alternatives that serve the same end use to provide transparent evidence for regulatory and policy deliberation purposes of how much added TBL cost is incurred by society to meet certain water reuse requirements. This provides sound evidence to enlighten broader policy and regulatory debates about treatment requirements and goals to avoid codifying requirements or practices that are not aligned with intended uses and associated risks. Note that in some instances treatment technologies with higher TBL costs are required for an intended application. However, it is important to clearly understand the TBL costs of each process so that informed decision making can be made and that "overtreatment" is not provided.

With the expectation that the need for developing new sources of affordable water supply will grow significantly in the near future in both arid and less arid climates, the proper examination of TBL costs of water reuse is especially important to assist utilities in the proper selection of treatment to help meet that need. In addition, a better understanding of TBL costs will help those communities developing new water reuse regulations and policy to properly address the financial, environmental, and social components included in a TBL analysis. Finally, although the present research addresses water reuse only, the TBL approach is equally applicable toward evaluating the full suite of water supply and demand alternatives.

1.2 Water Reuse in the United States and Australia

1.2.1 Quantity and Types of Water Reuse

Water reuse is practiced in many states throughout the United States and Australia for a variety of applications. Water reuse typically is divided into two major categories: nonpotable reuse and potable reuse. Of the many uses for nonpotable water, the applications using the largest amount of reclaimed water in the United States and Australia are landscape irrigation (e.g., parks and golf courses), agricultural irrigation, and industry (primarily cooling water). The primary applications of potable reuse are groundwater recharge, seawater intrusion barriers, and augmentation of reservoirs supplying raw water to potable water treatment plants.

The quantity of water reused nationally in the United States is not well defined, but estimates provided by the U.S. Geological Survey in 1995 and the U.S. Environmental Protection Agency (EPA) in 2004 state values of 1057 mgd (4000 mld) and 1690 mgd (6397 mld), respectively (National Research Council, 2012). Although many states practice water reuse, California and Florida are by far the largest practitioners with estimated annual demands of 597 mgd (2260 mld) and 722 mgd (2733 mld), respectively. Water reuse demands in California are driven by its semi-arid climate, large potable water consumption as a result of its considerable population and heavy agricultural industry in the central part of the state. Florida's drivers for water reuse are somewhat different. Although Florida supports a large population and a significant agricultural community like California, its annual precipitation is approximately 50 inches per year, which is much higher than in the central and southern part of California. However, more than half of Florida's precipitation usually falls during the summer months of June through September (Southeast Regional Climate Center, 2012). Consequently, the other 8 months are much drier and require supplemental water for irrigating crops and landscapes. In addition, strict regulations for wastewater effluent discharge to some waterways have encouraged water reuse in Florida. Both California and Florida actively collect data regarding their water reuse programs. Other states that actively practice water reuse include Texas, Arizona, Nevada, Colorado, New Mexico, Virginia, Georgia, and Hawaii.

Water reuse is also practiced in arid locations around the world, such as Israel, Portugal, Spain, Africa (Namibia), and Australia. Singapore has also implemented a large water recycling program through construction of six water reclamation plants (called NEWater plants) for potable and industrial reuse. With respect to the total amount of water reuse practiced internationally, China and Mexico reuse the most at an estimated amount of 3,900 mgd (14,800 mld) and 3,800 mgd (14,400 mld), respectively (Jimenez and Asano, 2008). However, much of this reuse is untreated wastewater for agricultural irrigation. Qatar, Israel, and Kuwait practice the most amount of reuse on a per capita basis (Jimenez and Asano, 2008). For example, Qatar reuses approximately 45 gallons per capita per day (170 L/day) versus 5 gallons per capita per day (19 L/day) in the United States.

1.2.1.1 California

In 2009 California reused approximately 669,000 ac-ft of water per year (597 mgd; 2,260 mld). Figure 1.1 shows where the reclaimed water was used (Newton et al., 2011). The use per category varies significantly across the state. For example, more than 80% of the recycled water used in the Central Valley is for agricultural irrigation. Less than 15% of the recycled water used in the remainder of the state is used for agricultural irrigation. Approximately 19% of California's recycled water is for potable use, which can require a high level of treatment for direct groundwater recharge or injection to prevent seawater intrusion. The remaining recycled water is used for nonpotable applications, such as agricultural and landscape irrigation (61%), which require significantly lower levels of treatment.

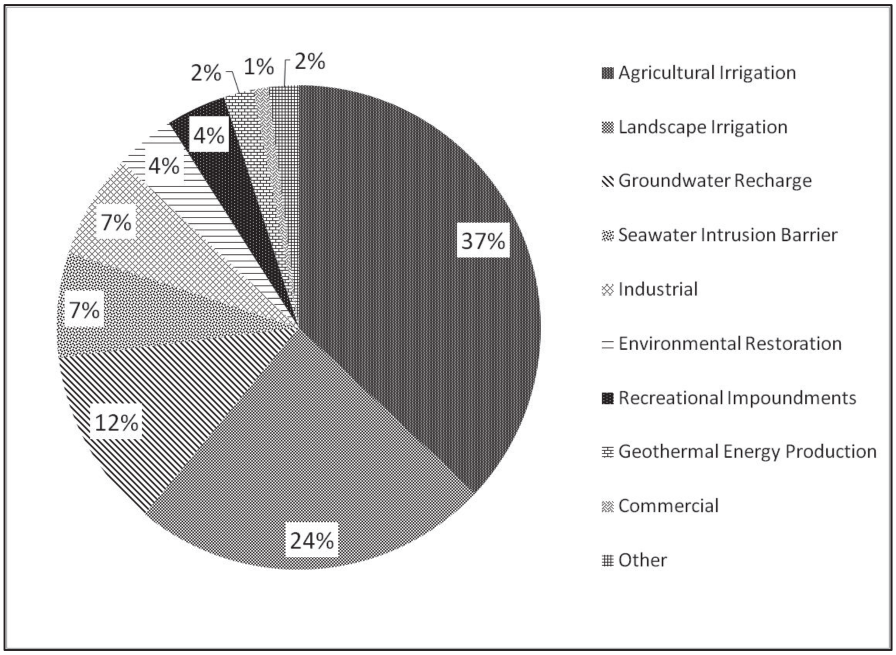

Figure 1.1. Reclaimed water use in California.
Source: Newton et al., 2011

1.2.1.2 Florida

Chapter 62-610 of the Florida Administrative Code (2013) requires owners of domestic wastewater facilities to submit annual reports documenting numerous items pertaining to their water reuse systems. This information allows Florida to accurately report water reuse within the state on an annual basis. In 2012, Florida reused approximately 812,000 ac-ft of water per year (725 mgd; 2744 mld). Figure 1.2 shows the division of reclaimed water use in Florida (Florida Department of Environmental Protection, 2012). Landscape irrigation, which is by far the largest use, consists of golf courses, residential lawns, parks, and other areas accessible to the public. Landscape irrigation is consistently the largest use throughout the state, except in northwest Florida where agricultural irrigation is the dominant use. Approximately 13% of Florida's recycled water is for potable use through rapid infiltration basins for groundwater recharge of potable aquifers, which typically requires a high level of treatment. The remaining 87% of recycled water is used for nonpotable applications requiring a lower level of treatment. Recent regulatory action in Florida will likely lead to more reuse especially in Southern Florida; the 2008 Ocean Outfall Act requires that at least 60% of the wastewater flow discharged to the ocean in Southern Florida be reused by 2025, which is equivalent to 178 mgd (Meeker, 2011).

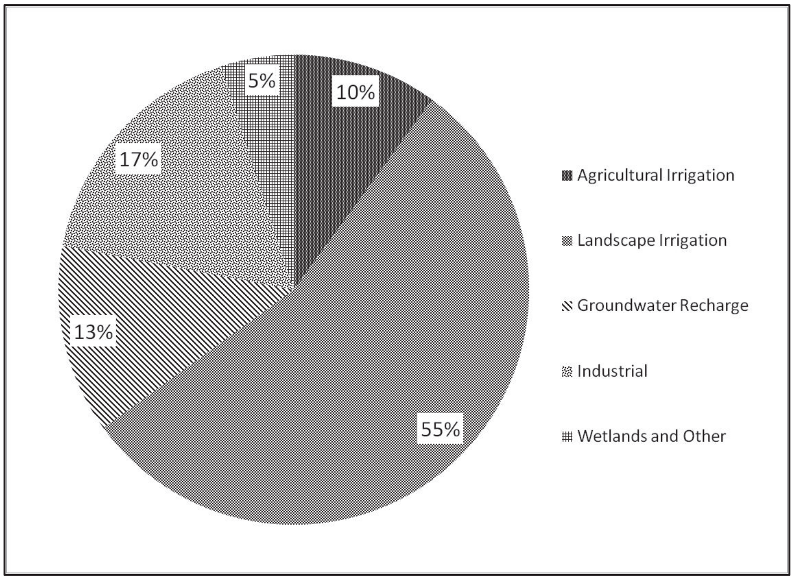

Figure 1.2. Reclaimed water use in Florida.

Source: Florida Department of Environmental Protection, 2012

1.2.1.3 Texas

The annual estimated use of reclaimed water in Texas is reported to be between 177,000 ac-ft per year (Arroyo, 2010) and 480,000 ac-ft per year (Texas Water Development Board, 2012), with nonpotable reuse accounting for about 70% and indirect potable reuse accounting for about 30%. Recent drought conditions in Texas have led more utilities to consider water reuse. For example, the Colorado River Municipal Water District began operation of a 1.8 mgd direct potable reuse plant in 2013 to secure additional water supply for the towns of Big Spring, Odessa, and Midland. The plant provides advanced treatment of wastewater effluent from Big Spring prior to pipeline blending of raw water from Spence Reservoir, which is then treated at the Big Spring WTP (Water Desalination Report, 2013).

1.2.1.4 Virginia and Georgia

Although neither Virginia nor Georgia reuse large quantities of reclaimed water on a statewide basis, both have implemented large indirect potable reuse projects that are significant from a historical, technological, and capacity basis. For example, the Upper Occoquan Service Authority's Millard H. Robbins, Jr. Water Reclamation Plant has supplemented a major drinking water reservoir in Northern Virginia for more than 30 years. Its current capacity is 54 mgd (204 mld) with an annual average flow of approximately 32 mgd (121 mld). Similarly, Gwinnett County's 60 mgd (227 mld) F. Wayne Hill Water Resources Center supplements a major drinking water reservoir in metropolitan Atlanta.

1.2.1.5 Australia

The estimated annual use of reclaimed water in Australia in 2010 was 270 mgd (1022 mld; Pink, 2012). Annual percentages generated by the Australian Bureau of Statistics show that the largest user of recycled water in Australia is the agricultural industry (Figure 1.3). Note that other water sources in addition to municipal wastewater have been captured in this graph as reuse water. Storm water can be collected using infrastructure separated from the sewerage systems and—depending on its intended use—may or may not be treated before being supplied as reuse water. The supply of water sources as reuse water is analogous to that of municipal reuse but is typically less regulated and thus more widespread in rural areas.

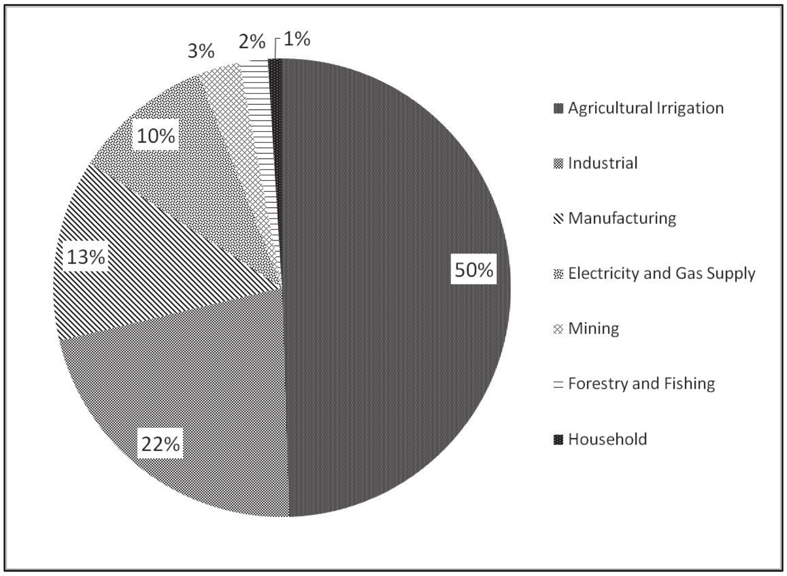

Figure 1.3. Percentage reuse in Australia by user type.

Source: Pink, 2012

1.2.2 Future of Water Reuse

As population increases and communities appreciate the difficulty in securing new water supplies, water reuse is expected to grow in the coming years. Other factors, such as localized drought severity and increased community and regulatory pressure may also increase the application of water reuse. For example, California's 2009 Recycled Water Policy, as adopted by the State Water Resources Control Board, strongly encourages increasing the use of recycled water by at least 1 million ac-ft per year by 2020 and 2 million ac-ft per year by 2030. California recycled approximately 669,000 ac-ft per year in 2009; therefore, increasing this total by 1 or 2 million ac-ft per year is substantial. In Texas, the 2012 State Water Plan expects an increase in water reuse from 480,000 ac-ft per year in 2010 to about 614,000 ac-ft per year in 2060 (Texas Water Development Board, 2012). Increase in water reuse is also expected in other arid states as well as some non-arid locations depending on site-specific conditions.

Implementing these large projected increases in water reuse will likely include a combination of nonpotable and potable reuse projects. However, expansion of existing nonpotable reuse systems, or development of nonpotable reuse in urbanized areas, could be highly costly because of the large spatial distribution of demands and the high costs of dual-piping systems (Dietrick et. al, 2011; Tchobanoglous and Leverenz, 2012). Consequently, interest in potable reuse, both indirect and direct, has increased significantly in these geographic areas (e.g., Southern California) because of the suspected lower cost of potable reuse. Implementation of potable reuse usually involves more advanced technology at higher costs and with more energy consumption but often with lower distribution costs. Therefore, a good understanding of the TBL costs associated with treatment selection is critical for proper selection and implementation of these projects. Note that the broader issue of determining the best end uses of reuse water, including potable versus nonpotable reuse, is an interesting question to consider as part of regional water supply planning but is beyond the scope of this document.

However, the TBL approach included in this document can help inform that decision by showing how to select the treatment technologies with the lowest TBL cost for a given potable or nonpotable end use. This information could then be used to determine whether reuse should be best developed as potable or nonpotable by factoring in costs of both treatment and distribution.

1.2.3 The Effect of Total Dissolved Solids on Water Reuse

Dissolved solids, such as sodium, sulfate, and chloride, are typically added to water during the domestic water cycle. As reported by Thompson et al. (2006), approximately 200 mg/L to 400 mg/L of salt is typically added to the wastewater stream from various sources, such as human excretion, gray water, water softeners, and industrial contributions, although these contributions can be highly site-specific, especially the contribution from water softeners. For communities with high total dissolved solids (TDS) concentrations in their potable water supplies, salt addition through the domestic water cycle can make the implementation of water reuse problematic because of the potential negative impact of elevated TDS on irrigated vegetation, industrial components, and potable water aesthetics (e.g., taste, glass spotting). Table 1.1 summarizes some of these negative effects and potential mitigation techniques without using a salt removal treatment process.

Water reuse is practiced successfully in many locations throughout the world without the use of salt removal technologies. For example, Florida, which leads the United States in reuse, has few plants that require salt removal to achieve the desired level of water quality. Nevertheless, some users of reclaimed water have experienced negative effects resulting from elevated TDS concentrations, and this will likely continue as water reuse increases into the future. This is especially evident in geographic locations that have water supplies with high TDS concentrations. Consequently, TDS removal or finished water blending may be required for some utilities considering water reuse. Treatment technologies used for TDS removal can be highly expensive and consume large amounts of power. In addition, the waste stream generated from these technologies is highly concentrated in salt, which can be costly and environmentally challenging to manage. Therefore, proper understanding of the TBL effects associated with salt removal is an important consideration when considering water reuse in areas with high TDS concentrations.

Table 1.1. Negative Effects of Elevated TDS on Water Reuse Applications

Affected Item	Negative Effects	Mitigation Techniques
Vegetation and soil	High salt concentrations can reduce water uptake in plants and limit plant growth. High concentrations of specific ions, such as chloride and boron, can damage vegetation. High concentrations of sodium, with respect to calcium and magnesium, can lead to soil structure problems, such as soil dispersion, reduced permeability, and surface crusting. The water's sodium adsorption ratio (SAR) and conductivity are typically measured to characterize the potential effect on the soil.	Irrigate crops / vegetation with higher tolerance to salt (e.g., cotton is much more tolerant to salts than broccoli). Blend with other waters to reduce concentrations of specific harmful ions. Reduce quantity of salt contribution in domestic cycle (e.g., reduce number of water softeners used).
Industrial components	High chloride concentrations can cause corrosion of metallic components, even some stainless steels.	Consider the use of alternative metallic components, such as titanium or 316SST, in lieu of traditional 304SST components.
Potable water	EPA has established a secondary maximum contaminant level (MCL) for TDS at 500 mg/L for aesthetic reasons (salty taste, spotting)	Blend with other potable water supplies prior to distribution to reduce TDS concentration. Conduct public outreach to determine if exceeding 500 mg/L is problematic.

1.3 Water Reuse Regulations

Reuse regulations significantly influence the treatment provided in water reuse schemes, and regulations for nonpotable reuse are considerably different from potable reuse regulations. Following is a brief summary of potable and nonpotable reuse regulations and the resultant treatment implications.

1.3.1 Nonpotable Reuse Regulations and Treatment Implications

Regulations for reclaimed water production and utilization in the United States and Australia are similar in that neither country has federal regulations, only guidelines. The *2012 Guidelines for Water Reuse* (EPA, 2012a) and the *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks* (NRMMC, EPHC, AHMC, 2008) provide a framework for the management of recycled water quality and to encourage the development of consistent state regulations. However, in practice water reuse schemes are regulated by state-issued legislation, guidelines, codes, and standards.

A recent overview of the regulation of water reuse in Australia has been included in a report titled *Recycled Water Use in Australia: Regulations, Guidelines and Validation Requirements for a National Approach* (Power, 2010). This report provides a review and comparison of the regulatory processes and guidelines in place for each Australian state and territory. It describes the similarities and differences in how the different regulators manage recycled water. The review highlights that although each Australian jurisdiction acknowledges the management framework set out within the national guidelines, it is not applied consistently.

Table 1.2 contains a summary of the status of regulation within states and territories in the United States and Australia.

Nonpotable reuse regulations often differ depending on the proposed use—with stricter treatment requirements typically mandated for those uses that have a higher likelihood of public exposure. Unrestricted urban irrigation is an example of an end use that poses one of the highest risks of public exposure. Unrestricted urban irrigation involves the use of reclaimed water where public exposure is likely (e.g., parks and playgrounds) thereby necessitating a high degree of treatment. Table 1.3 summarizes the unrestricted urban irrigation regulations for key states in the United States and Australia. The table shows that Australian regulations focus on log reduction values (LRVs) for targeted pathogen removal. United States regulations are more focused on surrogate bacteriological measurements, high solids removal to improve disinfection efficacy, and specific required treatment technologies.

Table 1.2. Summary of U.S. and Australian State Nonpotable Reuse Regulations and Guidelines

State or Territory	Regulations	Guidelines	None	Urban–Unrestricted	Urban–Restricted	Agricultural–Food Crops	Agricultural–Process and Nonfood Crops	Impoundments–Unrestricted	Impoundments–Restricted	Environmental Reuse	Industrial Reuse	Groundwater Recharge–Nonpotable
USA												
Alabama		❋			❋		❋					
Alaska	❋						❋					
Arizona	✓			✓	✓	✓	✓		✓	✓	✓	✓
Arkansas	❋					❋						
California	✓			✓	✓	✓	✓	✓	✓		✓	✓
Colorado	✓			✓	✓						✓	
Connecticut			×									
Delaware	✓			✓	✓	✓	✓	✓	✓		❋	
District of Columbia			×									
Florida	✓			✓	✓	✓	✓			✓	✓	✓
Georgia		✓		✓	✓		✓					
Hawaii		✓		✓	✓	✓	✓		✓		✓	✓
Idaho	✓			✓	✓	✓	✓				✓	✓
Illinois	✓			✓	✓		✓					
Indiana	❋			❋	❋	❋	❋					
Iowa	✓				✓		✓					
Kansas		❋		❋	❋	❋	❋				❋	
Kentucky			×									
Louisiana			×							✓		
Maine			×									
Maryland		✓		✓	✓		✓			✓	✓	✓
Massachusetts	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Michigan	❋					❋	❋					
Minnesota		✓		✓	✓	✓	✓	❋			✓	
Mississippi	❋				❋		❋				❋	
Missouri	✓				✓		✓		❋	❋	❋	
Montana	✓			✓	✓	✓	✓	✓	✓		✓	✓
Nebraska	❋			❋	❋	❋	❋	✓	✓		❋	✓
Nevada	✓			✓	✓		✓		✓	✓	✓	
New Hampshire			×									
New Jersey	✓	✓		✓	✓	✓	✓				✓	
New Mexico		✓		✓	✓	✓	✓		✓	✓	✓	
New York			×									
North Carolina	✓			✓	✓	✓	✓			✓	✓	
North Dakota		✓		✓	✓		✓	✓		✓	✓	✓
Ohio		✓		✓	✓		✓					
Oklahoma	✓			✓	✓		✓				✓	
Oregon	✓			✓	✓	✓	✓	✓	✓		✓	✓
Pennsylvania		✓		✓	✓	✓	✓	✓	✓	✓	✓	
Rhode Island		✓		✓	✓		✓				✓	
South Carolina	✓			✓	✓		✓					
South Dakota		❋			❋	❋	❋			❋		❋

Table 1.2. Summary of U.S. and Australian State Nonpotable Reuse Regulations and Guidelines (continued)

State or Territory	Regulations	Guidelines	None	Urban–Unrestricted	Urban–Restricted	Agricultural–Food Crops	Agricultural–Process and Nonfood Crops	Impoundments–Unrestricted	Impoundments–Restricted	Environmental Reuse	Industrial Reuse	Groundwater Recharge–Nonpotable
Tennessee		❋		❋	❋		❋	❋	❋	❋	❋	
Texas	✓			✓	✓	✓	✓	✓	✓	✓	✓	
Utah	✓				✓	✓	✓		✓	✓	✓	
Vermont	✓				✓		❋					
Virginia	✓			✓	✓	✓	✓	✓	✓	✓	✓	❋
Washington		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
West Virginia	❋					❋	❋					
Wisconsin	❋					❋	❋				❋	❋
Wyoming	✓			✓	✓	✓	✓				✓	
Australia												
Australia Capital Territory	✓			✓	✓				✓			
New South Wales	✓			✓	✓	✓	✓		✓		✓	✓
Northern Territory	✓			✓	✓	✓	✓				✓	
Queensland	✓			✓	✓	✓	✓	×	✓	✓	✓	✓
South Australia	✓			✓	✓	✓	✓					✓
Tasmania	✓			✓	✓	✓	✓			✓	✓	✓
Victoria	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Western Australia	✓			✓	✓	✓	✓			✓	✓	

Note: U.S. information (EPA, 2012a) is up-to-date as of October 2012; Australian information (Power, 2010) is up-to-date as of May 2010.

✓ = intent of regulation / guideline is for the oversight of water reuse

❋ =intent of regulation / guideline is for the oversight of wastewater disposal and water reuse is considered incidental

× = no reuse guidelines or regulations but may permit reuse on case-by-case basis

Table 1.3. Unrestricted Urban Landscape Irrigation Regulations for Key U. S. and Australian States

Location	Virus	Protozoa	Bacteria				TSS	Turbidity	Treatment Technology Requirements	Reference
			E. coli	Fecal Coliforms	Total Coliforms	Enterococci				
Queensland	No LRV target	No LRV target	No LRV target. <100cfu/100ml	n/a	n/a	n/a	n/a	n/a	n/a	The State of Queensland (Department of Natural Resources and Water) (2008)
Victoria	Sufficient log reductions to achieve <1/50L.	Sufficient log reductions to achieve <1/50L.	Sufficient log reductions to achieve <10/100 mL.	n/a	n/a	n/a	n/a	n/a	Must include a pathogen reducing disinfection step (chlorination or detention lagoons).	EPA Victoria (2003)
Arizona	n/a	n/a	n/a	No detect (avg); 23/100ml (max)	n/a	n/a	n/a	2 NTU (avg); 5 NTU (max)	Secondary treatment, filtration and disinfection.	Arizona Administrative Code Title 18. Environmental Quality
Colorado	n/a	n/a	Geo mean: <126/100ml; Max: 235/100 ml	n/a	n/a	n/a	n/a	3 NTU (avg); 5 NTU (95%)	Secondary treatment, filtration and disinfection	CDPHE, Water Quality Control Commission Regulation No. 84
California	n/a	n/a	n/a	n/a	2.2/100ml (avg); 23/100ml (max in 30 days)	n/a	n/a	2 NTU (avg); 5 NTU (max)	Oxidation, coagulation, filtration and disinfection.	California Code of Regulations Title 22.
Florida	n/a	n/a	n/a	75% of samples below detect; 25/100ml (max)	n/a	n/a	5 mg/L	n/a	Secondary treatment, filtration and high-level disinfection.	Florida Administrative Code Rule 62-610 Reuse of Reclaimed Water and Land Application
Texas	n/a	n/a	n/a	20/100ml (avg); 75/100ml (max)	n/a	4/100ml (avg); 9/100ml (max)	n/a	3 NTU	n/a	Texas Administrative Code Title 30. Environmental Quality (2013)

Note: NTU = nephelometric turbidity unit

To achieve the requirements outlined within the various regulations for unrestricted urban irrigation, tertiary filtration and disinfection are often sufficient—and in many cases required. For example, Title 22 (California Office of Administrative Law, 2009) requires that recycled water undergo tertiary filtration and disinfection to meet water quality criteria. As a reference to the Title 22 Regulations, the California Department of Public Health (CDPH) developed the *Treatment Technology Report for Recycled Water* (CDPH, 2009) which provides a list of certified alternative filtration (granular media filters, cloth media filters and membrane technologies), and disinfection (ultraviolet [UV] disinfection, pasteurization, and ozone/peroxide) technologies that have been prevalidated and are accepted as providing adequate performance to meet water quality criteria. This contrasts with regulations in many U.S. and Australian states where no standard validation procedures exist for recycling treatment processes.

Water quality parameters that need to be considered by individual end users are not regulated by most states and territories. In some instances recycled water schemes will only address water quality specifications related to health risks, and any further treatment required by end users (e.g., low ammonia for some industrial applications) must be performed at the end user's site. In other instances where the source water quality may be poor (e.g., high TDS), some utilities elect to provide additional treatment, such as reverse osmosis (RO), to facilitate the use of recycled water for "high-end" customer applications, such as boiler water feed for industrial applications. In some areas where TDS, select ions or the SAR is high, water quality of reuse water can cause problems with golf course irrigation. A paper by Komor et al. (2011) describes a cost−benefit investigation at three golf courses in Orange County, California. The investigation looked at the tradeoffs between installing a partial RO treatment system to reduce salt content of recycled water and continuing to irrigate with recycled water with a high salt content. Table 1.4 summarizes the benefits of both options. Note that in many geographic locations the water quality of reclaimed water is sufficiently good to allow irrigation of golf courses without RO treatment.

Table 1.4. Identified Benefits with and without Additional RO Treatment for Golf Course Irrigation

Without RO	With RO
Lower capital cost	Reduced salt content of product water resulting in:
Lower costs avoided by not requiring additional power consumption, treatment chemicals (antiscalant, NH_3, acid and base addition), cartridge filter replacement, membrane replacement, and additional labor hours for RO system operation.	• Decrease leaching water quantity required because of longer duration before salt buildup in soil • Decrease in requirement for soil improvement chemical (gypsum) application • Decrease in turf replacement, repair and herbicide application owing to healthier turf-grass (lower course maintenance costs)
Nutrients (nitrogen and phosphorus) in recycled water reduce or eliminate need for fertilizer application.	Turf grows slower because of reduced nutrients; mowing frequency is reduced.
No brine stream to address (can be very costly where ocean disposal is not an option).	Reduces nutrient content may result in less algal growth in storage ponds.

Source: Komor et al., 2011

Another example of where water quality for the end user has driven a utility to consider constructing additional treatment processes to reduce certain water quality parameters (salinity and SAR) is at the Western Treatment Plant in Melbourne, Victoria. This plant has historically supplied recycled water to the Werribee Irrigation District, a predominantly agricultural area that grows food for human consumption. Over the years, the salinity of the recycled water increased, and in 2009 it was approximately 2200 µS/cm (approximately 1300 mg/L TDS). A range of options was investigated to determine the costs of reducing the salt content of the recycled water to different concentration specifications (CH2M HILL, 2009). For example, one option was investigated to reduce the water's conductivity to 1000 µS/cm for the purpose of reducing salt's effect on crop growth. Ultimately, it was decided that additional treatment would not be provided because the high implementation costs outweighed the benefit of lower salt concentrations. Note that the end of this investigation coincided with the beginning of a period of rain, which lowered the demand for recycled water in the district, thereby reducing the pressure on the utility to reduce salt concentrations. Rainfall also has the potential to flush soils at these locations, which might reduce the potential negative effects of salt buildup.

Numerous treatment technologies can be used for implementation of nonpotable reuse projects. The most significant factors influencing the selection of treatment processes usually include regulatory requirements, reclaimed water quality, end user requirements, and public influence. Selection of the most appropriate technologies is dependent on these factors, but consideration should be given to TBL costs associated with each treatment process because of the differing and often significant economic, environmental, and social effects that treatment technologies can have. A nonpotable reuse case study highlighting this point is presented in Section 1.4: Potential for Overtreatment in Water Reuse.

1.3.2 Potable Reuse Regulations and Treatment Implications

The two categories of potable reuse are indirect and direct. Indirect potable reuse involves the discharge of treated water into an environmental receiving body (e.g., reservoir, groundwater aquifer) where it is subsequently withdrawn and treated for distribution in a drinking water system. Direct potable reuse follows the same principle except there is no intermediate receiving water body and treated reclaimed water is piped directly to the drinking water plant or into the potable water distribution system. Therefore, the main difference between indirect potable reuse and direct potable reuse is that indirect potable reuse includes an environmental barrier that provides natural treatment and increased retention time to allow mitigation in the event of water quality degradation. The level of treatment and online automation needed to implement direct potable reuse is currently being studied by the water reuse industry.

Table 1.5 lists some well-known examples of indirect and direct potable reuse schemes currently in operation worldwide. Historically, the majority of potable reuse schemes have been in the indirect category—with the one exception of the direct potable reuse scheme practiced in Windhoek, Namibia, since 1968. However, recently much more attention has been given to direct potable reuse as evidenced by projects in Texas and New Mexico, and California's recent legislation requiring the state to study the feasibility of direct potable reuse by 2016 (California Office of Administrative Law, Section 13562). Note that a significant amount of unplanned, or "de facto," indirect potable reuse occurs throughout the world. As reported in the 2012 *Water Reuse* report by the National Research Council (NRC, 2012), "The de facto reuse of wastewater effluent as a water supply is common in many of the nation's water systems, with some drinking water plants using waters from which a large fraction originated as wastewater effluent from upstream communities, especially under low-flow conditions." Therefore, although not widely understood, indirect potable reuse is fairly common throughout the world.

Table 1.5. Examples of Indirect and Direct Potable Reuse Schemes

Indirect	Direct
NEWater, Singapore	Windhoek, Namibia
Montebello Forebay Groundwater Recharge Project, Los Angeles County, California	Big Spring, Texas, United States
Orange County Water District Groundwater Replenishment System, Orange County, California	Cloudcroft, New Mexico, United States
Western Corridor Recycled Water Scheme, South East Queensland, Australia	
Upper Occoquan Service Authority, Centreville, Virginia	

Although potable reuse has been practiced since the 1960s, its application is not as prevalent as nonpotable reuse (see Section 1.2) and, therefore, regulations have not been developed within certain states in many locations. Although potable reuse guidelines have been developed in the United States and Australia, no federal regulations currently exist in either country. However, a few states (e.g., California and Florida) have developed comprehensive potable reuse regulations because of the significant amount of potable reuse practiced in those locations. Some other states (e.g., Georgia, Texas) have not developed potable reuse regulations but allow the practice on a case-by-case basis with project specific permits established accordingly. Table 1.6 summarizes the potable reuse regulations that are in place in states where augmentation of drinking water supplies using reclaimed water is specifically permitted. The federal guidelines from Australia and the United States are also presented.

Examination of Table 1.6 reveals the following:

- Most regulations and guidelines are focused on pathogen removal, organic removal, nitrogen removal, and compliance with drinking water regulations.
- Multiple barrier advanced treatment is required in most U.S. locations.
- The Australian requirement to achieve significant log reduction of viruses, protozoa, and bacteria ultimately results in multiple barriers of advanced treatment because of the limitations in achieving validated log reductions across just one treatment process.
- California's total organic carbon (TOC) limit of 0.5 mg/L for 100% injection of recycled water (no diluent water) is much more stringent than that required by Florida and EPA (3 mg/L and 2 mg/L, respectively). This has led to significantly different treatment approaches between the western and eastern United States for potable reuse projects, which is further explained in Section 1.4, *Potential for Overtreatment in Water Reuse*.
- Use of soil aquifer treatment via spreading basins for potable reuse treatment is allowed in California and can reduce treatment costs significantly, because it can avoid the use of mechanically intensive equipment (e.g., MF, RO, and UV advanced oxidation process [UVAOP]) and the power and chemical consumption associated with these treatment processes. California regulations require filtration and disinfection of secondary effluent prior to spreading basin application. In addition, blending water (referred to as diluent water by California) is required when soil aquifer treatment (SAT) is implemented to meet TOC requirements. At SAT project startup, a maximum of 20% recycled water can

be used for recharge, unless the regulators approve an alternative initial recycled water percentage. The percentage can be eventually increased provided the TOC of the recycled water after SAT treatment is less than 0.5 divided by the recycled water percentage. For example, to achieve a 50% recycled water percentage, the TOC of the recycled water after SAT must be less than 1 mg/L (0.5 / 0.5 = 1 mg/L).

- Advanced treatment typically is not needed to meet the 10 mg/L total nitrogen (TN) limit stipulated by California and Florida provided the wastewater treatment plant practices include nitrification and denitrification treatment processes. Note that wastewater treatment plants in Florida that are required to practice advanced wastewater treatment are required to meet limits of 5/5/3/1 (all in mg/L) for BOD_5/TSS/TN/TP. In addition, more stringent numeric nutrient limits currently are being considered in Florida.

Various treatment technologies have been employed to meet these regulatory requirements and project specific water quality goals. California has traditionally used soil aquifer treatment where effluent is applied via surface spreading basins or dual membrane (microfiltration / ultrafiltration [MF/UF] plus RO) with direct injection. Projects in the eastern United States have been implemented using granular activated carbon (GAC) and natural treatment processes. The international community has primarily used a dual membrane approach, with the exception of Windhoek, Namibia. Table 1.7 shows some operational potable reuse projects and the treatment technologies employed.

Table 1.6. Select Potable Reuse Regulations in the United States and Australia

Location	Selected Application	Virus	Protozoa	E. coli	Total Coliform	Total Organic Carbon (TOC) Limit	Total Nitrogen Limit	Treatment Technology Requirements	Other Requirements	Reference
Australia[a]	Indirect and direct potable reuse	LRV 9.5 log	LRV 8 log	LRV 8.1 log	n/a	n/a	n/a	n/a	Health-based targets calculated using QMRA with tolerable risk of 10^{-6} DALYs. Must also satisfy Australian Drinking Water Guidelines. Campylobacter target LRV: 8.1 log.[d]	NRMMC; EPHC; AHMC (2008)
Queensland	Indirect potable reuse	LRV 9.5 log	LRV 8 log	LRV 8 log	n/a	n/a	n/a	n/a	Helminth target LRV: 8 log. Must also meet chemical water quality standards as listed in section 18D, schedule 3B.	The State of Queensland (Department of Natural Resources and Water) (2008)
EPA[a]	Groundwater injection into potable aquifers	n/a	n/a	n/a	Not detectable	2.0 mg/L (waste-water origin)		Secondary, filtration, disinfection, advanced treatment	≤2 NTU, 1 mg/L chlorine residual (min), ≤0.2 mg/L TOX, pH = 6.5 to 8.5, must meet drinking water standards, groundwater retention of at least 2 months for injection projects.	EPA (2012a)
California	Surface Spreading or groundwater injection	LRV 12 log	LRV 10 log	n/a	≤ 2.2 / 100 mL	0.5 mg/L / RWC[b]	10 mg/L	For spreading application: oxidation, filtration, disinfection, SAT For groundwater injection[c]: oxidation, filtration, disinfection, RO, AOP	Industrial pretreatment and source control program required. Minimum 2 month retention time underground required. 1 log virus reduction credit given per month if subsurface retention. 10-log protozoa reduction credit given for spreading projects having at least 6 months' retention time. Must meet drinking water MCLs. For groundwater injection projects, AOP must reduce 1,4-dioxane by at least 0.5 logs.	Groundwater Replenishment Reuse Draft Regulation (CDPH, 2013)
Florida	Groundwater Injection for groundwater with TDS<3000 mg/L	n/a	n/a	n/a	Not detectable	3.0 mg/L	10 mg/L	Filtration, disinfection, multiple barriers for pathogens and organics, pilot testing required	≤20 mg/L CBOD5, ≤5 mg/L TSS, ≤0.2 mg/L TOX, must meet primary and secondary drinking water standards	Florida Administrative Code Rule 62-610 Reuse of Reclaimed Water and Land Application

[a] EPA and Australia have guidelines in place for potable reuse, but no regulations
[b] The recycled water contribution (RWC) is the quantity of recycled water applied at a recharge site divided by the sum of recycled water applied at a recharge site and diluent water used for blending.
[c] Alternative treatment technologies can be used with regulatory approval.
[d] QMRA = quantitative microbial risk assessment; DALY = disability adjusted life year

Table 1.7. Treatment Technologies Employed at Operational Potable Reuse Plants

Project	Geographic Location	Type of Potable Reuse	Year First Operational	Capacity	Current Advanced Treatment Process
Montebello Forebay, Sanitation Districts of Los Angeles County, CA	Coastal	Groundwater recharge via spreading basins	1962	44 mgd (167 mld)	GMF + Cl_2 + SAT (spreading basins)
Windhoek, Namibia	Inland	Direct potable reuse	1968	5.5 mgd (21 mld)	O_3 + Coag + DAF + GMF + O_3/H_2O_2 + BAC + GAC + UF + Cl_2 (process as of 2002)
Upper Occoquan Service Authority,Centreville,VA	Inland	Surface water augmentation	1978	54 mgd (204 mld)	Lime + GMF + GAC + Cl_2
Hueco Bolson Recharge Project, El Paso, TX	Inland	GW recharge via direct injection and spreading basins	1985	10 mgd (38 mld)	Lime + GMF + Ozone + GAC + Cl_2
Clayton County Water Authority, GA	Inland	Surface water augmentation	1985	18 mgd (68 mld)	Cl_2 + UV disinfection + SAT (wetlands)
West Basin Water Recycling Plant, CA	Coastal	GW recharge via direct injection	1993	12.5 mgd (47 mld)	MF + RO + UVAOP
Scottsdale Water Campus, AZ	Inland	GW recharge via direct injection	1999	20 mgd (76 mld)	MF + RO + Cl_2
Gwinnett County, GA	Inland	Surface water augmentation	2000	60 mgd (227 mld)	Coag/floc/sed + UF + Ozone + GAC + Ozone
NEWater, Singapore	Coastal	Surface water augmentation	2000	146 mgd (5 plants)	MF + RO + UV disinfection
Los Alamitos Seawater Intrusion Barrier, Long Beach, CA	Coastal	GW recharge via direct injection	2006	3.0 mgd (11 mld)	MF + RO + UV disinfection
Chino Basin Groundwater Recharge Project, Chico, CA	Inland	GW recharge via spreading basins	2007	18 mgd (68 mld)	GMF + Cl_2 + SAT (spreading basins)
Groundwater Replenishment System, Orange County, CA	Coastal	GW recharge via direct injection and spreading basins	2008	70 mgd (265 mld)	MF + RO + UVAOP + SAT (spreading basins for a portion of the flow)
Western Corridor Recycled Water Scheme; Queensland, Australia	Coastal	Surface water augmentation	2009	66 mgd via three plants (250 mld)	MF + RO + UVAOP
Cloudcroft, NM	Inland	Direct potable reuse through spring water augmentation	2009	0.1 mgd (0.4 mld)	MF + RO + UVAOP
Arapahoe County/Cottonwood, CO	Inland	GW recharge via spreading	2009	9 mgd (34 mld)	SAT (via RBF) + RO + UVAOP
Big Spring Reclamation Project; TX	Inland	Direct potable reuse through raw water blending	2013	1.8 mgd (6.8 mld)	MF + RO + UVAOP

Source: Adapted from Drewes and Kahn (2010); Asano et al. (2007)

Notes: ARR = Aquifer Recharge and Recovery; BAC = Biological Activated Carbon filtration; Cl_2 = Chlorine Disinfection; Coag = Coagulation; DAF = Dissolved Air Flotation; GAC = Granular Activated Carbon; GMF = granular media filtration; GW = groundwater; H_2O_2 = Hydrogen Peroxide; MF = Microfiltration; O_3 = Ozone; RBF = riverbank filtration; RO = Reverse Osmosis; SAT = Soil Aquifer Treatment; UF = Ultrafiltration; UV = Ultraviolet; UVAOP = UV Advanced Oxidation Process

As shown in Table 1.7, the treatment provided in potable reuse projects is typically a combination of multiple barriers for the removal of pathogens and organics. Multiple barriers for pathogens typically are provided through a combination of filtration (granular or membrane), coagulation, softening, and disinfection (chlorine or UV). Multiple barriers for organic removal typically is provided through a combination of advanced treatment processes (RO, GAC, SAT, UVAOP, ozone), although conventional treatment processes (coagulation, softening) also provide removal at some locations. All potable reuse plants listed in Table 1.7 include a robust organics removal process of GAC, RO, or SAT, which act as an effective barrier to bulk and trace organics and are the backbone of the potable treatment process:

- **SAT based.** Where SAT is used, advanced treatment beyond GMF and disinfection is not always employed. This is especially relevant in California where recharge of a major potable water aquifer has occurred via spreading basins since 1962.
- **GAC based.** GAC is used at a number of locations for the removal of bulk and trace organic compounds. GAC has a long history of use in potable reuse projects with operational installations in Virginia (1978), Texas (1985), Georgia (2000), and Colorado (2010). RO is not used where GAC is used.
- **RO based.** RO has become the gold standard for potable reuse projects in California and internationally (e.g., Singapore and Australia) because of its excellent performance in the removal of dissolved solids and trace organics. California regulations require the use of RO for direct injection potable reuse projects or a comparable alternative with regulatory approval. RO creates a concentrate stream that can be difficult and costly to dispose of, especially at inland locations. Most locations where RO has been implemented are located near the ocean where disposal of RO concentrate is convenient and much less costly than inland locations.

The use of SAT can only be implemented in areas with favorable geological conditions and, therefore, cannot be implemented at all locations. Conversely, RO and GAC can be implemented at any location because they are engineered processes. Consequently, the use of RO and GAC is more prevalent than SAT for potable reuse projects and this trend will likely continue as more projects are implemented. Data on the removal of bulk organic matter and trace organics at several full-scale GAC and RO plants are shown in Table 1.8. Note that both processes provide excellent removal of organic matter and neither GAC nor RO can remove all constituents below detection limits. RO does provide for a lower overall dissolved organic carbon concentration, but note that the GAC effluent dissolved organic carbon concentration is lower than many raw waters provided to drinking water treatment plants. However, for water supplies with high dissolved solids content, partial or full RO treatment may be necessary to avoid cycling up of salts in both the potable and reclaimed water.

Note that UVAOP has been implemented for most recent potable reuse projects to remove CECs and other compounds not well removed by RO (e.g., nitrosamines). The addition of ozone, or ozone with hydrogen peroxide, also has gained recent attention as a potential replacement for UVAOP and currently is being used at plants in Gwinnett County, Georgia and Windhoek, Namibia. Ozone has shown excellent removal of CECs (Snyder et al., 2007). However, unlike UVAOP, ozone is not effective in removing nitrosamines (unless coupled with a biological process, such as SAT or BAC) and therefore an alternative mitigation technique would be required if nitrosamines are of concern.

Table 1.8. Bulk and Trace Organics Measured in Finished Water at Indirect Potable Reuse Plants

	GAC-Based Plants		RO-Based Plants	
Constituent	**GAC1[a]**	**GAC2[b]**	**RO1[b]**	**RO2[b]**
Bulk Organics:				
Dissolved Organic Carbon (mg/L)	2.7		Estimated at <0.5 mg/L based on 99% rejection by RO	
Trace Organics:				
Sulfamethoxazole	4.2	BDL30	BDL30	
Carbamazepine	53.7			
Gemfibrozil	2.1	BDL10	BDL10	BDL10
Diclofenac	BDL1	BDL10	BDL10	BDL10
Naproxen	BDL2; BDL0.5	BDL10	BDL10	BDL10
Metoprolol		BDL10	BDL10	16.5
Propranolol		BDL10	BDL10	23
Ciprofoxacin	BDL50	BDL30	BDL30	
Enrofloxacin	BDL50	BDL30	BDL30	
Norfloxacin	BDL50	BDL30	BDL30	
Ofloxacin		BDL30	BDL30	
Trimethoprim	BDL1; BDL0.25	BDL30	BDL30	
Ibuprofen	BDL50	BDL10	BDL10	BDL10
Indomethacin		BDL10	BDL10	BDL10
Ketoprofen		BDL10	BDL10	BDL10
Bisphenol-A	BDL5; BDL100			
NDMA	BDL2; 2.8			
Estrone	BDL0.5			
17B-estradiol	BDL0.5			
Ethinylestradiol	BDL0.5			
Nonylphenol	BDL500			
Acetaminophen	BDL5; BDL500			
Caffeine	19; BDL50			

[a] Schimmoller and Angelotti (2011); samples are an average of two sampling events; except NDMA (four samples)

[b] Sedlak et al. (2005); one sample for some parameters, average of two samples for others

Notes: All units in ng/L except where noted otherwise; BDL: Below Detection Limit at stated concentration

Selection of a potable reuse treatment plant's backbone organics removal approach (GAC, RO, and/or SAT) is dependent on many factors including raw water quality, finished water quality goals, cost, geographic considerations, type of potable reuse, public perception, and other site-specific factors. Although the RO-based approach appears to be gaining popularity and has been implemented in most of the recent potable reuse projects, all three types of organic removal processes have been successfully implemented at full scale, and careful consideration of all TBL factors should be given to each approach prior to treatment selection to truly understand all cost, environmental, and social effects.

1.4 Potential for Overtreatment in Water Reuse

A number of different treatment technologies are commercially available when implementing nonpotable and potable reuse projects. For example, California has approved 45 different filtration systems for use at nonpotable reuse treatment plants, with 19 GMF types, 19 membrane systems, and 7 cloth filters (CDPH, 2009). Consequently, selection of the appropriate treatment process can be difficult and is sometimes based on the perception that more advanced treatment is better without an indepth consideration regarding numerous economic, environmental, and social factors. In some cases, a similar level of treatment can be provided at lower costs and with fewer environmental and social effects. Treatment trains that are perceived as "more advanced" or "higher tech" do not always provide more appropriate treatment and can result in higher TBL costs.

1.4.1 Types of Overtreatment

Water reuse is typically divided into nonpotable and potable reuse applications—with a much higher level of advanced treatment typically employed for potable reuse applications. The quantity of reclaimed water used for each type varies significantly depending on local considerations, as described in Section 1.2, but a relative ranking has been developed and is presented in Table 1.9. Because each state does not account for reclaimed water use to the same degree or in the same fashion, the rankings are somewhat subjective but are considered generally accurate through detailed investigation of information provided by states that practice the largest amount of water reuse (e.g., Florida, California, Texas, New South Wales, Victoria). The treatment that would likely be required beyond secondary treatment to meet regulations is also included in the table.

Table 1.9. Ranking and Treatment Requirements for Different Reclaimed Water Use Categories

Ranking (relative amount of reclaimed water used annually)	Reclaimed Water Use Category	Potable or Nonpotable Reuse?	Treatment Typically Required Beyond Secondary Treatment to Meet Regulations
Highest	Landscape irrigation (e.g., golf courses, parks, lawns), toilet flushing, vehicle washing	Nonpotable	Tertiary filtration and disinfection
	Agricultural irrigation of fodder crops and processed food crops	Nonpotable	None
	Potable reuse through groundwater recharge, seawater intrusion barrier, or drinking water reservoir augmentation	Potable	Advanced water treatment through multiple barriers to remove pathogens and organic
	Industrial cooling	Nonpotable	Tertiary filtration and disinfection; nitrification (as necessary)[a]
	Irrigation of food crops eaten raw	Nonpotable	Tertiary filtration and disinfection
Lowest	Other (many other reuse applications exist, but the overall quantity reused in these categories is relatively small)	Nonpotable	Varies

[a] Some cooling water systems require very low levels of ammonia depending on the metallurgy utilized at the industrial plant and other concerns. Therefore, if nitrification is not practiced at the wastewater treatment plant (WWTP), an ammonia removal process may be required for this application.

Examination of Table 1.9 reveals the following:

- The use of tertiary filtration and disinfection for treatment of secondary effluent is a common requirement for reclaimed water use in many nonpotable reuse applications. Because treatment beyond normal secondary levels is required from a regulatory perspective for many of these applications, the potential exists for utilities to apply more treatment than necessary (overtreatment) as they are determining what treatment to provide. A case study from Santa Rosa, California, highlights this potential and is described in more detail later.
- Implementation of potable reuse projects traditionally has included multiple treatment barriers to remove pathogens and organic compounds for the protection of public health. A number of treatment processes are effective at meeting public health objectives, but they vary in their advantages and disadvantages depending on local water quality, state regulations, public perception, receiving water quality, site constraints, and environmental issues. For this reason, selection of the treatment processes that comprise a potable reuse treatment plant's multiple barriers has varied significantly between projects. Case Study 2 presented later describes the differences between the treatment processes implemented for potable reuse projects located in the western and eastern United States.

- A significant volume of reclaimed water is used for irrigation of fodder and processed food crops. As shown in Table 1.9, secondary treatment is standard for this end use and cases for overtreatment appear rare according to the literature reviewed. The lack of regulatory or other sources of pressure for additional treatment is reassuring because of the long successful use of reclaimed water for these applications. Therefore, the focus of this research did not include overtreatment of reclaimed water for fodder and processed food crops.

1.4.1.1 Case Study 1: Santa Rosa Recycled Water System

In 2004 the City of Santa Rosa (Sonoma County, California) adopted the Incremental Recycled Water Program (IRWP) Master Plan to expand its existing recycled water system. The IRWP plan included expansion of several water reuse components, including agricultural irrigation, landscape irrigation, and water supply to a geothermal power plant. The plan also proposed significant surface storage of recycled water to match seasonal reuse demands and a new river discharge for times when storage is full and recycled water demands are low. The proposed master plan was criticized by the local Open Space and Water Resource Protection and Land Use (O.W.L.) Foundation which claimed in a letter that "the word 'recycled' in the IRWP nomenclature is misleading and gives the impression that wastewater is somehow safe enough to dispose in a public drinking water supply, like the Russian River." (O.W.L. Foundation, 2006). The letter expressed concern about dangerous drugs and chemicals in the water and recommended treatment matching Orange County's Groundwater Replenishment System that uses MF, RO, and UVAOP. The letter further stated that in this treatment process "all chemical compounds that are not the molecule H_2O can be taken out of the sewage water." Not only is this statement incorrect because it is known that these processes do not remove all chemicals, but it recommends a treatment train without understanding the site-specific issues and the potential environmental impact and social effects of this decision. For example, if RO is implemented, where will the concentrate waste—which contains all of the chemicals present in the wastewater but at higher concentrations—be disposed, and what is the resulting environmental impact? Also, how much energy is required to run this process (and the increased GHG emissions), and how does that compare with the environmental risks of lower treatment approaches? Answers to these questions and many other TBL issues are critical in selecting treatment processes to allow for informed decision making that is defensible to project stakeholders and the public. This information would be highly beneficial for discussions with groups such as the O.W.L. Foundation, as it would allow comparison of economic, environmental, and social effects of different treatment alternatives, which could provide impartial selection criteria for such projects.

1.4.1.2 Case Study 2: Potable Reuse Dichotomy between Western and Eastern United States

Fifteen potable reuse schemes are operational in the United States as of 2010, with projects in California, Virginia, Georgia, Texas, Arizona, Colorado, and New Mexico (Drewes and Khan, 2010). Eight of these schemes use RO as the primary mechanism for organics removal, four use GAC, and three use SAT. The use of SAT is not always feasible because of site constraints and geological conditions. RO and GAC are often easier to implement from an engineering and construction perspective but are usually more costly. RO has predominantly been used in the western United States, whereas GAC is predominantly used in the East. For example, in areas where SAT is not utilized, 80% of the projects implemented in the West have used RO (8 out of 10 projects), compared to 0% in the East (0 out of 2 projects—both projects use GAC). Regulations, geographic location, and source water quality have driven this dichotomy in potable reuse treatment. In California, state reuse regulations require utilities to provide RO and advanced oxidation treatment for potable groundwater recharge applications where SAT is not used (CDPH, 2013). A TOC concentration of less than 0.5 mg/L must be achieved to allow complete reuse of treated water without additional blending water. RO also removes dissolved solids, which can prevent increased salinity levels in recharged aquifers. In contrast, the approach taken in Virginia and Georgia for potable reuse has been significantly different. Implementation of the Upper Occoquan Service Authority's (UOSA) indirect potable reuse project in northern Virginia began in 1978 to consolidate 11 small WWTPs that were causing significant eutrophication in a downstream drinking water reservoir into one regional advanced treatment plant. The primary purpose of the regional plant (current capacity is 54 mgd [204 mld]) was to protect the downstream drinking water reservoir, and the water quality parameters included in the discharge permit were established for this purpose: chemical oxygen demand (COD) <10 mg/L; total kjeldahl nitrogen (TKN) < 1 mg/L, total phosphorus (TP) <0.1 mg/L, and turbidity <0.5 NTU. The 60 mgd (227 mld) potable reuse project in Georgia's Gwinnett County is similar to UOSA in that protection of the downstream drinking water reservoir (Lake Lanier) was the primary purpose of the locally developed discharge permit for the advanced treatment plant, which included the following limits: COD <18 mg/L, NH_3 <0.4 mg/L, TP <0.08 mg/L, and turbidity <0.5 NTU. UOSA and Gwinnett County both successfully use a GAC-based treatment train to meet their discharge limits, whereas California uses RO-based and SAT-based treatment trains. Table 1.10 summarizes the main factors affecting selection of advanced treatment processes at these locations.

Table 1.10. Significant Factors Affecting Selection of Advanced Treatment Processes in California, Virginia, and Georgia

Parameter	California (for direct groundwater recharge; no SAT)	UOSA (Northern Virginia)	Gwinnett County, GA
Potable reuse regulations	Yes (draft form)	Yes (Occoquan Policy)	No
Organics limit	TOC ≤ 0.5 mg/L / RWC[a]	COD ≤ 10 mg/L	COD <18 mg/L
Regulatory treatment required	RO and Advanced Oxidation[b]	UOSA plant treatment train	None specified
TDS concern	Yes; TDS is high in some locations	No; Reclaimed water TDS is < 500 mg/L	
Total Nitrogen	Several coastal WWTPs do not practice nitrification / denitrification; RO provides a nitrogen barrier in these cases to meet the 10 mg/L TN limit	Both wastewater treatment plants practice nitrification / denitrification and therefore additional nitrogen removal is not required	
Ease of RO concentrate disposal	Historically less expensive through ocean disposal	Expensive because of inland location and difficulty in accessing ocean for disposal	

[a] The RWC is the quantity of recycled water applied at a recharge site divided by the sum of recycled water applied at a recharge site and diluent water used for blending.

[b] Alternative treatment technologies can be used with regulatory approval.

The primary difference between California and the eastern United States is California's requirement for RO treatment driven by the very low TOC limit, TDS concerns, and statewide regulatory mandate for RO. In contrast, RO treatment is not required at the Virginia and Georgia potable reuse plants because of the higher discharge limit for organics (COD based). Consequently, GAC is used for organics removal at these plants because of its significantly lower total costs and ability to meet the required COD limits easily. Naturally, the question arises as to which treatment approach is more appropriate because both RO and GAC have been used successfully for many years at full-scale facilities. The answer is often location-specific and dependent on numerous issues that will be examined in detail in this report. The intent of this research is to determine TBL costs for different treatment approaches that will provide regulators, water utilities, and practitioners with an indepth understanding of the consequences of regulatory requirements and treatment selection decisions.

Note that the RO-based treatment approach was recently viewed as the gold standard across the world for potable reuse and has been implemented in many of the recent international potable reuse projects (e.g., Singapore NEWater, Western Corridor Recycled Water Program in Brisbane, Australia). Because of the high-energy requirements for RO and costly disposal requirements of its concentrate waste for inland locations, it may not be the preferred alternative in all cases after careful consideration of all TBL factors. This is supported in a recently published NRC report titled, *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater* (NRC, 2012):

> A portfolio of treatment options, including engineered and managed natural treatment processes, exists to mitigate microbial and chemical contaminants in reclaimed water, facilitating a multitude of process combinations that can be tailored to meet specific water quality objectives. Advanced treatment processes are also capable of addressing contemporary water quality issues related to potable reuse involving emerging pathogens or trace organic chemicals. Advances in membrane filtration have made membrane-based processes particularly attractive for water reuse applications. However, limited cost-effective concentrate disposal alternatives hinder the application of membrane applications for water reuse in inland communities.

1.4.2 Overtreatment Scenarios for Analysis

Cases of overtreatment in the water reuse industry do not appear widespread; however, because water reuse has grown significantly in recent years and is expected to grow more as population densities increase and water scarcity amplifies, a clear understanding of the TBL costs for different treatment approaches is beneficial to current and future water reuse practitioners.

On the basis of the case studies presented earlier and the ranking of reclaimed water uses and treatment required outlined in Table 1.9, TBL costs for two scenarios were developed for evaluation in this research:

- **Scenario 1 (S1):** A nonpotable reuse scenario comparing a "filtration and disinfection" treatment approach for landscape irrigation to an alternative treatment approach using membrane filtration. Two membrane filtration treatment trains will be compared to the GMF approach: one using MF for solids and pathogen removal analogous to GMF and one using RO for removal of dissolved solids and/or organics that may be requested in unique situations.
- **Scenario 2 (S2).** A potable reuse scenario comparing California's "RO-Advanced Oxidation" approach to the East Coast's "GAC-based" approach. Three concentrate

management approaches will be analyzed for the RO-based approach: ocean disposal, mechanical evaporation, and evaporation ponds.

These scenarios are not exhaustive, because many treatment process selections are available during the implementation of nonpotable or potable reuse projects. For example, use of soil aquifer treatment can be an effective and efficient potable reuse treatment process and should be considered in geographic locations that support its use. However, because the practicality of its use is site-specific, cost estimates using this technology are generally not transferrable, and more of the recently implemented potable reuse projects are using mechanically based technologies, SAT treatment has not been included in the potable reuse treatment scenario analyzed. The scenarios selected for analysis represent approaches frequently considered and therefore will be directly applicable to many utilities during implementation of their reuse projects. Analysis of these scenarios also provides a framework that can be applied to the TBL evaluation of other treatment train comparisons. These scenarios are fully described in Chapter 2, Triple Bottom Line Methodology. Note that the intent of this research is not to criticize those technologies that have higher TBL costs, because in some cases those technologies are necessary for the intended application. Instead, the intent is to clearly understand the TBL costs of each process so that informed decision making can be made and that "overtreatment" is not provided when it is unnecessary.

1.5 Use of Triple Bottom Line in the Reclaimed Water Industry

1.5.1 What is Triple Bottom Line Accounting?

The three components that comprise the TBL are financial, social, and environmental. As such, TBL accounting offers an alternative to evaluating organizational performance purely on the basis of the direct financial return to the organization to include the environmental, social, and financial elements that matter to stakeholders both internal and external to the organization (Cristiano and Henderson, 2009). TBL is not a new concept; Spreckley (1981) is credited with first recommending assessing organizational performance along these three dimensions. However, it was more than a decade before the phrase "TBL" was coined by Elkington (1994) when the TBL accounting framework became the means by which organizations could assess attainment of their sustainability goals (Slaper and Hall, 2011). By balancing environmental and social effects with financial ones, organizations avoid achieving financial gains at the expense of the environment and societal aims.

Utilities involved in water reuse and other organizations that understand and strive to improve their performance along each of these dimensions are sending the signal that they are well managed and that they take a long-term perspective on their operations (Kenway, et al., 2007). For the purposes of this report, these three elements are defined as follows:

- Environmental elements include effects on natural resources (e.g., land, air, and water) and the flow of ecosystem services that directly and/or indirectly support human wants and needs for current and future generations. This includes resources (e.g., water, energy, chemicals, land, and materials) that reuse water utilities rely on as "inputs," as well as resources that are affected by discharges, air emissions, or solid waste disposal in the course of "producing" or using reuse water. It is important to note that a disconnection can exist between perceived risks on the part of the public and actual risks based on sound science. In such circumstances it can be important to expend resources to bring perceived risks and actual risks into closer alignment to avoid making faulty decisions or the appearance of flawed decisions.

- Social elements relate to quality of life that are deemed important from a societal perspective and are not otherwise covered by the financial or environmental dimensions. Examples of social elements include human health, worker safety, education, and crime. Of these social factors, it is likely that human health is the only one that would be affected by different water reuse treatment trains. For example, different reuse treatment trains have different energy requirements and thus vary in terms of their emissions of air pollutants damaging to human health.
- Financial elements include the direct costs and returns to the organization, as well as the financial effects on stakeholders outside of the organization. For example, water reuse treatment trains can differ in terms of costs to the end user. The primary example is landscape irrigation whereby the amount of nutrients remaining in the reuse water after treatment can affect expenditures on fertilizers by the end user.

As Kenway, et al. (2007) note, TBL reporting on beneficial and adverse effects makes the full social cost of water alternatives transparent to decision makers. This is important to facilitating selection of the least costly reuse treatment alternative for society as a whole. It is interesting to note that through adopting TBL accounting, some utilities and private sector organizations as described in Section 1.5.2, have begun to factor broader societal costs and benefits into their decisions, making them more like federal agencies, which are required to apply cost−benefit analyses to capture the full social costs and benefits of their regulations. Such analyses have improved over the years, evolving from limited analysis of the more easily quantifiable benefits and costs (usually market goods and services) to include environmental and social factors (Chesnutt and Pekelney, 2005). Thus, like TBL accounting, economic cost−benefit analysis includes market goods and services as well as environmental and social services that are not exchanged in markets. In addition, costs and benefits to all members of the public are “counted,” thus capturing the effects that are external as well as internal to the organization. Cost−benefit analysis is consistent with quantifying environmental and social effects using monetary or nonmonetary metrics as long as the effects are counted only once (no double counting). In these ways, cost−benefit analysis is an economic accounting methodology for assessing changes in societal welfare as opposed to a financial analysis to address the financial performance of a company (De Souza et al., 2011). As Cristiano and Henderson (2009) and others have noted, the financial analysis is important for advising providers on the costs of the reclaimed water project or program and whether or not the revenue stream will be sufficient to cover those costs. However, the cost−benefit analysis reveals whether the program is beneficial from the broader societal perspective. Cristiano and Henderson observe that utilities, acting in the public interest, may select the project that maximizes societal net benefits, even if the project is not profitable. In such situations societal economic welfare is improved by the action, and public subsidies are warranted.

Perhaps the most important distinction between generic TBL and TBL that relies on cost−benefit analysis accounting principles is that practitioners of TBL can choose which effects they want to include and no strict guidelines compel what to measure or how. In contrast, cost−benefit analysis provides a framework and measurement tools and approaches for identifying, and quantifying the effects of an action, policy, or program to make an informed decision about whether societal welfare is improved or diminished by the action. If the action has a significant effect on human welfare, then the cost−benefit analysis attempts to account for it. This does not mean that all effects must be quantified in monetary units, but it does recognize that society considered the environmental and social outcomes in the decision, and thus placed a value on them, whether they were monetized or not.

As described in more detail in the Methodology section, this research uses a cost−benefit analysis approach toward TBL accounting. Each of the water reuse treatment trains are compared in terms of their full social costs and benefits. Environmental and social effects are quantified in their natural units (e.g., kWh of energy utilization, tons of carbon dioxide [CO_2] equivalents) as stakeholders are interested in tracking how alternatives directly contribute to certain societal goals, including energy conservation and reducing GHG emissions. Where reasonable, effects are then quantified in dollars to facilitate comparing alternatives on the basis of a single measure of net social cost. Environmental and social effects that were not expressed in monetary terms are quantified or qualitatively characterized in the summary comparison of alternative treatment trains to ensure their consideration in identifying the TBL preferred alternative.

Finally, this TBL approach also relies on life-cycle assessment (LCA), a second well-established method for evaluating alternatives. By incorporating LCA into the approach toward evaluating treatment train alternatives, this analysis considers effects that are upstream of the water reuse treatment facility (e.g., at the power plant that produces the energy to run the water reuse treatment plant), as well as downstream effects (e.g., brine waste disposal from the reuse water treatment plant). The application of cost−benefit analysis and LCA approaches into the TBL framework addresses the research objective which is to create a framework document to help ensure that the right process and technology is applied to match water quality with its intended use, without expending unnecessary funds, energy, and GHG emissions to treat water beyond what is suitable or necessary for the intended application. Then, by applying the TBL framework to pairs of treatment train alternatives, the project provides documented and transparent evidence—for regulatory and policy deliberation purposes—of how much added cost (including external, nonmarket costs) is incurred by society to meet some water reuse regulatory requirements. This provides sound evidence to enlighten broader policy and regulatory debates about treatment requirements that are out of synch with intended uses and associated risks.

1.5.2 Where Else Has Triple Bottom Line Been Applied?

Not all TBL applications rely on the foundations of cost−benefit analysis and LCA. TBL accounting approaches have been widely applied for assessing sustainability performance and have taken many forms depending on the sustainability goals of the user. The one commonality across all TBL applications is that performance is evaluated on multiple dimensions. Recent example companies include General Electric, Unilever, Proctor and Gamble, 3M, and Cascade Engineering. As companies gain appreciation for the interrelationships among their environmental, social and financial effects on other stakeholders and their own direct financial interests, this trend is expected to grow (Slaper and Hall, 2011). These corporations are in good company. According to Musikanski (2010) the International Survey of Corporate Responsibility Reporting in 2008 found that 80% of Global Fortune 250 companies prepared TBL reports. This included 74 of the 100 top revenue producing companies in 22 countries. The most often cited reasons for preparing the reports including both ethical and economic drivers.

Fell (2007) and Senge et al. (2008) cite the growing interest by nonprofit organizations in TBL accounting, especially as partners with industry. Often this takes the form of directly considering how companies rely on the services of the environment as well as their effects on ecosystem services. One notable example is the partnership between The Nature Conservancy and Dow Chemical which announced a $10 million, 5 year collaboration that aims to make ecosystem services a major part of Dow's business (Baldwin et al., 2011). The study is examining how Dow's business decisions affect natural capital and the associated value of ecosystem services, as well as how ecosystems affect Dow's business. For example, Dow owns and controls significant amounts of land and intends to figure out how nature might be affecting their bottom lines and act accordingly by managing natural resources for the long run, just as they would any other part of their core business. By accounting for the existing and potential future relationships between natural capital/ecosystems services and Dow's actions, the company will be taking the first step toward optimally managing those resources. Decisions on how to use and manage natural capital can then be made explicit and can be compared to "business as usual" on the basis of the company's bottom line and on metrics tied to environmental sustainability (e.g., biodiversity, GHG emissions and carbon offsets, water quantity and quality, and habitat for species of concern).

The Ford Foundation, RSF Social Finance, and the Gates Foundation provide examples of how nonprofit organizations are relying on TBL accounting (Slaper and Hall, 2011; RSF Social Finance). In their cases the objective is often to evaluate the performance of their grant-making activities (Slaper and Hall, 2011; RSF Social Finance). Similar to corporations, nongovernmental organizations can tailor the TBL to their own specifications. This can mean developing metrics or key performance indicators for the financial, environmental and social outcomes that are most directly tied to their mission. Then these key performance indicators must be weighted in some manner or scaled in order to rate alternatives. This may be as simple as developing a TBL score card or may involve a formal decision-making process, such as multiobjective decision analysis. Such applications may or may not impose the rigor of cost−benefit analyses.

The government sector (especially state, local, and regional authorities) has embraced TBL accounting as a decision-making tool and also as a means of evaluating and monitoring sustainability performance and to encourage economic growth while achieving environmental and social sustainability goals. Slaper and Hall (2011) point to examples throughout the United States including state authorities in Maryland, Minnesota, Vermont, and Utah; and local authorities in the San Francisco Bay area, northeast Ohio, Cleveland, and Grand Rapids Michigan, as well as communities across the European Union. As with corporations and the nongovernmental agencies, these governmental authorities have considerable latitude in choosing the indicators to include in their TBL accounting, as well as how they use the information.

Compelling examples of TBL reporting also abound in the water industry, including those from Sydney Water in 2005 and Yarra Valley Water, also in 2005, as described in Kenway et al. (2007). Each of these utilities adopted TBL reporting to wide acclaim. In the case of Sydney Water, the TBL reporting began as an effort to give a more complete accounting of performance to gain stakeholder trust and to improve the regulatory review process. Today, Sydney Water's TBL scorecard provides evidence of how the utility has changed the way it does business. For example, its environmental management plans "include detailed safeguards that ensure projects are managed in an environmentally sound manner." Yarra Valley Water, Victoria, already had a culture that favored transparency in reporting when it adopted the Global Reporting Initiative (GRI, 2003) as a guide in developing the factors to consider in its TBL report. Nonetheless, this guide enabled the utility to be more comprehensive in its approach. The belief was that through TBL reporting the utility gained greater stakeholder trust. In addition, decision making involving tradeoffs among sometimes competing social, environmental, and financial objectives has improved.

The Seattle Public Utilities (SPU) provide a prime example of a cost–benefit analysis approach within a TBL framework that is consistent with the present application. The utility began by subjecting all of its capital projects to this evaluation process, considering the financial, environmental, and social benefits and costs over the life of the project. This evaluation process included all capital and operating costs, as well as the financial, social, and environmental costs and benefits that are external to SPU, such as changes in noise levels and amenities, as well as effects on the landscape, habitat for wildlife, water quality, and other factors that affect well-being. The result is to support decisions that lead to the appropriate levels of service, efficient utilization of resources, and reporting on TBL indicators of interest to stakeholders.

1.5.3 Triple Bottom Line and Cost–Benefit Analysis Applied to the Water Reuse Sector

Cost–benefit analysis and TBL reporting also have been applied to the water reuse sector (EPA, 2004; Raucher, 2006; Hernández et al., 2006; Cristiano and Henderson, 2009; Kfouri, 2009; Stratus Consulting, 2011; Hernández-Sancho et al., 2011; De Souza et al., 2011). This body of work informs the approach described in greater detail in Section 2.2.2 Accounting Methodology. The EPA Water Reuse Guidelines (EPA, 2004, 2012a) emphasize the importance of matching the treatment technology to the end use and taking social and environmental factors into consideration. The economic cost–benefit analysis framework described in Raucher (2006) provides detailed guidance on identifying the internal and external benefits and costs of water reuse projects to support decision-making on the basis of full social cost accounting rather than purely financial considerations. The specifics on benefit and cost categories to consider are based on a comparison of reclaimed water to other water supply alternatives. However, the same framework is applicable to evaluating alternative reuse treatment trains and end uses. Stratus Consulting (2011) applies this framework in a cost–benefit analysis of water supply alternatives for the El Paso, Texas, water utilities. In this analysis, water reuse and desalination alternatives are compared to a plan relying on expanding traditional water supply resources.

A similar guidance document for evaluating water reuse projects prepared by De Souza et al., (2011) is especially useful for California practitioners as it considers applicable state and federal regulations. Like the Raucher guidance on which it is largely based, this document distinguishes between financial and economic full social cost analyses while recognizing that each has a role in supporting decisions. This document considers water reuse in the broader context of integrated watershed management, which involves evaluating alternative demand management approaches, as well as a range in water supply alternatives. Of particular relevance to the present research is the guidance on matching water quality to use (De Souza et al., 2011) to achieve the most efficient solution from the broader societal perspective. Not all end uses require or benefit from the same level or type of treatment. The California example demonstrates the importance of aligning regulations for treating reclaimed water to the end uses to avoid overtreatment or under+treatment.

Several international guidance documents and case studies have also demonstrated the importance of evaluating water reclaimed using a cost–benefit analysis approach. Özerol and Günther (2005) note how the lack of a systematic evaluation procedure and guidelines inhibited the expansion of reclaimed water in the water-constrained Mediterranean region. In a Water Week 2009 presentation, Kfouri (2009) promoted cost–benefit analysis as the preferred assessment method of wastewater reuse in Morocco to select the scheme with the greatest net social benefit. Urkiaga et al. (2008) argued that comprehensive cost–benefit analysis considering social and environmental benefits and opportunity costs is just as necessary as internal financial feasibility assessments for identifying and selecting the most suitable treatment trains and end use alternative. Hernández-Sancho et al. (2011) and Molinos-Senante et al. (2011) evaluated 13 water reuse projects in Valencia, Spain, and concluded that each of them was beneficial from the full social cost perspective; however, some projects would not have been approved on a purely financial basis. They concluded that society would have been the loser had the decision been made on a purely financial basis.

In summary, cost−benefit analysis is a systematic and comprehensive accounting framework for assessing alternatives and identifying the alternative that provides the greatest net gain in societal welfare. It considers all three dimensions of the TBL within a consistent framework. The financial factors are expressed in monetary units; whereas, social and environmental factors can be expressed in monetary or nonmonetary units. Although each benefit and cost can only be "counted" once to avoid double counting, stakeholders may also be interested in reviewing the environmental and social outcomes in their natural units. Applications of the cost−benefit analysis approach toward TBL assessments to evaluate water reuse versus alternative water supply sources have demonstrated how factors that are external to the organization but positively or negatively impact other members of the public can play an important role in identifying the preferred alternative. The external net benefits of water reuse can be dramatic, especially in terms of sustaining water resources while accommodating consumptive uses of water. However, some have noted that the failure to apply such a systematic evaluation scheme consistently can lead to failure to identify the treatment train with the greatest net social benefit and could lead to rejecting all reuse alternatives. Whether the objective is to determine the preferred treatment train for a given end use or optimize on matching the water supply opportunities and end users as part of an integrated watershed plan, applying the comprehensive consistently framework will avoid such costly mistakes.

1.6 Financial Costs and Energy Consumption of Water Reuse Treatment

Accurate cost estimation and energy consumption predictions are important in all TBL analyses to allow for good decision making. A comprehensive cost estimating tool was used in this research to generate accurate cost estimates (see Section 2.2, Triple Bottom Line Approach); however, it is important to compare cost estimates to full-scale cost and energy data to validate accuracy of the estimates. Consequently, full-scale cost and energy data were collected from two sources for this research: costs and energy use reported in the literature and costs and energy use collected from a utility survey. The literature review is discussed in this section. The utility survey is discussed in Chapter 3.

1.6.1 Financial Costs for Water Reuse Treatment

A comprehensive summary of water reuse treatment financial costs currently is not available. In addition, the literature is limited in cost−prediction algorithms for treatment plants, most likely because of the wide variability in costs across regions, markets, and time that cause serious problems in the development of accurate cost predictions. Cost data for individual plants are often presented in technical papers and conference proceedings, but detailed design and construction data are not usually provided—creating problems in comparing costs to other treatment plants.

A further complication related to the financial costs of water reuse treatment is that the treatment provided to produce reclaimed water for beneficial use is not uniformly owned by the same type of utility. In some cases, the tertiary treatment provided to create reuse water is owned by the wastewater utility at the wastewater treatment site. In other cases, the tertiary treatment provided is owned by a water utility at a remote location. Two high-profile examples of this are as follows:

- The Groundwater Replenishment System (GWRS), in which secondary effluent from the wastewater treatment plant owned by Orange County Sanitation District is pumped to the water reuse treatment plant that is owned by Orange County Water District (OCWD). Costs for water reuse treatment in this case are reported by OCWD and only include advanced treatment (MF-RO-UVAOP).
- Water reuse treatment processes provided at multiple plants owned by the Los Angeles County Sanitation Districts (LACSD) are colocated with the wastewater treatment process. For example, tertiary treatment in the form of GMF and disinfection is provided at many of LACSD's WWTPs to produce reuse water. Costs for water reuse treatment in this case are included in the costs for the entire WWTP, which creates difficulty in comparing costs to utilities that operate stand-alone water reuse plants such as GWRS.

Because of these different utility approaches to water reuse, costs reported by utilities are not always comparable because they often include other elements specific only to the reporting utility and not directly related to water reuse treatment. Despite these problems, some reports recently have been published that include water reuse treatment costs that allow comparison to costs presented later in this report. Following is a summary of some of the recent documents and tools and the observed limitations:

- **EWATRO: information system for the Evaluation of Wastewater Treatment and Reuse Options** (European Commission, 2001). Development of this tool was funded by the European Commission to estimate treatment costs for wastewater and reuse treatment schemes at a user inputted flow. The tool provides annualized treatment costs that include both capital and operation and maintenance (O&M) costs. In most cases, costs include wastewater treatment and reuse treatment without the ability to segregate costs for each treatment portion. For example, the "filtration" module includes costs for primary treatment, secondary treatment, and filtration. In addition, the costs do not allow segregation between capital and annual O&M costs. The tool also does not allow modification of design criteria, which can have a large influence on capital and O&M costs. For example, the frequency of GAC regeneration significantly affects O&M costs, but the regeneration frequency used in the tool is not listed and does not allow modification.
- **National Research Council's report titled *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater*** (NRC, 2012). This report includes capital and annual O&M costs for some potable and nonpotable reuse plants, which are summarized in Table 1.11. Note that a number of the examples cited included costs associated with wastewater treatment (e.g., activated sludge secondary treatment), which make the data not directly applicable to this research and therefore are not included in the table.

Table 1.11. Costs for Nonpotable and Potable Reuse Treatment, as Reported in *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater*

Plant	Treatment Processes	Plant Capacity (mgd)	Average Output (mgd)	Capital Cost ($ million/mgd capacity)	Annual O&M Cost ($/kgal treated)
Nonpotable Reuse Plants					
Denver Water Recycling Plant	BAF-coag-floc-sed-GMF- Cl_2	30	6	$3.0 million/mgd	$1.06/kgal
West Basin, California	coag-floc-sed-GMF- Cl_2	40	18	$3.5 million/mgd	$1.02/kgal
Potable Reuse Plants					
GWRS, Orange County, California	MF-RO-UVAOP	70	68	$6.9 million/mgd	$1.16 / kgal
West Basin, California	MF-RO-UVAOP	12.5	9	$10.6 million/mgd	$2.38 / kgal

Notes: Costs are reported in 2009 USD. To convert mgd to mld, multiply by 3.785

Source: NRC, 2012

1.6.2 Energy Consumption for Water Reuse Treatment

Previous researchers (Cooley and Wilkinson 2012) have done a good job of summarizing energy use for various water reuse treatment processes. Table 1.12 shows energy use ranges for treatment of secondary effluent based on case studies collected from 11 reuse plants. Cooley and Wilkinson also prepared a tool to estimate energy use for water systems that included water extraction, conveyance, treatment, and distribution. The tool provides a good summary of low, average, and high values for various treatment processes as well, but it does not allow input of different design and operational criteria to customize the values for site-specific information.

Table 1.12. Energy Use Ranges for Treatment of Secondary Effluent

Reuse Treatment Train	Energy Use (kWh/million gallons)	Notes
Tertiary Treatment for Nonpotable reuse (GMF + Cl_2 or UV)	982–1800	Data from five reuse plants providing nonpotable water for irrigation and industrial reuse
Dual membrane treatment for potable reuse (MF/UF + RO +UV or UVAOP)	3220–4674 (one outlier reported at 8300)	Data from six dual-membrane plants

Source: Cooley and Wilkinson, 2012

Chapter 2

Triple Bottom Line Methodology

2.1 Treatment Scenarios Analyzed

Two scenarios were developed for detailed TBL evaluation based on the treatment requirements, ranking of reclaimed water uses, and case studies presented in Chapter 1. These scenarios are not exhaustive because many treatment process selections are available during the implementation of nonpotable or potable reuse projects. However, these scenarios represent approaches frequently considered and therefore will be directly applicable to many during implementation of reuse projects. Analysis of these scenarios also provides a framework that can be applied to the TBL evaluation of other treatment train comparisons. Two scenarios were considered: one nonpotable reuse scenario and one potable reuse scenario.

2.1.1 Scenario 1: Nonpotable Reuse for Landscape Irrigation

Scenario 1 (S1) is a nonpotable reuse scenario for landscape irrigation that compares a granular media filtration (GMF) treatment approach to a membrane based treatment approach. Both approaches utilize disinfection after filtration and both are compliant with California's Title 22 requirements for unrestricted reuse. GMF has been used successfully in nonpotable reuse applications for decades; however, the recent popularity of membrane filtration has led to more membrane use in a number of reuse applications. Process flow diagrams for this scenario are divided into S1A, which represents the GMF treatment approach; S1B, which represents an MF-based treatment approach; and S1C, which includes RO membranes. Scenario S1C addresses the potential situation where advanced treatment (e.g., RO membranes) is requested for actual or perceived needs without understanding the corresponding TBL effects. For example, a user may request RO treatment to reduce reclaimed water's TDS concentration for less effect on irrigated vegetation or an advocacy group may want to remove more CECs using RO to reduce a perceived effect on the environment or downstream users (see Case Study 1 in Section 1.4.1).

Scenarios 1A, 1B, and 1C are shown in Figures 2.1, 2.2, and 2.3 respectively. More detailed process flow diagrams are provided in Appendix A. Detailed design criteria used for each treatment process is presented in Chapter 4. Assumptions critical to the development of this scenario are included in Table 2.1.

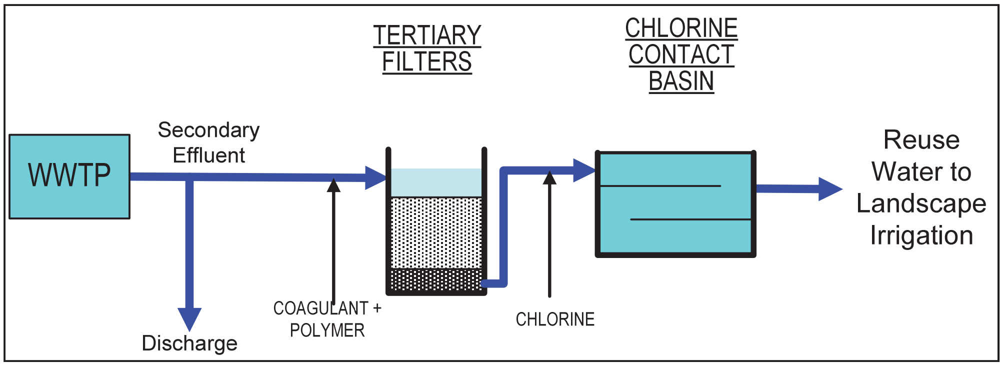

Figure 2.1. Scenario 1A: Reuse treatment for landscape irrigation using conventional treatment.

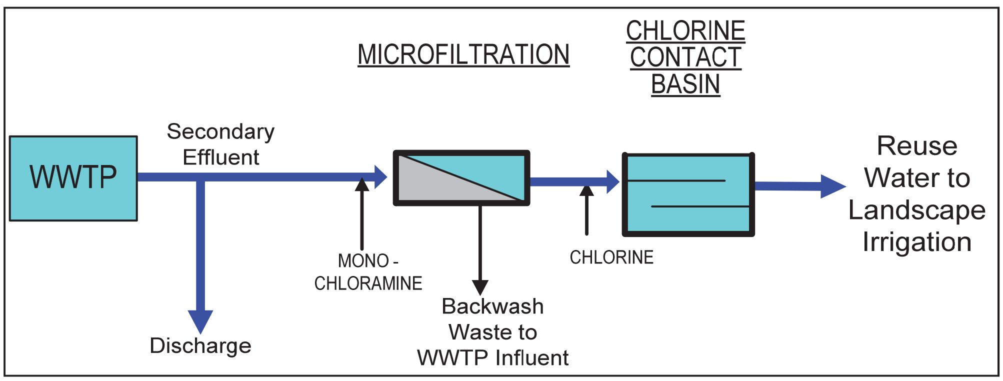

Figure 2.2. Scenario 1B: Reuse treatment for landscape irrigation using microfiltration treatment.

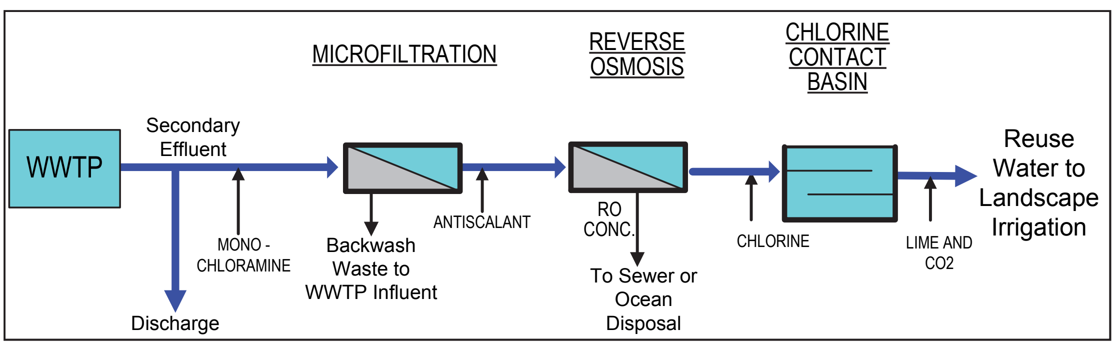

Figure 2.3. Scenario 1C: Reuse treatment for landscape irrigation using reverse osmosis treatment.

Table 2.1. Critical Assumptions for Development of Scenario 1

Item	Discussion
Reuse plant treats secondary effluent with a TDS of less than 1000 mg/L, chloride less than 200 mg/L, and a low SAR to electrical conductivity (EC) ratio.	Although the ion distribution for each reclaimed water effluent must be analyzed for its suitability to irrigation applications, in general TDS above 1000 mg/L or chloride above 200 mg/L, or high SAR/EC ratios can significantly limit the use of reclaimed water for landscape irrigation because of negative effects on vegetation and soil infiltration characteristics. However, depending on the specific type of vegetation that is irrigated and the actual concentration of specific anions and cations, use of the reclaimed water may still be possible.
For Scenario 1C, water reuse plant is located where ocean or sewer disposal is readily available.	RO concentrate handling costs can be expensive, especially at locations where sewer or ocean disposal is not available (e.g., inland). These costs are fully examined in Scenario 2.

2.1.2 Scenario 2: Potable Reuse for Reservoir Augmentation

Scenario 2 (S2) is a potable reuse scenario comparing the RO-based approach (MF-RO-UVAOP) used extensively in California and internationally to the GAC-based approach used in the eastern United States for reservoir augmentation. This scenario addresses the situation where a utility implements the more recently recognized RO-based approach for potable reuse without understanding the potential TBL effects, especially for inland locations where RO concentrate disposal can be particularly challenging. Multiple concentrate handling approaches are analyzed for this scenario including ocean disposal, mechanical evaporation, and evaporation ponds. Process flow diagrams for this scenario are divided into S2A, which represents the GAC-based approach and S2B, which represents the RO-based approach. These scenarios are shown in Figures 2.4 and 2.5 respectively. More detailed process flow diagrams are provided in Appendix A. Note that although California has several potable reuse projects using RO for groundwater recharge, currently there are no surface water augmentation projects in California. Surface water augmentation with RO technology for potable reuse was chosen in this research for analysis because of its implementation in other locations (e.g., Australia, Singapore) and potential future application in California and other parts of the world. Although surface water augmentation for potable reuse was selected for analysis, the results from this research could also be applied to groundwater injection projects provided site specific groundwater basin water quality requirements were met (e.g., TDS limits).

Assumptions critical to the development of Scenario 2 are included in Table 2.2. Note that the GAC-based approach used along the eastern United States has been modernized in Scenario 2A to include unit processes that would likely be implemented today during the design of a GAC-based treatment process. These enhancements include an ozone-BAC process for pathogen, TOC, and trace organics removal and UV disinfection in lieu of chlorine disinfection to eliminate production of chlorinated disinfection byproducts. In addition, a coagulation–flocculation–sedimentation process has been added to the GAC-based treatment train for additional organics removal to reduce competition of adsorption sites on the GAC to improve removal of trace organics. Depending on the specific organic characterization of the water, this process may not be necessary at all locations. Both treatment trains 2A and 2B provide multiple barriers to organics and pathogens, which is important to all potable reuse projects. Table 2.3 shows the barriers provided by each treatment train.

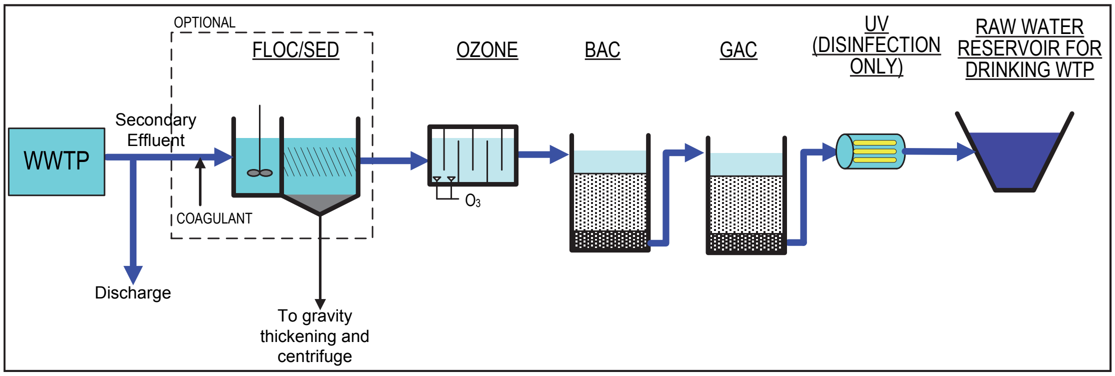

Figure 2.4. Scenario 2A: Reuse treatment for potable reuse using a GAC-based treatment approach.

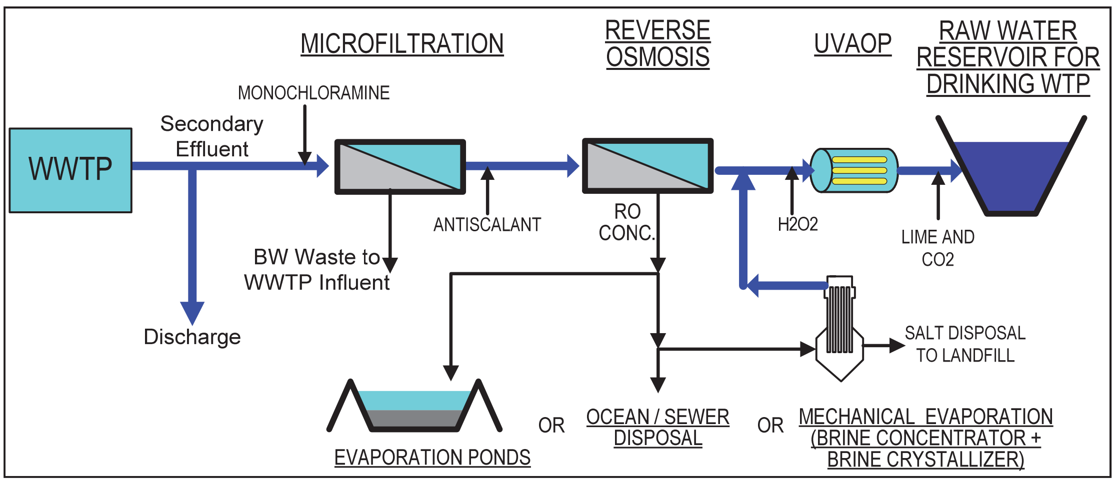

Figure 2.5. Scenario 2B: Reuse treatment for potable reuse using a RO-based treatment approach.

Table 2.2. Critical Assumptions for Development of Scenario 2

Item	Discussion
Water reuse plant is located at an inland location where ocean disposal is not readily available.	Disposal of RO concentrate has historically been much easier and less costly for facilities located along the coast because of the availability of ocean disposal. However, because of the increased difficulty in permitting new ocean disposals, the increased interest in potable reuse at inland locations where ocean disposal is not available, and the perception by many that RO technology must be used for potable reuse, it was assumed that ocean disposal would not be available in development of this alternative. Therefore, RO concentrate handling and disposal costs were included in this alternative.
Climate at plant location is semiarid or arid.	Semiarid and arid locations have evaporation rates that are high enough to allow consideration of using evaporation ponds for RO concentrate handling. This allows for alternative comparison to mechanically intensive RO concentrate handling technologies, such as brine concentrators and crystallizers.
WWTP practices nitrification and denitrification, which results in a total nitrogen concentration of less than 10 mg/L	More stringent WWTP nutrient discharge regulations being discussed and implemented in many states will likely result in significantly lower total nitrogen values in secondary effluent. For example, Florida's proposed Numeric Nutrient Criteria will likely require total nitrogen concentrations of less than 5 mg/L in the effluent from many WWTPs. These lower total nitrogen concentrations will reduce treatment requirements at potable reuse plants because nitrogen removal will not be required to meet the nitrate MCL of 10 mg/L that is often required at potable reuse plants. Many WWTPs located away from the coast in California include biological nitrogen removal and produce total nitrogen effluent below 10 mg/L.
WWTP secondary effluent TDS is less than 500 mg/L or blending with other waters is provided	The GAC-based train (S2A) does not remove TDS. Thus, to meet EPA's secondary MCL of 500 mg/L for TDS, the WWTP secondary effluent TDS concentration must be less than 500 mg/L or blending with other waters is required. For locations that have higher TDS levels and no blending is available, the GAC-based train could still be implemented based on public acceptance of a higher TDS concentration or partial RO treatment for TDS removal.
Regulatory limits for TOC that follow the East Coast's Regulatory Approach and EPA's 2012 Water Reuse Guidelines	TOC regulations can dictate the type of treatment process required. For example, in California a TOC concentration of less than 0.5 mg/L must be achieved for groundwater recharge via direct injection (not surface spreading) unless the reuse water is blended with other supplies. From a practical standpoint, RO is the only treatment process that can meet this requirement. In contrast, regulations and permitted projects in other states are not this strict with respect to TOC, which allow other advanced organic removal processes such as GAC to be considered. For example, potable reuse projects in Virginia and Georgia are permitted with a COD limit of 10 mg/L and 18 mg/L, respectively, which is approximately equivalent to a TOC concentration of 3 to 6 mg/L. Potable reuse regulations in Florida require a TOC of less than 3 mg/L. The 2012 EPA Water Reuse Guidelines suggest a TOC of less than 2 mg/L. The target finished water TOC for this scenario is nominally 3 mg/L.

Table 2.2. Critical Assumptions for Development of Scenario 2 (continued)

Item	Discussion
Reuse plant influent is withdrawn from WWTP prior to chlorination to avoid formation of NDMA	NDMA has been shown to form during the chlorination process at WWTPs, especially when chloramines are used for disinfection. Withdrawal of secondary effluent prior to chlorination for reuse treatment allows for alternative treatment processes to be considered that don't include NDMA removal. For example, UVAOP provides excellent NDMA removal, but consumes large amounts of power. Alternative oxidation technologies that don't remove NDMA well, such as ozone, can provide a similar removal of other contaminants with potentially lower TBL costs. Note that ozone also has the potential to form some NDMA, but this will be well removed in the downstream BAC process. Ozone can also form bromate in some waters; in these cases ammonia addition may be needed to inhibit bromate formation.

Table 2.3. Pathogen and Organic Barriers Provided by Alternative Potable Reuse Treatment Trains

Treatment Train	Number of Significant Pathogen Barriers	Number of Significant Organic Barriers
Scenario 2A (COAG/ O_3-BAC/GAC/UV)	Three: (1) Coagulation, sedimentation, and BAC filtration; (2) Ozone; (3) UV	Three: (1) Coagulation and sedimentation; (2) Ozone and BAC filtration; (3) GAC
Scenario 2B (MF/RO/UVAOP)	Three: (1) MF; 2) RO; (3) UVAOP	Two: (1) RO; (2) UVAOP

Note: Not all treatment barriers provide equivalent removal, but each barrier does provide significant removal. For example, RO removes more TOC than coagulation and sedimentation, but coagulation and sedimentation can provide significant TOC removal (>20%) at proper chemical doses and pH conditions.

2.1.3 Potable Reuse Risk Assessment

A reasonable question typically posed when discussing potable reuse is, "Are potable reuse systems protective of public health?" More specifically, when comparing alternative treatment trains for potable reuse the question becomes, "Are the treatment trains comparable for protecting public health?" Although this question is more fully addressed in other publications (NRC, 2012), it is briefly discussed here to provide background on the validity of the treatment trains selected for comparison in this research. As discussed earlier, full-scale potable reuse projects on the East Coast of the United States and in Namibia, Africa, have successfully utilized a GAC-based approach, whereas the U.S. West Coast and other international locations have successfully implemented full-scale RO-based projects (in addition to SAT-based approaches). No known adverse health effects exist at any of the facilities at either of these locations; in addition, drinking water regulations have been met consistently in the respective potable distribution systems. The proposed RO-based treatment processes in the present research matches the West Coast model for direct groundwater injection, and the proposed GAC-based treatment process enhances the East Coast model through the addition of ozone and BAC upstream of GAC, and UV in lieu of chlorine disinfection downstream of GAC. Therefore, the treatment systems evaluated in this research are at least as protective of human health as the full-scale potable reuse systems that have operated successfully to date.

Health risks typically are separated into two types: acute and chronic. Acute risks in water are represented by pathogens, including bacteria, protozoa, and viruses, which can cause severe illness, such as giardiasis, immediate and often, whereas chronic risks generally are associated with some inorganic (e.g., arsenic) and trace organic chemicals (e.g., trihalomethanes, NDMA) that are suspected carcinogens. Acute health risks are addressed adequately in both proposed potable reuse treatment trains through redundant treatment barriers for removal and inactivation of pathogens. Indeed, as will be discussed, both potable reuse treatment trains compare favorably to traditional drinking water sources in this regard. As shown in Table 2.3, three barriers to pathogens are provided for each proposed potable reuse treatment train.

Recently, new concerns have been raised about the potential for, yet generally unknown, chronic health effects related to the thousands of chemicals present at trace levels, referred to as contaminants of emerging concern (CECs) and the efficacy of water treatment processes to remove these contaminants. Each treatment process differs in its effectiveness at removing these compounds and although CECs may be detectable, the concentrations are very small. The presence of CECs leads some to ask, What are the costs and benefits of trading known costs for uncertain risk reduction? Are there unknown chemical constituents in the water (“unknown-unknowns”) that could potentially justify treating at higher levels to reduce their concentrations? Research has shown that both potable reuse treatment trains examined in this study already provide multiple unit processes that are effective barriers to a wide range of CECs. The RO-based approach provides substantial removal through RO and UVAOP, and the GAC-based approach provides significant removal through ozone-BAC and GAC. In addition, these processes are redundant in the removal of some CECs (provide multiple barriers to their passage) and are complementary in the removal of others. For example, both ozone and GAC are effective barriers to the anticonvulsant drug carbamazepine, but only GAC (and not ozone) acts as an effective barrier to the flame retardant TCEP (Snyder et al., 2007, and Sacher and Thoma, 2011). At the present time, treatment for all CECs does not appear to be a differentiator among potable reuse treatment trains. Although health effects of many CECs—either alone or as mixtures—are not known at the extremely low concentrations typically detected in wastewater effluent, the proposed treatment trains do reduce the concentrations of many of these chemicals to a significant degree. Meanwhile, EPA is prioritizing and studying a number of chemicals through their candidate contaminant list program.

Furthermore, the quality of the reuse water produced by both potable reuse treatment trains is already of high quality and has been characterized to be of better quality than many drinking water supplies. The Risk Exemplar presented in the 2012 National Research Council’s “Water Reuse” report (NRC, 2012) compared the risks associated with two potable reuse schemes to a common drinking water supply that was considered safe but subject to upstream wastewater discharges. Although the analysis was an exemplar and site-specific analysis is required for specific projects, the NRC report concluded that the risk associated with 24 chemical contaminants, including many CECs, and four pathogens does not exceed common drinking water supplies and may be orders of magnitude lower than some approved drinking water systems. That is, potable reuse is already as safe as or safer than other sources of drinking water supply.

It is important to understand the context for comparing potable reuse treatment trains in terms of the level of treatment provided. Both trains compared in this research achieve a very high level of treatment, at or above many other sources of potable water supply. They both produce treated water that complies with drinking water standards and will be blended with other water supplies and undergo treatment at the downstream drinking water plant, which represents additional barriers to pathogens and trace organics. In addition, each goes well beyond those drinking water standards by also addressing the potential health risks associated with CECs. Any advantages that one may have over the other by providing a greater degree of CEC removal cannot at this point be translated into a greater degree of health risk reduction. “Higher” levels of treatment do not necessarily reduce health risks, but can be costly or consume large quantities of natural resources. By determining the known financial, environmental, and social costs (i.e., TBL effects) of treatment, a utility can make an informed decision about the benefit of providing a “higher” level of treatment if the costs of doing so are greater. To help guide selection of the treatment process, known costs can then be weighed against any differences in the quality of the potable reuse water, additional environmental impacts, and any unknown risk reductions.

2.2 Triple Bottom Line Approach

2.2.1 Identifying the TBL Factors

As described in Section 1.5, this research uses a cost–benefit approach toward TBL accounting. Each of the water reuse treatment trains is compared in terms of its economic costs and benefits to society and the environment, and not simply to those internal to the utility. The objective is to quantify the most significant factors in monetary terms to facilitate comparisons among alternatives on the basis of societal welfare. In addition to quantifying effects in dollars, it can be important to some stakeholders to readily compare alternatives on the basis of their environmental or social metrics, such as energy utilization, GHG emissions, and human health effects. Thus, these factors also are tracked in their “natural” units. However, to the extent that they also are quantified in dollars, these benefits and costs are only to be “counted” once.

This TBL approach incorporates principles from LCA to identify the questions enabling a more complete accounting of effects over the life cycle of the water reuse treatment process. Specifically, this analysis requires asking the following questions:

1. *What are the social costs and benefits incurred at the treatment plant itself?* Addressing this question includes capturing the direct costs of treatment, as well as external costs that are due to the treatment process (e.g., ecological footprint of the treatment facility, capital and operation and maintenance [O&M] costs of treatment, utilization of energy, and chemicals to “produce” reclaimed water). These effects originating at the plant are called “direct effects” as they emanate directly from the treatment phase of the process.

2. *What are the net social costs and benefits caused by producing and transporting inputs to the water reuse treatment process?* This question indicates that one must look “upstream” of the water reuse treatment facility to capture external environmental impacts created prior to any utilization of the *inputs* in the water reuse treatment process (e.g., energy must first be produced at a power plant thereby creating GHG emissions and other emissions of air pollutants harmful to human health). For our purposes, these are called “upstream effects.”

3. *What are the net social costs and benefits to the end users “downstream” of the treatment process, where the “end users” can be households, businesses, industry or the environment (e.g., disposal or utilization of brine waste from the reuse water treatment plant, effects of the nutrients in reuse water on agricultural or landscape irrigation end*

users; discharge of reuse water to surface waters or percolation into groundwater)? Effects that occur posttreatment are appropriately called "downstream effects."

In identifying the social costs and benefits of each reuse treatment train, the alternatives are compared with each other and not to other water supply alternatives, such as desalination or reservoir expansions. That is, the decision to employ a reuse alternative is taken as a given for the purposes of this analysis. Thus, any social benefits and costs that are common to all reuse alternatives are not considered here, because they would not be of value in differentiating among reuse treatment trains. However, TBL assessment of reuse water in relation to other water supply alternatives, such as reservoir creation, water conveyance, and desalination is an important topic in its own right and has been addressed by Stratus Consulting (2011) and others.

These TBL questions are illustrated in Figure 2.6 TBL Factors to Consider in Selecting a Water Reuse Treatment Process. Note that the "direct TBL effects" and the "upstream TBL effects" occur on almost all water reuse projects in differing degrees, but the "downstream effects" are project specific and the applicability of each must be determined for each project analyzed.

Direct TBL Effects (Effects that are controlled by the water utility)

- **Financial Costs (Construction, Engineering, O&M)**
- **Environmental and Social Factors**
  - Direct air emissions (e.g., because of GAC regeneration)
  - Energy use
  - Chemical use
  - Water efficiency

Upstream TBL Effects (Effects that occur because of a water utility's actions but are controlled by another entity)

- **Financial Costs (addressed under Direct TBL Effects)**
- **Environmental and Social Factors**
  - Energy use
    - effects on water resources, surface waters, solid waste, and land resources
    - GHG emissions
    - Other air emissions
  - Transportation of chemicals
    - GHG emissions
    - Other air emissions

These Effects occur in differing degrees across almost all water reuse projects

Downstream TBL Effects owing to Byproducts (Effects that occur because of byproducts released by the water utility)

- **Financial Costs (Addressed under Direct TBL Effects)**
- **Environmental and Social Factors**
  - Ecosystem footprint (e.g., evaporative ponds for brine disposal)
  - Other ecosystem footprint—Residuals disposal (e.g., in landfill)
  - Transportation externalities (for disposal of residuals)
    - GHG emissions
    - Other air emissions
  - Discharge of water carrying nutrients or TDS to surface waters
  - Discharges of pollutant loads to groundwater

Downstream TBL Effects on End Users (Effects that occur to the end user of the reclaimed water) and TBL effects downstream of the end user (e.g., runoff from irrigated agriculture and landscape irrigation)

- **Financial Costs (End user Operations:** Adjustments to fertilizer use, salinity/soil management, mowing operations)
- **Environmental and Social Factors**
  - Possible impact to vegetation and soil (addressed under financial effects on end user)
    - TDS, electroconductivity, chloride, SAR
  - Pollutant Loads to Surface Waters (application at agronomic rates mitigates this impact)
  - Pollutant Loads through Discharge to Groundwater

These effects are project specific and the applicability of each must be determined for each project analyzed

Figure 2.6. TBL factors to consider in selecting a water reuse treatment process.

Notes: Some water reuse projects, such as those that include treatment wetlands, may not include some effects (e.g., chemical use)

The TBL endpoints associated with each of the reuse treatment trains included in the present analysis were identified by answering these questions with the aid of a literature review of other TBL applications and a workshop with the Project Advisory Committee. The resultant TBL endpoints and the methodologies for measuring them are discussed next.

2.2.2 Accounting Methodology

The list of financial, environmental, and social benefits and costs resulting from the identification step are summarized in Figure 2.6. Financial effects are quantified in dollars, whereas, physical, environmental, and social effects are quantified in their natural units (e.g., kWh of energy utilization, tons of CO_2 equivalents) as stakeholders are interested in tracking how alternatives directly contribute to certain societal goals, including energy conservation and reducing GHG emissions. Where reasonable, these effects are then quantified in dollars to facilitate comparing alternatives on the basis of a single measure of net social cost. Where it is not reasonable to quantify environmental or social effects in monetary terms, such effects are quantified or qualitatively characterized in the summary comparison of alternative treatment trains to ensure their consideration in identifying the TBL preferred alternative.

As discussed, each of the TBL effects is grouped by category: direct effect of treatment process, upstream of treatment, or downstream of treatment. Each of these types of effects and the associated measurement methodology are described in turn. The application of the methodology to each treatment train is reserved for Chapter 4, Triple Bottom Line Costs.

2.2.2.1 Direct Effects

The direct TBL factors include the financial costs to construct and operate the water reuse facility (e.g., capital, materials, operation and maintenance, engineering design). With the exception of land intensive approaches (e.g., evaporation ponds) that are described further later, land acquisition costs for the facility are not included as the facility footprint is small and similar across treatment trains. In addition, the environmental and social factors to consider in the reuse treatment process include energy utilization, use of chemicals, and the efficiency of converting source water for reuse. Each environmental or social factor is considered separately in order to apply the most appropriate methodology for including it in the TBL. Those factors that are quantified in natural units and in dollars are only counted once for the purpose of comparing the net present value (NPV) of alternatives.

Direct Effects—Financial Costs

Capital and O&M cost estimates for each treatment train were developed using CH2M HILL’s proprietary parametric cost estimating program (CPES) for water and wastewater treatment plants. The parametric cost estimating program uses fundamental design criteria for treatment processes, general arrangement drawings based on actual plant designs, and an extensive water treatment cost database from constructed plants to generate detailed quantity takeoffs and reliable cost estimates. The costs are for a complete and fully operational water reuse plant (excludes wastewater treatment through secondary treatment) with the necessary site development, electrical, computer, operations and maintenance buildings, and miscellaneous support infrastructure included in a typical plant. Standard percentages for items, such as overhead and profit, contingency, engineering, and bonds and insurance, are applied to the construction cost estimate to generate a total capital cost estimate. These percentages, as well as site allowance percentages, are shown in Table 2.4. Capital costs for all scenarios were developed for plant capacities of 5 mgd, 20 mgd, and

70 mgd (19 mld, 76 mld, 265 mld). Annual costs were based on an average flow of 60% of plant capacity to mimic the variability of seasonal demands and water supply. The detailed cost breakdown provided by the CPES cost model for one of the treatment processes (GMF) is provided in Appendix B to demonstrate the comprehensive approach for cost estimating used in this research.

Table 2.4. Site Allowances, Contractor Markups, and Non-Construction Costs

Item	Allowance
Site Allowances	
Site work (roads, fences, landscaping, etc.)	6%
Plant computer (supervisory control and data acquisition [SCADA])	2%
Yard electrical (primary feed, switchgear, generator)	5%
Yard piping (process piping, chemical piping, fire loop, service water, natural gas)	15%
Contractor Markups	
Overhead	7%
Profit	10%
Mobilization / bonds / insurance	3%
Contingency[a]	30%
Nonconstruction Costs	
Engineering	7%
Construction management	7%

[a] Contingency not applied to mechanical evaporation and evaporation ponds facility costs, because the scope of these expensive large facilities are well defined.

Annual O&M costs include labor, power, consumables, and regular replacement for items with an expected life of less than 30 years (e.g., membranes). Labor costs were based on data collected from the participating utilities, as further explained in Chapter 3, Utility Survey. Power costs were estimated by calculating the equipment and building electrical power draw and applying a unit power cost of $0.08/kWh.[1] The cost for consumables (e.g., chemicals) was estimated on the basis of the calculated annual average usage times a unit cost for each consumable. Unit costs for chemicals were obtained from participating utilities, and the researchers' experience. A plant life of 30 years and a discount rate of 3% were used for the base case NPV analysis. A 7% discount rate was used for sensitivity analysis. This discount rate is the factor multiplied by future benefits and costs to convert them to current dollars for the purpose of measuring all effects in common units so that they can be aggregated for making meaningful comparisons among benefits and costs that occur at different points in time. Additional details about the NPV calculations are discussed in Chapter 4.

[1] As of October, 2012, the national average price of energy for the industrial sector was $0.0665/kWh and the average across all sectors was $0.0976/kWh. U.S. Energy Information Administration, Form EIA-826, 'Monthly Electric Sales and Revenue With State Distributions Report. U.S. Energy Information Administration, Form EIA-923, 'Power Plant Operations Report downloaded from http://www.eia.gov/electricity/monthly/pdf/epm.pdf.

The capital and O&M costs included in this document should only be used for comparison among the treatment trains and should not be applied to any actual projects. The costs are considered accurate for comparison purposes but could vary significantly in different locations of the world, depending on local market conditions and site-specific factors. In Chapter 4, the CPES cost estimates are compared to the cost data collected from the literature review presented in Chapter 1 and the utility survey presented in Chapter 3.

Direct Effects—Environmental and Social Factors

Facility Footprint

Each water reuse treatment facility requires taking a certain amount of land from other uses. However, the facility footprint is likely to be relatively small and similar across treatment trains. In contrast, the footprint associated with byproducts, such as the brine waste stream from the RO technology, is substantial and is addressed later under Downstream Effects.

Other Direct Effects of Plant Construction

Generally plant construction is associated with a variety of environmental costs including air pollution onsite and from transporting materials to and from the construction site, water pollution from storm water runoff from the site, noise from operating heavy machinery, and congestion along the construction transportation routes. It is assumed that these factors are sufficiently similar across treatment technologies, especially given the environmental requirements to control air emissions and discharges to surface waters. Therefore, such environmental effects will not be further considered in the TBL. The one clear exception is natural treatment systems, which can still require transportation of material to and from the site by heavy trucks, as well as short-term air and water pollution. However, natural treatment systems can well be expected to provide a net environmental benefit over the life of the project.

Direct Effects of Facility Operation

In general, water reuse treatment processes are relatively low direct emitters of air pollutants and GHG emissions.

Energy Utilization

Each water reuse treatment process consumes energy to run the plant. Although the monetary cost of the energy is included in the cost of operating the facility, stakeholders may be interested in tracking and comparing the life-cycle energy requirements across treatment trains. On the social level, reliance on energy imports has been considered a threat to national security and protecting energy interests often has dominated United States foreign policy. Developing and producing energy is resource intensive and creates a range in environmental externalities depending on the source. This topic is explored further in the section Upstream Effects. The direct power requirements for operating the water reuse facility are computed within CPES and are reported in the TBL summary table as a direct effect of the treatment process.

Direct GHG Emissions and Other Air Emissions

Direct emissions are GHG sources that the entity directly owns or controls. These emissions are put into four categories: stationary combustion, mobile combustion, process related, and fugitive emissions. Direct emissions commonly are referred to as Scope 1 emissions by many reporting protocols. Aside from a small amount of light vehicle use, it has been assumed no direct emissions result from operating the typical reuse treatment processes. The one exception is the GAC treatment process where the utility owns and operates a GAC regeneration furnace. Table 2.5 shows actual emissions data from performance testing of a GAC regeneration furnace at the Upper Occoquan Service Authority's (UOSA) Millard H. Robbins, Jr. Regional Water Reclamation Facility. Data are based on samples collected after an afterburner and wet scrubber located downstream of the multiple hearth regeneration furnace. GHG and air emissions produced during GAC regeneration include byproducts from the burning of the fuel source (natural gas to both the regeneration furnace and afterburner) and the release of chemicals adsorbed onto the GAC during the heating process (e.g., organic carbon mineralized to CO_2). Data in Table 2.5 were used for calculation of direct GHG and other air emissions during GAC regeneration. Note that much of the air emissions shown in Table 2.5 are not actually released to the environment at UOSA. Instead, UOSA beneficially uses the carbon dioxide in the stack gas for recarbonation of lime treated water by quenching, cooling, compressing, and diffusing the stack gas into the liquid treatment process. Therefore, the GHGs and other air emissions shown in Table 2.5 for GAC regeneration only apply if the stack gas is not diffused into the treatment plant's liquid stream or if GAC is regenerated offsite.

Table 2.5. GHG and Other Air Quality Parameters in GAC Regeneration Process Exhaust Prior to Diffusion in Recarbonation Basins at the UOSA Millard H. Robbins, Jr. Regional Water Reclamation Facility

	Measured Value		GAC Processed		Exhaust Flow SCFM	Natural Gas Flow	
Parameter	**PPM**	**lb/hr**	**lb/hr**	**lb/1000 lb**		**SCFH**	**ft^3/lb GAC**
NO_x	115.37	0.68	500	1.36	825	2117	4.2
SO_x	0.29	0.0024	500	0.0048	825	2117	4.2
CO	74.81	0.27	500	0.54	825	2117	4.2
VOC	1.25	0.0026	500	0.0052	825	2117	4.2
PM_{10}	--	0.00189	500	0.00378	825	2117	4.2
CO_2	105,000	584.6	500	1189	825	2117	4.2

Note: CO_2 generation is expected to vary from 1000 lb/1000 lb of GAC to 1600 lb/1000 lb of GAC depending on combustion temperature, amount of water, and amount of carbon adsorbate removed.

Chemicals

The financial costs of chemicals used in treating the reuse water also are included in the treatment cost comparison. However, like energy, tracking chemical usage is important to some stakeholders. The production and transportation of chemicals can be energy intensive and can have adverse effects on the environment, as well as create human health and safety concerns from transporting hazardous chemicals and storing them onsite. Chemical inputs by type and quantity are computed within CPES and are quantified as a direct effect. The upstream usage of energy to produce and transport the chemicals is discussed under Upstream Effects.

Water Efficiency

The source water is the final input to the reuse treatment process that is compared across treatment trains. Treatment processes differ in terms of the efficiency with which they convert source water to reuse water. Because of societal interest in conserving water, the amount of source water that is wasted is tracked separately from the financial calculation. This quantity is calculated within CPES.

2.2.2.2 Upstream Effects

Upstream Effects—Financial Factors

The financial cost of the inputs to the water reuse treatment process is accounted for under direct effects. There are no additional financial costs to consider.

Upstream Effects—Environmental and Social Factors

The upstream TBL environmental effects refer to the unmitigated external effects from producing or transporting inputs to the reuse treatment plant, where, besides the source water, the primary inputs to the reuse treatment process are energy and chemicals. The environmental externalities associated with energy generation include air emissions, water resource use, water discharges, solid waste generation, and land resource use, where the specific effects depend on the generation source. Most notable among the air emissions are the GHG emissions (CO_2, methane [CH_4] and nitrous oxide [N_2O]) and criteria air pollutants (particulate matter [$PM_{2.5}$], nitrogen oxides [NO_x] and sulfur dioxide [SO_2]) from producing energy, especially energy derived from burning fossil fuels. According to EPA (2007), fossil fuel-fired power plants are responsible for 67% of the nation's SO_2 emissions, 23% of NO_x emissions, and 40% of made CO_2 emissions, contributing to acid rain, smog and haze. The methods for accounting for GHG emissions and the criteria air pollutants, SO_2, and NO_x from electricity generation are described in this section.

The environmental externalities associated with producing the chemicals that are used to treat reuse water also include energy generation with all of the associated externalities as previously mentioned. In addition, chemical inputs must be transported to the treatment facility. The process of transporting the chemicals creates additional externalities in the forms of GHG emissions and other air emissions from mobile sources (Ammonia [NH_3], NO_x, and carbon monoxide [CO]). This section describes each of these externalities.

Energy Use

Energy Use—Water Resources

Water resource use in energy generation is a growing concern because of increasing demand for scarce water resources. Water resources are used for steam production and cooling as well as for cleaning equipment and removing impurities, such as from coal mining (EPA, 2007). Cooling such as for nuclear power plants and coal- and oil-fired plants can sometimes require that large quantities of water be withdrawn from surface waters, raising the temperature of receiving waters and necessitating care to minimize other effects on fish and other aquatic life from impingement and entrainment. Such cooling also can lead to large evaporative losses. It is worth noting that these are strong arguments for using reclaimed water for cooling water to avoid such adverse effects on water resources. Finally, one renewable source, hydroelectric generation, can affect water resources by altering stream flow, fish passage, and water quality and temperature. The effects on water resources from generating electricity are not assessed quantitatively for the purposes of this TBL. However, this qualitative discussion serves to amplify that treatment trains with higher energy requirements will result in concomitant larger demands on limited water resources.

Energy Use—Surface Waters

Under the U.S. Clean Water Act, discharges to the nation's surface water require permits that are intended to regulate pollutant loads—including conventional pollutants and toxics as well as changes in temperature. Less direct discharges can reach surface water through drilling activities that leak to groundwater and through accidental releases, such as pipeline ruptures. Although unintentional, these damages also must be mitigated. It is worth noting that obtaining permits for new discharges can be difficult for receiving waters that are already at capacity. Nonetheless, whereas some forms of energy generation are potentially more damaging to water resources than others, water discharges generally are mitigated through regulatory compliance. For this reason, quantitative information on water discharges resulting from energy generation is not included for the purposes of this TBL.

Energy Use—Solid Waste

Depending on the source, electricity generation can result in producing solid waste, hazardous waste, or neither—as is the case with natural gas, hydroelectric, and nonhydroelectric renewable energy. Coal burning leaves an ash residue, and the coal cleaning process produces other solid waste that is deposited in landfills or recycled. The wastewater sludge from refining oil can include toxic compounds and require disposal as hazardous waste. Burning municipal solid waste and biomass reduces the amount of waste that must be disposed at the landfill; however, in the case of municipal solid waste, this can require disposal as hazardous waste depending on the content. Nuclear power generation leads to radioactive waste, which requires the most complex disposal methods. The solid waste discharges associated with producing energy are only described qualitatively for the purpose of this TBL.

Energy Use—Land Resources

The final natural resource affected by electricity generation is land. Almost all forms of electricity generation require constructing facilities on land, thus destroying the ecosystem system within the footprint of the facility. The size of the footprint depends on the technology, as do the opportunities for minimizing and mitigating effects on land resources. Nuclear power generation may require multiple facilities, but it also requires buffers that can have the effect of preserving tracts of land that may otherwise be developed. However, future land uses may be limited because of storing possible radioactive waste. Coal- and oil-fired plants can require large tracts of land and can lead to contaminated soils and waterways. Surface mining of coal can be devastating to the landscape requiring extensive restoration efforts. Municipal solid waste burning facilities have a footprint that can be mitigated by locating the facility at the landfill. Hydroelectricity generation can alter land resources dramatically in the process of constructing dams and flooding an area to create lakes. Other renewable energy sources including solar, geothermal, wind, and biomass also can leave a footprint depending on the situation. For example, solar and wind power can require large tracts of land that could be incompatible with maintaining quality habitat for certain wildlife. Burning biomass can require devoting land to growing select crops for burning as fuel. This TBL does not attempt to account specifically for the land use aspects of using electricity to power reuse treatment facilities. However, to the extent that one treatment train requires more electricity than another, it will also have a larger footprint on the ecological landscape.

As described previously, electricity generation can affect air, water, and land resources through multiple pathways. However, specific effects are generally source and location dependent—making it difficult to draw conclusions other than the obvious. Namely, by using more energy than necessary, the plant not only wastes energy but also causes adverse effects on other natural resources. In the case of air emissions, at least, it is possible to go one step farther and quantify the social costs of electricity generation. The next two sections describe the methodologies for estimating the GHG emissions and emissions of criteria air pollutants, as well as the associated economic valuation methodologies.

Energy Use—Greenhouse Gas Emissions

Multiple sources of GHG emissions vary in amount depending on the treatment technology selected. At the input stage of the life-cycle process, these include the embodied energy to construct the water reuse plant, the GHG emissions released while producing the energy to run the water reuse facility, and the GHG emissions from producing and transporting the chemicals used in the treatment process. Each of these sources of GHG emissions is discussed in turn.

The GHG emissions associated with constructing the water reuse facility are very small relative to the other sources of GHG emissions and are not expected to vary significantly across treatment trains. Therefore, they are not considered further. The GHG emissions associated with energy production rely on CPES for the estimates of energy utilization for each treatment process used. The methodology used to develop readily comparable estimates of GHG emissions is based largely on the *General Reporting Protocol* (v1.0) published by The Climate Registry modified to include significant supply chain GHG emissions. This methodology is mostly consistent with ISO 14040 *Life Cycle Assessment* and ISO 14064-1 *Greenhouse Gases* but is not designed to include those life cycle sources deemed *de minimis*.

GHGs generated during the operation of treatment processes were determined for each treatment process. Direct emissions were considered under Direct Effects. Indirect emissions are addressed here.

Indirect GHG Emissions—Purchase and Consumption of Energy

These emissions are a result of the purchase and consumption of electricity. Although these emissions are outside the organization's boundary, most reporting protocols require quantification of these emissions to provide incentives for energy efficiency and conservation. Indirect emissions from electrical purchase are typically referred to as Scope 2 emissions in most reporting protocols. Emission factors for the purchase of electricity are shown in Table 2.6. The EPA's eGRID data (EPA, 2012b) that averages emission factors for 26 subregions across the United States that have different sources of energy were used to determine the total CO_2 equivalent (CO_2e) from the purchase of electricity. For the purpose of this analysis, to compute the various emission factors, it is assumed that the energy source for powering the reuse plant is proportionate to the average electricity generation mix for the United States, which is coal (44.47%), oil (1.12%), gas (23.31%), other fossil fuel (0.34%), biomass (1.38%), hydro (6.80%), nuclear (20.22%), wind (1.86%), solar (0.02%), geothermal (0.38%), and other unknown purchased fuel (0.10%) (EPA, 2012b). The corresponding average national output emission rate for CO_2 is 1216.18 lb/MWh, for CO_4 is 0.02403 lb/MWh, and for N_2O is 0.01808lb/MWh (EPA, 2012b).

Table 2.6. Green House Gas Emission Factors for Electrical Consumption

Emission Factor	Value (lb/MWh)
CO_2	1216.18
CH_4	0.02403
N_2O	0.01808

Source: EPA eGRID2012 Version 1.0, Year 2009 Summary Tables (EPA, 2012b)

When converting to CO_2 equivalents, all emissions must first be converted to common units and second multiplied by their global warming potential (GWP) (TranSystems, 2012). To compare GHG emissions from varying sources, CO_2, CH_4, and nitrous oxide (N_2O) emissions were converted into a common unit. The commonly accepted unit is carbon dioxide equivalents, or CO_2e. Table 2.7 presents the GWP for NH_4 and N_2O. CO_2 equivalents are calculated by multiplying the emissions for each gas by the GWP shown in the table.

Table 2.7. Global Warming Potential

Gas	GWP
CO_2	1
CH_4	21
N_2O	310

Source: California Climate Action Registry, General Reporting Protocol, Reporting Entity Wide Greenhouse Gas Emissions, Version 3.0, April 2008

Energy Use—Other Air Emissions (Criteria Air Pollutants and Air Toxics)

As mentioned, electricity generation, especially through burning fossil fuels, is a major source of emissions of the criteria air pollutants, NO_x and SO_2. Using the same national average electricity generation mix as for CO_2 equivalents, the corresponding national average output emission rates for NOx equals 1.216 lb/MWh and for SO_2 equals 3.0811 lb/MWh (EPA, 2012b; TranSystems, 2012). Concentrations of these pollutants lead to higher incidences of health effects including acute respiratory ailments, asthma, and hospital admissions because of a variety of symptoms. They are also considered precursors emissions of particulate matter ($PM_{2.5}$), with even greater adverse health effects, especially heart disease and premature mortality. The EPA does not provide similar estimates for the emissions factor for direct emissions of $PM_{2.5}$ at the national scale. However, a rough order of magnitude estimate is obtained by dividing the estimate for 2012 national energy output produced by electricity generating units as provided by the U.S. Energy Information Administration (2012) by national direct emissions of primary $PM_{2.5}$ from EPA's National Emissions Inventory (EPA, 2012c). This calculation is shown in equation (1).

$PM_{2.5}$ tons/thousand MWh = 303,000 tons/2343,786 thousand MWh = 0.00012928 tons/MWh or 0.259 lb/MWh. (1)

These emission factors are summarized in Table 2.8.

Table 2.8. Criteria Air Pollutant Emission Factors for Electricity Generation

Emission Factor	(lb/MWh)
NOx	1.216
SO_2	3.081
$PM_{2.5}$	0.259

Source: EPA 2012c, U.S. Energy Information Administration, 2012.

A second form of air pollution from coal and oil fired power plants is air toxics. Only recently have electric generating units been required to reduce emissions of air toxics with the release of the Final Rule, effective April 16, 2012 (EPA, 2012c). The Mercury and Air Toxics Standards (MATS) will reduce emissions of mercury, arsenic, chromium, and nickel, and other air toxics, as well as acid gasses and will further reduce particulate matter. Facilities will have at least 3 years and some may take as many as 4 years to implement the controls fully. At full implementation, the rule is expected to reduce the amount of mercury emitted from power plants by 90% and to reduce 88% of acid gas emissions from this source. It is also estimated that the rule will result in a 41% cut in sulfur dioxide emissions beyond the reductions attributed to the Cross State Air Pollution Rule. EPA determined that the associated benefits to human health and the environment from reducing air toxics will be accomplished without materially reducing electricity generation from coal and oil fired power plants. For this reason, this TBL does not count reductions in air toxics as a benefit of saving energy.

GHG Emissions and Other Air Emissions from Generating Electricity to Produce Chemicals

Producing the chemicals that are used to treat reuse water can be an energy-intensive process, resulting in GHG emissions and other air emissions. These emissions are accounted for in the same way as described under the section Energy Use.

Transportation Externalities

Transporting chemicals to the treatment plant contributes to air pollution through fuel combustion. Those treatment processes that rely on large quantities of chemicals will have larger GHG emissions, as well as other air emissions.

Indirect GHG Emissions—Transporting Chemicals

The GHG emissions resulting from transporting chemicals also are estimated within CPES. These indirect emissions are among the class of sources in which an organization has significant control or influence and that occur within its boundaries. Most of these GHG emissions result from contracted services for upstream and downstream activities, such as product manufacturing, transportation, and disposal. These emissions sources are referred to as optional indirect, or Scope 3 emissions, because most reporting protocols do not require organizations to report these emissions as a part of their inventory. Table 2.9 shows the emission factors and assumptions for chemical delivery. These same factors and assumptions are used for residuals disposal, which is addressed under the topic, Downstream Effects.

Table 2.9 describes the emissions factors for mobile combustion emissions, along with the assumptions for vehicle fuel economy. Most of the assumptions in Table 2.9 are relatively straightforward. That is, it is reasonable to assume that the standard delivery truck is heavy-duty diesel. However, the one-way trucking distance is difficult to generalize and will vary by the utility's location in the country and in relation to major chemical manufacturing centers. For example, in the United States, the bulk of the lime manufacturing occurs in the Midwest, chlorine and caustic soda come from the gulf region, and many other chemicals are manufactured locally in multiple parts of the country. Much of the long-haul transport is likely by rail or by barge before ultimately transferring to trucks. For these reason, 100 miles is used as a convenient estimate of the one-way travel distance. If the travel distance turns out to be a key parameter, this factor will be varied to test sensitivity of the results.

Table 2.9. Emission Factors for Mobile Combustion

Item	Value
Truck type	Heavy-duty Diesel
Percentage of highway driving	55
Chemical delivery (one-way)	100 miles
Residuals delivery (one-way)	50 miles
Percentage of city driving	45
Highway fuel economy (mi/gal)	10
City fuel economy (mi/gal)	8
CO_2 emission factor (lb/gal)	21.958
CH_4 emission factor (tons/mi)	$5.62 X 10^{-9}$
N_2O emission factor (tons/mile)	$5.29x10^{-9}$

Source: OfficeClimate Action Registry, General Reporting Protocol, Reporting Entity Wide Greenhouse Gas Emissions, Version 3.0, April 2008

Other Air Emissions—Transporting Chemicals

CPES does not calculate the other types of air emissions from trucks delivering chemicals to the treatment plant; instead they are estimated using EPA's MOVES (Motor Vehicle Emission Simulator). It is an advanced tool used for estimating emissions from highway vehicles (http://www.epa.gov/otaq/models/moves/index.htm). As this tool was originally intended to be used to estimate emissions for existing fleets of vehicles with known specifications and documented mileage and operation logs, the model inputs must be standardized for the present purpose of comparing treatment trains. The model inputs include vehicle age, specific vehicle upgrades for emission reduction, engine horsepower, vehicle speed, idling time, and refueling controls, among others. For the GHG emissions, these emission factors are for a standard heavy-duty diesel vehicle with standard fuel economy as shown in Table 2.9.

For consistency, in order to evaluate NH_3, NO_x, $PM_{2.5}$, and CO emissions and emission factors from mobile combustion, it was required to take information from MOVES and make some additional assumptions for a generic heavy duty truck. The assumptions are in Table 2.10. Using the Operating Mode Bin, emission rates for NH_3, CO, $PM_{2.5}$, and NO_X are estimated based on MOVES and reported in Table 2.11. Similar factors were not estimated for SO_2, because the national data indicate that such emissions are small in relation to the other pollutants (EPA, 2013). Specifically, the quantity of SO_2 emissions are less than a third as great as the tons of NH_3, under 20% of the NO_x quantity and less than 1% of $PM_{2.5}$ emissions.

Table 2.10. Standardized Assumptions for Chemical Delivery Trucks

Item	Value
Vehicle model year	2002
Horsepower	250
Power scaling factor for heavy-duty trucks	17.1
Scaled tractive power bin[1]	12–18
Vehicle speed	>50 mph
Operating mode bin[2]	37

Source: "Development of Emissions Rates for the MOVES Model," March 2010

[1]Scaled tractive power bin is obtained by dividing horsepower and the power scaling factor

[2]Operating mode bin is from the scaled tractive power bin and vehicle speed

Table 2.11. Mobile Source Emission Factors for Ammonia, Carbon Monoxide, and Nitrogen Oxide

Gas	Emission Factor (grams/mi)
Ammonia (NH_3)	0.027
Carbon monoxide (CO)	1.6
Nitrogen oxide (NO_x)	36
Particulate matter ($PM_{2.5}$)[1]	0.6

Sources: Updates to the Greenhouse Gas and Energy Consumption Rates in MOVES2010a, August 2012 and Technical Guidance on the Use of MOVES2010 for Emission Inventory Preparation in State Implementation Plans and Transportation Conformity," EPA-420-B-10-023, April 2010.

[1]$PM_{2.5}$ emission rate is in grams/hr, with an average vehicle speed of 50 mph and operating mode bin based on the vehicle information as shown

It should be noted that the NO_x emission factor would be significantly lower if the vehicle is of a newer model as NO_x restrictions on new vehicles are more stringent. Also, if most of the transportation occurs at lower speeds, NO_x emission rates will be reduced significantly. The same can be said for PM emissions on newer vehicles. With model years beginning in 2007, diesel particulate filters are equipped on all heavy-duty vehicles dropping the emission rates significantly. The emission rate for 2007 and newer vehicles would be between 15 to 20 times lower than a 2002 vehicle, keeping vehicle speeds and operating bin modes the same.

Valuing the GHG Emissions

The estimated quantities of GHG emissions are reported in tons of CO_2 equivalents, independent of the source of the emissions. To assign an economic value to these emissions, estimates are selected from the document prepared by the Interagency Working Group on the Social Cost of Carbon (2010). The Working Group was charged with developing estimates to support analyses of regulations and other applications involving BCA, especially under Executive Order 12866. The approach taken toward estimating the economic value of reducing carbon emissions is by monetizing the damages avoided by reducing GHG emissions. The final recommendations reflected the large uncertainties involved in developing the estimates by providing a range in values corresponding to different modeling assumptions and discount rates. All estimates are intended to include changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services resulting from climate change. The range in estimates is not static over time but rather increases in response to changing conditions. Specifically, the social cost of carbon increases over time both because of more significant changes in climatic conditions and cumulative stresses on physical and economic systems.

The Working Group's recommended time series uses a 3% discount rate and conservative modeling assumptions. The 3% discount rate series represents the central tendency of the range in discount rates that were considered, although the group also calculated the social cost of carbon at 2.5% and 5%. The results for the social cost of carbon range from $0.012/lb in 2012 to $0.022/lb in 2042, all in 2012 dollars. The Working Group goes on to recommend capturing the uncertainties underlying the estimates using a probability density function for equilibrium climate sensitivity. Of particular concern are the low probability−high impact events. This scenario corresponds to the 95th percentile estimate across all three of the climate change integrated assessment models (at the 3 discount rate). In 2012 dollars, this estimate for the social cost of carbon ranges from $0.038/lb in 2012 to $0.068/lb in 2042.

Even as the Interagency Working Group finalized its analyses and recommendations, it recognized that the estimates were sensitive to the limited state of knowledge and the group was committed to continue the research and reassess the social cost of carbon in 2 years. Indeed, the release of the report has spurred much debate with the general consensus that the Interagency Working Group has underestimated the social cost of carbon. For example, the results did not sufficiently account for the low probability and high impact tail of the distribution (Dietz, 2012). The failure to adequately consider damages' uncertainty is compounded for a risk adverse society. Considered jointly, the effect is to triple the estimate of the social cost of carbon (Kopp, et al., 2012). Others have estimated that the estimate is off by more than an order of magnitude (Ackerman and Stanton, 2012). Nonetheless, as the Interagency Working Group has not yet updated its figures, for the purposes of this TBL the two value streams as reported are used to value the social cost of carbon. Although this may result in an underestimate of the value of reducing GHG emissions, it still serves to show the sensitivity of the results to assumptions about the social cost of carbon. It is important to note that because the social cost of carbon is already represented in NPV terms, it must be kept separate from the rest of the NPV calculations in the TBL.

Valuing the Other Air Emissions

Electricity Generation

As mentioned, electricity generation, especially through burning fossil fuels, is a major source of emissions of the criteria air pollutants, NO_x and SO_2, and a significant source of $PM_{2.5}$. Using the same national average electricity generation mix as for CO_2 equivalents, the corresponding national average output emission rates for NO_x equals 1.216 lb/MWh and for SO_2 equals 3.0811 lb/MWh (EPA, 2012b; TranSystems, 2012). Concentrations of these pollutants lead to higher incidences of health effects including acute respiratory ailments, asthma, and hospital admissions because of a variety of symptoms. They are also considered precursors emissions of particulate matter ($PM_{2.5}$), with even greater adverse health effects, especially heart disease and premature mortality. As previously described, the national average for direct emissions of primary $PM_{2.5}$ are estimated to be approximately 0.259 lb/MWh. EPA has developed an Environmental Benefits Mapping and Analysis Program (BenMAP) for estimating the location specific changes in human health and associated monetary values on the basis of changes in the concentrations of certain air pollutants and the underlying incidences of illnesses in the local population (Abt Associates, 2012). For situations where it is not practical to collect the data and run the model, EPA also has provided a reduced form benefit tool to assist with estimating the expected monetized health effects of air emissions (EPA, 2013). For the purpose of the present TBL of reuse treatment trains, the national averages for monetized values per ton of direct emissions of $PM_{2.5}$ and the $PM_{2.5}$ precursors (NO_x and SO_2) emissions from electricity generating units are selected from these reduced form tables (EPA, 2013). Additional details on the basis for these estimates are found in Fann et al. (2012). For the base case using the 3% discount rate, in 2012 dollars, over the facility operation period 2016 to 2045, these figures increase from $5475/ton to $7791/ton reduction in NO_x emissions; from $36,852/ton to $54,751/ton reduction in SO_x emissions; and finally, from $136,877/ton to $200,051/ton reduction in direct $PM_{2.5}$ emissions. These values are increased gradually over time to reflect changing conditions. Whereas the EPA (2013) report provides results for snapshots in time for the years 2016, 2020, 2025, and 2030, values for each year of operation are obtained by linear interpolation among analysis years and extrapolating for the years following 2030.

For sensitivity analysis, EPA also reports the values corresponding to a 7% discount rate. Both the 3% base case and the 7% sensitivity results are shown in Table 2.12, expressed in $2012/lb. For the 3% base case the reductions in NO_x emissions range from $2.74/lb in 2016 to $3.9/lb in 2045. The SO_2 emissions reductions are valued at $18.43/lb in 2016 and $27.38/lb by 2045. Direct emissions of $PM_{2.5}$ emissions range from $68.44/lb to $100.03/lb. At the 7% discount rate the values are smaller at $2.42/lb for reduction in NO_x emissions, $16.32 in reduced SO_2 emissions, and $63.17 in lower $PM_{2.5}$ emissions in year 2016. By 2042 the values rise to $3.58/lb for NO_x, $25.27/lb for SO_2, and $89.50/lb for $PM_{2.5}$ reductions achieved in 2045. It is important to note that for these estimates the discount rate is applied to lagged effects (e.g., premature mortality that is prevented in a future year as opposed to the same year as the reduction in emissions). This discounting of delayed benefits is not to be confused with discounting the stream of benefits from annual reductions in emissions over the analysis period to calculate NPV. The stream of annual benefits of reductions in NO_x, SO_2 and $PM_{2.5}$ emissions must still be discounted to calculate the NPV of the emissions over the life of the treatment facilities.

Table 2.12. Benefits of Reducing $PM_{2.5}$ and $PM_{2.5}$ Precursors from Electricity Generation

	$2012/lb	
	2016	2045
NO_x (3)%	$2.74	$3.9
NO_x (7%)	$2.42	$3.58
SO_2 (3%)	$18.43	$27.38
SO_2 (7%)	$16.32	$25.27
$PM_{2.5}$ (3%)	$68.44	$100.03
$PM_{2.5}$ (7%)	$63.17	$89.50

Transportation

The second source of air emissions is from mobile sources. The EPA has produced national averages for the value per ton of reductions in NO_x, SO_2 and direct emissions of $PM_{2.5}$ from on-road mobile sources applying the same methods as for electricity generation described in the preceding section (Abt Associates, 2012; EPA, 2013). However, as mentioned, emission factors are not available for SO_2 as they are expected to be quite small and insignificant relative to the emissions of the other criteria air pollutants. Therefore, SO_2 emissions associated with trucking chemicals to the treatment plant are not considered in the TBL. At the 3% discount rate and using 2012 dollars, the benefits per ton from reducing $PM_{2.5}$ emissions from on-road mobile sources increase from $379,044 in 2016 to $610,682 by 2045. The corresponding benefits per ton from reducing NO_x emissions rise from $7686 in 2016 to $11,792 in 2045. Table 2.13 reports the values in terms of $2012/lb and includes both the 3% base case and the corresponding values using a 7% discount rate for lagged effects. In terms of $/lb, the PM $_{2.5}$ values are about 50 times the magnitude of the NO_x values. Unfortunately, the EPA does not have national averages for the dollar value per ton of reducing NH_3 or CO emissions. Thus, these emissions are quantified in their physical units, and benefits are described in qualitative terms.

Table 2.13. Benefits of Reducing $PM_{2.5}$ and $PM_{2.5}$ Precursors from On-Road Mobile Sources

	$2012/lb	
	2016	2045
NO_x (3%)	$3.84	$5.90
NO_x (7%)	$3.47	$5.26
$PM_{2.5}$ (3%)	$189.52	$303.34
$PM_{2.5}$ (7%)	$168.46	$263.23

2.2.2.3 Downstream Effects

Two types of downstream effects are to be considered in a TBL accounting of water reuse treatment processes. First, after the reuse water is treated, TBL effects may result from residuals generated from the treatment process. This can include RO brine disposal to evaporative ponds or coagulated solids disposal to a landfill, for example. Second, there may be TBL effects on the end user—including costs incurred by end users as a result of water quality. Both types of downstream effects are included in the following discussion. For each type of downstream effect, residuals of the reuse treatment process are discussed first followed by treatment-related effects on the end user or as a result of the end use.

Downstream Effects—Financial Factors

Financial Costs of Managing Residuals from the Reuse Treatment Process

The first form of downstream financial cost effects is associated with disposing of residuals from the treatment process. Examples of residuals include brine residual from the RO treatment process, and other solid waste discharges from the treatment process. Such financial costs are estimated within CPES. For example, the capital and operating costs associated with implementing RO concentrate treatment through brine concentration followed by crystallization is calculated within CPES as part of the RO treatment train. Similarly, landfill disposal costs for sludge disposal of coagulated solids are estimated using trucking and landfill tipping costs.

Financial Costs to End User of Reuse Water Owing to Quality of Reuse Water

The second type of downstream financial impact relates to costs incurred by the end user of the recycled water and depends on the source water quality and the method of treatment. For example, differing levels of nutrient removal can influence the fertilizer management and mowing costs for landscape irrigation. The source water quality and method of treatment can also affect the overall salinity or TDS levels and the ion balance as measured by the SAR and EC relationship. If the recycled water has high TDS levels or high SAR/EC ratios, increased user costs may be incurred through adding soil amendments, such as gypsum or apply excess water to leach salts and prevent salt buildup in the soil profile. Conversely, for extremely low TDS RO water, pipe corrosion may be problematic, as well as irrigation of some clay or sodic soils or to wetlands. Consequently, minerals may need to be added to the water through chemical addition or water source blending before finished water discharge.

One study, by Komar et al. (2011) involved a comparative analysis of the costs and benefits of different treatment technologies for golf course irrigation water. They noted that depending on the method of treatment, recycled water could reduce fertilizer requirements while increasing mowing frequency. The required management of water storage, salinity control through leaching, and associated management costs also were considered. Technologies, such as RO and onsite desalination that lowers salinity levels, reduce the need for these mitigation measures, but they substantially increase the cost of treatment. The authors concluded that the extra cost of treatments that reduce salinity exceeds the cost of the mitigation measures.

Although use of RO water generally eliminates most salinity issues with recycled water irrigation, some potential management problems exists with use of extremely low TDS water. This is seen in agriculture when rainfall occurs or very low TDS surface waters are irrigated over sodic soils. As explained in Oster and Jayawardane (1998), the surface soil structure can be degraded and the hydraulic conductivity of surface soils can be reduced dramatically under rainfall or irrigation with extremely low TDS waters. This can result in soil crusting, increased runoff of applied water, and poor aeration in the root zone. An example of this situation has been documented in irrigated lands served by the Friant−Kern Canal in the San Joaquin Valley of California where snowmelt runoff ranging in EC of 0.05 to 0.1 dS/m (approximately 32 to 64 mg/L TDS) is used for irrigation water (Ayers and Westcot, 1989).

Considerations for salinity management with recycled water irrigation has been studied extensively and several best practices guides are available to help recycled water purveyors and water users to appropriately manage salinity at the irrigation end use (Tanji et al., 2008; Wu et al., 2009, Wu and Dodge, 2005). An online Salinity Management Guide (WateReuse Foundation, 2007) is also available to assist recycled water purveyors and users in managing recycled water salinity for irrigation uses.

The control of recycled water salinity at the water utility level can be managed either through treatment to remove dissolved constituents or through source control in the water received by the water reclamation facility. As explained by Welch (2006a and b), recycled water in San Diego County typically ranges from 750 mg/L to more than 1200 mg/L TDS. Approximately half of the TDS is contributed through source potable water supplies, and the other half is the result of concentration through consumptive uses, commercial and industrial discharges, in-home water softeners, and sewer inflow and infiltration. Consequently, several options may be available for controlling recycled water salinity at the source as an alternative to RO treatment.

In summary, any costs that are handled by the reuse treatment facility (e.g., brine disposal, sludge disposal) will be included as an output from CPES. Costs that are borne by the end user (e.g., fertilizer, managing salinity) as previously described, are in qualitative terms on the basis of the empirical literature. The implication from the literature on TDS is that the costs to the end user generally are less than the costs of advanced treatment to remove salinity so that RO treatment should not be decided solely on the basis of eliminating salinity, except in circumstances where the reuse opportunity is dependent on eliminating salinity. Even then, utilities should consider managing salinity at the source before going to RO. However, if RO should prove advantageous for other reasons, the ancillary benefit of eliminating salinity management considerations for the end user is a consequence. Another finding from the literature relates to the level of nutrients in treated reuse water. RO removes the nutrients, which can lead to higher costs to the end user for fertilizers and lower costs for mowing. Although these effects on the end user are not likely to be the deciding factor in selecting a treatment technology, they do suggest that it is important to educate the end user on the nutrient content of the recycled water. Applying reuse water at agronomic rates will help the end user to control costs and also to limit the nutrient content in runoff (Arrington and Melton, 2010; Arrington, 2012).

Downstream Effects—Environmental and Social Factors

Ecosystem Footprint from Residuals of the Reuse Treatment Process

As was mentioned under the Direct Effects discussion, the treatment technologies each have a relatively small facility footprint. However, the technologies do differ in terms of the ecological footprint because of residual disposal. Evaporation ponds for disposal of RO concentrate is the most significant example, as it can require hundreds of acres depending on the flow rate, even when volume reduction technologies are implemented upstream of the evaporation ponds. Such ponds completely eliminate the preexisting ecosystem resulting in long term, if not permanent losses in ecosystem services, which warrant inclusion in the TBL accounting. One approach toward tracking the effect from the residual disposal imprint is to record the number of acres lost by type of ecosystem. However, this approach does not take the quality or functionality of the ecosystem into account and is thus not a factually satisfying measure of the reduction in the value of the natural capital. An alternative approach involves weighting each acre by a measure of its quality or functionality so that degraded ecosystems are valued lower than pristine ecosystems. Expressed in another way, the value of the ecosystem is determined by the quality and quantity of the flow of ecosystem services to people, including current and future generations. Thus, the value of the natural capital will be larger, the greater will be its functionality, and the longer the ecosystem can sustain the flow of ecosystem services into the future. In this way, the importance of ecosystem support services becomes readily apparent. Once the underlying support structure of the ecosystem becomes compromised, the flow of ecosystem services diminishes as does the value of the natural capital.

The first scenario, nonpotable reuse for landscape irrigation, places the treatment facility inland, near an urbanized area within an arid region of the country. Such areas include the Great Basin, located primarily in Utah and Nevada; the Colorado Plateau of Utah, Colorado, Arizona, and New Mexico; the Mojave Desert of California, Nevada, Utah, and Arizona; the Sonoran Desert of California, Arizona, and northern Mexico; and the Chihuahuan Desert of New Mexico, Texas, Arizona, and northern Mexico. These areas include major population centers, such as Las Vegas, Phoenix, Tucson, Salt Lake City, and El Paso. Inland urbanized areas also exist in Australia, although they are less common, because a large portion of the population lives in coastal areas. Ecosystem services provided by drylands include pollination and seed dispersal, climate regulation through vegetation cover, outdoor recreation opportunities, open space for pleasing viewscapes, habitat for wildlife, and basic ecosystem support services, such as soil formation and nutrient cycling (Millennium Ecosystem Assessment, 2005). Assessing losses in ecosystem services can be a data and time intensive undertaking when it is necessary to identify and measure each type of ecosystem service separately. Instead, a second approach adopted for the present purpose relies on a single ecological currency to capture the overall functionality of the ecosystem. This approach toward assessing the change in value of natural capital—or the net environmental benefit resulting from the proposed action—has its basis in the Habitat Equivalency Analysis Method and is consistent with economic cost−benefit analysis.

As applied here, this practical approach relies on a desktop GIS exercise and rapid assessment protocols to capture three essential pieces of information: (1) the size of the ecosystem footprint in acres; (2) the type of ecosystem; and (3) the average quality or functionality of the ecosystem relative to a reference habitat (measured as a percentage of the fully functioning reference habitat). The rigor of the rapid assessment protocol can range from a detailed listing of site characteristics and a rating scale for each characteristic to relying on the best professional judgment of a knowledgeable expert, which is what is employed in this example. The expert identifies the affected habitat as being in excellent, good, fair, or poor condition for an ecosystem of that type and in that eco-region. For quantification purposes, these qualitative rankings of the affected habitat in relation to a fully functioning reference habitat are converted to a numerical score and ecological currency as follows:

- Excellent: 76 to 100% with a midpoint of 88% ecosystem service acre years (or SAYs)
- Good: 51 to 75% with a midpoint of 63% SAYs
- Fair: 26 to 50% with a midpoint of 38% SAYs
- Poor: 1 to 25% with a midpoint of 13% SAYs

Thus, an ecosystem that is rated as excellent relative to a fully functioning reference habitat provides 0.88 SAYs. To assess the total loss, the SAYs are aggregated across acres and years and discounted to give the NPV of the ecological service losses in units of the ecological currency, discounted service acre years or DSAYs. See Appendix C. Assessing Net Environmental Benefits Using an Ecological Currency for additional details.

Additional potential environmental concerns related to evaporative ponds include

- airborne emissions from the dry beds after evaporation
- salt spray
- runoff from the ponds
- effects on wildlife attracted to the ponds and exposed to excess salinity and other constituents
- groundwater contamination from pond water seepage

Measures to mitigate for some of these effects are considered standard practice. For example, the ponds are bermed to prevent runoff and ameliorate salt spray. Misters are located distant from the fence line to minimize over-spray falling on neighboring properties. Ponds are double-lined to prevent seepage to groundwater. Smaller ponds may use netting or noise-makers to prevent waterfowl from landing on the ponds. Nonetheless, the ponds as an attractive nuisance for wildlife can be an important consideration and may require more elaborate mitigation to avoid liability under the Migratory Bird Treaty Act (U.S. Congress, 1976).

Numerous alternatives to evaporation ponds for handling RO concentrate and include volume reduction technologies, mechanical evaporation through brine concentration and crystallization, deep well injection, ocean disposal, and sewer disposal, to name a few. However, these technologies are not land intensive and therefore their facility footprints are considered insignificant, which matches the approach taken for the reuse treatment processes as described. Some of these technologies can have other significant effects, such as significant energy consumption, which are captured in the Direct Effects and Upstream Effects categories.

Other Ecosystem Footprint–Chemical Solids Disposal

Various chemical solids can be produced through the treatment process, and if so, will require disposal. For example, chemical coagulation can produce a large volume of solid materials through chemical addition and complexing with the water and compounds they are targeted to remove. Chemical treatment solids can be recycled to the WWTP or handled at the water reuse plant, and then trucked to a landfill, land applied directly (rarely), or comingled with biological solids from the wastewater treatment process and land applied as fertilizer to farmlands. Thus, the manner of solids disposal can be a factor to consider in comparing the ecological footprint of treatment trains, especially in the case of landfill disposal. Conversely, to the extent that the solids are put to a beneficial reuse, (e.g., fertilizer) the need to track the ecosystem footprint is mitigated. As the effects depend on how the chemical solids are handled, these effects are treated qualitatively within this generalized TBL framework. It is also worth noting that the decision to employ a chemical coagulation process is not limited to one type of treatment or another but rather is a variation across treatment technologies.

Ecosystem Footprint from the End User

There are no anticipated effects on the ecosystem footprint by the end user of the reuse water independent of the reuse treatment train—except in the situation where the end user opts to treat the water as a way to manage excess salinity in the reuse water, for example. In this case the ecosystem footprints would be similar to the residuals case described in the preceding section.

Energy Use—Disposal of Residuals from the Reuse Treatment Process

Just as with direct effects, and upstream effects, the treatment technologies can differ in terms of their energy requirements for residual disposal. Energy utilization will be estimated within the CPES cost model and recorded in kWh, and the associated environmental externalities (GHG emissions, other air emissions) also will be treated in the same way as other direct effects.

Energy Use —GHG Emissions

The GHG associated with residuals disposal are estimated along with the other components of the reuse treatment process within CPES.

Energy Use—Other Air Emissions

The emissions of criteria air pollutants associated with residuals handling and energy utilization are estimated along with the other components of the reuse treatment process within CPES.

Transportation Externalities

Transporting residuals to the disposal site contributes to air pollution through fuel combustion. Those treatment processes that have relatively large quantities of residuals will have larger GHG emissions, as well as other air emissions.

Indirect GHG Emissions—Transporting Residuals

The method of estimating the GHG emissions resulting from transporting residuals is the same as for transporting chemicals as described under Upstream Effects.

Other Air Emissions—Transporting Residuals

The method of estimating the other air emissions resulting from transporting residuals is the same as for transporting chemicals as described under Upstream Effects.

Energy Use by the End User

The method of treating the reuse water is not expected to affect the energy use requirements of the end user unless the end user opts for additional treatment (e.g., to manage salinity). Other behavioral responses to differentials in the quality of reuse water, such as applying more or less fertilizer to the landscape or increasing or decreasing the amount of irrigation may or may not affect energy demands by the end user. Such potential effects are addressed qualitatively in this analysis.

Discharges or Runoff to Surface Waters from the Water Reuse Treatment Process

A reuse water source supplier may have more water than is needed by the end user. If the end user does not need all of the reuse water that can be supplied, the remainder will be treated according to wastewater discharge requirements and discharged to receiving waters. Because existing wastewater discharges are permitted, these regulations are assumed to protect the environment adequately regardless of flow, and therefore additional costs have not been added. Alternatively, if the reuse water provider accepts more source water than can be sold immediately, the provider, in some cases, recharges the excess reuse water and extracts it later for use in higher demand periods (e.g., reclaimed water aquifer storage recovery [ASR]). Thus, the direct discharge of neither unsold source nor treated reuse water to surface water is not considered further in this TBL.

Discharges or Runoff to Surface Waters of Reuse Water after it has been Delivered to the End User

The use of recycled water for irrigation end use is regulated and standard permit conditions specify the use of public exposure controls, such as irrigation buffers, application timing, public contact control and notification, and control of wind drift, runoff, and ponding. The level of public exposure controls that are required depend on the level of recycled water treatment. However, direct discharge to surface waters is not allowed from recycled water irrigation areas. Some incidental discharge may occur owing to accidental over-spray outside of the use area or tailwater releases from flood irrigation impoundments within agricultural reuse. However, very little recycled water that is used for landscape irrigation (e.g., golf courses, residences, and businesses) and for agricultural irrigation of crops, reaches surface waters. Consequently, the potential for recycled water to contribute to over-enrichment of surface waters is considered negligible. Outside of the irrigation season, surface runoff from rainfall may occur on sites irrigated with recycled water. When best practices for nutrient management are followed (e.g., adjusting fertilizer application for nutrients supplied through recycled water irrigation and normal soil and vegetation management practices), any nutrient releases to surface water should be no different than nutrients releases from sites irrigated with any other water source.

A study by Crook (2005) investigated the use of reclaimed water for a range in applications including parks, playgrounds, and schoolyards, more than 1600 in all across the United States. The key finding of this study was that irrigation of these areas by reclaimed water did not impose any measureable differences in known health risks to the children playing in the parks than the health risks associated with such facilities irrigated using potable water. It is worth noting that the reclaimed water was highly treated and disinfected.

In the 2010 report on Monitoring Strategies for Chemicals of Emerging Concern (CECs) in Recycled Water (Anderson et al., 2010), a Science Advisory Panel assembled by the California State Water Resources Control Board concluded that the standard permit conditions in place for landscape irrigation of Title 22 recycled water minimize unintentional public exposure to CECs. They also concluded that, whereas human exposure to CECs can occur through incidental and accidental consumption of recycled water from irrigation systems, it does not warrant a monitoring program for CECs to protect public health. Therefore, this potential source of TBL effects from different treatment technologies is not considered further.

Discharges to Groundwater of Residuals from the Water Reuse Treatment Process

With the exception of brine disposal by deep well injection, residuals from the water reuse treatment process are not discharged to groundwater. Even in the case of deep well injection, it is a misnomer to state that the brine is injected into groundwater available for potable use. Rather, it is injected into porous subsurface rock formations or aquifers with significantly high salinity, with the explicit requirement to avoid eventual contact with underground sources of drinking water. Thus, this disposal method is dependent on favorable hydrogeological conditions, such as is found in Florida.

In contrast to residuals, the reuse water itself is directly injected or percolated into groundwater to support potable or nonpotable reuse. The desired end use dictates the level of treatment as per the relevant state regulations or guidelines discussed in Section 1.3 Water Reuse Regulations. Thus, with the exception of potentially increasing the TDS of the groundwater, it is reasonable to assume that no unacceptable effects on groundwater are directly because of the water reuse treatment process.

Discharges to Groundwater after Reuse Water has been Delivered to the End User

Recycled water that is applied for irrigation above an aquifer used as a drinking water source can percolate down to the aquifer. This raises the question of the potential for the recycled water to contaminate the groundwater. One investigation focused on protection of the Edwards Aquifer Recharge Zone in Texas (Thomas et al., 2004) and addressed this issue through an extensively monitored recycled water irrigation pilot study. Type I recycled water (highest level of tertiary treatment classification in Texas) irrigated at two treatment levels (with and without an additional salt leaching fraction applied) and water from the Edwards Aquifer were applied to sprinkler irrigated turf test plots used to simulate landscape and golf course irrigation. Important results of this included (1) There was no difference in water quality of surface runoff resulting from rainfall events between recycled water and groundwater source treatments; (2) Because of the higher salinity of recycled water, the soil pore water percolating below the root zone had higher salinity levels (measured as EC) and higher sodium levels than in plots irrigated with lower salinity groundwater; (3) Aside from salinity and sodium differences, there was no difference in the quality of pore water percolating below the root zone soils between recycled water and groundwater source treatments; and (4) Because of the higher irrigation rates to manage a salt leaching fraction, rates of percolation back to groundwater were higher under the recycled water treatments, but the total quantity of recharge from recycled water use areas is small relative to recharge from the larger groundwater recharge zone. In summary, this study concluded that recycled water irrigation over the recharge zone would pose no statistically significant effect to the Edwards Aquifer water quality as compared to irrigation with potable Edwards Aquifer water.

Another study reports results from monitoring groundwater wells in areas using high-quality reclaimed water that conforms to Florida’s strict criteria for reclaimed water used for landscape irrigation (Arrington and Dent, 2008). The authors concluded that groundwater quality was maintained with the application of reuse water for 20 years to residential properties, parks, golf courses, and schools. Recipients of reuse water are required to follow stringent criteria for reuse application rates, and customers store the reuse water in ponds until it is used for irrigation. If reclaimed water seeps into the groundwater from the ponds, it does not lead to systemwide negative effect on groundwater quality for any of the monitored water quality parameters, including nitrates, TDS, arsenic, chloride, cadmium, lead, fecal coliform, and sulfates.

Depending on irrigation methods, there is a wide range of irrigation efficiencies and potential distribution of surface and subsurface return flows. A summary table of these factors based on guidance from the Washington State Department of Ecology (2005) for agricultural irrigation systems is provided in Table 2.14. For urban landscape irrigation (e.g., golf courses, residences, and businesses), application efficiencies should range between the values provided for sprinkler (solid set) and micro-irrigation with application efficiencies around 73 to 88%. With these systems, even under proper irrigation management at agronomic rates, between 3 and 15% of the applied irrigation water is expected to return to groundwater.

Table 2.14. Average Irrigation Application Efficiencies and Return Flows by Irrigation Method

Irrigation Method [1]	Application Efficiency, Ea (%)		Percent of Total Evaporated	Percent of Total Consumed	Return Flow	Return Flow to Surface Water	Return Flow to Groundwater
						% of AW with reclaimed water use restrictions [2]	% of AW with reclaimed water use restrictions [2]
	Range	Ave. Ea_{avg}	% Evap	% of AW	% of AW	(% of AW for typical agric. irrigation)	(% of AW for typical agric. irrigation)
Surface (furrow or border)	60–95	71	5	76	24	0 (12)	24 (12)
Surface (level basin)	80–95	85	5	90	10	0 (5)	10 (5)
Surface (wild flood)	35–60	50	5	55	45	0 (22.5)	50 (22.5)
Sprinkler (side-roll and hand-line)	60–85	75	11	85	15	0	15
Sprinkler (big gun)	55–75	65	10	75	25	0	25
Sprinkler (solid-set)	55–85	73	12	85	15	0	15
Center-Pivot	75–98	87	10	97	3	0	3
Lateral-Move	70–95	88	10	98	3	0	3
Micro-irrigation	70–95	88	5	93	7	0	7

Notes:

[1] This table summarizes by grouping several similar irrigation methods within like groups. See source table with reference and definitions for most factors.

[2] For typical unregulated agricultural applications without recycled water use, return flow distribution is assumed to be 50%/50% to surface and groundwater for surface irrigation methods and 0%/100% to surface and groundwater for sprinkler and micro irrigation methods. When recycled water is used and tailwater capture and recirculation is required by permit, the surface/flood irrigation return flow distribution is assumed to change to 0%/100% to surface and groundwater.

Ea = Irrigation application efficiency defined as the percentage of applied water that is effectively delivered into the crop root zone and results in satisfying crop consumptive use demands
AW = Applied Water

Salinity and nutrient management of groundwater basins is an important issue, especially within arid and semiarid regions where salinity tends to be higher and where groundwater is a more important source of potable water. In California, the State Water Resources Control Board adopted a new Recycled Water Policy in February 2009. Within the new policy is a requirement that Salt and Nutrient Management Plans be completed by recycled water providers and basin stakeholders to facilitate basinwide management of salts and nutrients from all sources. The purpose of these plans is to help optimize recycled water use while ensuring protection of groundwater supply and beneficial uses, agricultural beneficial uses, and human health. Proposed guidelines for preparing Salt and Nutrient Management Plans is now available for the San Diego Region (Welch, 2010) and for the Los Angeles Region (RWQCB, 2012).

The issue of recycled water irrigation return flows to groundwater and groundwater salinity management is most acute in extremely arid environments and in closed groundwater basins. Irrigation concentrates salts through the process of evaporation, which reduces the volume of water while leaving salts behind, resulting in higher concentration of salts in return flows to groundwater. Because of the evaporation-driven concentration of salts in response to irrigation and crop water use, any irrigation use of groundwater (recycled water or other water supplies) will tend to concentrate salts further within a closed groundwater basin. In these instances, a comprehensive assessment of the basin water and salt budget, additional salt source, and potential source control and treatment alternatives may be necessary to make informed decisions on the appropriate recycled water treatment approaches. From this discussion it must be concluded that the potential effects of reclaimed water ultimately discharged to groundwater is a factor to consider in the TBL cost−benefit analysis. The reuse treatment trains differ in terms of their salinity and nutrient content, which can have differential adverse effects on groundwater.

2.3 Summary

This section defines the key questions to address in order to identify the significant measurement endpoints in a cost−benefit approach toward TBL accounting as applied to a comparison of water reuse treatment options. It begins with the premise that a decision to reclaim water has been made but the treatment technology has not yet been selected. The purpose of the TBL accounting is to help guide that selection process. Therefore, only factors that may differ substantially in cost (financial, environmental, or social) across treatment trains are important to quantify, or when they cannot be quantified then described in qualitative terms. The next section applies this methodology to compare treatment trains. These results are then used to characterize the situations that may favor selection of one treatment train over another, as well as what data gaps a utility may need to fill before making that determination.

Chapter 3

Utility Survey

3.1 Utility Survey Approach

A significant part of the TBL analysis is estimating the financial costs, both capital and operating, of a reuse water treatment process. Capital costs and annual operation and maintenance (O&M) costs are dependent on many site-specific factors, such as the type of treatment processes provided, design and operational criteria for those treatment processes, raw water quality, treated water quality requirements, and local market conditions related to power, chemical and labor costs. The cost estimating tool used in this research (CPES) is designed to accommodate variations in these factors and has an extensive unit cost database to provide accurate cost estimates, but a utility survey was conducted with project participants to allow comparison of cost estimates to cost data from full-scale potable and nonpotable reuse plants. Cost estimates also will be compared to cost information collected from the literature, which was presented earlier in this report.

The utility survey included 188 questions related to the utility's operational water reuse plant. The survey was created in a web based survey tool (SurveyMonkey®; www.surveymonkey.com) to facilitate data collection and to create a user friendly interface. Website links were e-mailed to the utility partners for data entry. The utility survey questionnaire, which is included in Appendix D, was divided into the following categories:

- Utility information
- Treatment processes included in the wastewater treatment plant and the water reuse plant
- Water quality and flow data from the wastewater treatment plant and the water reuse plant
- Design and operating criteria for the treatment processes included in the water reuse plant
- Construction costs for all capital projects conducted at the water reuse plant
- Operational and maintenance costs for the water reuse plant
- End uses of the reclaimed water
- Regulatory requirements

The primary focus of the survey was to collect enough data from each water reuse plant to allow analysis and fair comparison of reported costs to those generated from the CPES cost estimating tool and costs collected from other water reuse plants. Much of the data collected provided specific information on plant design and operation that can significantly affect costs. For example, one reuse plant may operate an RO process at 75% recovery because of specific feed water quality conditions that lead to scale formation, whereas another plant may be able to operate at 85% recovery because of different water quality characteristics. This difference in design and operation can lead to significant differences in capital and operating costs that must be accounted for and explained.

The participating utilities included a good representation of potable and nonpotable reuse plants in the United States and Australia. The utilities surveyed are shown in Table 3.1 along with specific plant information relevant to this research. Data were collected from eight potable reuse plants and 13 nonpotable reuse plants; 4 of these plants operate as both potable and nonpotable reuse plants. Treatment processes at these plants included coagulation, flocculation, inclined plate sedimentation, lime softening, GMF, MF, UF, RO, BAC, GAC, powdered activated carbon (PAC), SAT, chlorine disinfection, UV disinfection, ozone disinfection and oxidation, and UVAOP.

3.2 Utility Survey Results

3.2.1 Operational Costs

Most plants surveyed had extensive data for annual operating and maintenance (O&M) costs for multiple years. The survey questions requested cost information per category (e.g., power, chemicals, labor) as well as raw usage data (e.g., pounds of chemical per year) to allow direct comparison among plants that are located in different geographies where unit costs may be significantly different. For plants where the reuse plant is colocated with the wastewater treatment plant (e.g., Gwinnett County), separation of cost data between the standard biological wastewater treatment process (primary treatment through secondary treatment) and the reuse treatment process (tertiary treatment) were not always available. Therefore, some reported costs include the entire treatment process (primary through tertiary treatment) and some only include the reuse treatment processes.

Data collected are summarized in Table 3.2. Although numerous site conditions influence annual operating and maintenance costs, the following general conclusions apply to the data presented:

- Annual O&M costs for nonpotable reuse plants ranged from $0.65/kgal to $1.55/kgal, with a median value of $1.11/kgal. However, for all but one plant, these costs included biological treatment costs, which are estimated at about $0.75/kgal[2]. Therefore, the annual O&M cost for just nonpotable reuse treatment is significantly lower than shown, and likely less than $0.5/kgal for the plants reporting costs. The 2012 National Research Council Report (NRC, 2012) reported nonpotable reuse costs ranging from $0.05/kgal to $1.18/kgal with an average of $0.69/kgal; however many of these plants included the costs for biological treatment and therefore do not reflect the cost for reuse treatment only.

- Annual O&M costs for the potable reuse plants ranged from $0.62/kgal to $2.43/kgal. Costs for the RO-based plants ranged from $1.14/kgal to $2.43/kgal. Costs for the GAC-based plants ranged from $0.62/kgal to $2.00/kgal; however, the GAC-based plant with an operational cost of $2.00/kgal included biological treatment. Assuming biological treatment costs are $0.75/kgal, the tertiary treatment annual O&M costs for the GAC-based plants shown likely range from $0.4/kgal to $1.25/kgal, which is lower than the RO-based plants. The National Research Council Report (NRC, 2012) reported potable reuse costs ranging from $0.31/kgal to $2.38/kgal with an average of $0.95/kgal;

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[2] Carlson and Walburger (2007) reported the energy use for conventional activated sludge wastewater treatment plants to range from 1400 kWh/MG to 2300 kWh/MG. Assuming an electrical energy cost of $0.08/kWh and that energy represents about 20% of the total O&M cost for a WWTP, the total O&M cost for a typical conventional activated sludge wastewater treatment plant is about $0.75/kgal. This can vary significantly from plant to plant and is dependent on numerous factors, such as treatment processes employed, solids handling approach, electricity cost, and other annual expenditures.

however, many of these plants included the costs for biological treatment and therefore do not reflect the cost for reuse treatment only.

- As expected, annual O&M costs for nonpotable treatment plants generally are lower than annual O&M costs for potable reuse plants.

O&M costs from each plant were analyzed further to identify trends among treatment plants. Figures 3.1 through 3.7 graphically show the cost distribution between categories for each plant. Figure 3.8 shows the costs for all plants on one figure. Inspection of these figures reveals that, in general, the most costly operational categories for water reuse plants are labor, power, and the chemicals used in water treatment. At some plants, other categories were also significant because of local conditions. For example, offsite disposal of residuals at the Leo J. Vander Lans Facility account for 10% of the total annual O&M costs, which is the most for this category for any of the facilities. Residuals disposal costs are high at this location, because RO concentrate and MF backwash waste must be discharged to the local sewer where use charges are much higher than discharge via ocean outfall such as for the Ground Water Replenishment System. Another example is the labor costs for the Denver Water Recycling Plant, which is reported to be 68% of the total annual O&M costs. Labor costs are high at this location, because the plant capacity is rather large to meet peak summer demands, but annual average flows are relatively small. In addition, economies of scale may result in higher labor costs at Denver Water. The Denver Water Recycling Plant is staffed to run only a tertiary treatment process, whereas operators at other plants also have responsibilities of numerous other wastewater treatment processes that drive down unit costs. Analysis of the three most costly categories common to each plant, labor, power, and chemicals, follows.

Table 3.1. Reuse System Information from Utility Survey

Utility Name	Plant Name	Location	Potable or Nonpotable Reuse?	Max Plant Capacity (mgd)	Annual Average WW Flow (mgd)	Annual Average Reuse Flow (mgd)	Reclaimed Water End Uses	Reuse Treatment Processes beyond Secondary Biological Treatment
Potable Water Reuse Plants								
Upper Occoquan Service Authority	Millard H. Robbins, Jr. Regional Water Reclamation Facility	Centreville, Virginia	Potable	54	31.5	31.5	Augmentation of surface water reservoir that is used for potable supply	Lime precipitation, two-stage recarbonation with settling, GMF, GAC, chlorination, dechlorination
Orange County Water District	The Groundwater Replenishment System	Fountain Valley, California	Potable	70	N/A	68	Groundwater replenishment of potable aquifer via surface spreading and for injection underground for a seawater intrusion barrier.	MF-RO-UVAOP
Gwinnett County	F. Wayne Hill Water Resources Center	Gwinnett County, Georgia	Potable	60	60	31.4	Water is discharged to Lake Lanier which is a major drinking water supply source for the City of Atlanta	Train #1: Solids Contact Clarifiers, GMF, ozone, BAC, ozone; Train #2: Floc/Sed, UF, ozone, BAC, ozone
Water Replenishment District of Southern C	Leo J. Vander Lans Water Treatment Facility	Long Beach, California	Potable	3	N/A	1.9	Seawater intrusion barrier in a potable aquifer	MF-RO-UV
El Paso Water Utilities	Fred Hervey Water Reclamation Facility	El Paso, Texas	Potable and Nonpotable	12	12	5.21	Potable aquifer recharge through direct injection; Nonpotable uses include industrial, irrigation, and construction uses	PACT Process (PAC added to activated sludge), lime settling, GMF, ozone, BAC, chlorination

Table 3.1. Reuse System Information from Utility Survey ***(continued)***

Utility Name	Plant Name	Location	Potable or Nonpotable Reuse?	Max Plant Capacity (mgd)	Annual Average WW Flow (mgd)	Annual Average Reuse Flow (mgd)	Reclaimed Water End Uses	Reuse Treatment Processes beyond Secondary Biological Treatment
Sanitation Districts of Los Angeles County	San Jose Creek Water Reclamation Plant	Whittier, CA	Potable and Nonpotable	100	76.1	33	Recharge of potable aquifer via spreading basins accounts. Nonpotable uses are for landscape irrigation.	GMF and chlorination (SAT provided downstream of treatment plant for potable groundwater recharge)
	Whittier Narrows Water Reclamation Plant	El Monte, CA	Potable and Nonpotable	15	8.7	7.5	Recharge of potable aquifer via spreading basins accounts. Nonpotable uses are for landscape irrigation.	GMF, chlorination, and UV (SAT provided downstream of treatment plant for potable groundwater recharge)
	Pomona Water Reclamation Plant	Pomona, CA	Potable and Nonpotable	15	8.65	7.4	Nonpotable uses are for landscape irrigation and industrial use; the potable aquifer is also recharged through percolation of some effluent through discharge to the unlined river.	GMF and chlorination (SAT provided downstream of treatment plant for potable groundwater recharge)
Nonpotable Water Reuse Plants								
Denver Water	Denver Water Recycling Plant	Denver, Colorado	Nonpotable	30	N/A	4.7	Cooling water, landscape irrigation, and zoo operations	BAF, floc/sed, GMF, chlorination
Sanitation Districts of Los Angeles County	Los Coyotes Water Reclamation Plant	Cerritos, CA	Nonpotable	37.5	28.7	3	Nonpotable uses include landscape irrigation and industrial use.	GMF and chlorination

Table 3.1. Reuse System Information from Utility Survey (continued)

Utility Name	Plant Name	Location	Potable or Nonpotable Reuse?	Max Plant Capacity (mgd)	Annual Average WW Flow (mgd)	Annual Average Reuse Flow (mgd)	Reclaimed Water End Uses	Reuse Treatment Processes beyond Secondary Biological Treatment
	Long Beach Water Reclamation Plant	Long Beach, CA	Nonpotable	25	18.25	6.3	Landscape irrigation.	GMF and chlorination
	Lancaster Water Reclamation Plant	Lancaster, CA	Nonpotable	17	14.1	4	Agricultural reuse, landscape irrigation.	Train #1: MBR/UV; Train #2: GMF and chlorination
	Palmdale Water Reclamation Plant	Palmdale, CA	Nonpotable	27	9.6	9.5	Agricultural reuse	Chlorination
	Saugus Water Reclamation Plant	Santa Clarita, CA	Nonpotable	6.5	5.8	0	Water is discharged to Santa Clara River, but can be used for reuse	GMF and chlorination
	Valencia Water Reclamation Plant	Santa Clarita, CA	Nonpotable	43.2	18.1	0.3		GMF and chlorination
City West Water	Altona Recycled Water Plant	Altona, Victoria (Australia)	Nonpotable	2.4	N/A		Landscape Irrigation (Train #1) and Industrial (Train #2)	Train #1(EC<600µs/cm): UF, RO, pH correction, chlorination; Train #2 (EC<100µs/cm): Train #1 water followed by 2nd pass RO, degasification, re-mineralization, chlorination
Hunter Water Corporation (Australia)	Branxton Reuse Plant	Branxton, New South Wales	Nonpotable	2.4	0.34	0.20	Golf course irrigation; agricultural irrigation	MBR with coagulant addition for P removal, chlorine disinfection

Notes: BAC = biologically active carbon ; BAF = biologically aerated filtration; GMF = Granular Media Filtration;; GAC = granular activated carbon; MBR = membrane bioreactor; MF = microfiltration; UF = ultrafiltration; RO = Reverse Osmosis; SAT = Soil Aquifer Treatment; UV = ultraviolet disinfection; UVAOP = ultraviolet advanced oxidation

Table 3.2 Reuse Plant O&M Costs

Plant Name	Average Annual Flow (mgd)[1]	Annual Costs per Category: Power	Chemicals	Residuals Offsite Disposal[3]	Materials, Maintenance and Repair	SCADA and Instruments	Vehicles	Lab and Monitoring	Labor	Misc.[2]	Total Annual Plant O&M Cost	Annual cost ($/kgal treated)	Annual cost ($/kgal capacity)	Notes
Potable Water Reuse Plants														
Millard H. Robbins, Jr. Regional WRF	31.5	$786,057	$1,346,900	$0	$1,239,878	$81,000	Included in other costs	$131,780	$3,242,031	$311,960	$7,139,606	$0.62	$0.36	GAC-based plant. All costs have been adjusted to reflect post-secondary treatment only.
The Groundwater Replenishment System	68	$7,775,000	$4,300,000	$0	$3,326,000	Included in other costs			$7,900,000	$5,000,000	$28,301,000	$1.14	$1.11	RO-based plant
F. Wayne Hill Water Resources Center	31.4	$2,424,930	$511,610	$2,540,090	$1,194,911	within eq. maint.	$54,340	within eq. maint.	$3,782,193	$558,204	$11,066,278	$0.97	$0.51	GAC-based plant. Costs are for the entire WWTP.
Leo J. Vander Lans WTF	1.9	$326,246	$93,000	$165,000	$300,000	$15,000	$0	$120,000	$680,000	$0	$1,699,246	$2.43	$1.55	RO-based plant
Fred Hervey WRF	5.427	$710,212	$1,138,118	$345,600	$348,000	within eq. maint.	$35,732	$14,050	$1,237,632	$139,000	$3,968,344	$2.00	$0.91	GAC-based plant. Costs are for the entire WWTP.
Potable and Nonpotable Water Reuse Plants														
San Jose Creek WRP	76.1	$4,527,177	$2,379,733	$0; All plants discharge residuals to Carson	$1,223,979	Included in other costs	$34,793	$2,182,857	$5,364,718	$2,312,868	$18,026,124	$0.65	$0.49	Costs are for the entire WWTP (primary through tertiary treatment);
Whittier Narrows WRP	8.7	$708,973	$214,917		$308,150		$5,747	$691,972	$1,250,124	$329,126	$3,509,009	$1.11	$0.64	

Table 3.2 Reuse Plant O&M Costs (continued)

Plant Name	Average Annual Flow (mgd)[1]	Annual Costs per Category: Power	Chemicals	Residuals Offsite Disposal[3]	Materials, Maintenance and Repair	SCADA and Instruments	Vehicles	Lab and Monitoring	Labor	Misc.[2]	Total Annual Plant O&M Cost	Annual cost ($/kgal treated)	Annual cost ($/kgal capacity)	Notes
Pomona WRP	8.65	$820,771	$246,476	Joint Plant	$177,833		$2,495	$719,572	$988,922	$315,634	$3,271,703	$1.04	$0.60	however, costs do not include costs for downstream SAT, which is provided to produce potable water.
Nonpotable Water Reuse Plants														
Denver Water Recycling Plant	4.7	$315,290	$323,576	$11,500	$109,000	$49,500	$4,852	$25,000	$1,804,000	$81,424	$2,642,718	$1.54	$0.24	
Los Coyotes WRP	28.7	$1,999,281	$823,631	$0; All plants discharge residuals to Carson Joint Plant	$718,467	Included in other costs	$20,672	$694,009	$3,111,124	$898,992	$8,266,177	$0.79	$0.60	Costs are for the entire WWTP (primary through tertiary treatment)
Long Beach WRP	18.25	$1,248,236	$664,646		$496,079		$8,340	$875,314	$1,631,481	$621,799	$5,545,895	$0.83	$0.61	
Lancaster WRP	14.1	$973,717	$784,197		$662,416		$6,560	$654,777	$1,340,585	$930,367	$5,352,619	$1.04	$0.86	
Palmdale WRP	9.6	$703,642	$272,058		$433,202		$23,081	$565,957	$1,221,119	$723,776	$3,942,834	$1.13	$0.40	
Saugus WRP	5.8	$522,791	$313,855		$225,110		$248	$565,681	$883,765	$367,898	$2,879,348	$1.36	$1.21	
Valencia WRP	18.1	$2,245,906	$1,711,233		$1,137,121		$10,699	$783,177	$2,953,218	$1,380,107	$10,221,461	$1.55	$0.65	
Altona Recycled Water Plant	N/A	No data provided owing to lack of representative data (plant recently commissioned)												
Branxton Reuse Plant	0.34	$130,785	$98,287	$55,242	$196,680	Included in other costs		$140,486	$290,914	$33,975	$946,369	$7.63	$1.08	

Notes:
1. Annual average flow shown is the total wastewater flow for those plants where wastewater and reuse facilities are co-located
2. Miscellaneous includes those costs not easily categorized, such as service contracts, consultant fees, office supplies. Also, the Groundwater Replenishment System budgets $5m/yr to replace consumables, such as membrane replacement and UV lamp replacement.
3. Residuals offsite disposal costs for the F. Wayne Hill plant include polymer costs for assistance in dewatering.
4. All costs shown are in U.S. dollars.
5. WRF = Water Reclamation Facility; WRP = Water Reclamation Plant; WTF = Water Treatment Facility

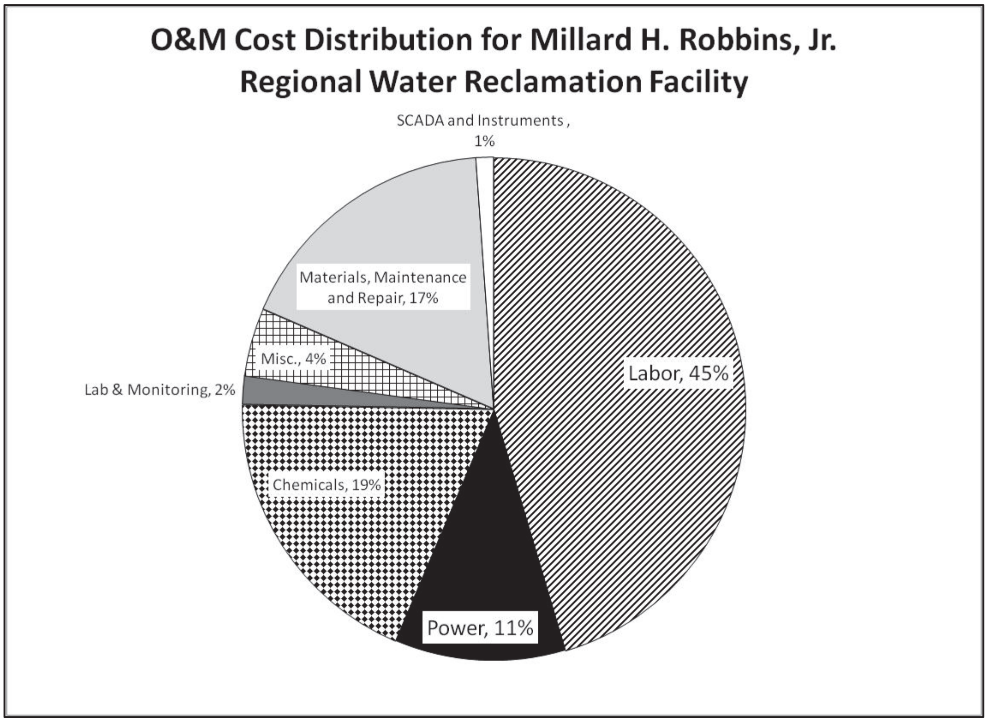

Figure 3.1. O&M cost distribution for Millard H. Robbins, Jr. Regional Water Reclamation Facility.

Note: Costs are for postsecondary treatment only.

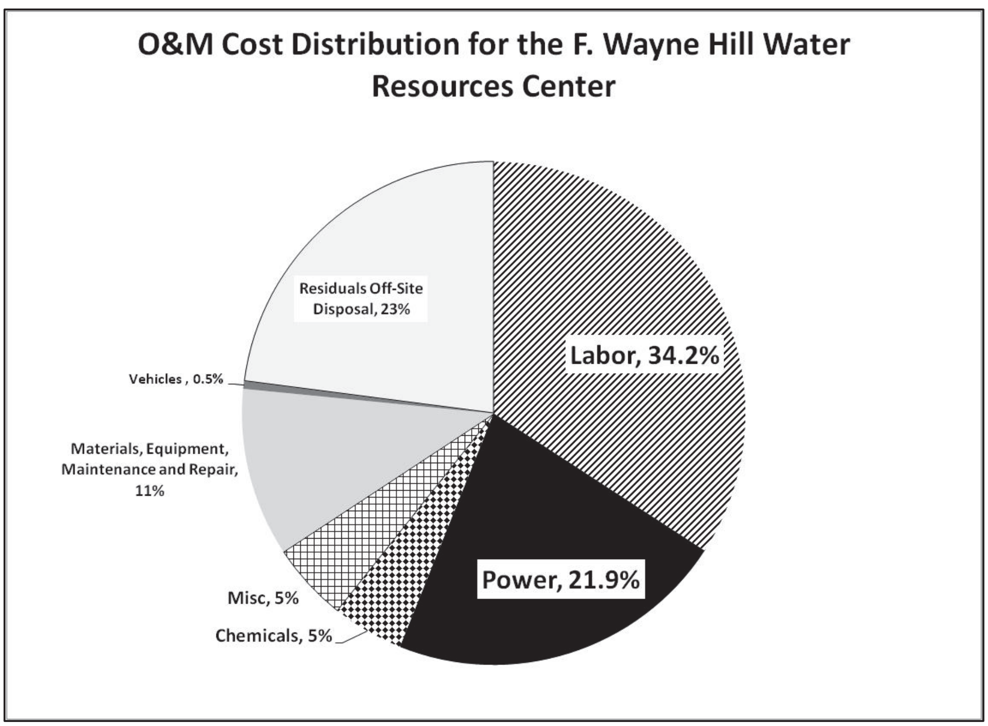

Figure 3.2. O&M cost distribution for F. Wayne Hill Water Resources Center

Note: Costs are for entire WWTP.

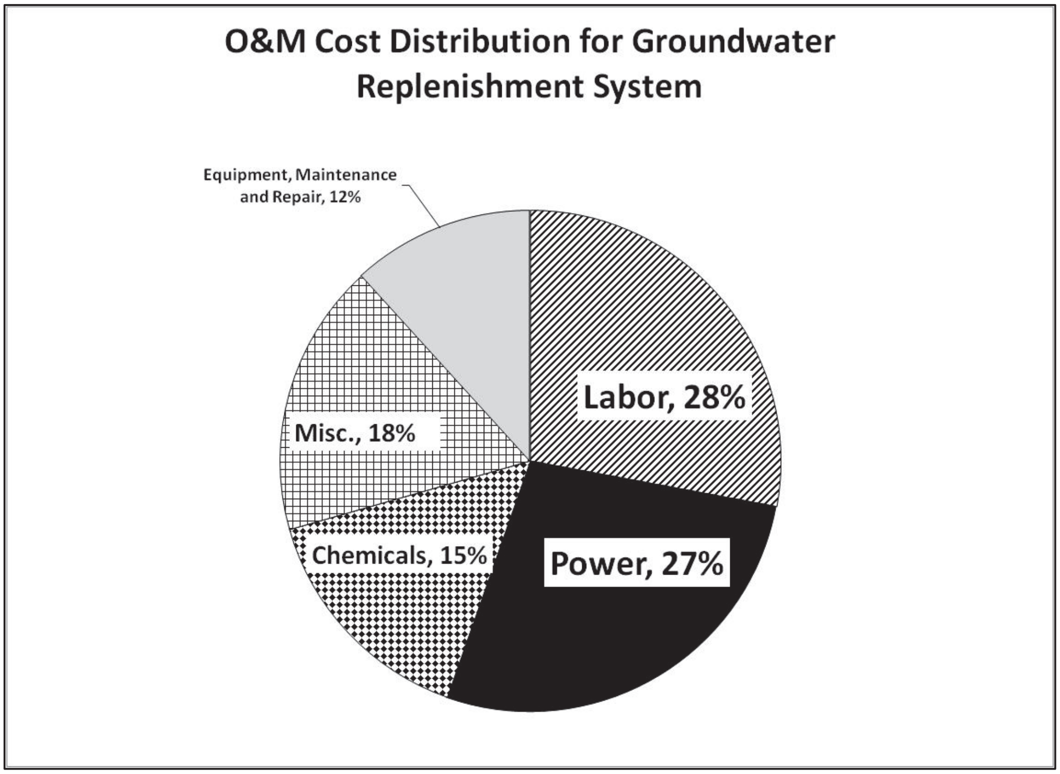

Figure 3.3. O&M cost distribution for groundwater replenishment system.

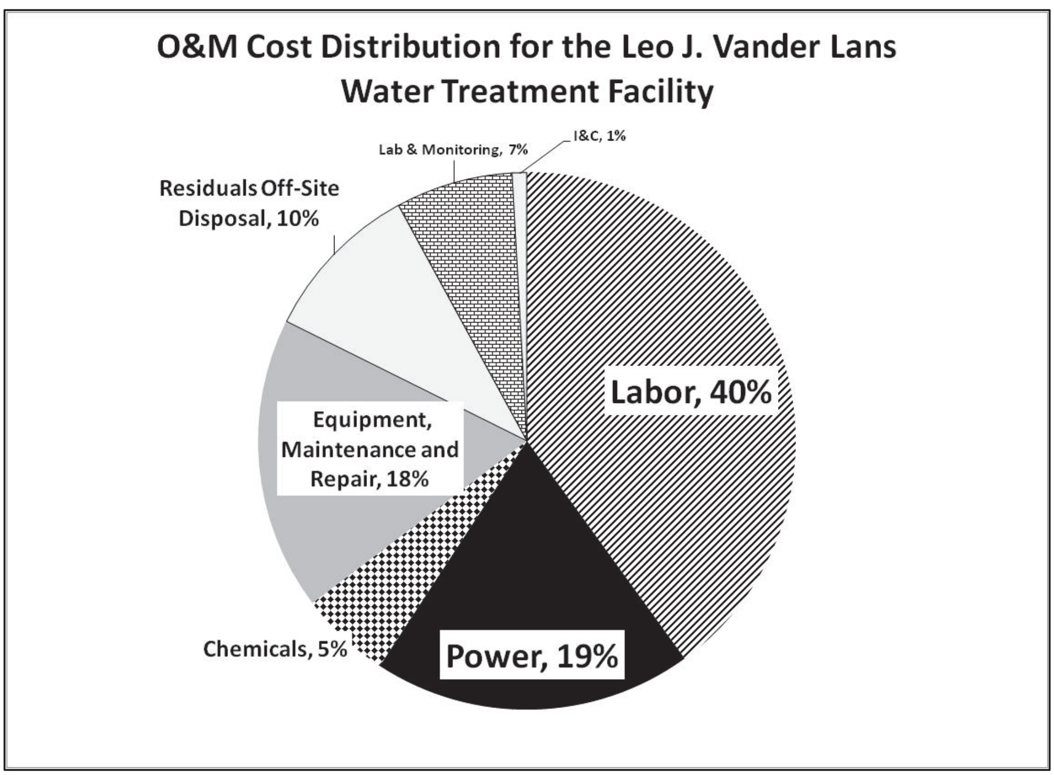

Figure 3.4. O&M cost distribution for the Leo J. Vander Lans Water Treatment Facility.

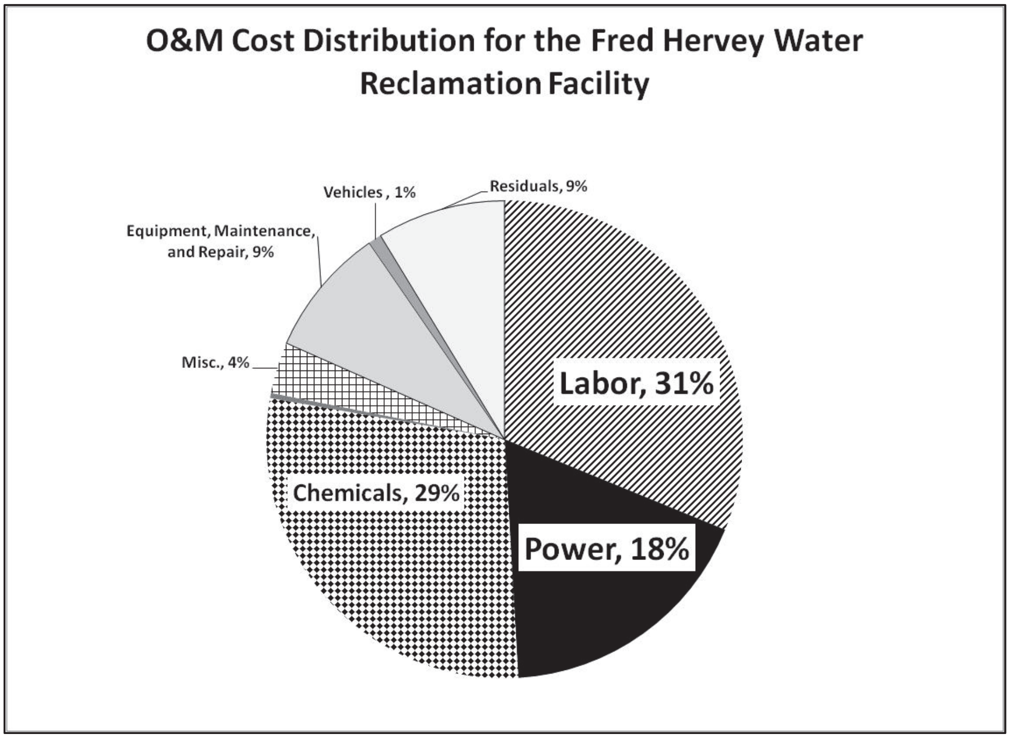

Figure 3.5. O&M cost distribution for the Fred Hervey Water Reclamation Facility

Note: Costs are for entire WWTP.

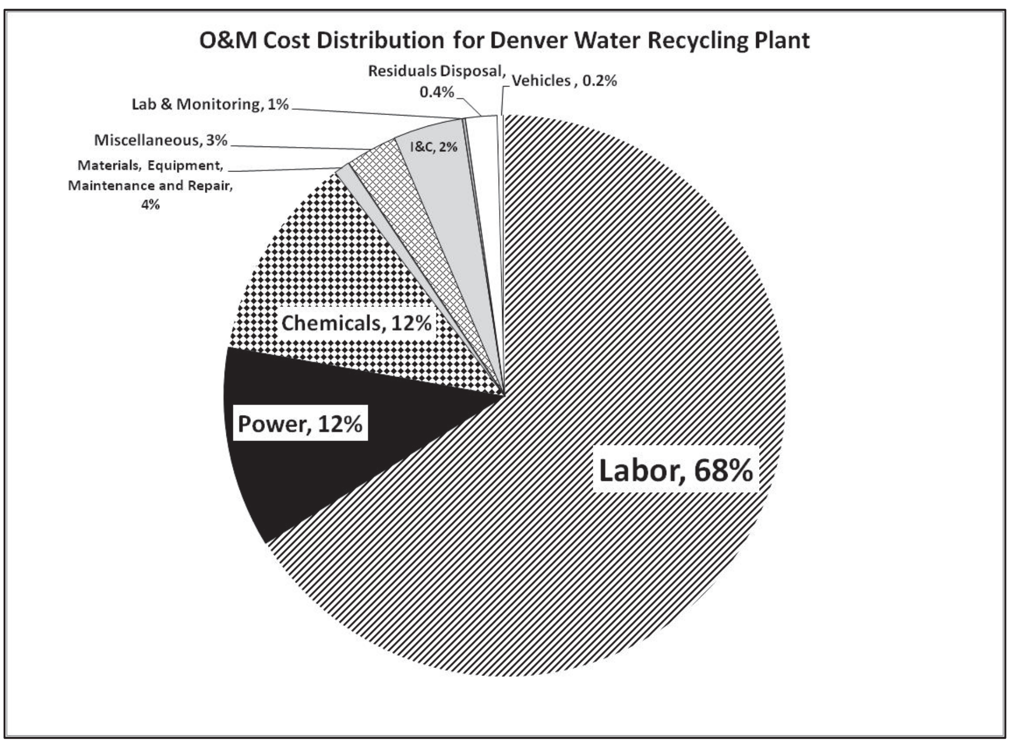

Figure 3.6. O&M cost distribution for Denver Water Recycling Plant.

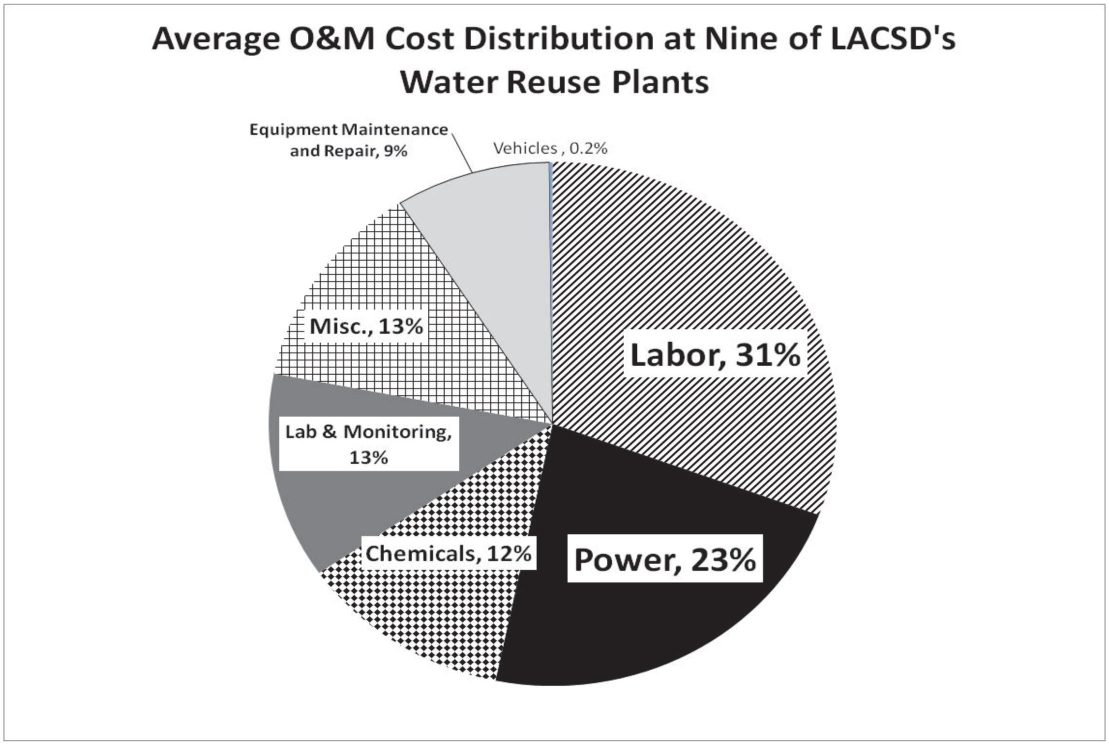

Figure 3.7. O&M cost distribution at nine of LACSD's water reuse plants.

Note: Costs are for entire WWTP.

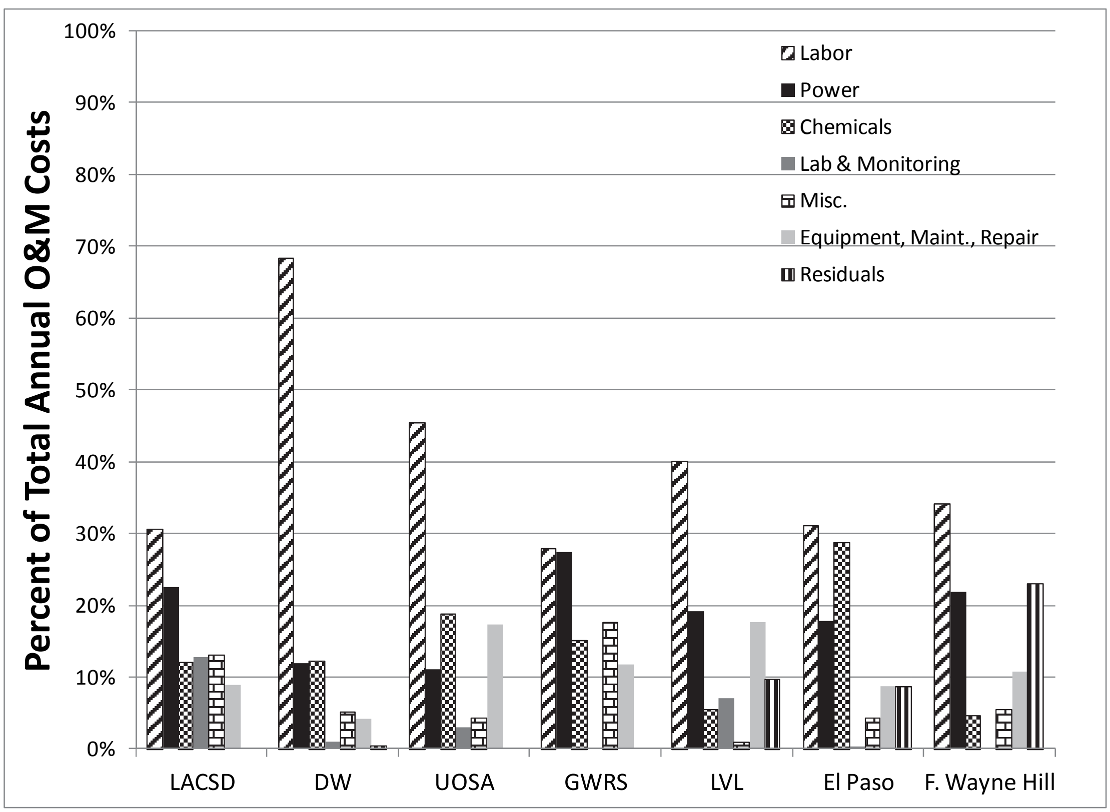

Figure 3.8. Comparison of O&M costs for all reclamation plants included in this survey.

3.2.1.1 Labor

Labor, which includes salary and fringe benefits for operation, maintenance, and administrative staff, represents the most costly expenditure at each of the plants studied and varied between 30 and 70% of the total annual costs. Labor costs are highly dependent on the local market conditions, plant age, plant size, and the degree of automation designed into the plant. As shown in Figure 3.9, larger plants can have significantly lower unit labor costs. For utilities surveyed in this study, the average unit labor cost for plants 15 mgd and larger was $0.07/gpd of treatment capacity versus $0.16/gpd of treatment capacity for plants less than 15 mgd. Plants using MF and RO membrane technology had higher unit costs ($0.11/gpd for a 70 mgd plant and $0.23/gpd for a 3 mgd plant), but because these data were only from two plants, it is not clear if these types of plants require more personnel to operate and maintain.

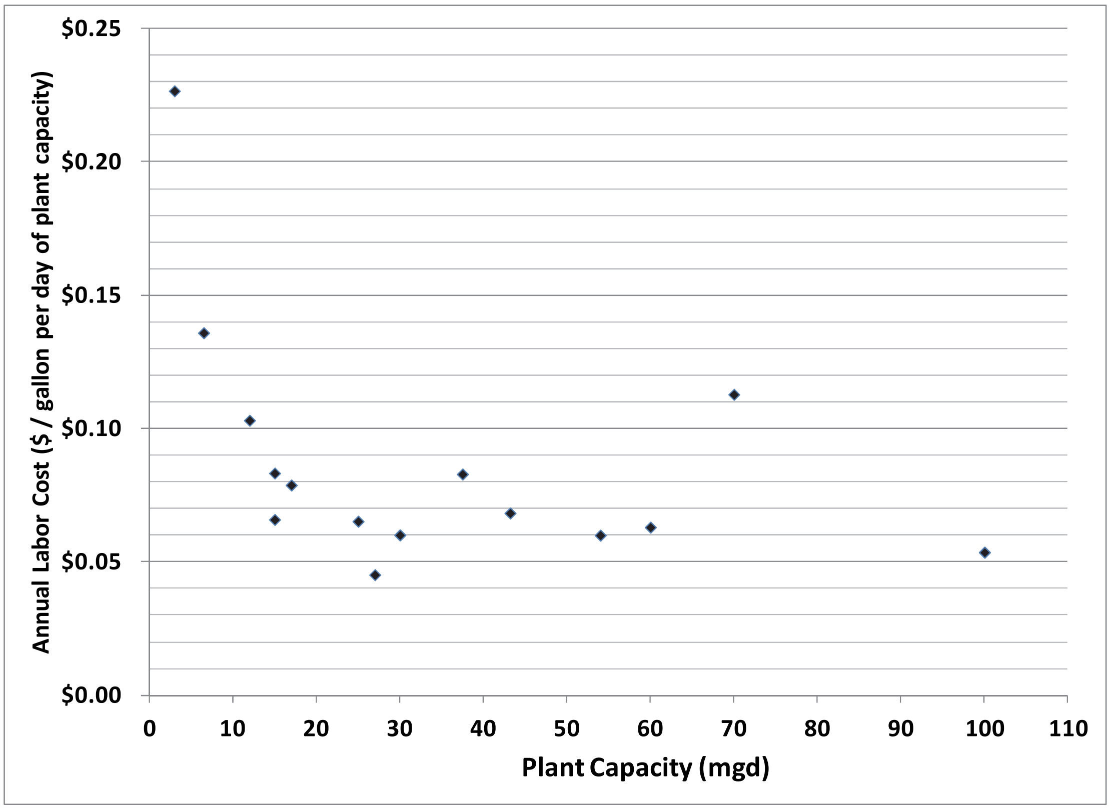

Figure 3.9. Unit labor costs per plant capacity.

3.2.1.2 Power

Detailed power data were collected from each plant to further analyze typical requirements for potable and nonpotable reuse plants. Power consumption data for each plant are shown in Table 3.3. For those plants where the biological wastewater treatment process was colocated with the reuse treatment process and separate power consumption data were unavailable, power consumption estimates for reuse treatment (tertiary treatment) were made by plant staff to allow for direct comparison to stand-alone reuse plants. For example, the Millard H. Robbins, Jr. Regional Water Reclamation Facility consumes approximately 3982 kWh/MG of electricity for its entire wastewater treatment process; on the basis of review of actual power meter readings at major motor control centers over a period of one year, it is estimated by plant staff that 29.5% of the total power use is for tertiary treatment (lime addition and residuals disposal, filtration, GAC adsorption, chlorine disinfection), resulting in approximately 1195 kWh/MG for tertiary potable reuse treatment. This allows for direct comparison to the potable reuse plants that are not colocated with a WWTP, such as the Groundwater Replenishment System, which consumes 4069 kWh/MG of electricity. Inspection of Table 3.3 reveals the following:

- Power consumption for potable reuse plants range from 1195 kWh/MG to 4069 kWh/MG.
- The RO-based plants use significantly more power than the GAC-based plants because of the mechanically intensive processes employed. The RO-based plants use more than 2.5 times as much electricity as the GAC-based plants (average of 3867 kWh/MG for RO-based versus 1400 kWh/MG for GAC-based).
- The energy consumption data collected for potable RO-based plants (3665 kWh/MG and 4069 kW/MG) correspond well with that reported by Cooley and Wilkinson (2012), where values ranging from 3680 kWh/MG to 3926 kWh/MG were reported for MF/RO/UVAOP treatment plants.
- Power consumption for the nonpotable reuse plants range from 593 kWh/MG to 2431 kWh/MG, with a median value of 898 kWh/MG. The Denver Water Recycling Plant at 2431 kWh/MG of power consumption is an outlier for nonpotable reuse plants, because its treatment process includes biological nitrification, which consumes significant power through near constant operation of aeration blowers.

3.2.1.3 Chemicals

Detailed chemical use data were collected from each plant to analyze typical requirements further for potable and nonpotable reuse plants. Annual chemical costs for various chemical categories are shown in Table 3.4. Note that the chemical costs for those plants where the biological wastewater treatment process was colocated with the reuse treatment process include chemicals used in the biological treatment process, although those quantities are typically small. Inspection of Table 3.4 reveals the following:

- Annual chemical costs for potable reuse plants range from $45/MG to $598/MG. No general trends are apparent, although the highest unit cost is at the Fred Hervey Facility because of the significant amount of lime, CO_2, and PAC added.
- Annual chemical costs for nonpotable reuse plants generally are lower than potable reuse plants with a range of $68/MG to $259/MG. The most significant cost is the disinfectant (typically chlorine) followed by the coagulant. Note that dechlorination costs are included, which would not usually be required for stand-alone reuse plants that do not discharge to the environment.

Table 3.3. Power Consumption at Water Reuse Plants [1]

Plant Name	Average Annual Flow (mgd)[2]	Annual Electricity Used (kwh/yr)	Electricity per unit of water treated (kwh/MG)	Electricity for Tertiary Treatment[3] (kwh/yr)	Electricity per unit of water treated for tertiary treatment (kwh/MG)	Notes
Potable Water Reuse Plants						
Millard H. Robbins, Jr. Regional Water Reclamation Facility	31.5	45,787,500	3,982	13,736,250	1,195	GAC-based
The Groundwater Replenishment System	68.0	101,000,000	4,069	101,000,000	4,069	RO-based
F. Wayne Hill Water Resources Center	31.4	56,324,126	4,914	N/A	N/A	GAC-based
Leo J. Vander Lans Water Treatment Facility	1.9	2,567,900	3,665	2,567,900	3,665	RO-based
Fred Hervey Water Reclamation Facility	5.4	9,083,963	4,586	3,179,387	1,605	GAC-based
Potable and Nonpotable Water Reuse Plants						
San Jose Creek Water Reclamation Plant	76.1	41,156,152	1,482	16,462,461	593	
Whittier Narrows Water Reclamation Plant	8.7	6,445,209	2,030	3,867,125	1,218	
Pomona Water Reclamation Plant	8.7	7,461,555	2,363	2,238,466	709	
Nonpotable Water Reuse Plants						
Denver Water Recycling Plant	4.7	5,970,785	3,480	4,170,785	2,431	See note 4
Los Coyotes Water Reclamation Plant	28.7	18,175,282	1735	6,361,349	607	
Long Beach Water Reclamation Plant	18.3	11,347,597	1704	3,971,659	596	
Lancaster Water Reclamation Plant	14.1	8,851,970	1720	3,098,189	602	
Palmdale Water Reclamation Plant	9.6	6,396,748	1826	3,518,212	1,004	
Saugus Water Reclamation Plant	5.8	4,752,642	2245	1,901,057	898	
Valencia Water Reclamation Plant	18.1	20,417,327	3090	11,229,530	1,700	
Altona Recycled Water Plant	N/A			N/A		
Branxton Reuse Plant	0.34	874,835	7049	N/A	N/A	

Notes:
[1] Natural gas is used at some facilities (for heating) but in general is a small percentage of the electricity costs
[2] Annual average flow shown is the total wastewater flow for those plants where wastewater and reuse facilities are co-located
[3] Electricity for tertiary treatment is estimated by plant staff and is for treatment and pumping systems downstream of secondary wastewater treatment
[4] Abnormally high power use at the Denver Water Recycling Plant because of the nitrification process used that requires constant operation of air blowers.

Table 3.4. Chemical Costs for Water Reuse Plants

Plant Name	Average Annual Flow (mgd)	Coagulant Cost ($/yr)	Polymer Cost ($/yr)	Disinfectant Cost ($/yr)	Dechlorination Cost ($/yr)	pH and Alkalinity Adjustment Cost ($/yr)	Miscellaneous Chemical Cost[1] ($/yr)	Annual Total Chemical Costs ($/yr)	Annual Total Chemical Costs ($/MG)
Potable Water Reuse Plants									
Millard H. Robbins, Jr. Regional Water Reclamation Facility	31.5	$75,944	$0	$81,696	$57,261	$1,264,460	$0	$1,479,361	$129
Groundwater Replenishment System	68			No breakdown provided				$4,300,000	$173
F. Wayne Hill Water Resources Center	31.4	$393,828	$0	$0	$0	$0	$117,782	$511,610	$45
Leo J. Vander Lans WTF	1.9			No breakdown provided				$93,000	$133
Fred Hervey WRP	5.2	$0	$3,275	$19,865	$0	$891,938	$170,590	$1,138,118	$598
Potable and Nonpotable Water Reuse Plants									
San Jose Creek WRP	76.1	$582,954	$636,196	$609,227	$462,249	$0	$0	$2,379,733	$86
Whittier Narrows WRP	8.7	$0	$23,384	$115,861	$68,608	$0	$0	$214,917	$68
Pomona WRP	8.65	$2,527	$17,581	$178,642	$32,764	$0	$0	$246,476	$78
Nonpotable Water Reuse Plants									
Denver Water Recycling Plant	4.7	$120,000	$52,492	$56,287	$2424	$92,373	$0	$323,576	$189
Los Coyotes WRP	28.7	$220,808	$233,927	$216,507	$127,820	$0	$0	$823,631	$79
Long Beach WRP	18.25	$1,046	$107,553	$366,840	$164,898	$0	$0	$664,646	$100
Lancaster WRP	14.1	$31,589	$0	$334,327	$384,864	$0	$0	$784,197	$152
Palmdale WRP	9.6	$92,254	$0	$176,885	$0	$0	$0	$272,058	$78
Saugus WRP	5.8	$787	$160,229	$99,993	$66,165	$0	$0	$313,855	$148
Valencia WRP	18.1	$420,135	$798,444	$323,691	$112,763	$0	$0	$1,711,233	$259

Notes:
[1] Miscellaneous chemicals include liquid oxygen, hydrogen peroxide, PAC, GAC
[2] Individual costs may not add up exactly to total costs in some cases because of rounding and some unaccounted for costs.

3.2.1.4 Other Costs

Unfortunately, the utilities surveyed do not equally account for all other costs realized at their plants. For example, some account for major equipment replacement as a "miscellaneous expense" whereas others include it in the "materials, maintenance, and repair" category. In addition, some account for categories such as "SCADA" and "lab" separately, whereas others include those costs in the "miscellaneous" or "material" categories. Consequently, because direct comparison among plants for other costs was not possible, additional cost data were collected from the two plants, UOSA's Millard H. Robbins, Jr. Regional Water Reclamation Facility and GWRS, to assist in determining appropriate cost estimates for these categories. Maintenance and repair costs for each plant were collected and compared to the plant's total construction cost. As shown in Table 3.5, the annual expenditure on maintenance and repair at both plants is about 1% of the plant's total construction cost. These costs specifically do not include major equipment replacement costs, such as membranes or GAC replacement, which are accounted for separately.

Table 3.5. Annual Material, Maintenance, and Repair Costs for Two Reuse Plants

Treatment Plant	Annual Cost for Material, Maintenance, and Repair	Percent of Treatment Plant's Total Construction Cost
Millard H. Robbins, Jr. Regional Water Reclamation Facility	$1,239,878	0.99%
The Groundwater Replenishment System	$3,326,000	1.14%

The remaining costs (instruments, SCADA, vehicles, lab, miscellaneous) reported to varying degrees by the participating utilities also were analyzed to assist in cost estimating for this research. These costs were relatively small and ranged from 0.2% to 0.4% of total construction costs.

Application of Operating Data from Utility Survey

The operating data collected from the utility survey were used in this research to calibrate the estimated annual operating costs for the scenarios analyzed and to assist in the determination of cost quantities for categories that are not easily estimated, such as annual maintenance and repair costs. On the basis of the survey data as presented, the following information describes how each category of annual costs was estimated for the scenarios analyzed:

- **Labor Costs:** Labor costs for plants less than 15 mgd will be based on $0.16/gpd of treatment capacity. Labor costs for plants more than 15 mgd will be based on $0.07/gpd of treatment capacity.
- **Power, Chemical, and Residuals Costs:** During development of the cost estimates prepared in this research, detailed calculations were made to determine power consumption, chemical quantities used, and residuals generated for each scenario analyzed at all flow rates (see Chapter 4). These calculations will therefore be used, because they represent the most accurate estimate of plant costs. However, the unit costs used in association with the calculations (e.g., $/gal for sodium hypochlorite) were based on actual unit costs reported by participating utilities. In addition, comparison of the calculated consumption quantities (e.g., annual power consumption) will be compared to actual data reported by participating utilities.

- **Equipment Replacement Costs:** These costs will be calculated using replacement frequency data reported by the participating utilities for major equipment requiring frequent replacement, such as MF membranes, RO membranes, UV equipment, and GAC.
- **Maintenance and Repair Costs:** An annual cost of 1% of the treatment plant's total construction cost will be used to account for maintenance and repair of buildings, site infrastructure, pipe, valves, instruments, electrical gear, and equipment not requiring regular replacement (i.e., replacement costs for equipment with an expected life of less than 10 years is accounted for separately).
- **Other Costs:** An annual cost of 0.3% of the treatment plant's total construction cost will be used to account for instruments, SCADA, vehicles, laboratory, and miscellaneous costs.

3.2.2 Construction Costs

Collection of construction cost data from the participating utilities proved exceptionally difficult and numerous problems were encountered, including incomplete cost information for entire project scope, inadequate description and understanding of project scope, combination of other project elements not related to treatment improvements without detailed cost breakdown, and incomplete and inaccurate construction cost data. Consequently, construction cost data for the plants included in the utility survey were not collected.

Construction cost estimates and O&M cost estimates for the scenarios described earlier are presented in Chapter 4, Triple Bottom Line Costs. Those estimated costs are compared to the actual plant costs provided by the utilities included in the survey as discussed.

Chapter 4

Triple Bottom Line Costs

4.1 Triple Bottom Line Design Criteria

Establishing detailed design criteria for each unit process included in a treatment train is critical for the development of accurate cost estimates. These design criteria, such as the filter loading rate for granular media filters (GMF) or the fluxes for membranes, define the quantity of material required for construction (e.g., media for GMF and membrane area for membranes) which ultimately controls the cost of a particular treatment train. Design criteria are based on professional experience and data collected during the utility survey of operating reuse plants (Chapter 3, Utility Survey). Tables 4.1 and 4.2 present the capital cost design criteria for scenarios 1A and 2A and 1B, 1C, and 2B, respectively. Detailed process flow diagrams (PFDs) and mass balances for each of the scenarios can be found in Appendix A. The nonpotable reuse Scenario 1C and the potable reuse Scenario 2B each apply the use of RO, which produces a concentrated discharge stream that must be treated or disposed of in a proper manner. Because multiple methods of concentrate disposal vary considerably in their TBL effects, depending on such factors as proximity to the coastline and availability and cost of land disposal sites, each of these scenarios includes three alternatives to concentrate management; ocean or sewer disposal, evaporation ponds, and mechanical evaporation. In addition, a hybrid alternative using partial brine concentration with evaporation ponds is discussed at the end of the chapter. The number of units in each treatment process (filters, UV trains, membrane trains, RO trains, etc.) listed in the tables were calculated using the CPES cost model (Chapter 2, Triple Bottom Line Methodology) and are based on the design criteria shown in Tables 4.1 and 4.2.

Annual operating and maintenance (O&M) costs were generated using the CPES life-cycle tools. The life-cycle tool uses outputs from the CPES capital costs modules to determine the plants' overall power and chemical usage, as well as residuals generated that require disposal. The costs assumptions used in the life-cycle tool are presented in Table 4.3. Again, the costs are based on professional experience and data collected during the utility survey.

Environmental costs of plant operation are calculated by applying a cost per pound of emissions following the methods described in Chapter 2. With the exception of the GHG emissions, these factors depend on the source and type of emission (e.g., trucking or energy utilization as shown in Table 4.4). Carbon dioxide equivalents carry the same cost regardless of the source or location of the emission, as the effects from GHGs are global rather than local. However, other emissions, such as NO_x, and $PM_{2.5}$, carry a higher per unit value when the source is from trucks that use diesel fuel rather than from electricity generation. A higher environmental cost is based on a greater negative effect on human health. The human health effects are estimated using BenMap, which relates changes in ambient air quality to changes in occurrences of respiratory illnesses, cardiovascular health issues, hospital admissions, emergency room visits, mortality, and other adverse effects based on epidemiological studies for the exposed population. The dollar value of the health effects also is estimated within BenMap based on the empirical literature on the cost of illnesses, lost wages, and, in the case of mortality, the value of a statistical life.

Table 4.1. Capital Cost Design Criteria for Scenarios 1A and 2A

Item	Value
Raw Water Equalization Tank HRT	15 min
Influent Pump Station	Vertical turbine pumps at 20 ft TDH
Rapid Mix Type	Inline mechanical mixer
Rapid Mix Velocity Gradient	1000 s^{-1}
Chemicals	
Chemical Storage	30 days at maximum flow and average dose conditions
Ferric Chloride Coagulant Dose	5 mg/L for Scenario 1A; 30 mg/L for Scenario 2A
Polymer Dose	0.1 mg/L
Chlorine Dose	5 mg/L
Ozone Dose (Scenario 2A only)	6 mg/L
Flocculation/Sedimentation (Scenario 2A Only)	
Flocculation Time	20 min
Flocculation Stages	3
Flocculation Velocity Gradient Per Stage	50 / 25 / 10 s^{-1}
Sedimentation Type	Inclined plate
Hydraulic Loading Rate (projected plate area)	0.32 gpm/sf
Number of floc / sed trains	1 for 5 mgd flow; 2 for 20 mgd flow; 4 for 70 mgd flow
Solids Withdrawal Pumps	3 @ 50% per train
Tertiary Filters (Scenario 1A Only)	
Filter Media	6 ft of 1.4 mm anthracite
Filtration Hydraulic Loading Rate	9 gpm/sf
Number of Filters	N+1 Configuration; Three 200 sf filters for 5 mgd case; Four 530 sf filters for 20 mgd case; Eight 795 sf filters for 70 mgd case
Filter Backwash Frequency	Once every 24 hours
Filter Backwash Waste Amount	3%of feed flow
Filter Backwash Tank Volume	Two filter backwash volumes
Contactors (Scenario 2A Only)	
Ozone Contactors	1 for 5 mgd flow; 2 for 20 mgd flow; 4 for 70 mgd flow
Ozone Contactor Detention Time	8 min (20-ft side water depth with 2 over/under cells)
Ozone Generators	2 @ 100% capacity for 5 mgd flow; 3 @ 50% capacity for both the 20 mgd and 70 mgd cases
BAC Filters (Scenario 2A Only)	
BAC Filter Media	6 ft of 1.4-mm GAC over 1 foot of 0.7-mm sand
BAC Filtration Hydraulic Loading Rate	9 gpm/sf

Table 4.1. Capital Cost Design Criteria for Scenarios 1A and 2A (continued)

Item	Value
Number of BAC Filters	N+1 Configuration; 3 filters at 205 sf each for 5 mgd case; 4 filters at 550 sf each for 20 mgd case; 8 filters at 820 sf each for 70 mgd case
BAC Filter Backwash Frequency	Once every 48 hours
Filter Backwash Tank Volume	Two filter backwash volumes
GAC Filters (Scenario 2A Only)	
GAC Influent Pump Station	Vertical Turbine Pumps at 20 ft TDH
GAC Filter Loading Rate	6 gpm/sf
GAC Empty Bed Contact Time	15 min
GAC Media Depth	12 ft
Number of GAC Adsorbers	N+1 configuration; 3 filters at 310 sf each for 5 mgd case; 4 filters at 820 sf each for 20 mgd case; 12 filters at 780 sf each for 70 mgd case
GAC Regeneration Frequency	Two scenarios analyzed: Once every 2 years and once every 8 years
GAC Regeneration	Offsite
Disinfection	
UV Disinfection Vessel (Scenario 2A Only)	Closed vessel
UV Disinfection Dose (Scenario 2A Only)	40 mJ/cm^2
Chlorine contact time,T10 (Scenario 1A Only)	90 min
Short Circuiting Factor (Scenario 1A Only)	0.7
Residuals Handling	
Number of Gravity Thickeners	1 at 25 ft diameter for 5 mgd flow; 2 at 40-ft diameter for 20 mgd flow; 2 at 70 ft diameter for 70 mgd flow
Gravity Thickener Hydraulic Loading Rate	200 gpd/sf
Gravity Thickener Solids Loading Rate	10 lb/d/sf
Number of Centrifuges	2 at 100% capacity
Dewatered solids concentration	20%
Solids Disposal	Offsite landfill
Misc.	
Enclosed Buildings	Rapid Mix; Electrical Rooms; Mechanical Rooms (e.g., blowers, pumps); Administrative; Chemicals, UV
Administrative Building Size	2500 sf for 5 mgd case; 5000 sf for 20 mgd case; 7500 sf for 70 mgd case

Table 4.2. Capital Cost Design Criteria for Scenarios 1B, 1C, and 2B (MF- or MF/RO-Based Approach)

Item	Value
Raw Water Equalization Tank HRT	15 min
MF Feed Pump Station	Submersible
Chemicals	
Chemical Storage	30 days at max flow and average dose conditions
Monochloramine Dose for Membrane Fouling Control	4 mg/L
Antiscalant Dose (Scenarios 1C and 2B)	3.5 mg/L
Sulfuric Acid Dose (Scenarios 1C and 2B)	25 mg/L
Finished Water Chlorine Dose for Disinfection (Scenarios 1B and 1C)	5 mg/L
Chlorine contact time(Scenarios 1B and 1C)	15 min
Average Finished Water Lime Dose (Scenarios 1C and 2B)	46 mg/L
Average Finished Water CO_2 Dose (Scenarios 1C and 2B)	10 mg/L
Microfiltration	
MF Strainers	Self-backwashing 300 µm for pressurized and 500 µm for immersed
Pressure MF Design Flux (for 5-mgd and 20-mgd plant sizes)	35 gfd (59 lmh)
Pressure MF Average TMP	16 psi (110 kPa)
Immersed MF Design Flux (for 70-mgd plant size)	20 gfd (42 lmh)
Immersed MF Average TMP	6 psi
MF Trains	N+1 Configuration; 4 trains at 5 mgd; 11 trains at 20 mgd; 13 at 70 mgd
MF Backwash Frequency	Once every 30 min
MF Maintenance Clean Frequency	Once every 3 days (sodium hypochlorite)
MF CIP Frequency	Once every 4 weeks
MF Cleaning Chemicals	Sodium hypochlorite; Sulfuric Acid with Citric Acid
MF Replacement Frequency	7 years
MF Recovery	95%
MF Break Tank Hydraulic Residence Time	15 min

Table 4.2. Capital Cost Design Criteria for Scenarios 1B, 1C, and 2B (MF- or MF/RO-Based Approach) (continued)

Item	Value
Reverse Osmosis (Scenarios 1C and 2B)	
RO Cartridge Filter Size	5 µm, horizontal configuration
RO Design Flux	12 gfd (20.4 lmh)
RO Feed Pressure	165 psi
RO Recovery	85%
Number of RO Stages	3
Number of RO Trains	N Configuration; 3 trains for 5 mgd; 5 trains for 20 mgd; 10 trains for 70 mgd
RO Element Size	8-in for 5 mgd plant capacity; 16-in for 20 mgd and 70 mgd plant capacities
RO CIP Frequency	Once every 6 months
RO Cleaning Chemicals	Acid: hydrochloric acid with citric Acid; Caustic: sodium hydroxide with SDBS
RO Replacement Frequency	5 years
UV AOP (Scenario 2B)	
UVAOP EEo	0.25 kwh / 1000gal / 1-log NDMA
UVAOP Average H_2O_2 Dose	3 mg/L
Zero Liquid Discharge Approach (Scenario 2B)	
Mechanical: Brine Concentrator Type and Number	Vapor compression falling film; 1 for 5 mgd; 2 for 20 mgd; 6 for 70 mgd
Mechanical: Brine Crystallizer Type and Number	Vapor compression falling film; 1 for 5 mgd; 2 for 20 mgd; 5 for 70 mgd
Evaporation Pond: Design Liquid Depth	6 ft
Evaporation Pond: Liner Type	Dual high-density polyethylene liner
Miscellaneous	
Enclosed Buildings	Rapid Mix; Microfiltration; Reverse Osmosis; Electrical Rooms; Mechanical Rooms (e.g., blowers, pumps); Administrative; Chemicals, UV
Administrative Building Size	2500 sf for 5 mgd case; 5000 sf for 20 mgd case; 7500 sf for 70 mgd case

Table 4.3. Operation and Maintenance Cost Design Criteria for all Scenarios

Item	Value
Cost Inputs	
Annual Plant Operating Usage	365 days / year
Annual Plant Operating Usage	24 hrs / day
Average Annual flow	60% of Plant Capacity (e.g., the average annual flow for a 20 mgd plant is 12 mgd)
Power Costs	
Electrical Power Cost	$0.08/kwh
Chemical Costs	
Hydrogen Peroxide (50% concentration)	$1125 / dry ton
Sodium Hypochlorite (12.5% concentration)	$1108 / dry ton
Sulfuric acid (93% concentration)	$162 / dry ton
Calcium hydroxide (hydrated lime; 94% concentration)	$179 / dry ton
Scale inhibitor (100% effective concentration)	$3312 / dry ton
Citric acid (50% concentration)	$2683 / dry ton
Sodium hydroxide (50% concentration)	$873 / dry ton
Sodium bisulfite (38% concentration)	$1119 / dry ton
Ammonia (29% concentration)	$434 / dry ton
Liquid Polymer (100% effective concentration)	$2967 / dry ton
Ferric chloride (40% concentration)	$840 / dry ton
CO_2 (100% concentration)	$138 / dry ton
Liquid Oxygen (100% concentration)	$105 / dry ton
Granular activated carbon	$2722 / dry ton
Sodium tripolyphosphate	$3327 / dry ton
Sodium dodecilsulphonate	$3327 / dry ton
MF Replacement Costs	
Replacement frequency	7 years
Module replacement cost (pressurized MF)	$2200/module
Module replacement cost (immersed MF)	$1000/module
RO Replacement Costs	
RO element replacement frequency	5 years
RO element replacement cost	$450/element for 8-in. element; $2,000/element for 16-in. element

Table 4.3. Operation and Maintenance Cost Design Criteria for all Scenarios (cont'd)

Item	Value
Cartridge replacement frequency	6 months
UV Disinfection (Scenario 2A) and UVAOP (Scenario 2B) Replacement Costs	
Operating pressure	medium pressure (S2A) / low pressure (S2B)
Lamp Replacement frequency	5000 hrs (S2A) / 12,000
Lamp Replacement cost	\$150 / lamp (S2A) / \$200 / lamp (S2B)
Ballast Replacement frequency	10 years
Ballast Replacement cost	\$4000 / ballast (S2A) / \$600 / ballast (S2B)
Sleeve Replacement frequency	3 years (S2A) / 5 years (S2B)
Sleeve Replacement cost	\$175 / sleeve (S2A) / \$100 / sleeve (S2B)
Intensity sensor replacement frequency	5 years
Intensity sensor replacement cost	\$2750 / sensor (S2A) / \$1800 / sensor (S2B)
Other Costs	
Labor costs	Plant Capacity ≥ 15 mgd: \$0.07 / gpd of treatment capacity Plant Capacity < 15 mgd: \$0.16 / gpd of treatment capacity
Maintenance and repair	1% of the treatment plant's total construction cost
Other O&M (includes vehicles, lab tests, SCADA, office equipment, other required misc expenses)	0.3% of the treatment plant's total construction cost
Mileage	Chemical Deliveries: 100 mi each way Solids Disposal in Landfill: 50 miles each way
Residuals Disposal	Haul Cost: \$25 / mi Landfill Dumping Charge: \$75/cy

Table 4.4. Greenhouse Gas and Emissions Cost Parameters

Item	3% Discount Rate (1st Year of plant operation)	7% Discount Rate (1st Year of plant operation)
Emissions from Electricity Generation		
CO_2e emissions	\$ 0.013/lb (\$ 0.041/lb[a])	
SO_2 emissions	\$ 18.43/lb	\$ 16.32/lb
NO_x emissions	\$ 2.74/lb	\$ 2.42/lb
$PM_{2.5}$ emissions	\$ 68.44/lb	\$ 63.17/lb
Emissions from Transportation		
CO_2e emissions	\$ 0.013/lb (\$ 0.041/lb[a])	
NO_x emissions	\$ 3.84/lb	\$ 3.47/lb
$PM_{2.5}$ emissions	\$ 189.52/lb	\$ 168.46/lb

[a] 95th percentile unit cost

4.2 Cost Calibration

Comparison of costs developed by the cost model to actual full-scale data is important to validate the model's accuracy. Two major cost categories typically are prepared for treatment plant cost estimates: capital costs for designing and constructing the treatment plant, and annual operating costs for operating and maintaining the plant. Capital costs are significantly more variable than annual operating costs because of economic fluctuations, raw material prices, local labor conditions, and site-specific conditions, to name a few. In addition, even though projects may have similar treatment processes, they often include significantly different construction elements (e.g., transmission pipeline, pump stations, special geotechnical conditions) that make comparison difficult. Conversely, operating costs can be much better estimated through detailed calculations of annual cost elements, including items such as power consumption, chemical costs, labor, and major equipment replacement. For example, annual power consumption can be calculated for a membrane treatment process based on an assumed operating pressure, average flow rate, and pump and motor efficiency. These data then can be compared to actual power consumption reported by full-scale operating plants. Consequently, more precise calibration of the estimated operating costs with full-scale operating plants can be made, whereas capital costs can only be more loosely compared to historical data. These calibration exercises are provided in the following sections.

4.2.1 Capital Cost Calibration

As discussed in Chapter 3, Utility Survey, collection of capital cost data from participating utilities was challenging for a variety of reasons. In addition, as described, capital costs are extremely variable because of numerous factors. Therefore, comparison of capital cost estimates to historical data was done primarily to confirm that costs are of the same order of magnitude. For example, Figure 4.1 compares the construction cost estimate developed by the cost model to the actual 2004 construction bid for the 70 mgd (265 mld) GWRS that uses MF-RO-UVAOP technology. Also shown is the escalated GWRS cost in 2012 dollars. The cost model is within 20% of the 2004 and escalated 2012 costs.

Note that although capital costs can vary significantly between actual projects that include similar treatment elements, the estimates included in this report are considered accurate for comparison purposes between alternatives, because the factors that can lead to significant cost differences among plants (e.g., economy, site conditions, additional project components) are assumed constant among the treatment alternatives evaluated.

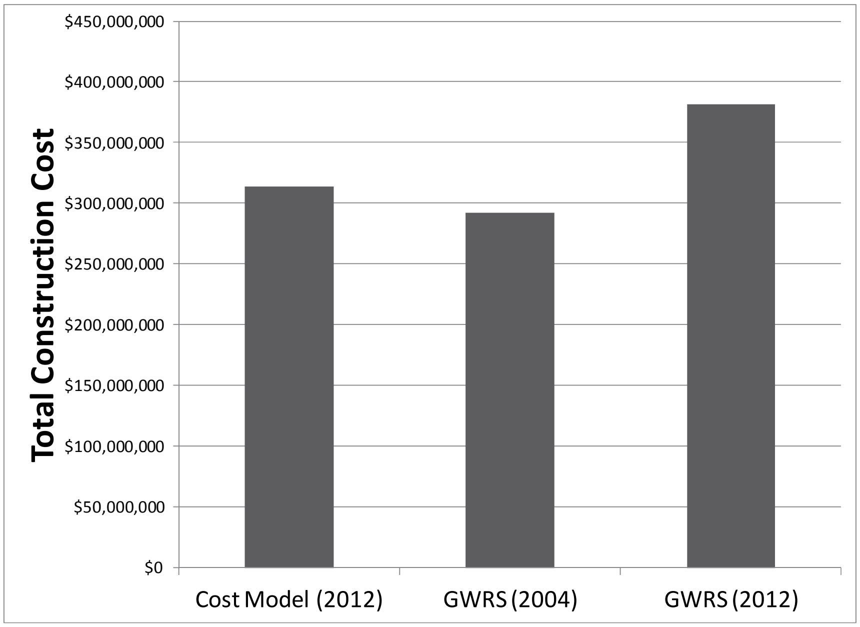

Figure 4.1. Total construction cost comparison between cost model and GWRS for a 70 mgd MF-RO-UVAOP plant with ocean discharge of RO concentrate.

4.2.2 Operating Cost Calibration

Calibration of operating costs was conducted for common categories applicable to the entire treatment plant, such as labor and maintenance and repair, and the major treatment processes included in the scenarios, such as MF, RO, UVAOP, chemicals, and GAC. Cost data from numerous plants were used to calibrate the common categories and cost data from two plants were used to calibrate the O&M costs for the treatment processes: GWRS plant data were used to compare costs for the MF, RO, UVAOP, and chemical processes and cost data from UOSA's Millard H. Robbins, Jr. Regional Water Reclamation Facility (UOSA) were used for the GAC cost comparison. Using the utility survey data and extensive discussions with plant staff, changes to select design criteria were made to better match plant operating data. For example, pump/motor efficiencies and operating pressure initially used in the cost estimating model did not match actual plant operating conditions which led to a significant difference in power consumption, especially for the RO treatment process.

Calibration of the cost model with GWRS annual operating costs was good for most categories (Figure 4.2). The difference shown in a few categories is caused by the following:

- **Labor Costs:** Annual labor costs are significantly different between the model and GWRS data because a unit labor cost of $0.07/gpd of treatment plant capacity was used in the model (see Chapter 3), whereas unit labor costs for GWRS are $0.11/gpd of treatment plant capacity. Higher unit costs for GWRS are likely because of more expensive labor in Southern California compared to other parts of the country. However, use of the average $0.07 unit cost in the cost model is appropriate to reflect a more typical cost for plants constructed elsewhere.

- **Major Equipment Replacement Costs and Other Costs:** The GWRS budget includes $5 million per year to cover future major equipment replacement and miscellaneous costs plus some contingency. The CPES cost model is based on the projected actual major equipment replacement costs and does not include contingency funds.

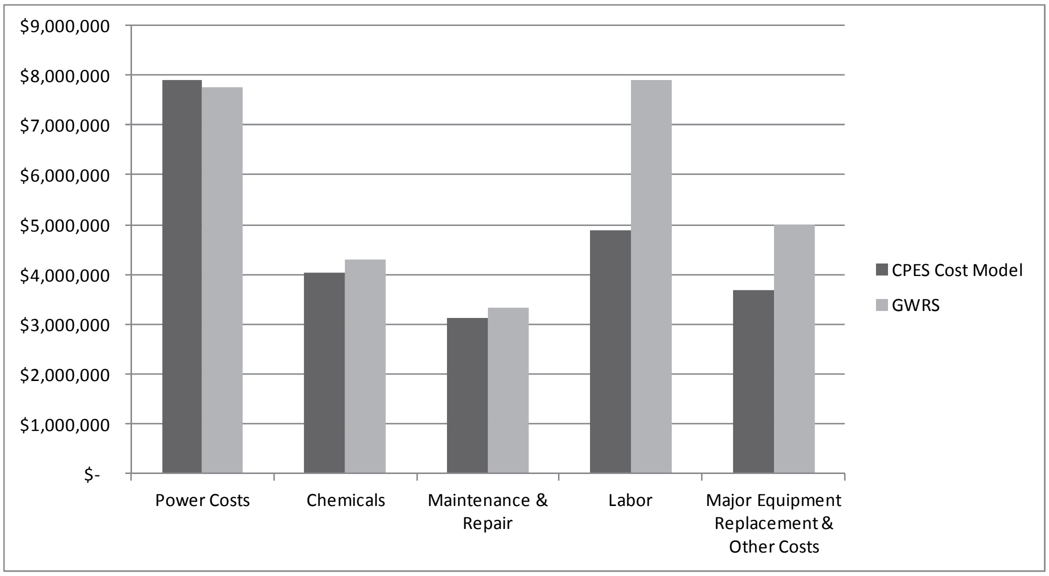

Figure 4.2. Annual O&M cost calibration between CPES cost model and GWRS actual costs.

Calibration of the GAC replacement frequency used in the cost model with full-scale plant data was also important, because GAC regeneration costs can represent a significant annual cost associated with GAC-based potable reuse treatment trains. Table 4.5 shows the GAC replacement / regeneration frequency at the UOSA plant for the past 4 years. Based on a total installed capacity of 4,000,000 pounds of GAC (1,814,400 kg), UOSA replaces approximately 21% of its installed GAC on an annual basis. This corresponds to a total GAC replacement frequency of once every 5 years. Data from El Paso's Fred Hervey Water Reclamation Facility indicate a replacement frequency of approximately once every 10 to 14 years. On the basis of this information, and because some utilities may elect to replace GAC more frequently, owing to site-specific conditions, GAC replacement costs were developed for two replacement frequencies in the cost model: once every 2 years and once every 8 years. The GAC replacement cost used for cost estimating was $2722 per dry ton ($1.36/lb; $3.00/kg), which was the average unit cost for GAC replacement for El Paso over the past 2 years. UOSA reports a much lower unit cost for new GAC at $0.80/pound ($1.76/kg), and because GAC is regenerated onsite, effective GAC replacement cost for all media replaced is in fact much lower. However, the GAC replacement cost for smaller treatment plants and plants without regeneration furnaces is more likely to be similar to El Paso's costs.

Table 4.5 GAC Replacement and Regeneration Data for the Millard H. Robbins, Jr. Water Reclamation Facility

Year	GAC Purchased for Attrition (pounds)	GAC Regenerated (pounds)	Total GAC Replaced ; New + Regenerated (pounds)	Percentage of Total Installed GAC Replaced per Year
2009	165,000	747,725		23%
2010	42,500	710,175		19%
2011	234,375	688,925	923,300	23%
2012	181,250	561,681	742,931	19%

4.3 Triple Bottom Line Costs

TBL costs were developed for both scenarios at three flow rates (5 mgd, 20 mgd, and 70 mgd) using the design criteria shown previously. All costs presented in this section are in 2012 U.S. dollars unless otherwise noted.

4.3.1 Scenario 1: Nonpotable Reuse for Landscape Irrigation

Scenario 1 is a landscape irrigation scenario comparing a GMF treatment approach (Scenario 1A) to an alternative treatment approach using membrane filtration. Two membrane filtration treatment trains are compared to the GMF approach: one using an MF treatment train for solids and pathogen removal analogous to GMF (Scenario 1B), and one using a RO treatment train for removal of dissolved solids or organics (Scenario 1C). Note that MF is required for RO pretreatment. Implementation of RO requires disposal of RO concentrate. For this scenario it is assumed that sewer or ocean disposal is available via an existing discharge line. Where sewer or ocean disposal of RO concentrate is not available, implementation of a ZLD concentrate management approach is necessary and is likely cost prohibitive for plants of significant size. The costs associated with RO concentrate handling are discussed in detail in Scenario 2. Detailed PFDs for each treatment train can be found in Appendix A. Simplified PFDs were presented earlier in Chapter 2 but are repeated here for convenience in Figures 4.3, 4.4, and 4.5 for each of the three Scenario 1 alternatives.

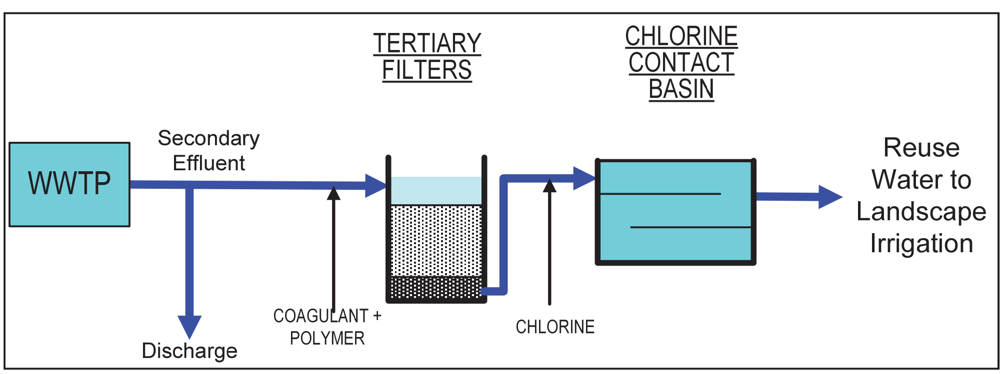

Figure 4.3. Scenario 1A: Reuse treatment for landscape irrigation using conventional treatment.

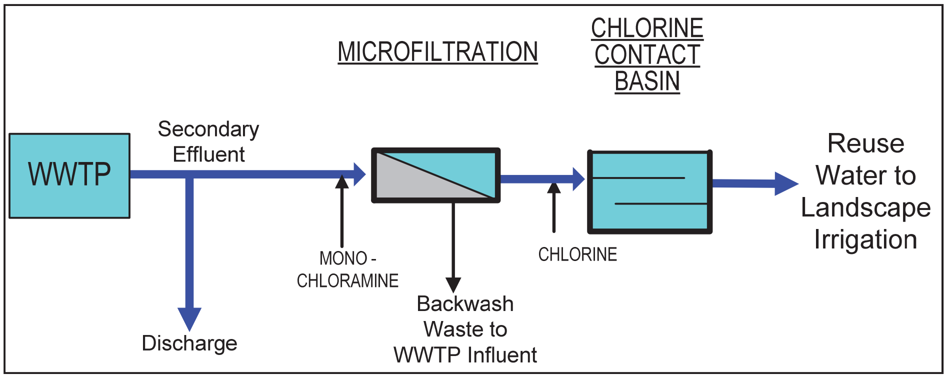

Figure 4.4 Scenario 1B: Reuse treatment for landscape irrigation using microfiltration treatment.

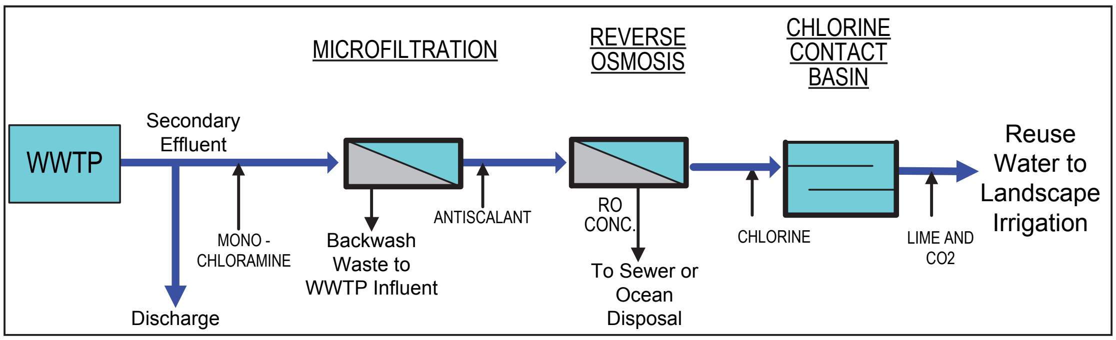

Figure 4.5. Scenario 1C: Reuse treatment for landscape irrigation using reverse osmosis treatment.

Capital and annual operating costs for all treatment trains analyzed in Scenario 1 are shown in Figures 4.6 and 4.7, respectively, as a function of flow rate. Pie charts also are included with these figures to show the cost breakdown by major cost category for each treatment train. Capital and annual operating costs include all items for a fully functional treatment plant (e.g., costs are included for all ancillary facilities, such as site development). More detailed cost breakdown is provided in Appendix E, including costs for each individual unit process. Annual operating costs are based on an average flow factor of 0.6; thus, for the 70 mgd plant, operating costs are based on an annual average flow of 42 mgd. Figure 4.8 shows the consumption of power and chemicals for each treatment process included in a given treatment scenario. Inspection of Figures 4.6, 4.7, and 4.8 reveals the following:

- **Lowest Cost:** The capital and annual operating costs for Scenario 1A (GMF-based) are the lowest for all flows analyzed and the cost differences (savings) increase with increasing flow rate.
- **Granular Media Filter versus Membrane Treatment Train:**
    - **Capital Costs:** At a flow rate of 5 mgd, the capital costs for Scenarios 1A, 1B, and 1C are $16 million, $21 million, and $47 million, respectively. These differences are due to the higher cost of MF and RO treatment, which grow more significantly at higher flows. Capital costs for Scenario 1B are about 50% higher than Scenario 1A at a flow of 20 mgd and 150% higher at a flow of 70 mgd. Capital costs for Scenario 1C are much higher than Scenario 1A: 215% higher at a flow of 20 mgd and 350% higher at a flow of 70 mgd. This increasing difference at higher flows is due to the

better economies of scale at higher flows that Scenario 1A provides because of its larger percentage of concrete construction (e.g., filters). Scenarios 1B and 1C include more mechanically intensive equipment (e.g., MF, RO) that does not realize as significant economies of scale.

- **Operating Costs:** At a flow rate of 5 mgd, the annual operating costs for Scenarios 1A, 1B, and 1C are $1.1 million, $1.3 million, and $2.3 million, respectively. The largest component of these costs is labor, which is $800,000/year for each treatment train for a plant capacity of 5 mgd. The cost savings associated with Scenario 1A increase with increasing flow rate but not as dramatically as the savings realized with capital costs. This is due to the equivalent labor costs used for all scenarios and the fact that labor costs comprise the largest percentage of overall operating costs (50–70%).

- **Cost Division Among Categories:**
  - **Scenario 1A:** The capital costs for filtration, site work, and basins and pump stations are the most significant elements for this scenario; each represent about 20 to 25% of total direct costs. Labor represents the most significant annual operating cost at 67% of total operating costs. Maintenance and repair (17%), chemicals (9%), and power (7%) are the remaining operating costs.
  - **Scenario 1B:** The capital cost for MF is the most significant cost category for Scenario 1B at 54% of total direct costs. Labor represents the most significant annual operating cost at 50% of total operating costs, but its percentage is lower than Scenario 1A because of the significant cost of MF module replacement. For example, replacement of all MF modules at the 20 mgd plant would cost approximately $3 million. Using a replacement frequency of once every 7 years, this represents an annualized cost of approximately $400,000/year.
  - **Scenario 1C:** The capital cost for MF and RO are the most significant cost categories for Scenario 1C at 30% and 35%, respectively, of total direct costs. Power (primarily for RO), chemicals, and maintenance and repair represent the most significant nonlabor operating costs. Periodic replacement of MF modules and RO elements also represent a significant expenditure.

- **Power Consumption:** Power consumption for all treatment trains are dominated by pumping costs, either to increase the plant hydraulic grade line to allow gravity flow (Scenario 1A) or to pump through the membrane treatment processes (Scenarios 1B and 1C). Total power consumption for Scenarios 1A and 1B are 1,800 MWh/year and 2,200 MWh/year, respectively for a 20 mgd plant capacity. Power consumption for Scenario 1B is 25% higher than Scenario 1A because of the headloss through MF membranes. When RO is added (Scenario 1C), power consumption increases significantly to 13,300 MWh/year, which is more than seven times higher than Scenario 1A. Where sewer or ocean disposal is not available and mechanical evaporation is utilized for concentrate handling, power consumption would increase substantially (see Scenario 2 discussion).

- **Chemical Consumption:** Although the type of chemicals used for Scenarios 1A and 1B is different, the total chemical consumption is similar at 190 tons/year and 230 tons/year, respectively for a 20 mgd plant capacity. However, Scenario 1C uses much more chemical at approximately 1900 tons/year, primarily owing to the RO process. For example, 75 tons/year of antiscalant and 525 tons/year of sulfuric acid is necessary to control RO scaling, and 840 tons/year of calcium hydroxide and 180 tons/year of CO_2 are required to stabilize the RO permeate.

The environmental costs associated with GHG emissions and other air emissions for the first year of plant operation (2016) are shown in Figures 4.9 and 4.10, respectively. These GHG emissions costs per increment of CO_2e are based on mean monetized social costs, including, but not limited to changes in agricultural productivity, health effects, flood damages, and losses in other valued ecosystem services. These costs are reported in U.S. dollars per pound of emission and all future costs are discounted at 3%. Appendix F includes graphs using 95th percentile estimates of social costs to reflect uncertainty in the CO_2e unit costs. These costs at the upper bound of the distribution are roughly three times as high as the mean value. The other air emissions are valued at the national average cost per pound for electricity generation and on-road mobile sources, depending on the source of the emissions. These costs are entirely due to premature mortality and other adverse health effects. Pie charts also are included with these figures to show the cost breakdown by scenario for electricity production, truck traffic and chemical production. A more detailed cost breakdown is provided in Appendix E. Figures 4.9 and 4.10 show the following about the monetized environmental costs associated with Scenario 1:

- **Lowest Cost:** The monetized costs for Scenario 1A are the lowest for all flows analyzed and the savings increase with increasing flow rate.
    - At a flow rate of 5 mgd the annual GHG costs for scenarios 1A, 1B, and 1C are \$12,000, \$19,000 and \$119,000, respectively. The annual costs for other air emissions for these scenarios are \$55,000, \$69,000, and \$454,000, respectively.
    - Monetized environmental costs for Scenario 1C costs are significantly higher than Scenarios 1A and 1B because of the large amount of power consumption associated with this scenario, primarily associated with RO. For example, at 70 mgd, the annual GHG and other air emissions costs for Scenario 1C are \$1.0 million and \$3.7 million, respectively.
- **Comparison Between GHGs and Other Air Emissions Costs:**
    - Environmental costs for other air emissions are more significant than environmental costs for CO_2 equivalent emissions because the monetized health effects of $PM_{2.5}$ and $PM_{2.5}$ precursors (SO_2 and NO_x) are much higher than the monetized health effects of CO_2. For example, the monetized health effects of $PM_{2.5}$ and SO_2 from electricity generation is \$136,877/ton and \$36,852/ton, respectively, versus \$26.91/ton for CO_2 equivalents. Higher quantities of CO_2 equivalents are released during electricity generation but not enough to offset the higher monetized health effects of $PM_{2.5}$ and its precursors. This result only holds true at the low end of values for CO_2 equivalents. At the upper end of the range of values for CO_2 equivalents, the monetized value of the GHG emissions associated with the treatment trains is similar to the monetized value of the other air emissions.
    - GHG costs are dominated by electricity production, which accounts for 70 to 90% of all environmental costs associated with each treatment train. GHG costs associated with chemical production are significant, ranging from 15 to 30% of total GHG emissions. GHG costs associated with trucking are low because of small quantity of CO_2 emissions from this source.

- Social costs for other air emissions are dominated by the release of SO_2 and NO_x from energy production, which represent approximately 80% of all other air emission costs. Other air emissions from trucking of chemicals and residuals are approximately 15% of the total.

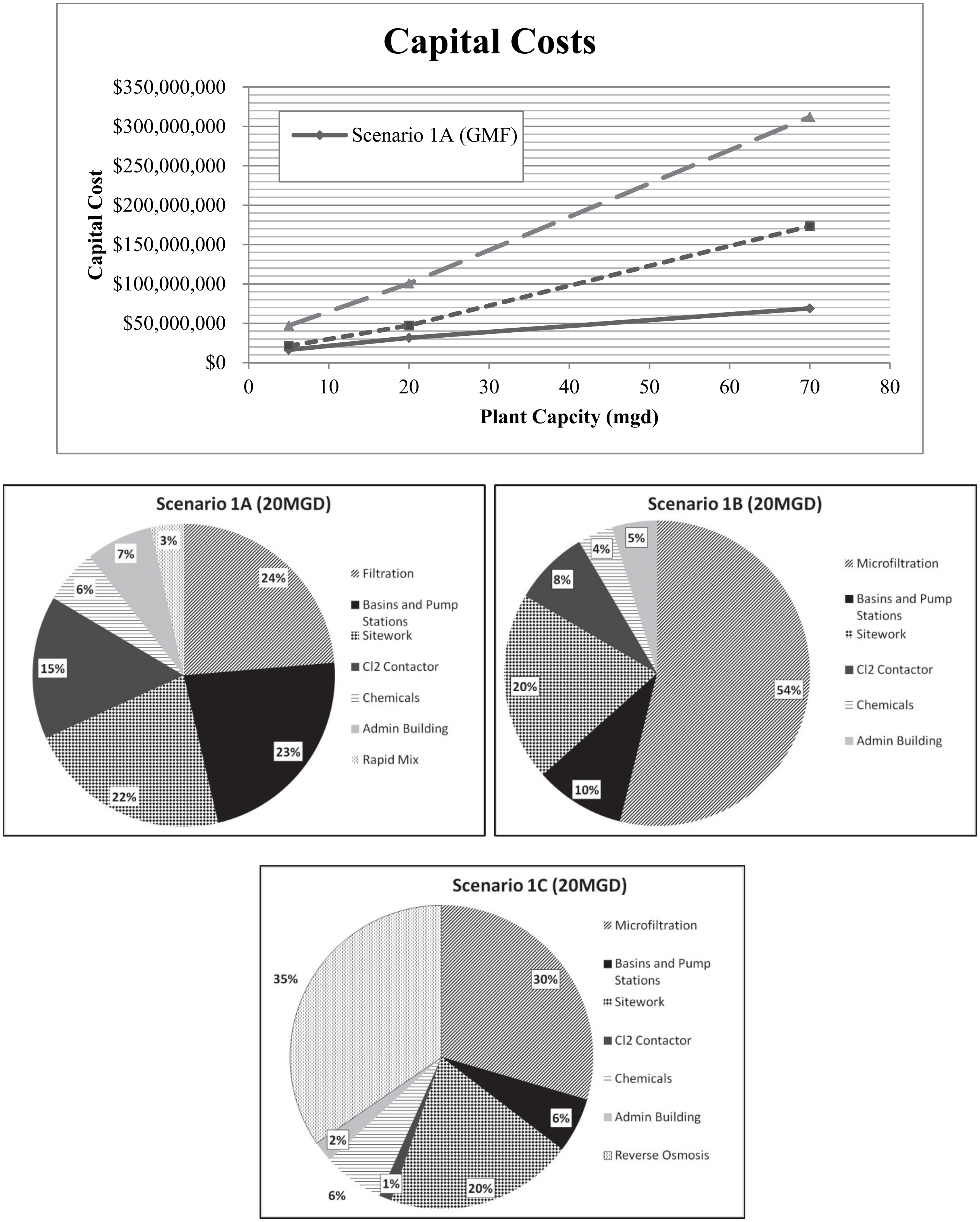

Figure 4.6. Capital costs for Scenario 1.

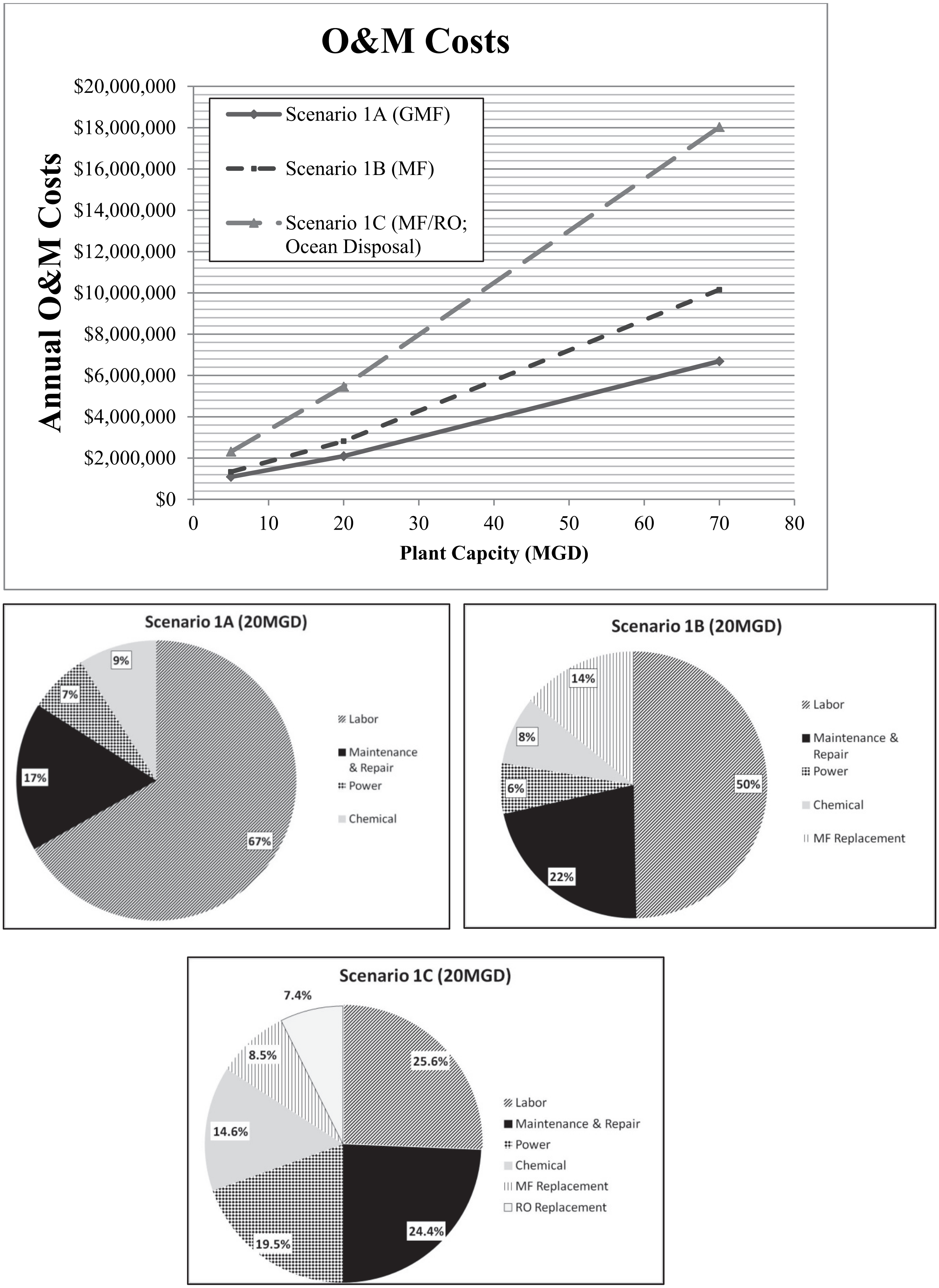

Figure 4.7. Annual operating costs for Scenario 1.

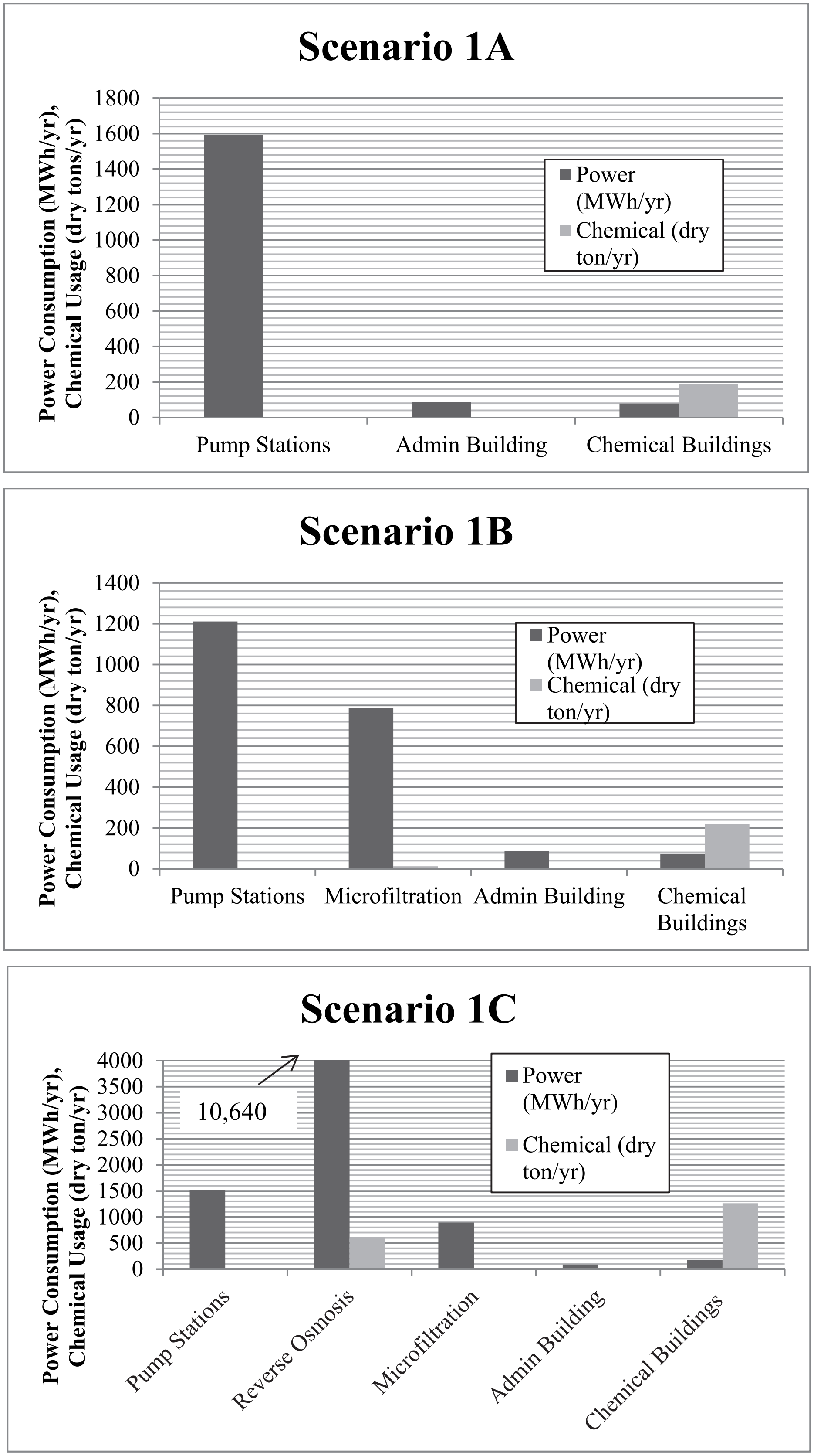

Figure 4.8. Power and chemical consumption for Scenario 1 (20 mgd plant capacity).

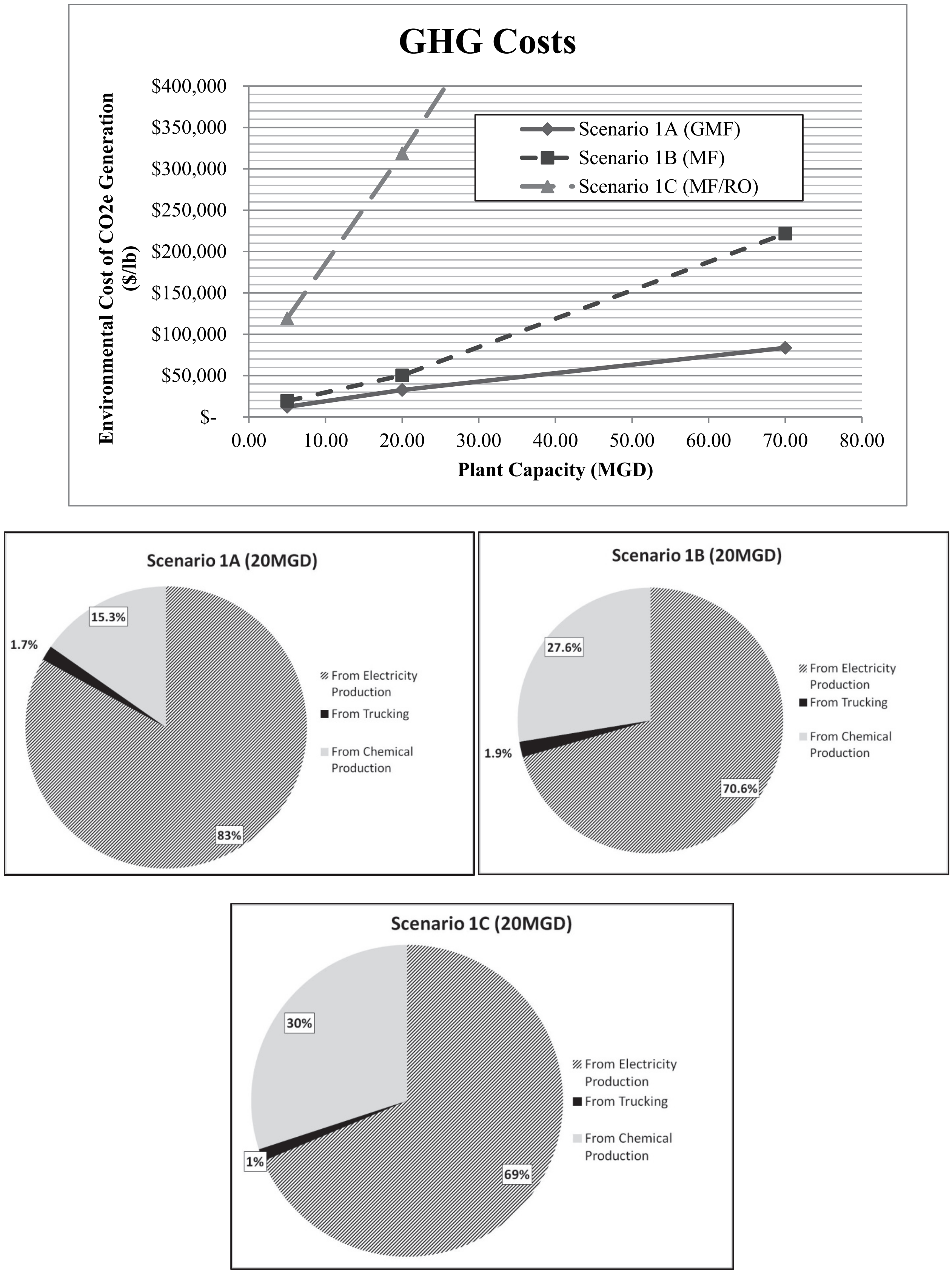

Figure 4.9. Annual greenhouse gas (GHG) costs for Scenario 1.

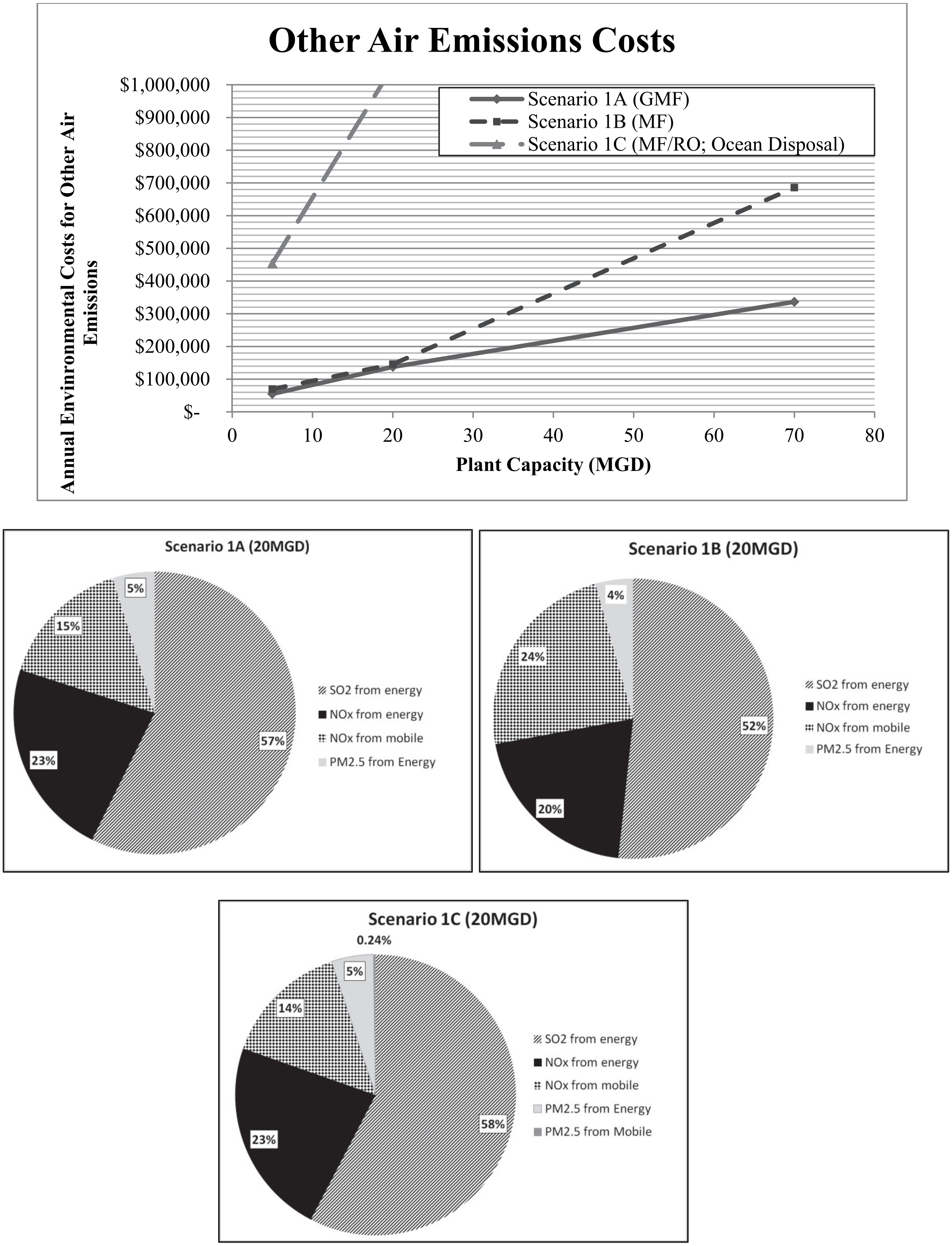

Figure 4.10. Other air emissions annual costs for Scenario 1.

4.3.2 Scenario 2: Potable Reuse

Scenario 2 includes comparison of the GAC-based potable reuse approach (Scenario 2A) to the RO-based potable reuse approach (Scenario 2B). Scenario 2B includes three concentrate handling approaches: ocean disposal, mechanical evaporation, and evaporation ponds. A hybrid approach combining the use of brine concentration and evaporation ponds is discussed at the end of the chapter. Detailed PFDs for each treatment train can be found in Appendix A. Simplified PFDs were presented earlier in Chapter 2 but are repeated here for convenience in Figures 4.11 and 4.12.

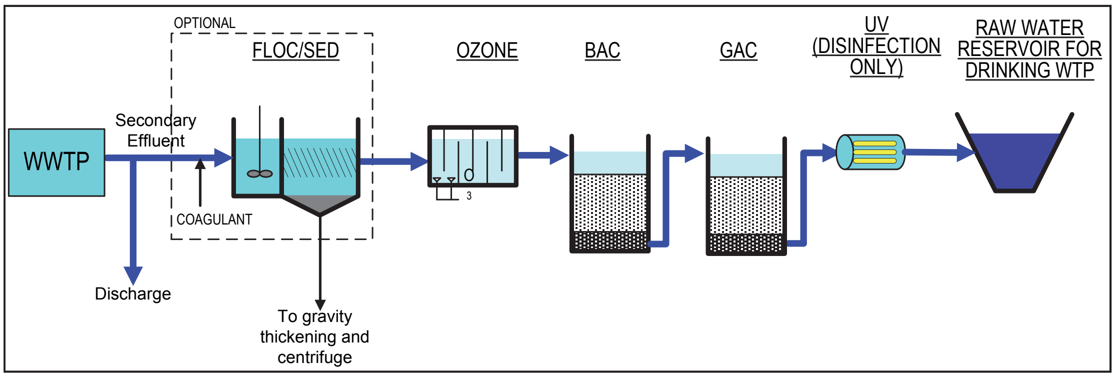

Figure 4.11. Scenario 2A: Reuse treatment for potable reuse using a GAC-based treatment approach.

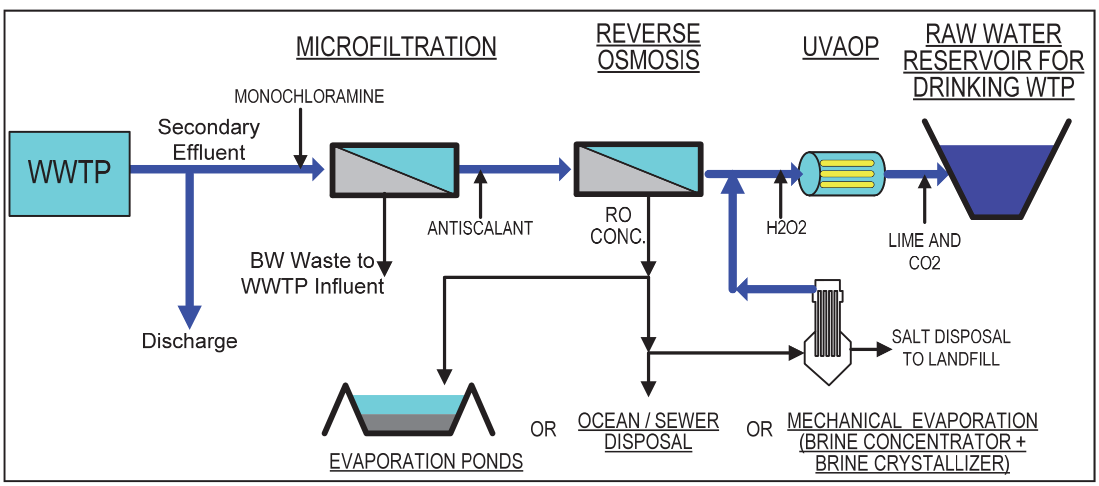

Figure 4.12. Scenario 2B: Reuse treatment for potable reuse using an RO-based treatment approach.

Capital and annual operating costs for all treatment trains analyzed in Scenario 2 are shown in Figures 4.13 and 4.14 as a function of flow rate. Pie charts also are included with these figures to show the cost breakdown per facility included in each treatment train. More detailed cost breakdown is provided in Appendix E. Annual operating costs are based on an average flow factor of 0.6; thus, for the 70 mgd plant, operating costs are based on an annual average flow of 42 mgd. Figure 4.15 shows the consumption of power and chemicals for each treatment process included in a treatment scenario. Inspection of Figures 4.13, 4.14, and 4.15 reveals the following about the capital and operating costs associated with Scenario 2:

- **Lowest Cost:** The capital and annual operating costs for Scenario 2A (GAC-based) are the lowest for all flows analyzed and the savings increase with increasing flow rate.

- **GAC-Based versus RO-Based Costs:** Scenarios 2A and 2B have similar capital and annual operating costs at low flow, but costs are significantlydifferent at higher flows:
  - At a flow rate of 5 mgd the capital costs for Scenarios 2A and 2B are $50 million and $52 million, respectively. However, the difference grows significantly at higher flows. Capital costs for Scenario 2B are about 30% higher at a flow of 20 mgd and 70% higher at a flow of 70 mgd. This increasing difference at higher flows is because of the better economies of scale for Scenario 2A at higher flows because of its larger percentage of concrete construction (e.g., ozone contactor, BAC filters, GAC adsorbers). Scenario 2B includes more mechanically intensive equipment (MF, RO, UVAOP) that does not realize as significant economies of scale.
  - At a flow rate of 5 mgd the annual operating costs for scenarios 2A and 2B are $1.9 million and $2.4 million, respectively. However, the difference grows significantly at higher flows. Annual operating costs for Scenario 2B are about 40% higher for the 20 mgd case and 50% higher for the 70 mgd case when compared to the 2-year GAC replacement frequency case for Scenario 2A. The cost difference between these scenarios is even greater if GAC is replaced on an 8-year frequency. The increasing difference at higher flows is because of higher power consumption and larger replacement costs associated with major process equipment associated with Scenario 2B (i.e., MF, RO, UVAOP).
- **Concentrate Handling Costs for Scenario 2B:** Where sewer or ocean disposal of concentrate is not available the need for concentrate management increases Scenario 2B capital and annual operating costs significantly:
  - At 5 mgd, the total plant capital cost using mechanical evaporation is approximately 30% more than ocean disposal ($67 million versus $52 million). Evaporation ponds are 75% higher than ocean disposal. If land has to be purchased for construction of the evaporation ponds, capital costs would increase further. At 20 mgd, the total plant capital costs for mechanical evaporation and evaporation ponds are 40% and 150% higher respectively, than for ocean disposal.
  - At 5 mgd, the total annual operating cost using the mechanical evaporation approach is approximately 60% more than the ocean disposal approach ($3.9 million versus $2.4 million). Evaporation ponds are approximately 60% higher than ocean disposal. At 20 mgd, the total operating costs for mechanical evaporation and evaporation ponds are 85% and 50% higher, respectively, than ocean disposal.
  - Where sewer or ocean disposal is not available, the capital and annual operating costs for concentrate handling is extremely high, which may limit the use of RO technology at inland locations.
- **Most Costly Treatment Processes:**
  - **Scenario 2A:** Ozonation and filtration (BAC and GAC) represent the most costly treatment processes to construct for Scenario 2A, comprising approximately 45% of the total direct costs. Excluding labor and miscellaneous maintenance and repair, replacement of GAC (2-year frequency) represents the most significant annual operating expense at 18% of total operating costs. Chemical costs, primarily from the use of liquid oxygen (for ozone generation) and ferric chloride, are next highest at 16% of total operating costs. The addition of ferric chloride for removal of organics and pathogens through coagulation and sedimentation adds significant cost to this treatment train. For a flow of 20 mgd, approximately $5.5 million in capital costs is

required for flocculation and sedimentation and another $4 million for solids handling (gravity thickener and centrifuge). Annual operating costs for ferric chloride addition and solids disposal are $500,000 and $300,000, respectively. Therefore, elimination of this process, which may not be needed in many potable reuse applications, could reduce total operating and construction costs by approximately 10 to 20%. GAC replacement frequency can have a large impact on annual operating costs. For example, at an average plant flow of 12 mgd (20 mgd plant capacity), annual GAC replacement costs for the 2-year and 8-year replacement frequencies are approximately $800,000 and $200,000, respectively.

  - **Scenario 2B:** The most costly treatment processes for Scenario 2B are MF, RO, and UVAOP. These three processes represent approximately 25%, 29%, and 14%, respectively, of total direct capital costs. Common plant site work costs (civil, yard piping, site electrical, and SCADA) are also a significant cost at 20% of total direct costs. Power to run these processes is the most significant nonlabor annual operating cost, representing approximately 22% of the total annual operating costs. Replacement costs for major equipment items (MF, RO, UVAOP) are significant at 19% of total annual operating costs.
  - **Scenario 2B (with concentrate handling):** Where ocean or sewer disposal of concentrate is not available for Scenario 2B, concentrate management handling costs are significant and dominate the overall plant costs. At a flow of 20 mgd, use of mechanical evaporation or evaporation ponds increases plant capital costs by $50 million and $180 million, respectively, and represent about 50% and 70% of total direct costs, respectively. Because mechanical evaporation is very power intensive, electrical power costs represent 50% of all operating costs in this approach. Conversely, evaporation ponds are passive and consequently the relative amount of cost expended on power is much lower.

- **Power and Chemical Consumption:** Power and chemical consumption represent the two largest nonlabor contributors to annual operating costs.
  - **Power:** Power costs for Scenario 2B are significantly higher than 2A because of the power-intensive equipment included with Scenario 2B. At 12 mgd average flow (20 mgd plant capacity), power costs for Scenarios 2A and 2B are $0.3 million and $1.3 million, respectively. RO is the most energy intensive treatment process included in this train. At 12 mgd average flow, it consumes approximately 1.2 MW (10,600 MWh/yr on an annual basis) , which is approximately 12 times higher than MF and 4 times higher than UVAOP. When concentrate handling is required and mechanical evaporation is used, the average power consumption for mechanical evaporation is 5.8 MW (51,000 MWh/yr on an annual basis) for the 20 mgd flow rate, which is 3.5 times higher than the combined use of all other treatment processes at the plant.
  - **Chemical Consumption:** The total chemical consumption for Scenarios 2A and 2B is 1770 tons/year and 1,860 tons/year, respectively for a plant capacity of 20 mgd. Chemical consumption for Scenario 2A is dominated by liquid oxygen for ozone generation and ferric chloride for coagulation, whereas Scenario 2B is dominated by sulfuric acid, calcium hydroxide, and CO_2. When concentrate disposal via mechanical evaporation is used, the total chemical consumption for mechanical evaporation is about 50% higher than Scenario 2B for the 20 mgd flow rate, primarily because of the higher acid requirement necessary to limit scaling in the mechanical evaporation process.

The environmental costs associated with GHG emissions and other air emissions are shown in Figures 4.16 and 4.17, respectively. Pie charts are also included with these figures to show the cost breakdown per facility included in each treatment train. More detailed cost breakdown is provided in Appendix E. Inspection of these figures reveals the following about the monetized environmental costs associated with Scenario 2:

- **Lowest Cost:** The monetized costs for Scenario 2A (GAC-based) are the lowest for all flows analyzed and the savings increase with increasing flow rate.
  - At a flow rate of 5 mgd the annual GHG costs for scenarios 2A and 2B-ocean disposal are $40,000 and $130,000, respectively. The annual costs for other air emissions for these scenarios are $150,000 and $500,000, respectively.
  - Scenario 2B-ocean disposal environmental costs increase significantly with flow because of the large amount of power consumption associated with this scenario. For example, at 70 mgd, the annual GHG and other air emissions costs for Scenario 2B are $1.2 million and $4.2 million, respectively.
- **Concentrate Handling Costs:** Where ocean disposal of concentrate is not available for Scenario 2B, implementation of concentrate management increases Scenario 2B environmental costs significantly:
  - The environmental costs for the mechanical evaporation approach are much more significant because of the increased power use in this treatment scenario. At 5 mgd, the annual GHG and other air emissions costs are $370,000 and $1.6 million, respectively.
- **Comparison Between GHGs and Other Air Emissions Costs:**
  - Other air emissions costs are more significant than CO_2 emissions costs because the monetized health effects of $PM_{2.5}$ and $PM_{2.5}$ precursors (SO_2 and NO_x) are much higher than the monetized health effects of CO_2. For example, the monetized health effects of $PM_{2.5}$ and SO_2 from electricity generation is $136,877/ton and $36,852/ton, respectively, versus $26.91/ton for CO_2 equivalents. Higher quantities of CO_2 equivalents are released during electricity generation, but not enough to offset the higher monetized health effects of $PM_{2.5}$ and its precursors.
  - GHG costs are dominated by electricity production, which accounts for 70 to 90% of all environmental costs associated with each treatment train. GHG costs associated with chemical production are significant, ranging from 6 to 27%. GHG costs associated with trucking are low because of small quantity of CO_2 emissions from this source.
  - Other air emissions costs are dominated by the release of SO_2 and NO_x from energy production, which represent approximately 60% and 25%, respectively, of all other air emission costs. Other air emissions from trucking of chemicals and residuals range from 3 to 17% of the total.

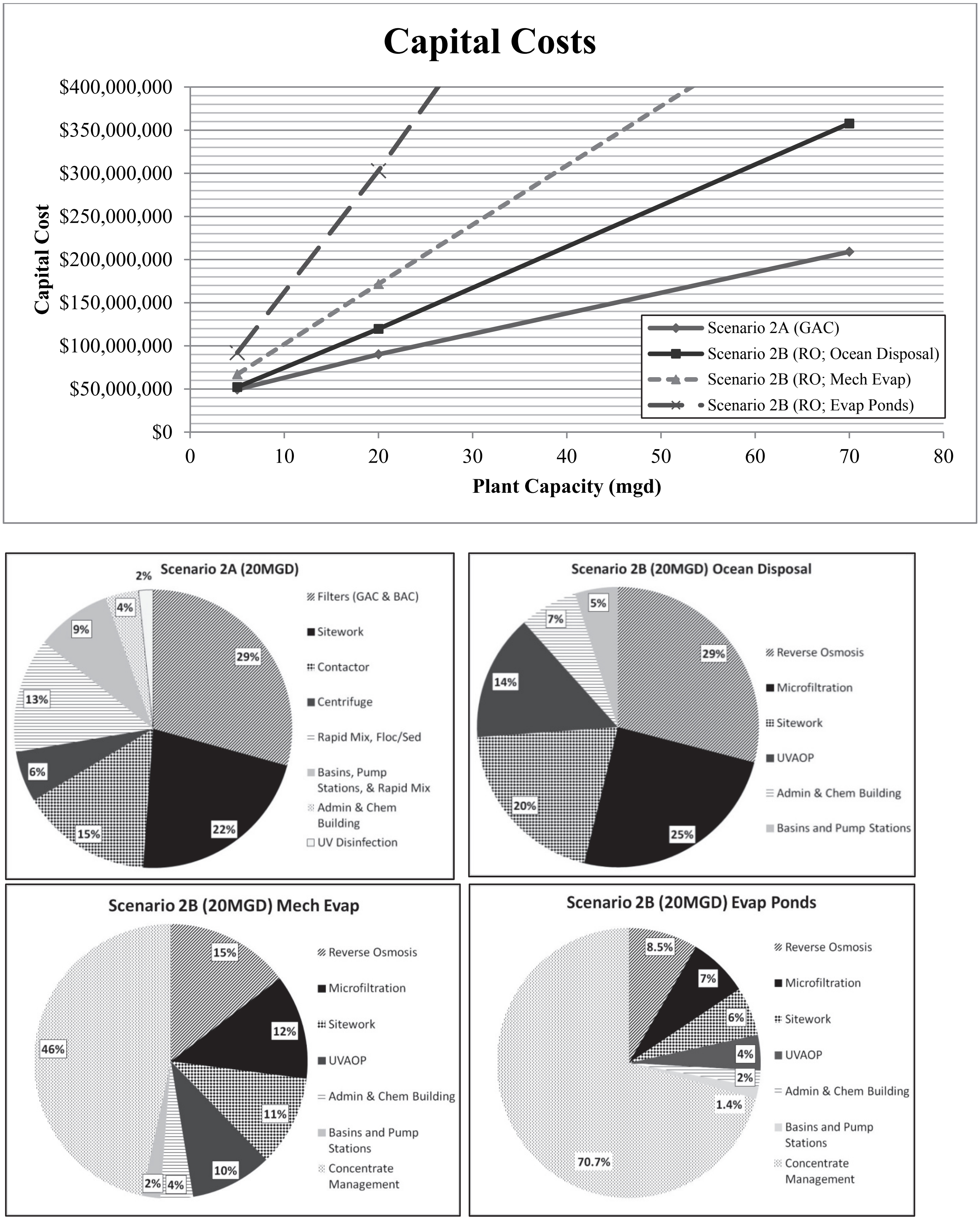

Figure 4.13. Capital costs for Scenario 2.

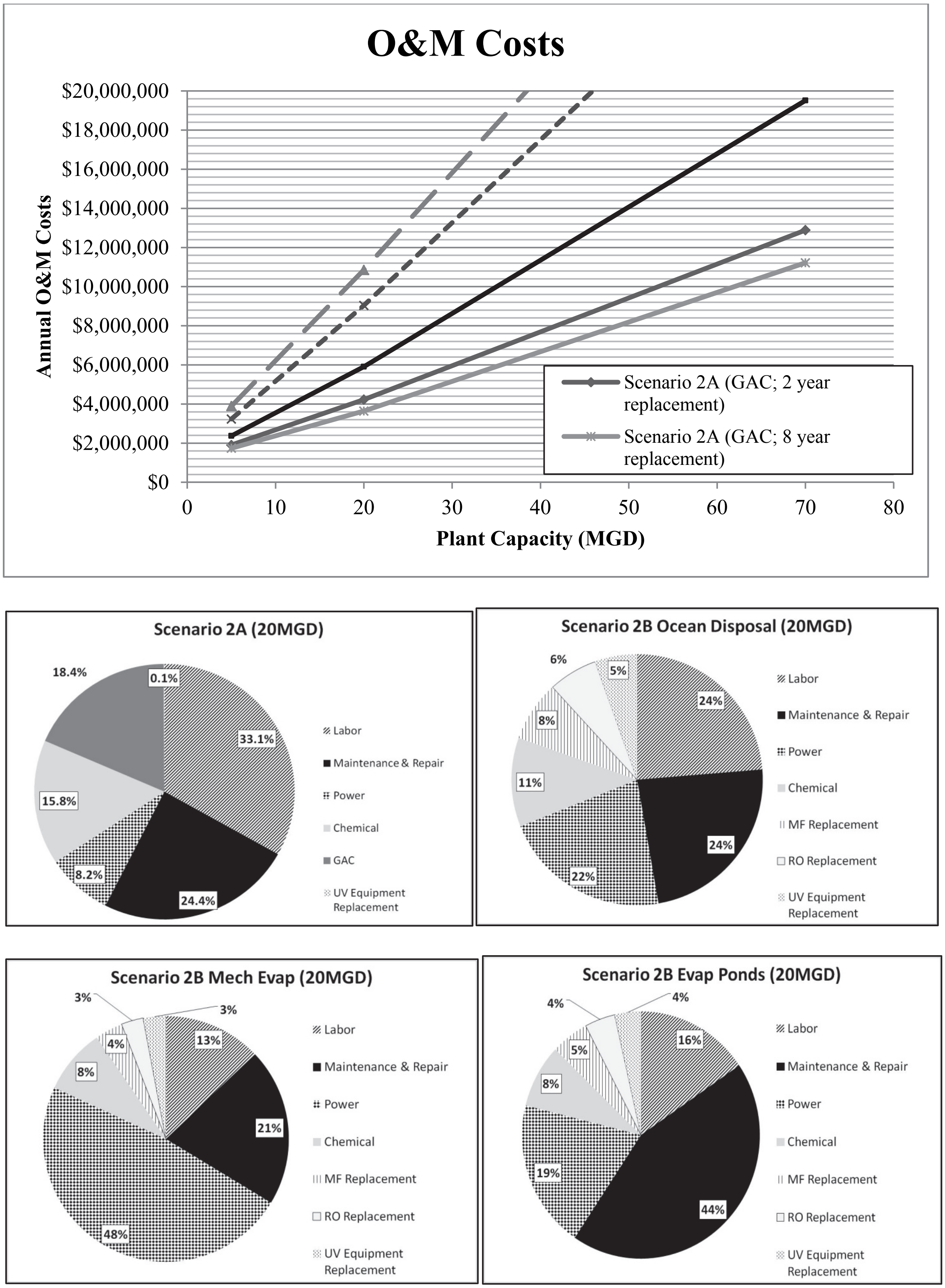

Figure 4.14. Annual operating costs for Scenario 2.

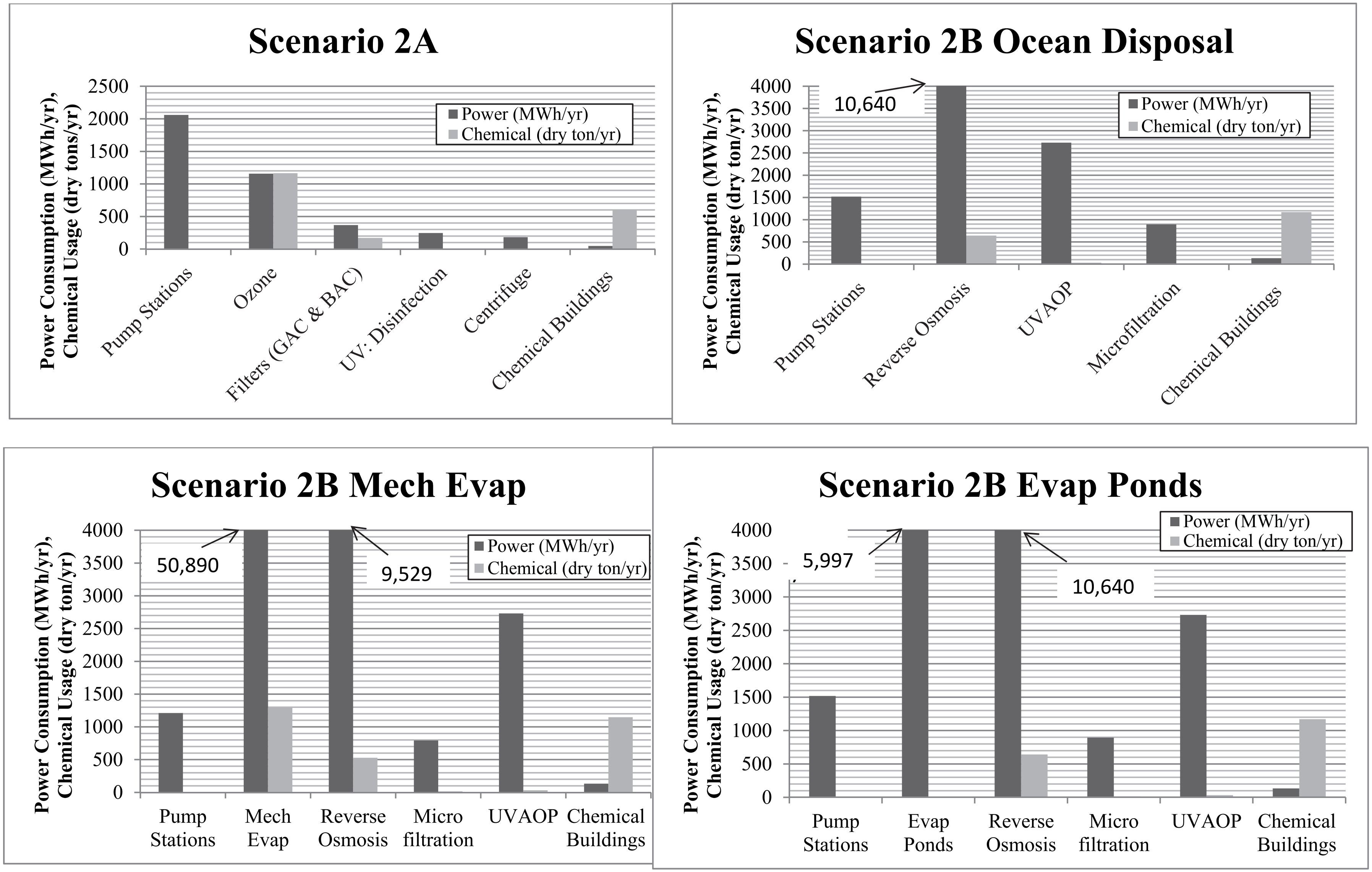

Figure 4.15. Power and chemical consumption for Scenario 2 (20 mgd plant capacity).

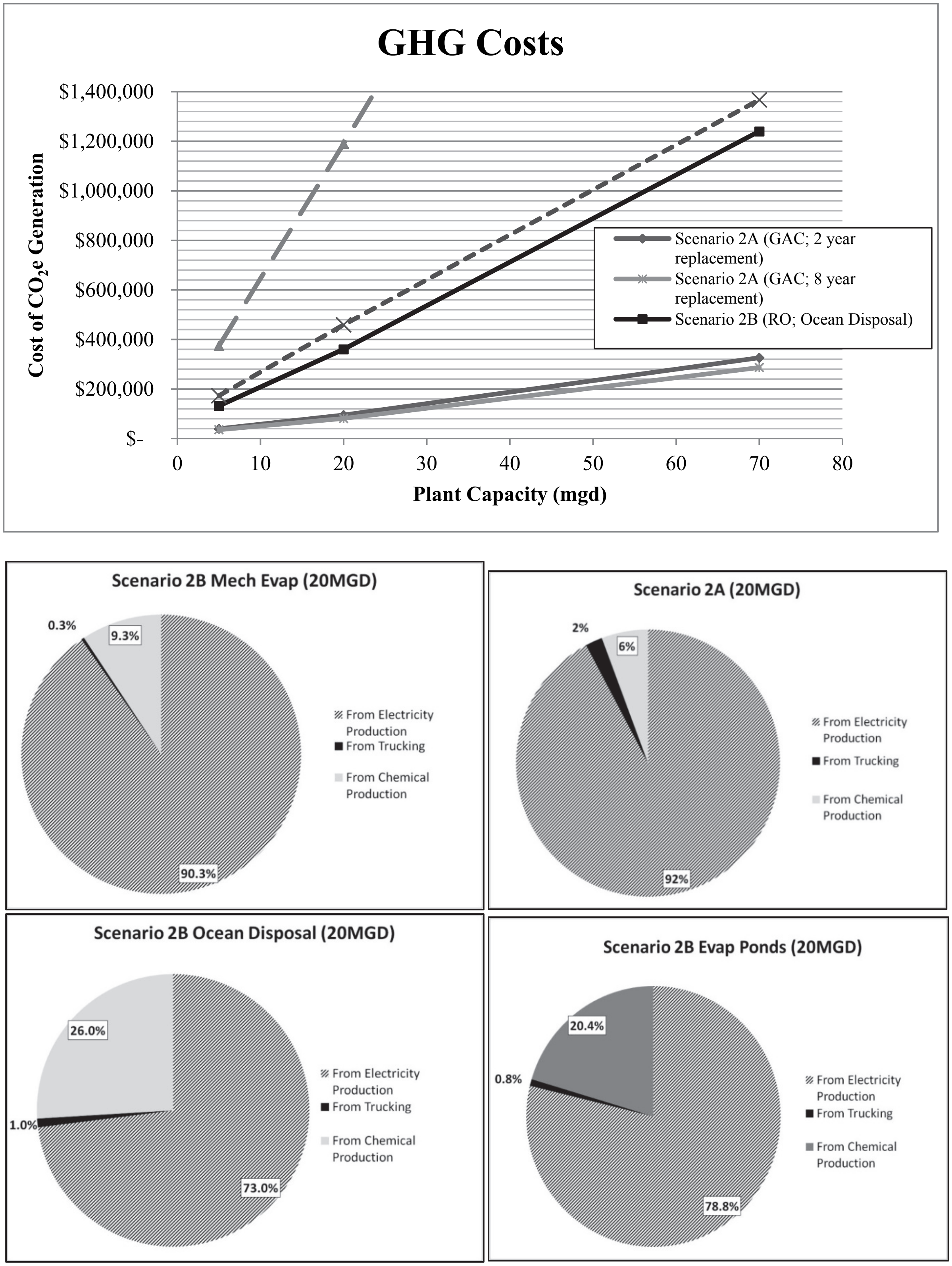

Figure 4.16. Annual greenhouse gas (GHG) costs for Scenario 2.

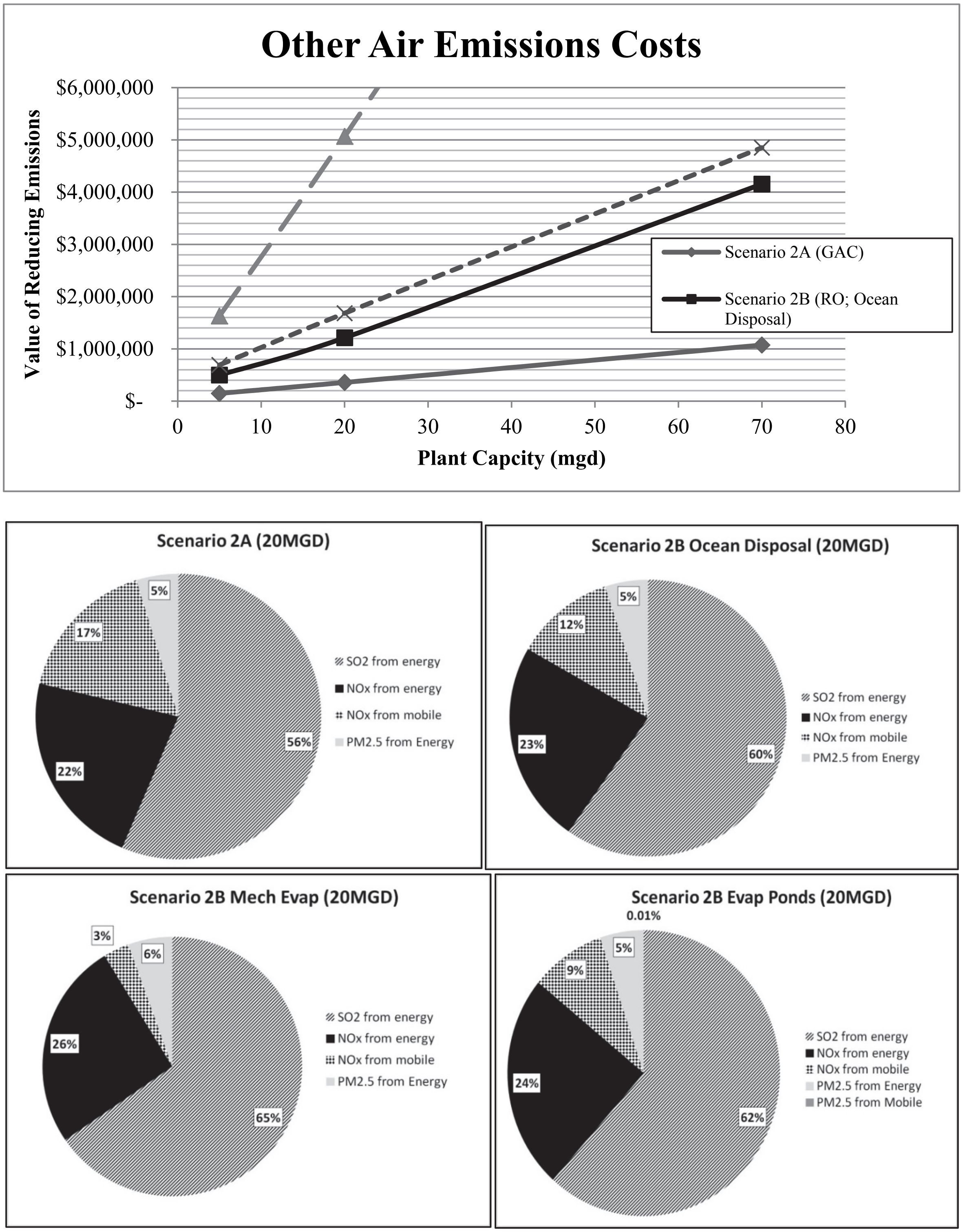

Figure 4.17. Other air emissions annual costs for Scenario 2.

4.3.3 Net Present Value Comparisons

This section provides the results from applying the TBL BCA accounting methodology to each of the treatment scenarios. For all scenarios, the NPV calculations assume that the facility is designed in 2012 and constructed between 2013 and 2015, with operation, maintenance and replacement costs distributed evenly over the life of the facility. Each facility is assumed to have a 30-year life (2016 to 2045) with annual operation and maintenance costs and replacement of worn equipment. Following Office of Management and Budget (OMB) Guidance, the NPV of the treatment trains is calculated at a 3% and 7% discount rate, except where otherwise noted (OMB, 2003). Factors that could not be quantified in monetary terms are described qualitatively.

4.3.3.1 Scenario 1 Nonpotable Reuse for Landscape Irrigation

Table 4.6 shows the NPV results for Scenario 1 nonpotable reuse for landscape irrigation, comparing a GMF-based process (Scenario 1A) to an MF-based process (Scenario 1B) and an MF- and an RO-based process (Scenario 1C). The environmental factors contribute a similar percentage to TBL costs for Scenarios 1A and 1B at each facility scale. This share hovers in the 5 to 8% range. However, the environmental costs jump substantially in the case of Scenario 1C, accounting for about 16 to 18% of the TBL costs. The NPV cost differences among scenarios are striking. Scenario 1A is the lowest cost option at each scale and also has the lowest environmental costs. The MF process alone increases the NPV capital and O&M costs relative to the granular media process by $8.6 million (25%) at the 5 mgd scale plant and $159 million (86%) at the 70 mgd facility. The environmental costs widen the gap between treatment train costs. Considering all quantified TBL costs, choosing Scenario 1B over Scenario 1A adds $9.4 million (26%) to a 5 mgd facility and $177 million (90%) to a 70 mgd facility. Although this cost difference is not trivial, it is dwarfed by the cost comparison between GMF and the combined MF and an RO process where NPV Capital and O&M costs are from 2.5 to 3.0 times larger, depending on the scale of the facility. Comparing the TBL costs, Scenario 1C is from 2.8 to 3.5 times higher than Scenario 1A, adding from $65 million to $509 million in NPV over the life of the 5 mgd to 70 mgd facility, respectively.

Table 4.6. NPV Results for Scenario 1: Nonpotable Reuse for Landscape Irrigation ($2012; 3% discount rate)

Plant Capacity	Treatment Trains			Difference (1B-1A)	Difference (1C-1A)
	1A (GMF-Based)	1B (MF-Based)	1C (MF+RO-Based)		
Financial NPV (Capital and O&M costs)					
5 mgd	$ 35,050,000	$ 43,640,000	$ 86,100,000	$8,590,000	$51,050,000
20 mgd	$ 67,440,000	$ 94,750,000	$ 192,960,000	$27,310,000	$125,520,000
70 mgd	$ 185,250,000	$ 344,600,000	$ 581,730,000	$159,350,000	$396,480,000
Environmental NPV (Monetized GHGs and Other Air Emissions)					
5 mgd	$ 1,800,000	$ 2,630,000	$ 15,770,000	$830,000	$13,970,000
20 mgd	$ 4,710,000	$ 6,580,000	$ 40,080,000	$1,870,000	$35,270,000
70 mgd	$ 11,350,000	$ 29,240,000	$ 124,370,000	$17,890,000	$113,020,000
Total NPV					
5 mgd	$ 36,850,000	$ 46,270,000	$ 101,870,000	$9,420,000	$65,020,000
20 mgd	$ 72,150,000	$ 101,330,000	$ 233,040,000	$29,180,000	$160,890,000
70 mgd	$ 196,600,000	$ 373,840,000	$ 706,100,0000	$177,240,000	$509,500,000

In addition to the quantified TBL costs, there are some qualitative TBL factors to consider in selecting the treatment train. These qualitative factors are described in Table 4.7. It is assumed that the ecosystem footprint of the facility does not vary to any significant degree across the treatment trains and is therefore not applicable to the decision. The treatment trains do differ in terms of their water efficiency. Scenario 1A at 97% is the most efficient at converting source water to reuse 'whereas Scenario 1C at 80% is the least efficient. At the present time, this is not likely to be an important differentiator in most decisions, but where competing uses for source water exist (e.g., maintaining instream flows) it could become a factor.

Next on the list are air emissions of ammonia and carbon monoxide. These are quantified in pounds per year but are not valued in monetary terms because of the lack of national average values for these pollutants. However, adverse human health consequences associated with these emissions can be estimated using EPA's BenMap model for the location of interest. Scenario 1A has the lowest emissions of both constituents, followed by Scenario 1B. Scenario 1C's emissions are about seven times as great as Scenario 1A's emissions.

The next factor relates to the potential for the landscape irrigation end user to incur costs that are due to the quality of the reuse water, especially because of nutrients or TDS. Scenarios 1A and 1B are similar with respect to nutrient and salinity content. As explained in more detail in Chapter 2, nutrients in reuse water can be beneficial for landscape irrigation, as their presence can reduce or eliminate the need to add fertilizers, resulting in a cost savings. However, some golf course owners have noticed an increase in mowing requirements and have had to control nuisance algae in their reuse ponds. The net financial effect of nutrients in reuse water thus varies across end users. Excess salinity in reuse water also can lead to higher management costs for the end user and adverse effects on vegetation, which may drive the implementation of RO in some cases.

Chapter 2 also addressed the question of differential effects of runoff to surface waters depending on the quality of the reuse water. It was concluded from the empirical literature that none of the reuse treatment scenarios differs from other water sources in this regard. However, when it comes to groundwater discharges, the salinity content of reuse can affect ground water resources in some circumstances. This is especially the case in closed groundwater systems in arid or semi-arid regions of the country. Because Scenario 1C removes TDS and the other two treatment trains do not, this can be a factor in selecting the preferred treatment train.

Table 4.7. Summary of Qualitative TBL Factors for Scenario 1: Nonpotable Reuse for Landscape Irrigation—the 20 mgd Case

Qualitative Factor	Scenario A	Scenario B	Scenario C
Ecosystem footprint	N/A	N/A	N/A
Water reuse efficiency (i.e., a measure of the percentage of the intake water that becomes reuse water supply)	97%	94%	80%
Air emissions of ammonia NH_3 from transporting chemicals and/or residuals (lb/year)	1.0	1.8	7.4
Air emissions of carbon monoxide (CO) from transporting chemicals and/or residuals (lb/year)	60	104	438
Landfill disposal of residuals	N/A	N/A	N/A
Qualitative assessment of financial effects on end users owing to quality of reuse water	1. Landscape irrigation cost savings or cost increase owing to nutrients in reuse water where the net effect depends on the relative economic significance of reductions in fertilizer applications versus potentially higher mowing costs or managing nutrients in reclaimed water storage ponds. 2. High TDS levels or high SAR/EC ratios can lead to increased user costs for managing this salinity (e.g., by adding soil amendments such as gypsum or applying excess water to leach salts and prevent salt buildup in the soil profile).		1. Low levels of chloride, sodium, and boron can be beneficial to crops that are sensitive to elevated concentrations of these ions. 2. Extremely low TDS water can contribute to pipe corrosion and can be problematic for irrigation of some clay or sodic soils or discharge to wetlands. Adverse effects can be mitigated by adding chemicals or by water source blending before finished water discharge.
Qualitative assessment of pollutant loads (run-off from landscape irrigation) to surface waters	Depending on irrigation methods, there is a wide range of irrigation efficiencies and potential distribution of surface and subsurface return flows. In areas that practice appropriate nutrient management measures, return flows to surface waters are not measurably different than other water sources.		Not measurably different than other water sources
Qualitative assessment of quality of discharges by end user to groundwater	Depending on irrigation methods, there is a wide range of irrigation efficiencies and potential distribution of surface and subsurface return flows. Reuse water applied to landscapes over potable groundwater supplies can show elevated levels of some constituents, but no research has shown concentrations at levels requiring mitigation. This is likely owing to careful management of reuse water for landscape irrigation. Elevated salinity levels can also be a concern especially in extremely arid environments and in closed groundwater basins. In such circumstances source controls (i.e., to reduce salinity content) or treatment technologies that reduce salinity may be necessary.		Scenario C will remove TDS, which may be beneficial in arid and semi-arid regions, especially in closed groundwater basins. Scenario C will also remove nutrients, but there are much less expensive ways to manage nutrients.
Qualitative assessment of risks to human health	Each treatment train is protective of human health. The public may have different perceptions of risks depending on the treatment train, suggesting that there may be costs associated with improving communication and outreach.		

Note: N/A = not applicable

The last qualitative factor relates to human health risks. Each treatment train is protective of human health, and there are no known differences in human health risks across treatment trains. However, there may be differences in public risk perceptions. This suggests that it can be important to address such perceptions through public outreach and communication to facilitate sound decision making.

4.3.3.2. Scenario 2: Potable Reuse

The NPV results for Scenario 2 Potable Reuse are reported in Table 4.8. Scenario 2A, the GAC-based treatment train has the lowest NPV costs in each category no matter what size facility. TBL costs for Scenario 2A range from $86 million for a 5 mgd facility to $466 million for a 70 mgd facility. The environmental costs range from $4.9 million to $37 million and account for about 6 to 8% of the TBL costs, respectively. The next least cost option is Scenario 2B1, the RO with ocean disposal treatment train. Looking only at the NPV capital and O&M costs, ignoring environmental costs for the moment, suggests that this scenario is somewhat comparable to Scenario 2A at the 5 mgd scale. Choosing the RO treatment train when ocean disposal is an option adds about $11.2 million (14%) to the capital and O&M cost of a GAC-based treatment train. This percentage increases rapidly with facility scale. For a 20 mgd facility, the cost increases by $59 million (36%) and for a 70 mgd facility, the incremental cost is $261 million, reflecting a 60% increase in capital and O&M costs over the GAC-based facility. However, once the environmental costs are taken into consideration, the gap between Scenario 2A and Scenario 2B with ocean disposal is much more significant, even for the 5 mgd facility. The incremental TBL cost differential between treatment trains increases to $24 million (28%). This TBL differential increases in significance with the scale of the facility. At 20 mgd, the TBL cost differential is $93 million (54%), and at 70 mgd the RO based facility with ocean disposal costs $381 million (82%) more than the GAC-based treatment train.

The NPV differences between the GAC-based treatment train and the RO-based treatment trains requiring alternative methods of brine disposal, such as would be necessary at inland locations, are quite dramatic at every scale. Choosing Scenario 2B RO-based with mechanical evaporation over 2A GAC-based would increase the cost by a factor of 2.2 to 3.6 times, for a 5 mgd to 70 mgd facility, respectively. Scenario 2B RO-based with evaporative ponds is similar; TBL costs for a 5 mgd and 70 mgd facility are 2.0 times and 3.7 times higher, respectively, than the 2A GAC-based approach.

Table 4.8. NPV Results for Scenario 2: Potable Reuse ($2012; 3% discount rate)

	Treatment Trains						
Flow	**2A (GAC-Based)**	**2B1 (RO-Based w/ Ocean Disposal)**	**2B2 (RO-Based with Mechanical Evaporation)**	**2B3 (RO-Based with Evaporation Ponds)**	**Difference (2B1-2A)**	**Difference (2B2-2A)**	**Difference (2B3-2A)**
Financial NPV (Capital and O&M costs)							
5 mgd	$80,960,000	$92,170,000	$ 133,430,000	$145,240,000	$11,210,000	$52,470,000	$ 64,280,000
20 mgd	$161,140,000	$219,925,000	$ 358,190,000	$449,570,000	$ 58,695,000	$ 196,960,000	$288,340,000
70 mgd	$428,970,000	$ 690,610,000	$ 1,128,780,000	$ 1,556,730,000	$261,490,000	$ 699,660,000	$1,127,610,000
Environmental NPV (Monetized GHGs and Other Air Emissions)							
5 mgd	$ 4,900,000	$ 17,790,000	$ 54,080,000	$ 24,000,000	$ 12,890,000	$ 49,180,000	$ 19,100,000
20 mgd	$ 11,990,000	$ 46,780,000	$ 175,000,000	$ 62,300,000	$ 34,790,000	$ 163,010,000	$ 50,310,000
70 mgd	$ 36,830,000	$ 156,100,000	$ 566,480,000	$ 175,480,000	$ 119,270,000	$ 529,650,000	$ 138,650,000
Total NPV							
5 mgd	$85,860,000	$109,960,000	$187,510,000	$169,240,000	$ 24,100,000	$ 101,650,000	$83,380,000
20 mgd	$173,130,000	$266,705,000	$ 533,190,000	$ 511,870,000	$93,485,000	$ 359,970,000	$338,650,000
70 mgd	$465,800,000	$ 846,710,000	$1,695,260,000	$ 1,732,210,000	$380,760,000	$1,229,310,000	$1,266,260,000

Water reuse efficiency also differs across treatment trains ranging from a low of 80% for the RO-based treatment trains involving ocean disposal or evaporative ponds to a high of 94% for the GAC-based treatment train, as well as the RO-based treatment with mechanical evaporation. This can be a consideration in situations where there are competing demands for reuse water or where it is limited in supply. For the 20 mgd facility, air emissions of ammonia and carbon monoxide are comparable across all scenarios and thus do not need to be considered in the TBL. Landfill disposal of residuals can be a consideration as landfill capacity shrinks, and new landfill sites must be developed, thus taking land out of other productive uses. The RO-based process with ocean disposal is the only scenario that requires no landfill space. RO with mechanical evaporation has relatively modest landfill space requirements, contributing about 320 cubic yards annually for a 20 mgd facility. The GAC-based treatment train generates 7820 cubic yards of solid waste annually, and the RO with evaporative ponds requires 48,741 cubic yards. This provides another reason why the RO with evaporative ponds treatment trains becomes less viable with increases in flow.

In most locations throughout the country, the quality of the reuse water is such that none of the treatment trains require additional management measures on the part of the end user. However, there are circumstances where the level of TDS in the source water can be problematic for Scenario 2A, the GAC-based treatment train, which unlike the RO-based treatment trains does not remove TDS during treatment. In regions of the country where the source water has a relatively high salinity content (e.g., Colorado River, some groundwater resources) and where blending with lower TDS water is not an option, this technology may result in water that exceeds the 500 mg level for TDS, which could lead to taste issues that some end users may choose to mitigate. At even higher TDS levels, the reuse water would not be acceptable, so other treatment technologies that remove TDS would be necessary. This can occur in closed groundwater systems, for example. Thus TDS is an important consideration in selecting the preferred treatment technology. For the locations where TDS is not a concern, this TBL analysis has shown that there are considerable cost savings from selecting a GAC-based approach over an RO-based approach at facilities of about 5 mgd and higher, but RO with ocean disposal appears to be a reasonable alternative for small facilities 5 mgd or less.

Table 4.9. Summary of Qualitative TBL Factors for Scenario 2: Potable Reuse for Reservoir Augmentation—the 20 mgd Case

Qualitative Factor	**Scenario A**	**Scenario B (RO; Ocean Disposal)**	**Scenario B (RO; Mech Evap)**	**Scenario B (RO; Evap Ponds)**
Ecosystem Footprint	N/A	N/A	N/A	1130 acres; results in a NPV loss of 9839 DSAYs
Water Reuse efficiency (i.e., a measure of the percentage of the intake water that becomes reuse water supply)	94%	80%	94%	80%
Air emissions of Ammonia NH3 from transporting chemicals and/or residuals (lb/year)	3	7	7	7
Air emissions of Carbon Monoxide (CO) from transporting chemicals and/or residuals (lb/year)	172	399	436	413
Landfill disposal of residuals (cubic yards/year)	2911	0	8327	14605
Qualitative assessment of financial effects on end users owing to quality of reuse water	In regions of the country where the source water has a relatively high salinity content (e.g., Colorado River, some ground water resources) and where blending with lower TDS water is not an option, this technology may result in water that exceeds the 500 mg/L level for TDS, which could lead to taste issues that some end users may choose to mitigate. At even higher TDS levels, the reuse water would not be acceptable so that other treatment technologies that remove TDS would be necessary.	none	none	none
Qualitative Assessment of perceptions of risks to human health	Each treatment process differs in effectiveness at removing various constituents of emerging concern and whereas some constituents may now be detectable with advances in technology, the concentrations are very small. Any differences in risk perceptions across treatment trains are not based on any differences in known risks.			

The final qualitative factor relates to human health risks. In general, potable reuse systems are protective of public health based on all drinking water standards and public health criteria. Each of the treatment trains discussed here are also comparable and protective of public health. Each treatment process differs in effectiveness at removing various constituents of emerging concern; and although some constituents may now be detectable with advances in technology, the concentrations are very small. Any differences in risk perceptions across treatment trains are not based on any differences in known risks. However, to the extent that public risk perceptions are not in line with known risks, it can be important to communicate effectively with the public about human risks, potable drinking water safety, and TBL costs of treatment to support sound decisions.

4.3.4 Sensitivity Analysis

A number of cost assumptions used in this research can affect the TBL costs estimated for the treatment trains included in the analyzed scenarios. For example, unit power and labor costs can vary significantly in different regions of the world. Similarly, chemical costs can vary depending on numerous factors, including geographic location, chemical volume ordered, and economic conditions. Table 4.10 shows the parameters expected to vary the most and the potential effect to the scenarios analyzed.

4.3.5 Reverse Osmosis Concentrate Handling Costs

As previously noted, treatment or disposal of RO concentrate can add significant costs to the RO-based treatment trains. In fact, where sewer or ocean disposal are not available, the TBL costs associated with concentrate management can be considered cost prohibitive. For example, a 20 mgd plant for Scenario 2B generates 3.5 mgd of concentrate which requires 1130 acres of evaporation ponds or 9.7 MW of power for mechanical evaporation.

The TBL costs associated with each of these options ($200 million and $318 million, respectively, over the RO-based ocean disposal approach) are prohibitively high and in almost all cases would be considered impractical since these costs are almost equivalent to the cost of the remaining treatment plant. In addition, the unquantifiable environmental impacts (see Table 4.9) are significant. The water industry generally has acknowledged this problem and has begun researching alternative concentrate management approaches—especially concentrate volume reduction technologies that reduce the environmental impact for final disposal step (e.g., crystallization, evaporation ponds, and deep well injection).

Although numerous technologies are being investigated, none at present have been proven at full-scale to substantially reduce concentrate handling costs to the extent that would allow implementation of RO-based plants at inland locations without significant additional costs. To illustrate this point, capital and annual operating costs for Scenario 2B were developed for a volume reduction approach using acid addition with a brine concentrator (but without the brine crystallizer) followed by evaporation ponds. Overall plant recovery was increased from 85 to 93% using this approach and concentrate flows to the evaporation ponds were reduced from 3.5 mgd to 0.15 mgd (assumes brine concentrator recovery of 95%). In an effort to reduce concentrate handling costs to the maximum extent possible for this analysis, the double liner required by some states for evaporation ponds was waived in lieu of a single liner that can be permitted in some states (e.g., Texas).

Figures 4.18 and 4.19 show the capital and annual operating costs of this approach compared to Scenarios 2A and 2B at 20 mgd plant capacity. Although capital and O&M costs are lower than either evaporation ponds or mechanical evaporation, they are still about 40% and 70% higher, respectively, than RO-based ocean disposal. The capital and O&M NPV for volume reduction is approximately $340 million, which is 5% and 25% lower, respectively, than mechanical evaporation and evaporation ponds. However, like these other concentrate management approaches, the NPV for volume reduction is significantly more than Scenario 2A (110% more) and Scenario 2B (50% more), suggesting that it may still be cost prohibitive to implement. Environmental costs, although not shown, are also significantly more than Scenario 2A and the RO-based ocean disposal approach.

Table 4.10. Sensitivity Analysis at 20 mgd Plant Capacity

Parameter	Assumed Value	Variability	Treatment Trains Impacted	Sensitivity Analysis
Financial Costs				
Electricity Cost	$0.08/kwh	The U.S. Energy Information Administration shows the average retail prices of electricity varying between $0.054/kwh and $0.1198/kwh for the contiguous United States (EIA, 2012). Cost in Hawaii and Alaska are much higher at $0.2698/kwh. Industrial costs in Europe averaged $0.15/kwh in 2012 (Eurostat, 2013). Costs for the Pacific and Middle Atlantic regions of the United States are reported by EIA at $0.0731/kwh and $0.0751/kwh, respectively. Because the Pacific and Middle Atlantic regions include some of the larger operational reuse plants in the world, they served as a basis for the power cost selection of $0.08/kwh included in the cost model.	The membrane based trains (S1B, S1C, S2B) are very power intensive and are most affected by changes to power costs.	At $0.08/kwh power costs for train S2B are $650,000 more than power costs for S2A. At $0.06/kwh, this difference reduces to $420,000. At $0.15/kwh, this difference increases to $1,400,000. Regardless of the unit power costs assumed, total annual O&M costs for Scenario 2B are more than total annual O&M costs for Scenario 2A.
Chemical Costs	Varies by chemical	Unit costs for chemicals can vary significantly by proximity to manufacturing plant, annual volume ordered, economic conditions, catastrophic occurrences affecting chemical production (e.g., hurricanes), supply / demand factors, and raw material prices. For example, from 2008 to 2009, 25 utilities reported an 80% average increase in the price of caustic soda (Henderson et al., 2009).	All treatment trains analyzed use significant quantities of chemicals and would therefore be affected by chemical cost variability.	Because of the different chemicals used by each treatment train and because price variability can occur for one chemical but not others, conducting a sensitivity analysis, chemical by chemical, would be complex and not particularly useful to this report. However, in general terms, Scenario 1C uses significantly more chemicals than Scenarios 1A and 1B (about eight times as much) and would therefore be more likely to be affected by chemical price changes. Similarly, Scenario 2B-ocean disposal uses more chemicals than Scenario 2A (about 30% more) and would therefore likely be more affected. Use of mechanical evaporation for RO concentrate handling would result in Scenario 2B using 60% more chemical than Scenario 2A. Scenarios 1A and 2A would likely remain the least expensive treatment trains regardless of chemical prices.
GAC Costs	$1.36/lb	El Paso Water Utilities reported GAC replacement costs of $1.36/lb and the Upper Occoquan Service Authority reported GAC replacement costs of $0.80/lb. Data collected for plants operated by CH2M HILL in 2011 indicated GAC replacement costs ranging from $0.72/lb to $3.05/lb. The higher unit price was likely a result of small ordered quantities (e.g., < 5000 lb).	Scenario 2A	At $1.36/lb for GAC replacement costs, Scenario 2A total annual O&M costs assuming 2 year GAC replacement frequency are $4.2 million. At $2.00/lb for GAC replacement, this cost increases to $4.6 million, which is still below the total annual O&M cost for Scenario 2B ($5.9 million). At $0.70/lb for GAC replacement, the Scenario 2A total annual O&M costs drop to $3.8 million. Therefore, GAC replacement costs do not affect the overall analysis between Scenarios S2A and S2B, because Scenario S2A always has lower annual O&M costs than Scenario S2B.
Labor Costs	$0.07 / gallon of capacity for plants >15mgd; $0.16 for plants <15mgd	Labor rates can be largely influenced by local factors such as regional economies, labor laws, and unionized labor. The number of staff employed can be influenced by the degree of automation incorporated and the number of mechanical equipment items and instruments requiring maintenance.	All	The utility survey conducted did not reveal significant differences in labor costs for the different types of treatment trains analyzed. In addition, all treatment trains analyzed can be automated to the same degree. Therefore, no labor cost differences between treatment trains of equivalent capacity were assumed in this analysis.

Table 4.10. Sensitivity Analysis at 20 mgd Plant Capacity (continued)

Parameter	Assumed Value	Variability	Treatment Trains Impacted	Sensitivity Analysis
Discount Rate	3%	OMB recommends sensitivity analysis on the discount rate (7%) owing to the many factors that can affect the rate and to the influence that the rate can have on project selection.	All	At the 7% discount rate all NPV costs and NPV cost differences are slightly smaller than at the 3% discount rate. However, the choice of discount rate had no effect on which treatment trains had the lowest TBL costs.
Environmental Costs				
Social cost of carbon	Mean of distribution at 3% discount rate	The estimate for the social cost of carbon (GHG emissions) is highly uncertain and is under revision. The recent empirical evidence suggests that it may be grossly underestimated, especially owing to the influence of events projected to occur with lower probability but large consequences. Although there are estimates that differ by an order of magnitude, for the purposes of this sensitivity analysis we chose to use the one estimate from Interagency Working Group on the Social Cost of Carbon (2010) that was intended to capture the extreme event tail of the distribution. This estimate is about three times as large as the base value used in the comparison of treatment trains.	All	The estimate of environmental costs is very sensitive to the estimate of the social cost of carbon as the GHG emissions account for about a third of the estimated environmental costs of each of the alternatives. Increasing these costs roughly by a factor of three adds about 50% to the total environmental costs of each of the alternatives measured relative to the base. The effect of the higher social cost of carbon is to widen the gap in TBL costs between scenarios and to make the cases for Scenario 1A Nonpotable Reuse and Scenario 2A potable reuse even stronger. In addition, even at the lower estimate for the social cost of carbon, the environmental costs contributed a substantial share to the TBL costs (from about 5% to 18% for Scenario 1 and from 7% to 28% for Scenario 2). The range in these percentages increase to 7% to 32% for Scenario 1 and 9% to 38% for Scenario 2. Thus uncertainty about the social cost of carbon can have a very important effect on TBL costs.
Cost of increasing air emissions	Variable depending on type and source	Our base case uses the lower of the two values reported by EPA. The upper end of the range is more than twice the estimate used in this TBL (e.g., \$136,877/ton versus \$273,754 for $PM_{2.5}$ emissions from electricity generating units and \$379,044/ton versus \$758,088/ton for highway truck emissions). The factor that causes the two estimates to diverge is the difference in the base case for the percentage of the population that is currently exposed to concentrations of $PM_{2.5}$ at the lowest measured level (LML). This effects the \$/ton for NO_X and SO_2 as well, because these pollutants are $PM_{2.5}$ precursors. The upper end of the \$/ton of these air pollutants is about 2.3 times the lower bound estimates. Even with using the lower bound estimate, it is important to note that the values are largely dependent on the estimate of the value of a statistical life. In 2012 this was estimated at \$8.4 million, which EPA has vetted with the Science Advisory Board. Nonetheless, this remains an area of active research and EPA anticipates revisiting how to best value reductions and increases in the risks of premature fatalities. Health effects that do not result in premature mortality generally are based on cost of illness (medical costs) and lost work days. These costs underestimate such health effects, because they do not include the disutility to the individual from being sick.	All	Given the uncertainty about the value of a statistical life and the base case for the percentage of the population that may already be exposed to measurable levels of $PM_{2.5}$, this TBL took the conservative approach of using the lower values provided by EPA. Even so, the premature mortality and morbidity effects contribute significantly to the TBL costs for each of the scenarios and account for roughly 2/3 of the monetized environmental costs. They widen the NPV costs between Scenarios 1A and 1B, as well as between 2A and 2B, making the case stronger for choosing 1A and 2A, whenever possible. Should future research lead to a reduction in the estimated value of a statistical life, this effect could be ameliorated somewhat but not to the point of favoring a different treatment train.

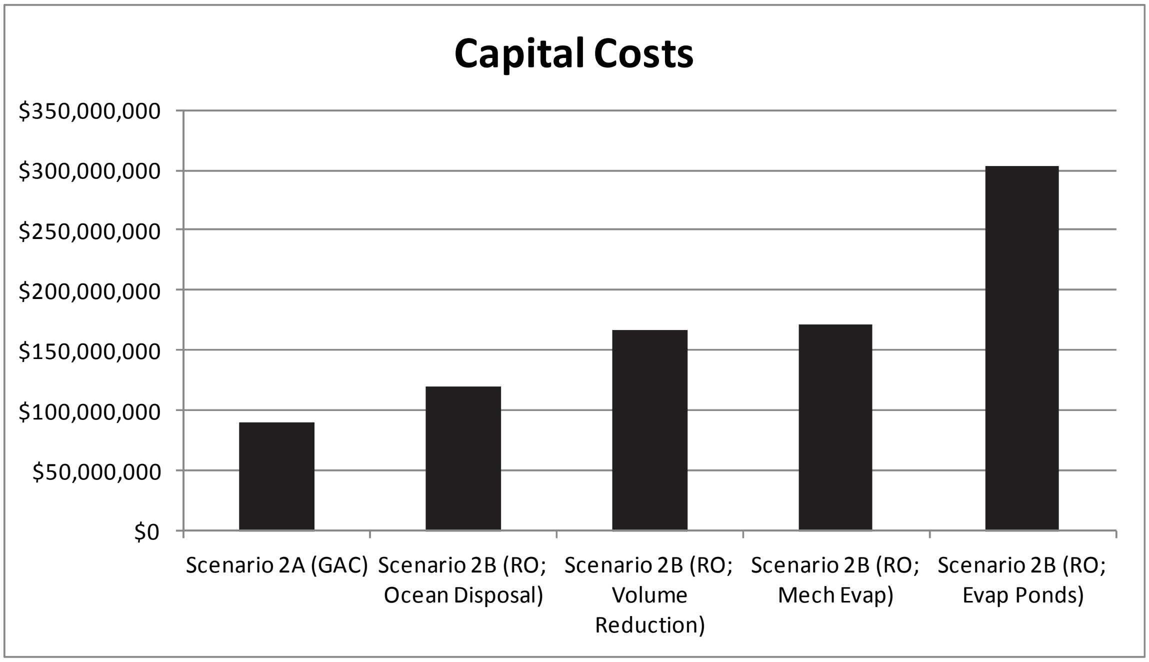

Figure 4.18. Capital costs of the RO-based volume reduction approach compared to Scenario 2B options at 20 mgd plant capacity.

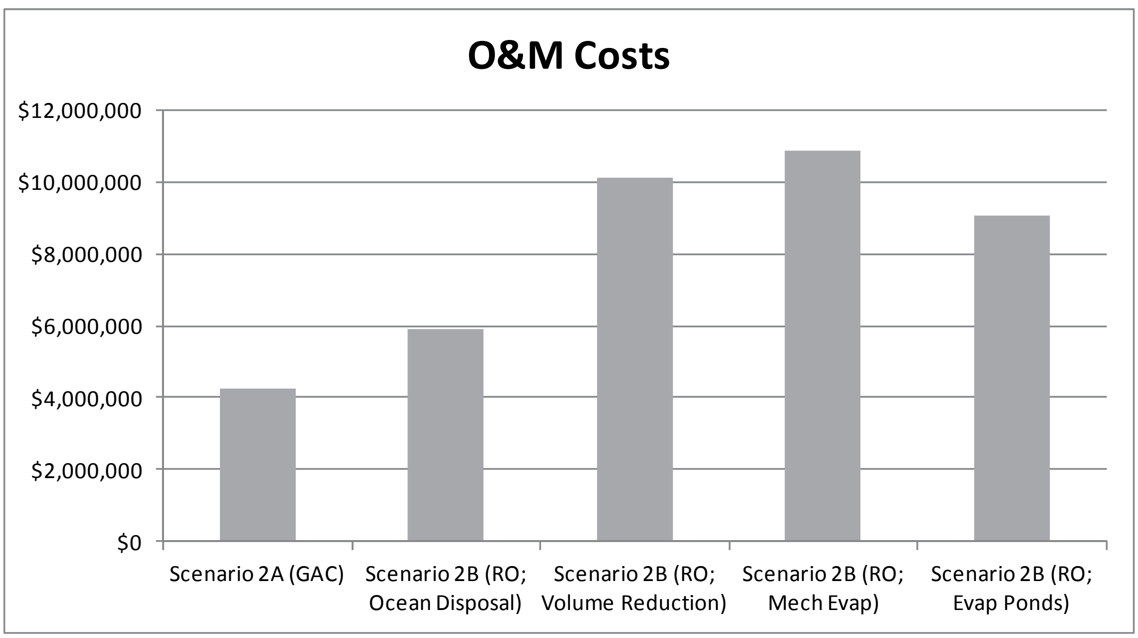

Figure 4.19. Annual operating costs of the RO-based volume reduction approach compared to Scenario 2B options at 20 mgd plant capacity.

Chapter 5

Current and Future Trends Affecting Overtreatment

Trends associated with policies, regulations, environmental sensitivities, and public awareness can affect the amount of treatment implemented at water reuse plants. This section identifies current and future trends that may lead to overtreatment.

5.1 California's Water Reuse Chlorine Disinfection Requirements

Water reuse in California is regulated by Division 4 (Environmental Health) of California's Title 22 Code of Regulations. Water reuse for unrestricted nonpotable use (e.g., irrigation of parks, school yards, golf courses, residential yards, food crops) requires that the water be "disinfected tertiary recycled water," which is defined as secondary effluent wastewater that is filtered and subsequently disinfected according to the following criteria:

> (a) The filtered wastewater has been disinfected by either:
>
> > (1) A chlorine disinfection process following filtration that provides a CT (the product of total chlorine residual and modal contact time measured at the same point) value of not less than 450 milligram-minutes per liter at all times with a modal contact time of at least 90 minutes, based on peak dry weather design flow; or
> >
> > (2) A disinfection process that, when combined with the filtration process, has been demonstrated to inactivate and/or remove 99.999% of the plaque-forming units of F-specific bacteriophage MS2, or polio virus in the wastewater. A virus that is at least as resistant to disinfection as polio virus may be used for purposes of the demonstration.
>
> (b) The median concentration of total coliform bacteria measured in the disinfected effluent does not exceed an MPN of 2.2 per 100 milliliters utilizing the bacteriological results of the last 7 days for which analyses have been completed and the number of total coliform bacteria does not exceed an MPN of 23 per 100 milliliters in more than one sample in any 30 day period. No sample shall exceed an MPN of 240 total coliform bacteria per 100 milliliters.

The CT requirement of 450 mg-min/L and the modal contact time of 90 min are partially based on virus inactivation testing done in California, which showed that these requirements were necessary to meet 5 log virus inactivation. Chlorine contact basins and chlorine dosing systems at water reuse plants in California have been designed to meet these criteria, which has resulted in very large basins. For example, at a plant flow of 20 mgd (76 mld) and a hydraulic short-circuiting factor of 0.7 (common for chlorine contact basins), the volume required to meet a modal contact time of 90 min and a CT of 450 is approximately 1.8 million gal (6.8 million L). At a basin water depth of 15 ft (4.6 m), chlorine contact basin would be approximately 250 ft long (76 m) by 65 ft wide (19.8 m), requiring a significant quantity of concrete.

Nitrification at WWTPs was not widely practiced when the 450 mg-min/L CT requirement was established in California. Consequently, monochloramine was predominately formed when chlorine was added to secondary effluent. Recent research by Munakata et al. (2009) has shown significant virus removal at lower contact times when free chlorine is used as a disinfectant (Munakata et al., 2009). Six log inactivation of poliovirus and 7 log inactivation of MS2 was achieved in a nitrified filtered effluent using a chlorine dose of 6 mg/L and a contact time of only 20 min. Free chlorine also inactivated total coliform below the detection limit (2.2. CFU/100mL). Because of the regulatory trend to reduce total nitrogen values to less than 10 mg/L, many wastewater treatment plants have provided nitrification (and denitrification) treatment that reduces the effluent ammonia concentration to consistently below 1 mg/L. Consequently, chlorine added for reuse disinfection often forms a free chlorine residual, which, according to recent research, requires much less contact time than monochloramine for equivalent disinfection. Using a contact time of 20 min for free chlorine, the chlorine contact basin volume for a plant flow of 20 mgd would be 0.4 million gal (1.5 million L), which is much less than the 1.8 million gal required for compliance with the Title 22 Regulations. The chlorine dose also would be reduced because of the shorter contact time. Negative TBL effects affected by requiring overtreatment through mandating a CT of 450 include higher capital and operating costs and higher greenhouse and air emissions because of chemical deliveries.

5.2 California's Groundwater Recharge Regulations

California's draft groundwater recharge regulations (CDPH, 2013) require full advanced treatment for potable reuse plants that directly inject water into the subsurface. Full advanced treatment is not required for potable reuse plants that percolate water into the subsurface with SAT. Full advanced treatment includes RO and advanced oxidation treatment processes as multiple barriers to trace organics and pathogens. Reverse osmosis treatment is specifically required to reduce the TOC concentration of wastewater origin to 0.5 mg/L; few other treatment technologies can meet this requirement. Historically, implementation of RO treatment along the California coast has not been onerous because of the relatively inexpensive disposal of RO concentrate to the ocean through existing permitted discharge lines. For example, disposal of the RO concentrate for the 70 mgd (265 mld) Groundwater Replenishment System, which began subsurface injection in 2008, is achieved through discharge to Orange County Sanitation District's ocean outfall, which was permitted and operational long before GWRS was built. However, compliance with a 0.5 mg/L TOC limit through implementation of RO treatment is not as simple at inland locations where RO concentrate handling and disposal can be very costly and environmentally challenging. In addition, disposal costs along the coast can be high if connection to an existing sewer/brine disposal line is not readily available and inexpensively implementable.

Because California has been a regulatory and technological leader in water reuse for many decades, other entities naturally look to California for guidance when developing water reuse regulations, policies, and projects. Requiring RO treatment to match California's regulations (for injection projects) is a logical first step for other entities because of its reputation as an absolute barrier to pathogens and its effectiveness in removing salt and trace organics. This is a trend seen at other locations that have recently implemented potable reuse projects, such as Singapore, Australia, and Texas, where RO treatment has been provided. However, as discussed in this report, alternative technologies to RO, including GAC and SAT-based treatment trains, should be considered for potable reuse by evaluating the relevant financial, social, and environmental aspects for various technologies at site-specific locations. Ultimately, RO treatment may be selected at some locations by the need for TDS removal, but there are alternatives for reducing TDS (e.g., blending source water) and in many locations TDS is not a concern. Therefore, a more complete consideration of other technologies using a TBL approach is important as potable reuse expands beyond California.

5.3 California's Salt and Nutrient Management Plans

Salinity and nutrient management of groundwater basins is an important issue, especially within arid and semi-arid regions where salinity tends to be higher and where groundwater is a more important source of potable water. In California, the State Water Resources Control Board adopted a Recycled Water Policy in February 2009 that requires "Salt and Nutrient Management Plans be completed by 2014 to facilitate basinwide management of salts and nutrients from all sources in a manner that optimizes recycled water use while ensuring protection of groundwater supply and beneficial uses, agricultural beneficial uses, and human health" (California State Water Resources Control Board, 2009). The purpose of these plans is to help optimize recycled water use while ensuring protection of groundwater supply and beneficial uses, agricultural beneficial uses, and human health.

The issue of recycled water irrigation return flows to groundwater is most acute in extremely arid environments and in closed groundwater basins. Irrigation concentrates salts through the process of evaporation which reduces the volume of water while leaving salts behind that can result in higher salt concentrations in groundwater basins. Because of the evaporation-driven concentration of salts in response to irrigation and crop water use, any irrigation use of groundwater (recycled water or other water supplies) will tend to further concentrate salts within a closed groundwater basin. In these instances, a comprehensive assessment of the basin water and salt budget, additional salt source, and potential source control and treatment alternatives may be necessary to make informed decisions on the appropriate recycled water treatment approaches. For groundwater basins where existing or projected salt concentrations are high, salt removal technology may be necessary to maintain acceptable groundwater salt concentrations, which may lead to overtreatment in some cases. Careful review of alternative treatment approaches, such as comparing TBL costs of sidestream RO treatment to full-stream RO treatment, are important because of the significant TBL costs associated with salt removal technologies and their associated concentrate handling approaches.

5.4 Heightened Awareness to Chemicals of Emerging Concern

Recent improvements in analytical techniques have lowered the detection limit significantly for the measurement of many chemicals in water. For example, the minimum reporting limit for the compounds carbamazepine (anticonvulsant) and tris (1-chloro-2-propyl) phosphate (TCPP) (flame retardant) are 2.5 ng/L and 0.5 ng/L, respectively at some labs in June 2013. Although many of these emerging chemicals are now being measured in our water supplies because of laboratories' ability to report in the parts per trillion levels, these compounds have likely been present for many decades. However, the recent ability to measure these compounds at extremely low levels has heightened the awareness of the public and the water industry to the potential health effects of these CECs.

Research has shown potential negative effects on aquatic life downstream of wastewater discharges because of the presence (in the discharge) of synthetic estrogen hormones (NACWA, 2009), but no known effects on human health in potable or nonpotable reuse has been documented. In fact, as discussed in Section 2.1.3, the NRC's 2012 Water Reuse report concluded that the risk associated with 24 chemical contaminants and 4 pathogens in potable reuse does not exceed common drinking water supplies and may be orders of magnitude lower than some approved drinking water systems. Nevertheless, the heightened awareness of the public and the water industry to CECs may lead to overtreatment in some cases, especially potable reuse, because of the desire to remove all chemicals to the greatest extent possible to protect against unknown risks. A clear understanding of the financial and social effects and environmental impacts of removing CECs to extensive degrees is critical to proper decision making. In addition, educating the public and improving risk communication methods may be warranted to avoid public misperceptions about the risks from CECs from determining reuse treatment selection.

5.5 Greenhouse Gases

Greenhouse gas emissions are contributing to climate change, which is now widely recognized as an issue of global concern. According to a recent report released by the World Bank, the situation for the world's poorest countries remains dire in terms of reduced food production, increased malnutrition rates, increased water scarcity, and setbacks in attaining economic and environmental sustainability even if the major polluting countries meet their emissions pledges and commitments under the United Nations Convention on Climate Change (World Bank, 2012). Developed countries are vulnerable to serious risks as well, but effects are expected to be most severe in tropical and subtropical areas. The severity and frequency of storms, heat waves, drought and flooding are all expected to increase but can be partially mitigated to the extent that global warming can be diminished. In 2007 the Intergovernmental Panel on Climate Change (IPCC) released its fourth assessment report clearly implicating GHG emissions for causing global warming with a global mean of 0.8 $^{\circ}$C above preindustrial levels (World Bank, 2012). Although the goal is to limit warming to 2 $^{\circ}$C, the planet could warm by 4 $^{\circ}$C if countries fail to meet commitments. Accounting for land use change as well as direct emissions, CO_2 emissions reached about 35,000 million metric tons in 2012, and absent further policies, are projected to rise to about 41,000 million metric tons per year in 2020 (World Bank, 2012). Ice coverage in Greenland, Antarctica, and the Arctic is receding as the oceans and atmosphere warms. In the Arctic alone, ice coverage has declined by half over the last 30 years. Sea level rise has increased to about 3.2 cm in the last decade. During the 20th century, average sea level rise was in the range of 15 to 20 cm; should the recent trend continue, the sea level could rise a total of 30 cm over the course of the 21st century. The fourth assessment report concluded that all parts of the world included in the analysis showed a net benefit from taking current action to reduce GHG emissions, including health benefits from reduced air pollution. The governments of developed and developing countries alike are encouraged to create incentives for producers and consumers to invest in low GHG products, technologies and services significantly. The trends in climate change coupled with the positive benefits from current action to reduce GHG emissions are likely to have a dampening effect on over treating reuse water. See Section 2.2.2, Accounting Methodology, for more discussion on greenhouse gas emissions.

5.6 Nutrient Regulations

For more than a decade, nutrients have consistently ranked as one of the top five causes of beneficial use impairment in U.S. waters (EPA, 2008). Whereas a certain amount of nitrogen and phosphorus is necessary for the health of the ecosystem, excess quantities of nutrients can be harmful to fish and biodiversity and cause algal blooms, changes in water clarity, and noticeable odors. Under the Clean Water Act, water bodies are protected to serve a designated beneficial use or uses. Designated beneficial uses describe the essential services that are provided by a particular water body—such as aquatic life support, recreational use (e.g., swimming, fishing, and boating), and drinking water supply. A variety of uses are affected by excessive nutrients, but the principal uses are aquatic life, recreation, and drinking water.

With a few exceptions (e.g., ammonia toxicity), nutrients do not directly affect uses. Unlike many toxins, which directly threaten human health or aquatic life, nutrients act through a series of causal pathways resulting in diminished water quality and thereby affecting designated uses (EPA, 2010). Nutrients can also alter the physical habitat. Excess plant and algal growth change the physical flow environment and, therefore, available habitat for movement, growth, and reproduction of a variety of invertebrate and vertebrate taxa (Allan, 1995). In addition, excess plant growth affects recreation, making swimming or boating impossible, or at least undesirable (Horner et al., 1983; Welch et al., 1988). Excess plant growth can also affect drinking water treatment by increasing treatment costs associated with filtration (Knappe et al., 2004). Last, nutrients affect the abundance of different plant and algal taxa (Allan, 1995; Wetzel, 2001; Dodds, 2006). Several eutrophic taxa—cyanobacteria— are also known to produce neurotoxins that are a threat to livestock and to human health (Carmichael, 2001; Crane et al., 1980; Knappe et al., 2004). Other taxa produce chemicals that are known to cause taste and odor problems in drinking water (Izaguirre et al., 1982; Knappe et al., 2004).

Although nutrient over-enrichment can be a problem, it can be difficult to establish a causal relationship between pollutant loads and excess nutrients. Nonetheless, because of the broad geographic scope associated with nutrient problems, EPA is under pressure from a conglomerate of environmental groups calling for regulations that require additional reduction of nitrogen and phosphorous in lakes, streams, and estuaries. The states are charged with adopting nutrient criteria unless they opt for federal criteria developed by EPA. In 2011, EPA issued a memorandum that allows the states to set priorities for achieving reductions in loadings of nitrogen and phosphorous while using the tools at their disposal to achieve and verify load reductions as they continue working on developing a plan for adopting numeric criteria. Specifically, states are expected to verify that existing point source controls are effective and states are using available funds and best management measures for nonpoint sources where the nutrient reductions are most needed.

As the states develop and implement strategies for reducing nutrients, the question of how the level of nutrients in reuse water can affect nitrogen and phosphorous loads is a consideration. As previously discussed, reuse water is not discharged directly to surface water. Treated wastewater is discharged to surface waters and is already regulated. Reuse water is reclaimed and put to beneficial use (e.g., turf irrigation) other than being directly discharged to surface waters. Care must be taken to ensure that reuse ponds do not qualify as "lakes" to avoid inadvertently applying nutrient criteria to such reuse ponds (Arrington and Melton, 2010). Because reuse water is not directly discharged to surface waters, "end-of-pipe" nutrient limits on reuse water do not apply. Indeed, regulating reuse water as if it was wastewater being discharged to surface waters would unnecessarily increase the costs of treating reuse water without necessarily reducing nitrogen and phosphorus loads from runoff, which are more a function of the fertilizer application methods that are applied to the landscape and any best management practices in place (Arrington and Melton, 2010). Removing nutrients in reuse water would result in overtreatment, increasing TBL costs.

Chapter 6

Summary and Conclusions

This research was conducted with the expectation that the need for developing new sources of affordable water supply will grow significantly in the near future in both arid and less arid climates. To set the boundaries on the analysis in this research, it was assumed that the decision to develop reuse water had been made. The focus of this research was to evaluate alternative water reuse treatment trains applying a cost−benefit analysis and LCA approach toward TBL accounting to better inform this decision, specifically to avoid cases of overtreatment. In the context of this research, overtreatment is defined by spending more than is necessary or causing adverse environmental impacts and social effects without providing counterbalancing benefits. To ensure a fair comparison, the treatment technologies were selected with the aim of providing comparable water quality. Any differences in water quality that remained were discussed in terms of the benefits associated with selecting one treatment technology over another and weighed against the differential in the costs of treatment. To this end, two scenarios were selected to represent the two broad types of reuse applications: Scenario 1: Nonpotable Reuse for Landscape Irrigation, and Scenario 2: Potable Reuse for Reservoir Augmentation. In addition, each of the scenarios was analyzed at three flows: 5 mgd, 20 mgd, and 70 mgd to show how TBL costs vary with flow and to determine whether conclusions about the lowest cost treatment train varies with flow. Considerably more treatment trains are available to those utilities considering water reuse than the trains analyzed in this research; however, the trains identified represent reasonable prototypes for options that are widely applicable and serve to illustrate the BCA TBL evaluation framework.

Table 6.1 summarizes the major financial and environmental costs and associated considerations when evaluating alternative treatment trains for the 20 mgd plant capacity. All these factors, either directly or indirectly, affect the total NPV of each treatment train option. For example, chemical consumption directly affects financial costs through the annual purchase of chemicals and indirectly affects environmental costs through the air emissions related to the production and delivery of the chemicals. Conclusions related to each of the scenarios follow the table.

Table 6.1. Major Financial and Environmental Costs and Associated Considerations for 20 mgd Plant Capacity

Scenario	Capital Cost	Annual O&M Cost	Annual Environ Cost[1]	Total TBL NPV	Power Consumption (MWh/year)	Chemical Consumption (dry tons/year)	Air Emissions (tons/year)	
							CO_2e	Other
S1A (GMF-CL2)	$32M	$2.1M	$0.17M	$72M	1,800	190	1,200	4.5
S1B (MF-Cl2)	$47M	$2.8M	$0.2M	$101M	2,200	230	1,900	5.2
S1C (MF-RO-Cl2)	$101M	$5.5M	$1.4M	$233M	13,300	1,900	11,800	34
S2A (Coag-Sed-O_3-BAC-GAC-UV)	$91M	$4.2M	$0.4M	$173M	4,400	1,770	2,900	11
S2B (MF-RO-UVAOP) w/ Ocean Disposal	$120M	$5.9M	$1.6M	$267M	16,000	1,860	13,400	30
S2B (MF-RO-UVAOP) w/ Mech Evap	$172M	$10.9M	$6.3M	$533M	65,400	3,020	44,200	150
S2B (MF-RO-UVAOP) w/ Evap Ponds	$303M	$9.0M	$2.2M	$512M	22,000	1,860	17,200	49

[1]These annual environmental costs reflect the first year of operation only. The environmental costs increase over time because of such factors as population growth, growth in real income and increasing concentrations of pollutants.

6.1 Scenario 1: Nonpotable Reuse for Landscape Irrigation

Scenario 1 is a landscape irrigation scenario comparing a GMF treatment approach (Scenario 1A) to an alternative treatment approach using membrane filtration. Two membrane filtration treatment trains are compared to the GMF approach: one using an MF treatment train for solids and pathogen removal analogous to GMF (Scenario 1B) and one that also adds an RO treatment train to Scenario 1B for removal of dissolved solids and organics (Scenario 1C). The major conclusions from comparing the treatment trains for the nonpotable reuse scenario are as follows:

- The NPV of all TBL costs (i.e., capital, annual operating and maintenance and annual environmental costs) for Scenario 1A (granular media filter-based) are the lowest of the three scenarios for all flows analyzed. For example, at the 3% discount rate, the total TBLNPV costs come to $72 million for the 20 mgd plant. This compares with $101 million for Scenario 1B and $233 million for Scenario 1C. Thus, the incremental TBL costs of choosing Scenario 1B over Scenario 1A is $29 million and for choosing Scenario 1C over 1A is $161 million. These cost differences are lower at the 5 mgd flow and significantly higher at the 70 mgd flow, $177 million and $510 million for Scenarios 1B and 1C, respectively.
- The capital and annual operating costs for MF-based treatment (Scenario 1B) are most competitive with granular media filter-based treatment (Scenario 1A) at plant capacities of 5 mgd and less. Capital and annual operating costs for MF treatment at 5 mgd are $21 million (compared to $16 million for Scenario 1A) and $1.3 million (compared to $1.1 million for Scenario 1A), respectively. These costs began to diverge above 5 mgd. For example, at a plant capacity of 20 mgd, the capital and annual operating costs for MF treatment are $47 million (compared to $32 million for Scenario 1A) and $2.8 million (compared to $2.1 million for Scenario 1A), respectively.
- With such large differences in TBL costs, especially at higher flow levels, it is important to understand the circumstances where any benefits from Scenario 1B or Scenario 1C may justify selecting one of these treatment trains over Scenario 1A. Although a number of qualitative factors were considered, the single most important one that could tip the balance in favor of Scenario 1C is the salinity content of the reuse water. Other differences are relatively minor or can be managed in most situations by other less costly means, but in closed groundwater systems; for example, the only option may be to opt for the more costly RO-based treatment process. However, before drawing this conclusion, it is important to determine existing water quality and explore other options, including blending at the source and management measures by the end user because of the high TBL costs for Scenario 1C.
- The capital and annual operating costs for RO-based treatment (Scenario 1C) for landscape irrigation are very high and greatly exceed the costs for typical treatment approaches (GMF or MF). The environmental costs are also much higher. For example, for a plant capacity of 20 mgd, the NPV of the environmental costs is $40.1 million. This compares with $6.6 million and $4.7 million in quantified environmental costs for Scenarios 1B and 1A, respectively. Consequently, careful consideration should be given to using this technology for landscape irrigation purposes because of the globally significant consequences from GHG emissions and local adverse human health effects from these and other air emissions.

- The filtration process (GMF, MF, and RO) for each treatment train represents the most costly component of the capital expenditure.
- Labor represents the most costly annual operating cost for all treatment trains analyzed. However, power and major equipment replacement costs become much more significant for the mechanically intensive treatment trains (i.e., MF and RO). These higher power requirements are the primary factor in driving the environmental costs of these technologies.

6.2 Scenario 2: Potable Reuse for Reservoir Augmentation

Scenario 2 includes comparison of the GAC-based potable reuse approach (Scenario 2A) to the RO-based potable reuse approach (Scenario 2B). Scenario 2B includes three concentrate handling approaches: ocean or sewer disposal, mechanical evaporation, and evaporation ponds. A hybrid approach combining the use of brine concentration and evaporation ponds is also discussed but not evaluated to the same degree as the other treatment trains. The major conclusions from comparing the treatment trains for the potable reuse scenario are as follows:

- The NPV of all TBL costs combined for Scenario 2A GAC-based treatment are the lowest of the four scenarios for all flows analyzed. For example, at the 3% discount rate, the total TBL NPV costs come to $173 million for the 20 mgd plant. This compares with $267 million for Scenario 2B (RO with ocean disposal); $533 million for Scenario 2B (RO with mechanical evaporation); and $512 million for Scenario 2B (RO with evaporative pond). Thus the incremental TBL costs of choosing Scenario 2B over Scenario 2A ranges from $94 million (54 percent) for the ocean disposal case to $360 million (208%) for the mechanical evaporation disposal case. These cost differences are lower at the 5 mgd flow ranging from $24 million (28%) to $102 million (119%) and quite a bit higher at the 70 mgd flow, $380 million (82%) and $1,229 million (263%) for Scenarios 2B ocean disposal and 2B mechanical evaporation, respectively.
- Considering just the life-cycle capital and O&M cost to the utility and ignoring the environmental costs, Scenario 2B with ocean disposal is most competitive with Scenario 2A at low flows. For the 5 mgd facility, these NPV costs differ by $11.2 million (14%). Therefore, where sewer or ocean disposal of RO concentrate is readily available for plant capacities of 5 mgd and less, an RO-based treatment train might result in competitive costs. However, for larger plant capacities and when environmental costs are considered, the TBL costs for the RO-based approach increase considerably. For example, the gap between Scenario 2A and Scenario 2B for a 5 mgd plant with ocean disposal widens to $24 million (28%) when environmental costs are included. For plant capacities between 20 mgd and 70 mgd, the difference increases significantly.
- Because of such dramatic differences in TBL NPV costs, especially for large plant capacities and where sewer or ocean disposal of RO concentrate is not available, one needs compelling benefits to justify RO over GAC-based treatment from a TBL perspective. That benefit is the very low salinity content of RO treated water in locations where the source water has excessively high TDS levels and blending with other less saline water sources is not possible. In these situations, TBL costs for the RO-based approach could possibly be reduced by implementing sidestream RO treatment. For example, assuming a secondary effluent TDS concentration of 1,000 mg/L and a finished water goal of 500 mg/L, only 50% of the water would require RO treatment to meet the TDS goal; the remainder of the flow could be treated with a less expensive treatment approach such as ozone/BAC/GAC. Although this sidestream treatment approach was not

analyzed in this report, it should be considered when comparing treatment options because of the lower TBL costs.

- In situations where TDS removal is required at locations where concentrate disposal via the sewer or ocean is not available (e.g., some inland locations), concentrate management TBL costs can be extremely high and possibly cost prohibitive. For example, a mechanical evaporation approach to concentrate management adds $52 million and $5 million/year in capital and annual O&M costs, respectively, to the ocean disposal approach for a 20 mgd plant. Similarly, an evaporation pond approach adds $183 million and $3.1 million/year in capital and annual O&M costs. A hybrid approach that incorporates volume reduction using a brine concentrator followed by evaporation ponds reduces costs some, but capital and annual O&M costs are still $47 million and $4.2 million /year higher, respectively, than the ocean disposal approach.
- The environmental costs for each scenario primarily are because of power requirements. The major power using and GHG emitting countries of the world have committed to reducing GHG emissions. Except in situations limited by excess TDS in source water, utilities have a clear opportunity to minimize GHG emissions while not sacrificing reuse water quality by choosing Scenario 2A over Scenario 2B. This choice also has the benefit of reducing other air emissions that are harmful to human health.
- Human health risks are not a differentiator among the four scenarios; however, perceptions of human health risks may vary across treatments. This is a risk communication issue of high importance lest uniformed risk perceptions lead to excessive overpayment for reuse water and significant adverse environmental and human health effects without achieving measurable reductions in risk.
- This research was intended to develop the TBL approach as it pertains to selecting water reuse treatment and illustrate the methodology with carefully selected treatments. The analysis of treatment did not exhaust all alternatives. For example, one alternative treatment process, soil aquifer treatment (SAT) for potable reuse, was not included in this research, although it is expected to have relatively low TBL costs. It may well be the preferred TBL alternative in certain locations. For example, the Montebello Forebay groundwater recharge project in Southern California has been successfully recharging a potable aquifer for more than 40 years using soil aquifer treatment via spreading basins. Treatment provided prior to SAT is tertiary filtration followed by chlorine disinfection.
- Sensitivity analyses included varying the discount rate and the monetary value of the environmental costs owing to GHG emissions; these analyses indicated that some of the cost differences may be less and others may be more than the base case, but the preferred TBL alternatives are not affected.

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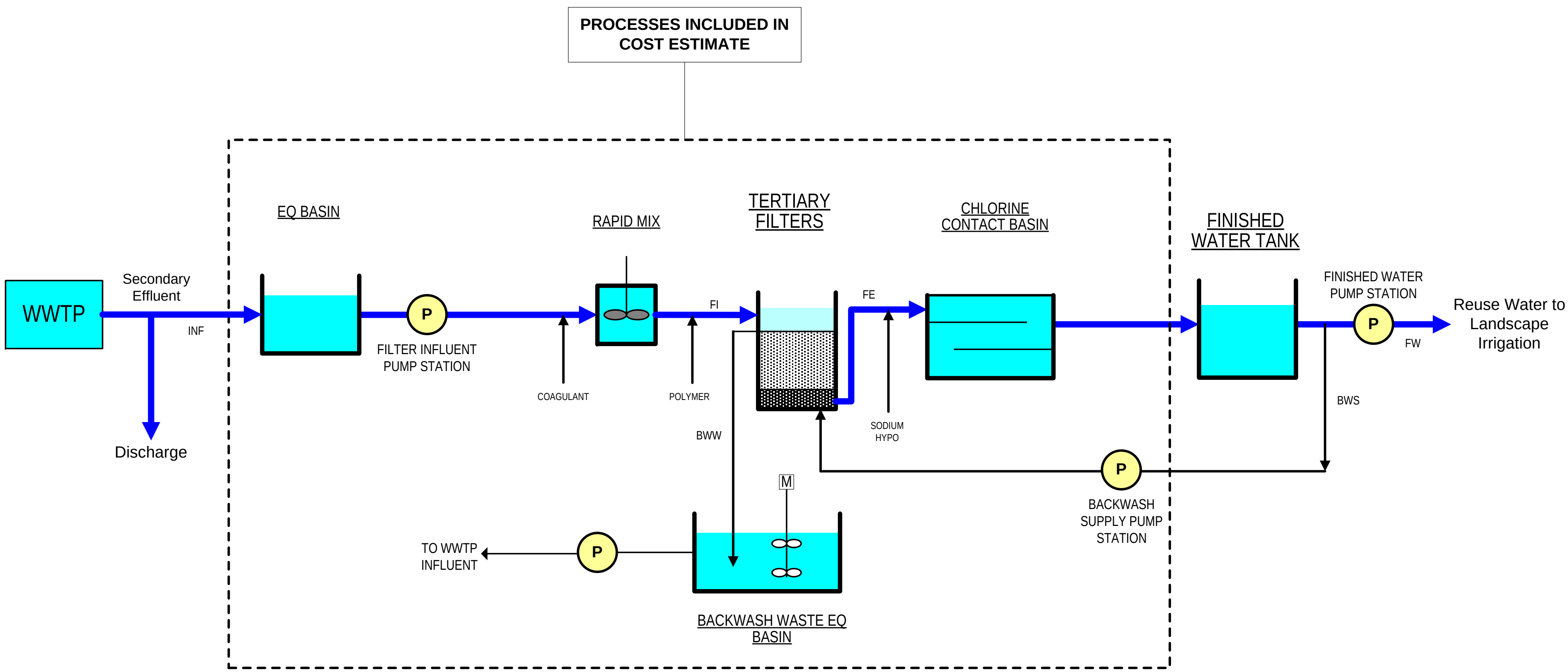
Appendix A

Detailed Scenario Process Flow Diagrams and Mass Balance Tables

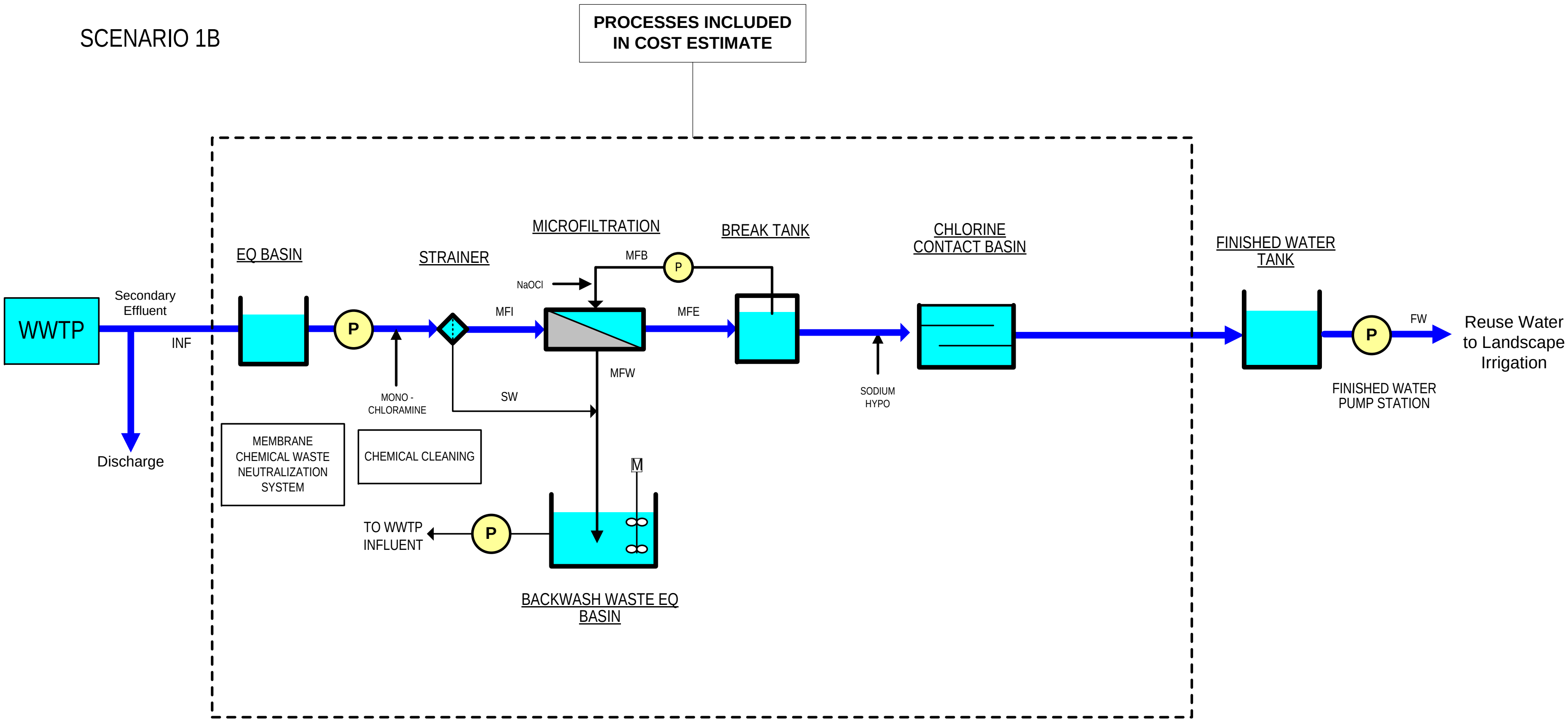
SCENARIO 1A



Scenario 1A (GMF) Flow Balance

Flow Streams	5 MGD	20 MGD Flow (MGD)	70 MGD	
Influent (INF)	5.15	20.62	72.16	
Filter Effluent (FE)	5.15	20.62	72.16	INF
Backwash Waste (BWW)	0.15	0.62	2.16	INF*0.03
Backwash Supply (BWS)	0.15	0.62	2.16	BWW
Finished Water (FW)	5	20.00	70.00	FE-BWS

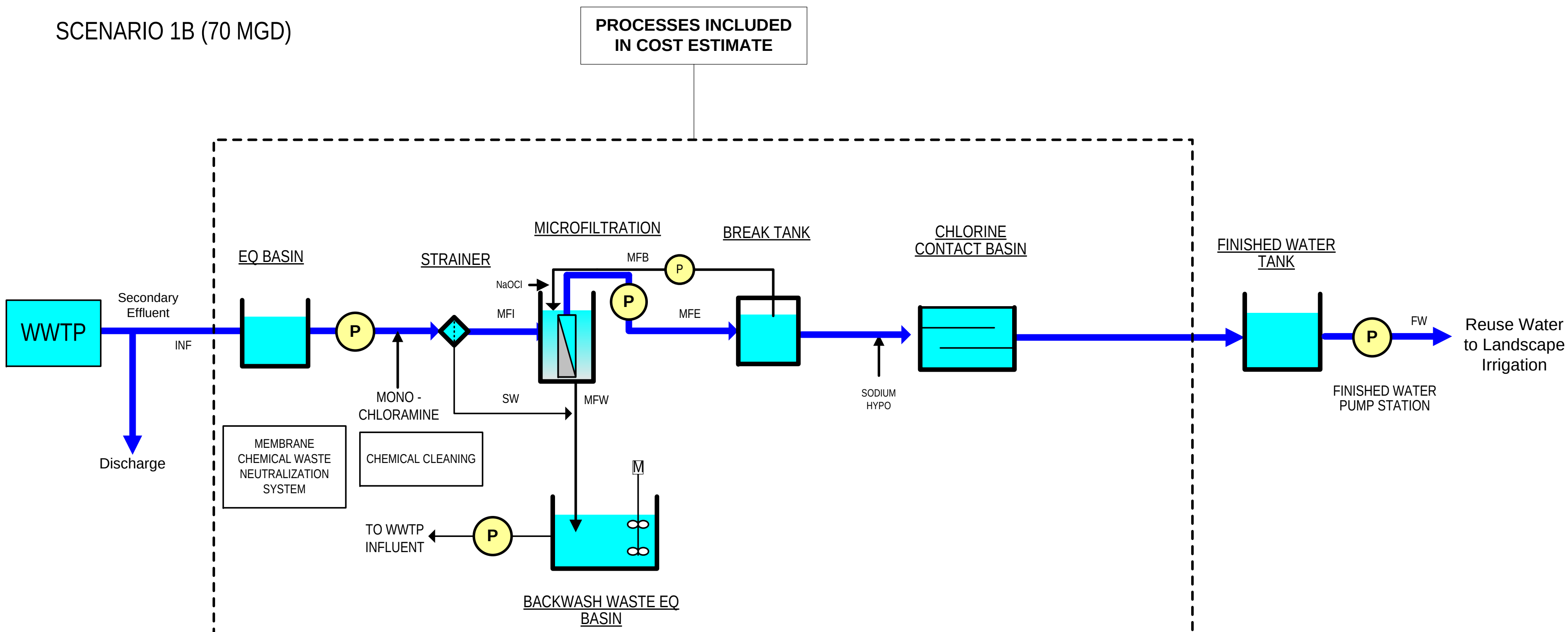
SCENARIO 1B



Scenario 1B (MF) Flow Balance

Flow Streams	5 MGD	20 MGD	
	Flow (MGD)		
Influent (INF)	5.32	21.27	
Microfiltration Influent (MFI)	5.26	21.05	INF*0.99
Strainer Waste (SW)	0.05	0.21	INF*0.01
Microfiltration Waste (MFW)	0.05	0.05	MFI*0.05
Microfiltration Effluent (MFE)	5.00	20.00	MFI*0.95
Finished Water (FW)	5.00	20.00	ROE

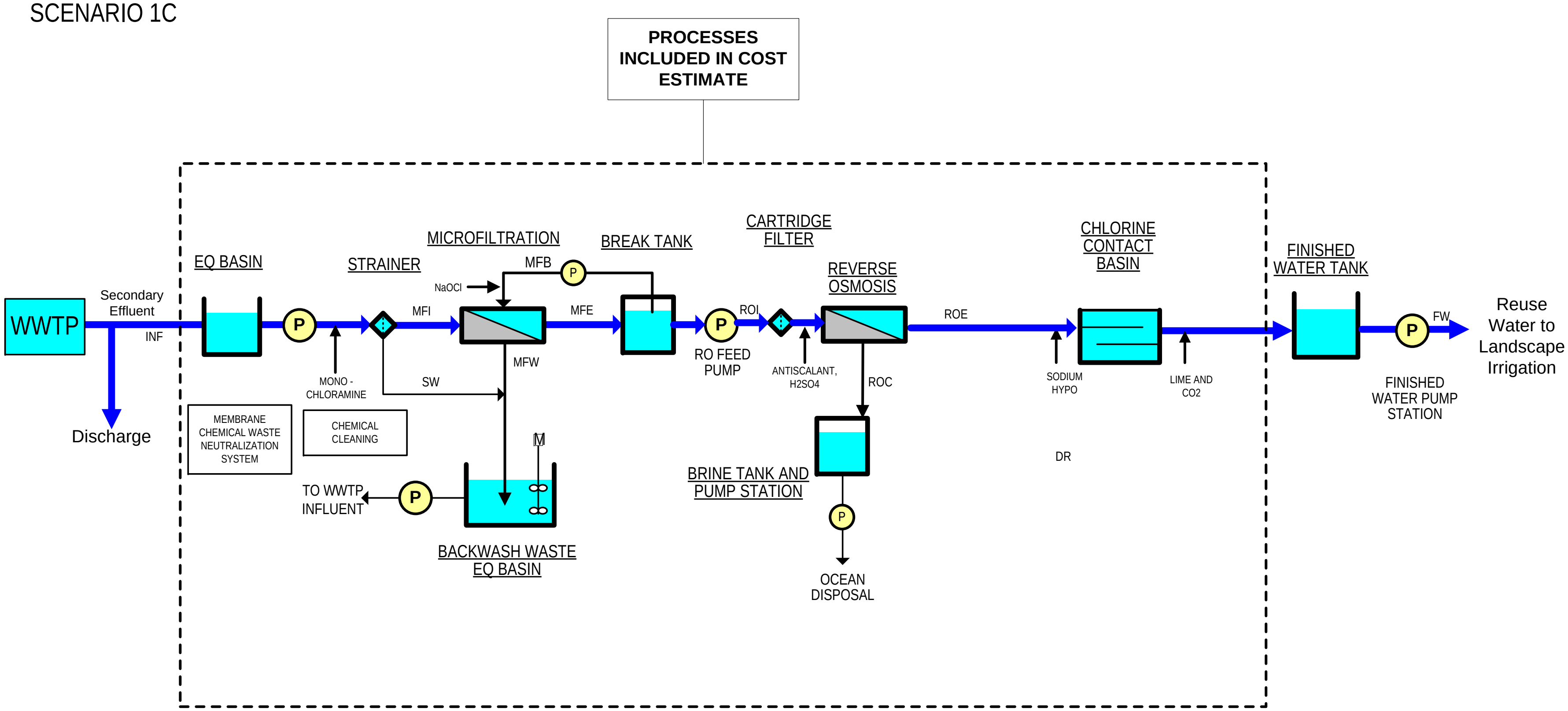
SCENARIO 1B (70 MGD)



Scenario 1B (MF) Flow Balance

Flow Streams	70 MGD Flow (MGD)	
Influent (INF)	74.43	
Microfiltration Influent (MFI)	73.68	INF*0.99
Strainer Waste (SW)	0.74	INF*0.01
Microfiltration Waste (MFW)	3.68	MFI*0.05
Microfiltration Effluent (MFE)	70.00	MFI*0.95
MFB		
Finished Water (FW)	70.00	ROE

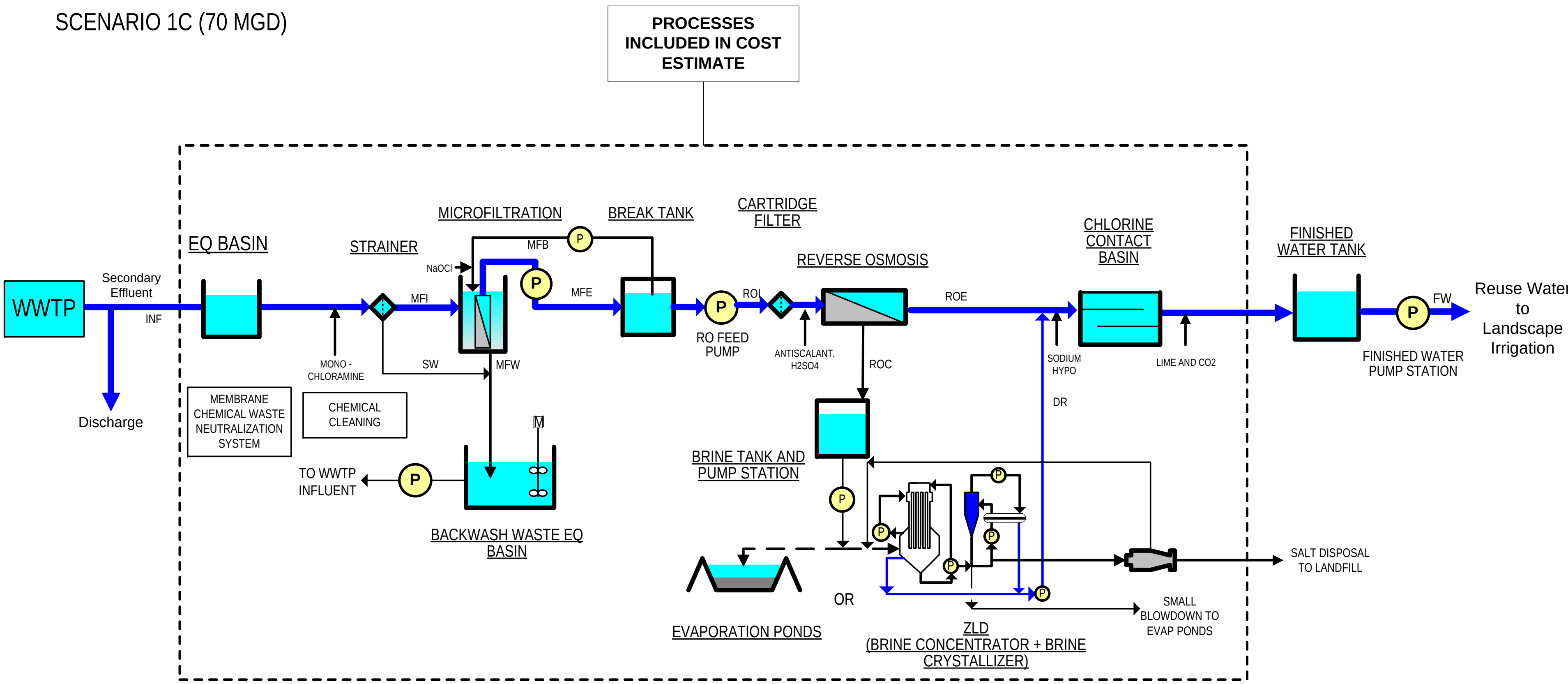
SCENARIO 1C



Scenario 1C (MF/RO; Ocean Discharge) Flow Balance

Flow Streams	5 MGD	20 MGD	
	Flows (MGD)		
Influent (INF)	6.25	25.02	
Microfiltration Influent (MFI)	6.19	24.77	INF*0.99
Strainer Waste (SW)	0.06	0.25	INF*0.01
Microfiltration Waste (MFW)	0.05	0.05	MFI*0.05
Microfiltration Effluent (MFE)	5.88	23.53	MFI*0.95
MFB			
Reverse Osmosis Influent (ROI)	5.88	23.53	MFE-MFB
Reverse Osmosis Effluent (ROE)	5.00	20.00	ROI*0.85
Reverse Osmosis Concentrate (ROC)	0.88	3.53	ROI*0.15
Finished Water (FW)	5.00	20.00	ROE

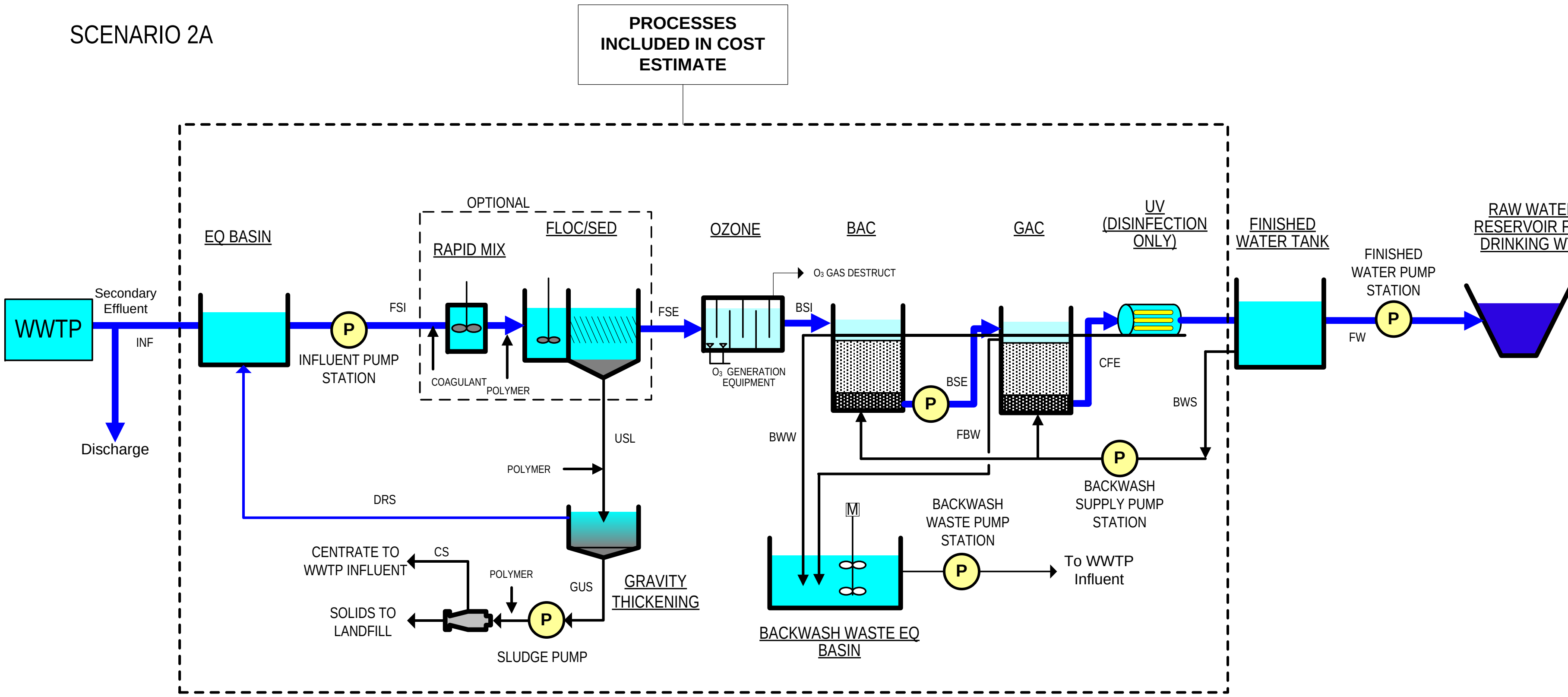
SCENARIO 1C (70 MGD)



Scenario 1C (MF/RO; Ocean Disposal) Flow Balance

Flow Streams	70 MGD Flows (MGD)	
Influent (INF)	87.56	
Microfiltration Influent (MFI)	86.69	INF*0.99
Strainer Waste (SW)	0.88	INF*0.01
Microfiltration Waste (MFW)	4.33	MFI*0.05
Microfiltration Effluent (MFE)	82.35	MFI*0.95
MFB		
Reverse Osmosis Influent (ROI)	82.35	MFE-MFB
Reverse Osmosis Effluent (ROE)	70.00	ROI*0.85
Reverse Osmosis Concentrate (ROC)	12.35	ROI*0.15
Finished Water (FW)	70.00	ROE

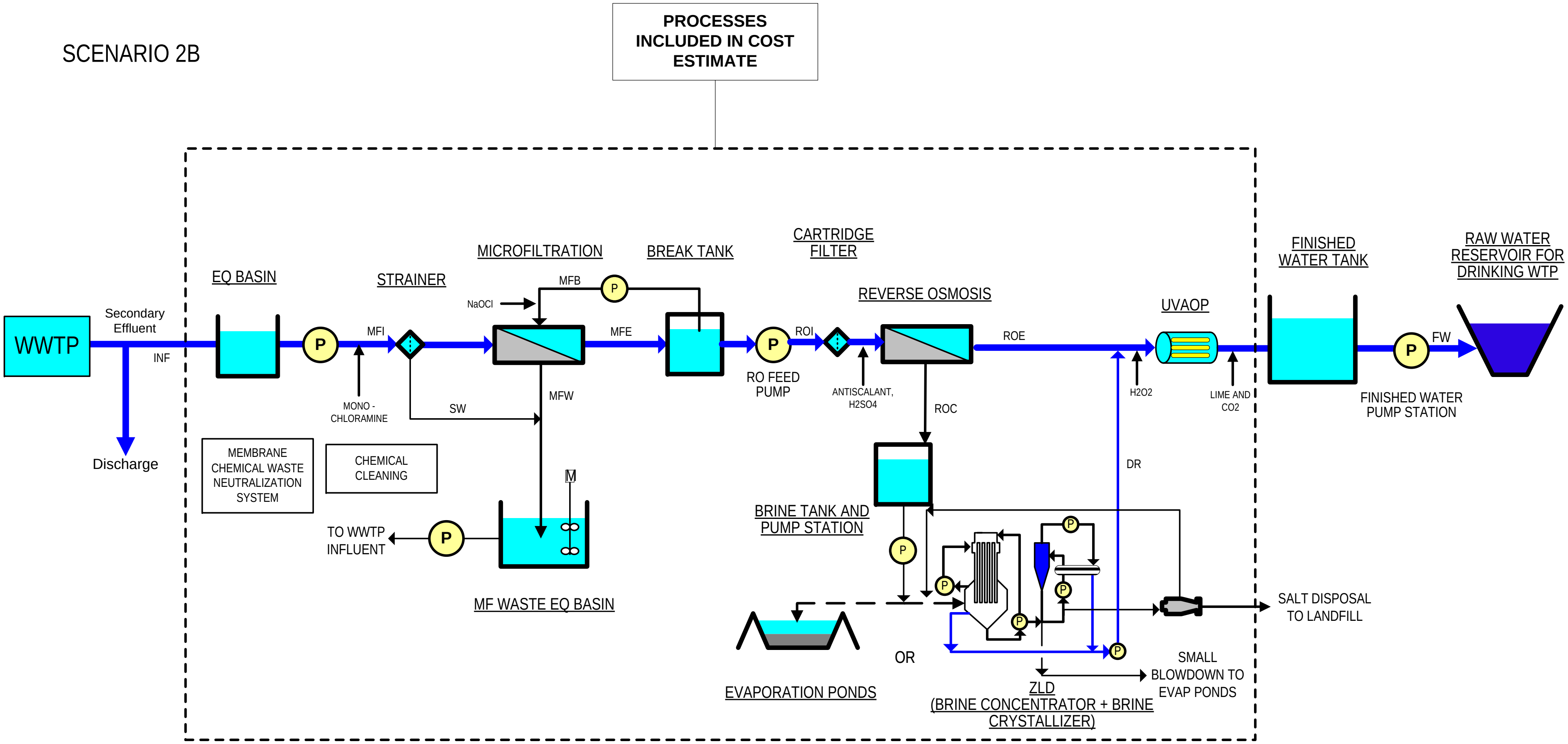
SCENARIO 2A



Scenario 2A (GAC) Flow Balance

Flow Streams	5 MGD	20 MGD Flows (MGD)	70 MGD	
Influent (INF)	5.32	21.29	74.51	
Floc/Sed Influent (FSI)	5.37	21.49	75.22	INF+DRS
Floc/Sed Effluent (FSE)	5.32	21.28	74.47	FSI*0.99
Sedimentation Basin Underflow (USL)	0.054	0.21	0.75	FSI*0.01
Gravity Thickener Decant Water (DRS)	0.051	0.20	0.71	USL*0.95
Gravity Thickener Underflow (GUS)	0.003	0.01	0.04	USL*0.05
Centrate (CS)				
Biological Filter Influent (BFI)	5.32	21.28	74.47	FSE
Biological Filter Effluent (BFE)	5.32	21.28	74.47	BFI
Biological Filter Backwash Waste (BWW)	0.16	0.64	2.23	BFI*0.03
Activated Carbon Filter Influent (CFI)	5.32	21.28	74.47	BFE
Activated Carbon Filter Effluent (CFE)	5.32	21.28	74.47	CFI
Activated Carbon Filter Backwash Waste (FBW)	0.16	0.64	2.23	CFI*0.03
Backwash Supply (BWS)	0.32	1.28	4.47	BFI*0.03+CFI*0.03
Finished Water (FW)	5.00	20.00	70.00	CFE-BWS

SCENARIO 2B



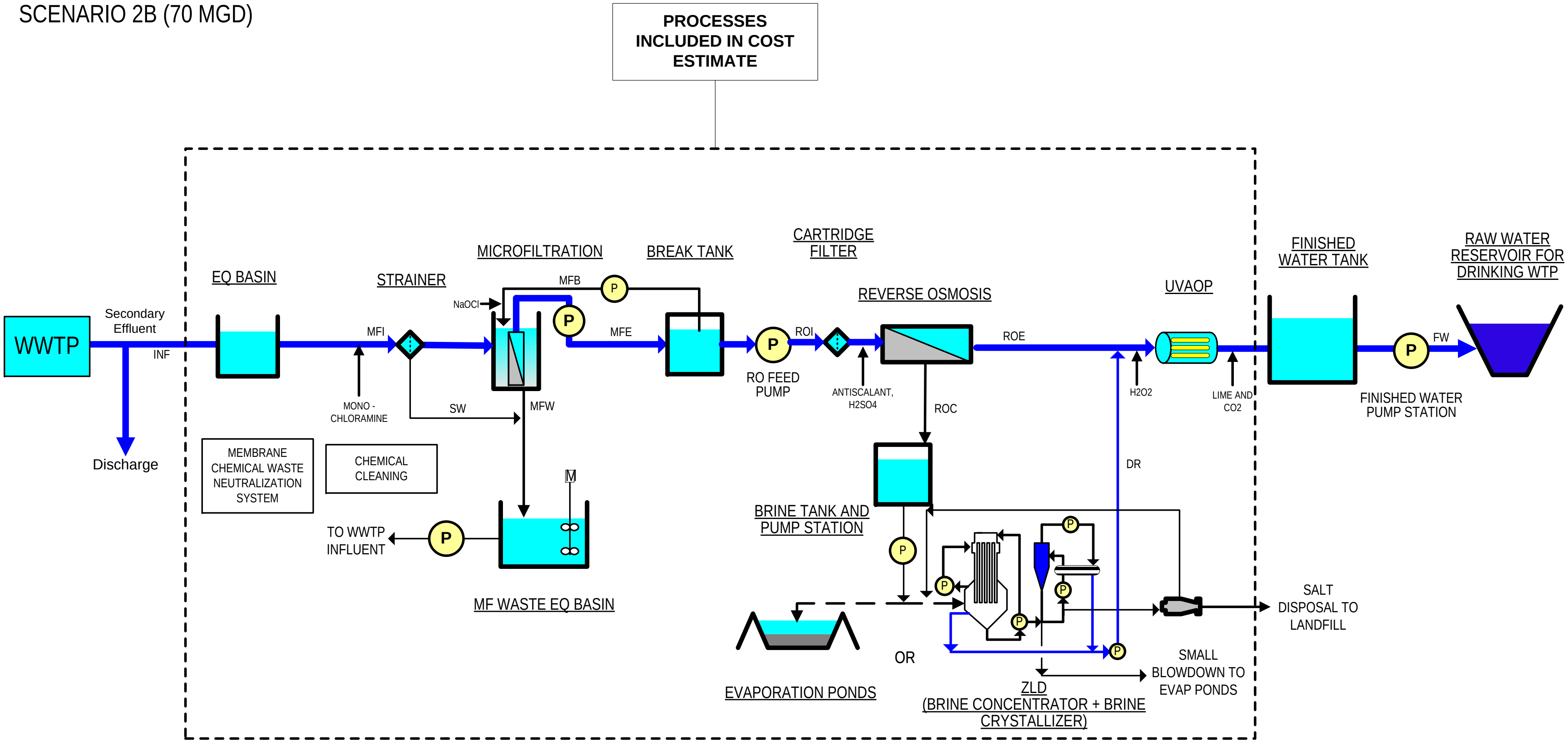
Scenario 2B (RO; Mech Evap) Flow Balance

Flow Streams	5 MGD Flows (MGD)	20 MGD	
Influent (INF)	5.32	21.27	
Microfiltration Influent (MFI)	5.27	21.05	INF*0.99
Strainer Waste (SW)	0.05	0.21	INF*0.01
Microfiltration Waste (MFW)	0.26	1.05	MFI*0.05
Microfiltration Effluent (MFE)	5.00	20.00	MFI*0.95
MFB			
Reverse Osmosis Influent (ROI)	5.00	20.00	MFE-MFB
Reverse Osmosis Effluent (ROE)	4.25	17.00	ROI*0.85
Reverse Osmosis Concentrate (ROC)	0.75	3.00	ROI*0.15
Distillate Return (DR)	0.75	3.00	ROC
Finished Water (FW)	5.00	20.00	ROE+DR

Scenario 2B (RO; Ocean Disposal and Evap Ponds) Flow Balance

Flow Streams	5 MGD Flows (MGD)	20 MGD	
Influent (INF)	6.25	25.02	
Microfiltration Influent (MFI)	6.19	24.77	INF*0.99
Strainer Waste (SW)	0.06	0.25	INF*0.01
Microfiltration Waste (MFW)	0.31	1.24	MFI*0.05
Microfiltration Effluent (MFE)	5.88	23.53	MFI*0.95
MFB			
Reverse Osmosis Influent (ROI)	5.88	23.53	MFE-MFB
Reverse Osmosis Effluent (ROE)	5.00	20.00	ROI*0.85
Reverse Osmosis Concentrate (ROC)	0.88	3.53	ROI*0.15
Finished Water (FW)	5.00	20.00	ROE

SCENARIO 2B (70 MGD)



Scenario 2B (RO; Mech Evap) Flow Balance

Flow Streams	70 MGD Flows (MGD)	
Influent (INF)	74.43	
Microfiltration Influent (MFI)	73.68	INF*0.99
Strainer Waste (SW)	0.74	INF*0.01
Microfiltration Waste (MFW)	3.68	MFI*0.05
Microfiltration Effluent (MFE)	70.00	MFI*0.95
MFB		
Reverse Osmosis Influent (ROI)	70.00	MFE-MFB
Reverse Osmosis Effluent (ROE)	59.50	ROI*0.85
Reverse Osmosis Concentrate (ROC)	10.50	ROI*0.15
Distillate Return (DR)	10.50	ROC
Finished Water (FW)	70.00	ROE+DR

Scenario 2B (RO; Ocean Disposal and Evap Ponds) Flow Balance

Flow Streams	70 MGD Flows (MGD)	
Influent (INF)	87.56	
Microfiltration Influent (MFI)	86.69	INF*0.99
Strainer Waste (SW)	0.88	INF*0.01
Microfiltration Waste (MFW)	4.33	MFI*0.05
Microfiltration Effluent (MFE)	82.35	MFI*0.95
MFB		
Reverse Osmosis Influent (ROI)	82.35	MFE-MFB
Reverse Osmosis Effluent (ROE)	70.00	ROI*0.85
Reverse Osmosis Concentrate (ROC)	12.35	ROI*0.15
Finished Water (FW)	70.00	ROE

Appendix B

Cost Model Output Example

	B	C	D	E	F	G	H	I	J	K	L
1	***Filters***										
2											
3	**Is This Facility Included in My Project? Yes**			To Summary Sheet							
4	Assumptions:										
5											
6	Based on Denver Water Reuse Project										
7	2 Basins @ 15 MGD each										
8	***If this is a Seawater Desalination Application, the materials in contact with seawater need to be corrosion resistant.***										
9	FILTER PARAMETRIC DESIGN APPROACH										
10	BASIS: DENVER REUSE PLANT, HDPE DUAL LATERAL UNDERDRAIN WITH MEDIA SUPPORT CAP, FRONT FLUME, & CONSTANT EFFLUENT FLOW CONTROL										
11											
12											
13	**Process User Inputs:**	**Value**	**Unit (English)**	**Value (Metric)**	**Unit (Metric)**	**Name**	**Comment**	**Red Flags**	**User Comments**		
14	1.) Is this a Seawater Desalination Application?	**No**	Y/N								
15	2.) Has the USER Contacted Equipment Suppliers to Obtain Equipment Quotes?	**No**	Y/N					Fixed			
16	3.) Input Filtration System Maximum Design Flow Rate	**21.28**	mgd	**80.55**	ML/d	Q					
17	4.) Input Filtration System Minimum Design Flow Rate	**6.00**	mgd	**53.83**	ML/d						
18	5.) Input HDPE Underdrain System Type	**LSL**	type			UT	LSL = Leopold Type SL; LS = Leopold Type S; TLP = Tetra Type LP; NP = IDI or GF Nozzle/Plenum Type				
19	Calculate Underdrain Profile Depth	0.67	ft	204.22	mm	UPD	LSL = 0.67 ft; LS = 1.08 ft; TLP = 0.75 ft; NP = 2.5625.				
20	6.) Input Bottom Media Effective Size	**0.90**	mm			BMES					
21	7.) Input Bottom Media Uniformity Coefficient	**1.40**	#			BMUC					
22	8.) Input Bottom Media Depth	**144.00**	in	**3657.60**	mm	BMD					
23	9.) Input Bottom Media Material	**GAC**	type				C = Coal, S = Sand, G = Garnet, GAC = GAC				
24	10.) Input Middle Media Effective Size	**0.00**	mm			MMES					
25	11.) Input Middle Media Uniformity Coefficient	**0.00**	#			MMUC					
26	12.) Input Middle Media Depth	**0.00**	in		mm	MMD					
27	13.) Input Middle Media Material	**C**	type				C = Coal, S = Sand, G = Garnet, GAC = GAC				
28	14.) Input Top Media Effective Size	**0.00**	mm	0.00	mm	TMES					
29	15.) Input Top Media Uniformity Coefficient	**0.00**	#			TMUC					
30	16.) Input Top Media Depth	**0.00**	in		mm	TMD					
31	17.) Input Top Media Material	**GAC**	type				C = Coal, S = Sand, G = Garnet, GAC = GAC				
32	Calculate Total Media Depth	12.00	ft	3657.60	mm	MD					
33	18.) Input GAC Replacement Frequency (number per year)	**0.50**	#								
34	19.) Input Maximum Design Filtration Hydraulic Loading Rate	**6.00**	gpm/sf	**14.67**	m/h	FHLR	Typical Range: 3 - 10 gpm/sf				
35	20.) Input Minimum Design Filtration Hydraulic Loading Rate	**2.00**	gpm/sf	**4.89**	m/h						
36	Calculate Active Filter Area = Q * 694 / FHLR	2462.95	sf	228.82	m2	AFA					
37	Calculate Emtpy Bed Contact Time at Maximum Design Filtration Hydraulic Loading Rage	14.96	min			EBCT					
38	Calculate Emtpy Bed Contact Time at Minimum Design Filtration Hydraulic Loading Rage	53.06	min			EBCT					
39	21.) Input Number of Active Filters with Maximum Design Flow Rate	**3.00**	#			#AF	Typical Range: ≥ 3.				
40	Calculate Individual Filter Area = AFA / #AF	820.98	sf	76.27	m2	IFA					
41	Calculate Individual Filter Dimension in Direction of Underdrain Lateral = IFA / 1.5 ^ 0.5	23.42	ft	7137.40	mm	IFW	For Leopold Type SL (LSL), IFW < 16 ft; For Leopold Type S (LS), IFW < 48 ft; For Tetra Type LP (TLP), IFW < 30 ft.				
42	Calculate Individual Filter Dimension Perpendicular to Underdrain Lateral = IFW * 1.5	35.08	ft	10693.40	mm	IFL					
43	22.) Input Number of Standby Filters with Maximum Design Flow Rate	**1.00**	#			#SF	Typically 1 minimum				
44	Calculate Total Number of Filters = #AF + #SF	4.00	#			#TF	Should be even number. If not, add active or standby filter				
45	23.) Input Desired Filter Bed Expansion During Backwash	**20.00%**	%			BEX	Typically minimum 20%				
46	Calculate Media Expansion Depth	2.40	ft	731.52	mm	EXD					
47	24.) Input Maximum Water Temperature	77.00	degrees F	**25.00**	degrees C	MWT					
48	25.) Input Maximum Backwash Supply Hydraulic Loading Rate	**25.00**	gpm/sf	**61.12**	m/h	BWSHLR	Calculate from CH2M HILL Backwash Rate Program				
49	Calculate Maximum Backwash Supply Flow Rate = BWSHLR * IFW * IFL / 694	29.58	mgd	111.96	ML/d	BWSFR					
50	26.) Input Filter Media Clean Bed Head Loss at Maximum Design Filtration Hydraulic Loading Rate	**2.50**	ft	**762.00**	mm	CBH	Calculate from CH2M HILL Clean Bed Head Loss Program				
51	27.) Input Underdrain Head Loss at Maximum Design Filtration Hydraulic Loading Rate	**1.00**	ft	**1.00**	mm	UDH	Determine from CH2M HILL Filter Design Guide. Typically 1-foot				
52	28.) Input Filter Effluent Piping Head Loss from Seal Weir Back to Filter Box with FE FCV 80% Open	**4.00**	ft	**4.00**	mm	FPH	Calculate from WinHydro. Typically 2 to 4 feet				
53	29.) Input Filter Influent/Backwash Wastewater Gullet Channel Width	**5.00**	ft	**5.00**	mm	GCW	Typically 4 ft. minimum for access				
54	30.) Input Filter Influent Channel / Backwash Wastewater Channel Width	**5.00**	ft	**5.00**	mm	FI/BWCW	Typically 4 ft. minimum for access				
55	Calcualte Filter Influent Isolation Gate Width	42.00	in	1066.80	mm		Typically requires 9 inches of concrete on both sides of gate.				
56	Calculate Number of Isolation Gates	2.00	#								
57	31.) Input Distance from Bottom of Wash Trough to Top of Expanded Media	**12.00**	in	**304.80**	mm	DTM	Typically 3 inches minimum				
58	32.) Input % Area of Wash Trough Coverage per Filter	**25.00**	%			WT%A	Typically 25%				
59	Calculate Wash Trough Coverage per Filter = IFW * IFL * WT%A / 100	205.38	sf	19.08	m2	WTC					
60	33.) Input Wash Trough Width	**2.00**	ft	**609.60**	mm	WTW	Typically 1.5 ft minimum				
61	34.) Input Wash Trough Type	**Conventional**	type			WTYP	Conventional or Media Retaining Type				
62	Calculate Number of Wash Troughs per Filter = WTC / WTW / IFW	4.00	#			#WT					
63	Calculate Depth of Wash Trough = (BWSFR * 694 / 7.48 / 60 / #WT / 2.49 / WTW) ^ (2/3) + .25 + .25	2.24	ft	683.05	mm	WTD	Includes 0.25 feet freeboard and 0.25 feet trough bottom thickness				
64	Calculate Distance Between Troughs = (IFL - # WT * WTW) / #WT	6.77	ft	2063.75	mm	DBT	Full Size Space between each trough, and Half Size Space between each end trough and wall				
65	Calculate Distance from Top of Media to Top of Trough = (BMD / 12 + MMD / 12 + TMD / 12) * (BEX) + (DTM / 12) + WTD	5.64	ft	1719.37	mm	TMTT					

	B	C	D	E	F	G	H	I	J	K	L
66	Calculate Ratio Distance Between Troughs: Distance from Top of Media to Top of Trough = DBT / TMTT	1.20	:1			RATIO	Typically between 1.0 to 2.0 (If error, change percent coverage or trough width)				
67	Calculate Typical Backwash Volume per Event	325019.74	gal	1230.33	m3		3 filter box volumes				
68	Calculate Filter Drain-Down Volume per Event	26770.33	gal	101.34	m3						
69	35.) Input Distance from Top of Wash Trough to Top of Gullet Channel Wall	4.00	ft	1219.20	mm	DTG	Typically 0.5 to 6 feet				
70	36.) Input Terminal Filter Head Loss Build-Up	10.00	ft	3048.00	mm	THL	Typically 8 to 12 feet, confirm with hydraulic analysis				
71	37.) Input Freeboard Above Operating Water Surface	2.00	ft	2.00	mm	FB	Typically 1 to 3 feet				
72	Calculate Gullet Channel Height = UPD + (BMD / 12 + MMD / 12 + TMD / 12) * (1 + BEX / 100) + (DTM / 12) + WTD + DTG	22.31	ft	6800.39	mm	GCH					
73	Calculate Filter Box Depth Based on Filter Seal Weir Set at the Same Elevation as the Top of the Filter Underdrain = UPD +SWH + FPH + UDH + CBH + THL + FB	21.67	ft	6605.02	mm	FBD	Setting Seal Weir and Top of Underdrain at Same Elevation Assures No Negative Pressure & Filter Air Binding				
74	Calculate Backwash Waste Channel Height = GCH - FIVSS - FICLEST	18.81	ft	5733.59	mm	BWWCH					
75	Calculate Filter Influent Channel Height = FBD - BWWCH - FICLEST	1.86	ft	566.63	mm	FICH	Assumes top of filter influent valve = top of gullet channel				
76	38.) Input Filter Seal Weir Head	1.50	ft	1.00	mm	SWH	Typically < 2 feet				
77	Calculate Filter Seal Weir Length = (Q)/(3.33 *SWH^1.5)	5.38	ft	1640.43	mm	SWL	Typically Use Trough Style Weirs to Reduce Area of Seal Weir Box				
78	39.) Input Length of Each Seal Weir Trough	2.00	ft	10.00	mm	SWTL	Typically < 20 feet to avoid intermediate structural support				
79	Calculate Number of Seal Weir Troughs	1.00	#			#SWT	Typically < 20 feet to avoid intermediate structural support				
80	40.) Input Seal Weir Trough Width	2.00	ft	609.60	mm	SWTW	Typically 1.5 ft minimum				
81	Calculate Depth of Wash Trough = (Q * 694 / 7.48 / 60 / #SWT / 2.49 / SWTW) ^ (2/3) + .25 + .25	4.02	ft	1226.09	mm	SWTD	Includes 0.25 feet freeboard and 0.25 feet trough bottom thickness				
82	Calculate Seal Weir Box Width = #SWT * SWTW * 2	4.00	ft	1219.20	mm	SWBW					
83	Calculate Seal Weir Box Depth = 1.5 + FEPHSS + SWTD + SWH + FB	15.02	ft	4578.89	mm	SWBD					
84	Calculate **Filter Flume Depth Below Underdrain Floor** (ft)	5.00	ft	1524.00	mm	FFD					
85	41.) Input Clear Distance Between Filter Effluent Piping in Gallery for Access	10.00	ft	3048.00	mm	GCD1	Typically 8 ft minimum				
86	42.) Input Clear Distance Between Filter Effluent Piping & Filter Box in Gallery for Access	3.00	ft	914.40	mm	GCD2	Typically 3 ft minimum				
87	43.) Input Clear Distance Between Filter Effluent Piping & Filter End Wall for Access	6.00	ft	1828.80	mm	GCD3	Typically 6 ft minimum				
88	Calculate Filter Gallery Width = MAX(GCD1+2*(BWSTL+BWSEL), GCD1+2*(GCD2+FEEL+FEVL+FETW+(BWSVSS-FEVSS)/12/2)	32.80	ft	9998.46	mm	FGW					
89	44.) Input Clear Distance Between Filter Effluent Piping & Gallery Floor	2.00	ft	609.60	mm	GCD4	Typically 1 to 3 feet				
90	45.) Input Backwash Air Scour Loading Rate	2.00	scfm/sf	0.61	m/min	ALR	Typically 2 to 4 scfm/sf				
91	Calculate Air Scour Blower Capacity = ALR * IFW * IFL, per each blower	1644.00	scfm	46.55	m3/min	ASBC					
92	46.) Input Number of Air Scour Blowers	0.00	#			NASB	Typically 1 duty and 1 standby				
93	Calculate Approximate Blower Outlet Gage Pressure at Standard Conditions = (FBD - FB + 2.31) / 2.31	9.52	psig	65.60	kPa	BOP	Includes 1 psig of air piping losses, calculate actual. Typically, total≤ 10 psig				
94	Calculate Blower Horsepower at Standard Conditions (sea level, 20 deg C, 36% RH) = (ASBC * .075 * 53.5 * 528 / 33000 / 0.283 / 0.7 * (((BOP + 14.7) / 14.7) ^ 0.283-1), per each	81.00	hp	60.40	kw	BHP	Revise for actual elevation and air temperature range. Warning... If Blower Horsepower exceeds 200, the Blower Building may be undersized.				
95	47.) Are filters covered?	Yes	Y/N								
96	48.) Do you have Particle Counters?	No	Y/N								
97	49.) Do you have a Combined FE Magmeter?	No	Y/N								
98	50.) Input Depth of Burial	2.00	ft	609.60	mm	DB					
99	51.) Input Cutback Slope	1.00	:1				Cutback slope should be 1:1 for depth of burial≤ 5 ft, and at least 1.5:1 for depth of burial > 5 ft.				
100	52.) Input Over Excavation Depth	1.00	ft	304.80	mm	OEXD					
101	Mechanical Sizing Requirements:										
102	**Pipe Name**	**Input Velocity**	**Unit (English)**	**Input Velocity**	**Unit (Metric)**	**Standard Pipe Size**	**Unit (English)**	**Nominal Pipe Size**	**Unit (Metric)**	**Name**	**Comments**
103	Air Scour Pipe	2500.00	fpm	762.00	m/s	12.00	in	300.00	mm	AMVSS	Typically 1,000 to 3,000 fpm
104	Filter Influent Header Pipe	5.00	fps	1.52	m/s	36.00	in	900.00	mm	FIPHS	Typically 3 to 5 fps
105	Filter Influent Pipe	3.00	fps	0.91	m/s	30.00	in	750.00	mm	FIVSS	Typically 2 to 5 fps
106	Filter Effluent Pipe	5.00	fps	1.52	m/s	24.00	in	600.00	mm	FEVSS	Typically 4 to 7 fps
107	Filter Control Valve Pipe	8.00	fps	2.44	m/s	16.00	in	400.00	mm	FECVS	Typically 8 to 12 fps, check control valve size for cavitation
108	Filter Effluent Header Pipe	5.00	fps	1.52	m/s	36.00	in	900.00	mm	FEPHSS	Typically 4 to 7 fps
109	Filter to Waste	5.00	fps	1.52	m/s	24.00	in	600.00	mm	FTWVSS	Typically 4 to 7 fps
110	Backwash Supply Pipe	6.00	fps	1.83	m/s	42.00	in	1050.00	mm	BWSVSS	Typically 3 to 6 fps
111	Backwash Waste Pipe	6.00	fps	1.83	m/s	42.00	in	1050.00	mm	BWWVSS	Typically 3 to 5 fps
112											
113	Mechanical Material Requirements:									For Entire Facility	
114	**Pipe Name**	**Pipe ID**	**Installation Type**	**Pipe Material**	**Pipe Lining Material**	**Pipe Coating Material**	**Pipe Diameter**	**Pipe Length**	**# Elbows**	**# Tees**	**# Crosses**
115	Air Scour Pipe	BAW	Exposed	Steel	None	None	12.00	282.27	16.00	4.00	2.00
116	Filter Influent Header Pipe	FIH	Buried	Steel	Cement Mortar	Fusion Bonded Epoxy	36.00	0.00	0.00	0.00	0.00
117	Filter Influent Pipe	FIH	Encased	Steel	Cement Mortar	Fusion Bonded Epoxy	30.00	0.00	0.00	0.00	0.00
118	Filter Effluent Pipe	FE	Exposed	Steel	Cement Mortar	Paint	24.00	65.61	4.00	4.00	0.00
119	Filter Effluent Pipe	FE	Encased	Steel	Cement Mortar	Fusion Bonded Epoxy	24.00	65.61	4.00	0.00	0.00
120	Filter Control Valve Pipe	FCV	Exposed	Steel	None	None	16.00	42.67	0.00	0.00	0.00
121	Filter Effluent Header Pipe	FEH	Encased	Steel	Cement Mortar	Fusion Bonded Epoxy	36.00	79.67	0.00	0.00	2.00
122	Filter to Waste	FTW	Exposed	Steel	Cement Mortar	Paint	24.00	43.34	6.00	0.00	0.00
123	Filter to Waste	FTW	Encased	Steel	Cement Mortar	Fusion Bonded Epoxy	24.00	188.33	0.00	2.00	0.00

	B	C	D	E	F	G	H	I	J	K	L
124	Backwash Supply Pipe	BWS	Exposed	Steel	Cement Mortar	Paint	42.00	205.34	2.00	6.00	0.00
125	Backwash Supply Pipe	BWS	Encased	Steel	Cement Mortar	Fusion Bonded Epoxy	42.00	48.00	2.00	0.00	0.00
126	Backwash Waste Pipe	BWW	Encased	Steel	Cement Mortar	Fusion Bonded Epoxy	42.00	10.00	0.00	0.00	0.00
127											
128	Electrical User Inputs and Sizing Requirements:										
129	53.) Is this a "Critical" Facility (requiring standby power)?	No	Y/N								
130	54.) Is there SWGR?	No									
131								MCC			
132	Item	Quantity	HP per Each	AFD's Required?	MCC Spaces for Motor Starters	MCC Spaces for AFD's less than 50hp)	MCC Spaces for Breakers	Total MCC Spaces	Number of MCC Sections for Motors, AFD's, & Breakers	Number of MCC Sections for Main Breaker, Metering, & Panelboards, and 1 Spare	MCC Total Width
133	Air Scour Blowers	0.00	81.00	No	0.00	0.00	0.00				
134	User Defined Item #1	0.00	0.00	No	0.00	0.00	0.00				
135	User Defined Item #2	0.00	0.00	No	0.00	0.00	0.00				
136	User Defined Item #3	0.00	0.00	No	0.00	0.00	0.00				
137	TOTAL		0.00		0.00	0.00	0.00	0.00	0.00	4.00	6.67
138											
139	Electrical Equipment Widths:										
140	**Equipment**	**Depth (ft)**									
141	MCC	0.00									
142	Small AFD's	0.00									
143	Large AFD's	0.00									
144	Switchgear	0.00									
145	Maximum Depth	0.00									
146											
147	Clear Distances:										
148	**Clear Distance**	**Width**	**Length**	**Comment**							
149	CD1		3.00	Clear Distance between wall and MCC	Typically 3 feet						
150	CD2		1.00	Clear Distance between MCC and Small AFD	Typically 1 foot						
151	CD3		0.00	Clear Distance between Small AFD and Large AFD	Typically Zero						
152	CD4		0.00	Clear Distance between Large AFD and Switchgear	Typically Zero						
153	CD5		0.00	Clear Distance between Switchgear and Contingency Space	Typically Zero						
154	CD6	4.00		Clear Distance behind Switchgear (If there is no Switchgear, this distance will be Zero)							
155	CD7	3.00		Clear Distance in front of Equipment	Typically 3 feet						
156	Contingency Length		0.00	Contingency length	Typically Zero						
157											
158	Electric Room Length (ft):										
159	CD1	3.00									
160	MCC	6.67									
161	CD2	1.00									
162	Small AFD's	0.00									
163	CD3	0.00									
164	Large AFD's	0.00									
165	CD4	0.00									
166	Swithgear	0.00									
167	CD5	0.00									
168	Contingency	0.00									
169	Total Length	10.67									
170											
171	Electric Room Width (ft):										
172	CD6	0.00	If there is no switchgear, this distance will be Zero.								
173	Maximum Equipment Depth	0.00									
174	CD7	3.00									
175	Total Width	3.00									
176											
177	**COST TABLE FOR MEDIA:**	**Quantity (CF)**	**$/CF (Uninstalled Cost)**	**$/CF (*Escalated* and Installed Cost)**							
178	Silica Sand	0.00	15.00	$ *18.51*							
179	Antracite Coal	0.00	20.00	$ *24.69*							
180	Garnet Sand	0.00	45.00	$ *55.54*							
181	GAC	39433.67	45.00	$ *55.54*							
182											
183	**Estimating Dimensions:**	**Value English**	**Unit (English)**	**Value Metric**	**Unit (Metric)**	**Name**	**Comment**	**Red Flags**	**User Comments**		
184	Backwash Supply Pipe Tee Length	5.50	ft	1676.40	mm	BWSTL	Lookup Value				
185	Backwash Supply Pipe Tee Width	4.50	ft	1371.60	mm	BWSTW	Lookup Value				
186	Backwash Supply Pipe Elbow Length	5.90	ft	1798.83	mm	BWSEL	Lookup Value				
187	Backwash Supply Isolation Valve Length	1.25	ft	381.00	mm	BWSVL	Lookup Value				
188	Backwash Supply - Flowmeter Reducer Length	8.67	ft	2641.60	mm	BWSFMRL					
189	Flowmeter Length	2.00	ft	609.60	mm	FML	Lookup Value				
190	Filter Control Valve Length	0.67	ft	203.20	mm	FCVL	Lookup Value				
191	Flowmeter - Filter Effluent Increaser Length	2.67	ft	812.80	mm	FMFERL					
192	Filter Effluent Pipe Tee Length	3.67	ft	1117.60	mm	FETL	Lookup Value				
193	Filter Effluent Pipe Tee Width	2.83	ft	863.60	mm	FETW	Lookup Value				
194	Filter Effluent Pipe Elbow Length	3.63	ft	1107.69	mm	FEEL	Lookup Value				
195	Filter Effluent and Filter to Waste Isolation Valve Length	1.00	ft	304.80	mm	FEVL	Lookup Value				
196	Filter Effluent Header Pipe Cross Length	4.83	ft	1473.20	mm	FEHCL	Lookup Value				
197	Filter Effluent Header Pipe Cross Width	4.83	ft	1473.20	mm	FEHCW	Lookup Value				
198	Filter to Waste Header Pipe Tee Length	3.67	ft	1117.60	mm	FTWHTL	Lookup Value				
199	Filter to Waste Pipe Elbow Length	2.83	ft	863.60	mm	FTWEL	Lookup Value				
200	Total Length of Individual Filter Piping	38.87	ft	11847.32	mm						
201	Filter (per Each):										
202	Slab on Grade (Includes Filter, Gulllet Channel, Filter Influent/Backwash Wastewater Channel):										
203	Length = IFL + FEWT	36.58	ft	11150.60	mm	FSOGL					
204	Width =	39.08	ft	11912.60	mm	FSOGW					
205	Concrete Thickness	24.00	in	551.18	mm		Model based on 24"				
206	Concrete Thickness	2.00	ft	609.60	mm	FSOGT					
207	Pipe Gallery Wall:										
208	Length = IFL + FEWT	36.58	ft	11150.60	mm						
209	Height = FBD + FFD	26.67	ft	8129.02	mm						
210	Concrete Thickness	18.00	in	551.18	mm		Model based on 18"				
211	Concrete Thickness	1.50	ft	457.20	mm	PGWT					
212	Gullet Wall:										
213	Length = IFL	35.08	ft	10693.40	mm						
214	Height = GCH	22.31	ft	6800.39	mm						
215	Concrete Thickness	14.00	in	500.38	mm		Model based on 14"				
216	Concrete Thickness	1.17	ft	355.60	mm	GWT					
217	Filter Influent / Backwash Waste Channel Walls:										
218	Number of Walls (2 per filter)	2.00	#			#W	Fixed				
219	Length = IFL + FEWT	36.58	ft	11150.60	mm						

	B	C	D	E	F	G	H	I	J	K	L
220	Height = FBD	21.67	ft	6605.02	mm						
221	Concrete Thickness	18.00	in	500.38	mm		Model based on 18"				
222	Concrete Thickness	1.50	ft	457.20	mm	FI/BWCST					
223	Filter Influent / Backwash Waste Channel Lower Elevated Slab:										
224	Length = IFL + FEWT	36.58	ft	11150.60	mm						
225	Width = FI/BWCW	5.00	ft	1524.00	mm						
226	Concrete Thickness	12.00	in	304.80	mm		Model based on 12"				
227	Concrete Thickness	1.00	ft	304.80	mm	FICLEST					
228	Filter Influent / Backwash Waste Channel Upper Elevated Slab:										
229	Length = IFL + FEWT	36.58	ft	11150.60	mm						
230	Width = FI/BWCW + (2 * FI/BWCWT)	8.00	ft	2438.40	mm						
231	Concrete Thickness	9.00	in	228.60	mm		Model based on 9"				
232	Concrete Thickness	0.75	ft	228.60	mm	FICUEST					
233	End Walls: (For Entire Filter Complex)						This accounts for common walls on individual filters				
234	Number of Walls	4.00	#								
235	Width = PGWT + IFW + GWT + GCW + (2* FI/BWCWT) + FI/BWCW	39.08	ft	11912.60	mm						
236	Height = FBD	21.67	ft	6605.02	mm						
237	Concrete Thickness	18.00	in	500.38	mm		Model based on 18"				
238	Concrete Thickness	1.50	ft	457.20	mm	FEWT					
239	Common Filter Influent Channel:										
240	Slab on Grade:										
241	Length = FI/BWCW + FI/BWCST	6.50	ft	1981.20	mm						
242	Width = 2*(FSOGW+PGWT)+FGW	113.97	ft	34738.06	mm						
243	Concrete Thickness	24.00	in	457.20	mm		Model based on 24"				
244	Concrete Thickness	2.00	ft	609.60	mm	FISOGT					
245	Common Filter Influent Channel Wall:										
246	Length = 2*(FSOGW+PGWT)+FGW	113.97	ft	34738.06	mm						
247	Height = FICH	1.86	ft	566.63	mm						
248	Concrete Thickness	18.00	in	457.20	mm		Model based on 18"				
249	Concrete Thickness	1.50	ft	457.20	mm	FIWCST					
250	Common Filter Influent Channel Elevated Slab:										
251	Length = 2*(FSOGW+PGWT)+FGW	113.97	ft	34738.06	mm						
252	Width = FI/BWCW + FI/BWCWT + FEWT	8.00	ft	2438.40	mm						
253	Concrete Thickness	9.00	in	228.60	mm		Model based on 9"				
254	Concrete Thickness	0.75	ft	228.60	mm	FICEST					
255	Filter Gallery:										
256	Slab on Grade:										
257	Length = (#TF/2*FSOGL)+SCW	97.17	ft	29616.40	mm						
258	Width = FGW + (2*PGWT)	35.80	ft	10912.86	mm						
259	Concrete Thickness = FEPHSS + 24	60.00	in	1524.00	mm						
260	Concrete Thickness	5.00	ft	1524.00	mm	FGSOGT					
261	Filter Gallery Elevated Slab:										
262	Length = (#TF/2*FSOGL)+SCW	97.17	ft	29616.40	mm						
263	Width = FGW+(2*PGWT)	35.80	ft	10912.86	mm						
264	Concrete Thickness	8.00	in	304.80	mm		Model based on 8"				
265	Concrete Thickness	0.67	ft	203.20	mm	FGEST					
266	Blower Room:										
267	Slab on Grade:										
268	Length	20.00	ft	6096.00	mm		Fixed				
269	Width = FSOGW	39.08	ft	11912.60	mm						
270	Concrete Thickness	12.00	in	609.60	mm		Model based on 24"				
271	Concrete Thickness	1.00	ft	304.80	mm						
272	Walls:										
273	Height = FBD	21.67	ft	6605.02	mm						
274	Concrete Thickness	8.00	in	500.38	mm		Model based on 8"				
275	Concrete Thickness	0.67	ft	203.20	mm						
276	Stair Case:										
277	Slab on Grade:										
278	Length	24.00	ft	7315.20	mm		Fixed				
279	Width	24.00	ft	7315.20	mm	SCW	Fixed				
280	Concrete Thickness	12.00	in	609.60	mm		Model based on 24"				
281	Concrete Thickness	1.00	ft	304.80	mm						
282	Walls:										
283	Height = FBD	21.67	ft	6605.02	mm						
284	Concrete Thickness	8.00	in	203.20	mm		Model based on 8"				
285	Concrete Thickness	0.67	ft	203.20	mm						
286	Electrical Room:										
287	Slab on Grade:										
288	Length	12.00	ft	3657.60	mm						
289	Width	4.33	ft	1320.80	mm						
290	Concrete Thickness	12.00	in	304.80	mm		Model based on 12"				
291	Concrete Thickness	1.00	ft	304.80	mm						
292	Walls:										
293	Height = FBD	10.00	ft	3048.00	mm		Fixed				
294	Concrete Thickness	8.00	in	304.80	mm		Model based on 8"				
295	Concrete Thickness	0.67	ft	203.20	mm						
296	Overall Dimensions:										
297	Total Filter SOG Length = (#TF/2*FSOGL)+FEWT+SCW+FI/BWCW+(2*FI/BWCST)+2(FSOGT)	79.67	ft	24282.40	mm	SOGL					
298	Total Filter SOG Width = 2*(FSOGW+FSOGT+PGWT)+FGW	113.97	ft	34738.06	mm	SOGW					
299	Total Filter Building Area	9079.61	sf	843.52	m2	BA					
300	Blower Room Area	781.67	sf	72.62	m2	BRA					
301	Stair Case Area	576.00	sf	53.51	m2	SCA					
302	Electrical Room Area	52.00	sf	4.83	m2	ERA					
303	Total Building Area	10489.28	sf	974.49	m2	TBA					
304	Filter Building Excavation Length	83.67	ft	25501.60	mm	EVD					
305	Filter Building Excavation Width	117.97	ft	35957.26	mm	EVD					
306	Stair Case Excavation Length	28.00	ft	8534.40	mm						
307	Stair Case Excavation Width	28.00	ft	8534.40	mm						
308	Blower Room Excavation Length	24.00	ft	7315.20	mm						
309	Blower Room Excavation Width	43.08	ft	13131.80	mm						
310	Electrical Room Excavation Length	16.00	ft	4876.80	mm						
311	Electrical Room Excavation Width	8.33	ft	2540.00	mm						
312	Filter Building Excavation Depth (DB + FGSOGT + FFD)	12.00	ft	3657.60	mm	EVD					
313	Stair Case Excavation Depth	12.00	ft	3657.60	mm						
314	Blower Room Excavation Depth	1.00	ft	304.80	mm						
315	Electrical Room Excavation Depth	1.00	ft	304.80	mm						
316											
317	**COST ESTIMATE**										
318	**Description**	**Quantity (English)**	**Unit (English)**	**Quantity (Metric)**	**Unit (Metric)**	**$/Unit**	**Total Cost**	**User Over-Write**	**Reference**	**Comments**	**User Comments**
319	SITEWORK:										
320	Filters										
321	Excavation	6117.59	CY	4677.23	m3	*$5.67*	$34,694		*02E*		
322	Imported Structural Backfill	731.12	CY	558.98	m3	*$42.97*	$31,417		*02SB*		
323	Native Backfill	1075.40	CY	822.20	m3	*$6.97*	$7,498		*02B*		
324	Haul Excess	5042.19	CY	3855.03	m3	*$6.97*	$35,154		*02HE*		
325	Stair Case:										
326	Excavation	724.76	CY	554.12	m3	*$5.67*	$4,110		*02E*		
327	Imported Structural Backfill	58.07	CY	44.40	m3	*$42.97*	$2,495		*02SB*		
328	Native Backfill	298.67	CY	228.35	m3	*$6.97*	$2,082		*02B*		
329	Haul Excess	426.10	CY	325.78	m3	*$6.97*	$2,971		*02HE*		
330	Blower Room:										
331	Excavation	45.67	CY	34.92	m3	*$5.67*	$259		*02E*		
332	Imported Structural Backfill	76.59	CY	58.56	m3	*$42.97*	$3,291		*02SB*		
333	Native Backfill	2.48	CY	1.90	m3	*$6.97*	$17		*02B*		
334	Haul Excess	43.19	CY	33.02	m3	*$6.97*	$301		*02HE*		
335	Electrical Room:										

	B	C	D	E	F	G	H	I	J	K	L
336	Excavation	6.54	CY	5.00	m3	*$5.67*	$37		*02E*		
337	Imported Structural Backfill	9.88	CY	7.55	m3	*$42.97*	$424		*02SB*		
338	Native Backfill	0.90	CY	0.69	m3	*$6.97*	$6		*02B*		
339	Haul Excess	5.64	CY	4.31	m3	*$6.97*	$39		*02HE*		
340	Allowance for Misc Items	5%				$124,797.12	$6,240				
341	Subtotal						$131,037				
342											
343	CONCRETE:										
344	Filters										
345	Foundation (Includes Filter, Gulllet Channel, Filter Influent/Backwash Wastewater Channel) (FSOGW * FSOGL * FOSGT) / 27 *#TF	423.64	CY	323.90	m3	*$382.16*	$161,900		*03F*		
346	Pipe Gallery Wall	216.82	CY	165.77	m3	*$683.50*	$148,195		*03W*		
347	Gullet Wall	135.29	CY	103.44	m3	*$683.50*	$92,470		*03W*		
348	Filter Influent / Backwash Waste Channel Walls	352.34	CY	269.38	m3	*$683.50*	$240,823		*03W*		
349	Filter Influent / Backwash Waste Channel Lower Elevated Slab	27.10	CY	20.72	m3	*$1,088.69*	$29,502		*03ES*		
350	Filter Influent / Backwash Waste Channel Upper Elevated Slab	32.52	CY	24.86	m3	*$1,088.69*	$35,403		*03ES*		
351	End Walls	188.21	CY	143.90	m3	*$683.50*	$128,640		*03W*		
352	Common Filter Influent			0.00	m3						
353	Slab on Grade	54.87	CY	41.95	m3	*$345.93*	$18,983		*03S*		
354	Common Influent Channel Wall	23.54	CY	18.00	m3	*$683.50*	$16,090		*03W*		
355	Common Influent Channel Elevated Slab	25.33	CY	19.36	m3	*$1,088.69*	$27,573		*03ES*		
356	Filter Gallery										
357	Slab on Grade	644.24	CY	492.56	m3	*$345.93*	$222,862		*03S*		
358	Filter Gallery Elevated Slab	85.90	CY	65.67	m3	*$1,088.69*	$93,517		*03ES*		
359	Pipe Supports	2.67	CY	2.04	m3	*$34.86*			*2 per filter*		
360	Blower Room										
361	Slab on Grade	28.95	CY	22.13	m3	*$345.93*	$10,015		*03S*		
362	Blower Room Walls	31.61	CY	24.17	m3	*$683.50*	$21,608		*03W*		
363	Stair Case										
364	Slab on Grade	21.33	CY	16.31	m3	*$345.93*	$7,380		*03S*		
365	Stair Case Walls	25.68	CY	19.64	m3	*$683.50*	$17,554		*03W*		
366	Electrical Room										
367	Slab on Grade	1.93	CY	1.47	m3	*$345.93*	$666		*03S*		
368	Electrical Room Walls	8.07	CY	6.17	m3	*$683.50*	$5,513		*03W*		
369	Allowance for Misc Items	5%				$1,278,692.91	$63,935				
370	Subtotal						$1,342,628				
371											
372	MASONRY:	**Moderate**									
373	CMU Filter Building	10489.28	SF	974.49	m2	*$139.44*	$1,462,630		*04BM*		
374	Blower Room	781.67	SF	72.62	m2	*$139.44*	$108,996		*04BM*		
375	Electrical Room	52.00	SF	4.83	m2	*$139.44*	$7,251		*04BM*		
376	Subtotal	11,322.94					$1,578,877				
377											
378	METALS:										
379	Metal Guardrail with Pickets	529.33	LF	161.34	m	*$76.69*	$40,596		(IFW + GWT + GCW + IFL) * #TF * 2		
380	Filter Access Hatch	20.25	SF	1.88	m2	*$116.45*			(BWWVSS + 2')^2		
381	Stairs (FBD * 12/8)	33.00	Risers			*$418.32*	$13,805		*05S*		
382	Allowance for Misc Items	10%				$54,400.40	$5,440				
383	Subtotal						$59,840				
384											
385	THERMAL & MOISTURE PROTECTION:										
386	Concrete Liner	0	SF	0.00	m2	**$16.00**	$0			$14/SF to $20/SF	
387	Allowance for Misc Items	10%				$0.00	$0				
388	Subtotal						$0				
389											
390	EQUIPMENT:							**Budgetary Quote:** *(CPES will automatically add Installation Factor)*			
391	Fabricated Slide Gates, 42-inch	2	EA			***$11,330.76***	$22,662				
392	Underdrain - Leopold Type SL	3,286	SF	305.29	m2	***$74.06***	$243,370				
393	Wash Troughs										
394	Conventional	393	LF	119.89	m	***$248.58***	$97,776				
395	Media Retaining	0	LF	0.00	m	***$563.68***	$0				
396	Media										
397	Bottom Media - GAC (ES=0.9 UC=1.4)	39,434	CF	1116.64	m3	***$55.54***	$2,190,331				
398	Middle Media - Coal (ES=0 UC=0)	0	CF	0.00	m3	***$24.69***	$0				
399	Top Media - GAC (ES=0 UC=0)	0	CF	0.00	m3	***$55.54***	$0				
400	Air Scour Blowers (81 hp each)	0	EA			***$96,156.50***	$0		0.00	<<<Effective HP (Based on 2 fixed backwashes per filter per day at 10 minutes per backwash)	
401	Allowance for Misc Items	10%				$2,554,138.26	$255,414				
402	Subtotal						$2,809,552		0.00		
403											
404	INSTRUMENTS & CONTROLS:										
405	Instruments										
406	Filter Effluent Magmeter (24-inch)	4.00	EA			***$21,046.66***	$84,187		1 per filter		
407	Combined Filter Effluent Magmeter (36-inch)	0.00	EA			***$29,668.97***	$0				
408	Isolation Valve Actuators	24.00	EA			***$5,366.64***	$128,799		6 per filter		
409	Control Valve Actuators	4.00	EA			***$5,366.64***	$21,467		1 per filter		
410	Turbidimeters	4	EA			***$3,319.68***	$13,279		1 per filter		
411	Particle Counters	0	EA			***$7,167.48***	$0		1 per filter		
412	Level Transmitters	4	EA			***$7,544.72***	$30,179		1 per filter		
413	Differential Pressure Transmitters	4	EA			***$7,544.72***	$30,179		1 per filter		
414	Filter Influent Level Transmitter	2	EA			***$7,544.72***	$15,089		2 per facility		
415	Air Scour Differential Pressure Transmitter	0	EA			***$7,544.72***	$0		1 per blower		
416	Air Scour Discharge Pressure Indicator Transmitter	0	EA			***$7,544.72***	$0		1 per blower		
417	Number of Analog I/O Counts	38	EA			***$221.26***	$8,496			Includes 20% Contingency	
418	Number of Digital I/O Counts	144	EA			***$52.40***	$7,546			Includes 20% Contingency	
419	Number of PLC's	1	EA			***$10,946.50***	$10,947				
420	I&C Conduit & Wire	3,665	LF	1116.99	m	***$10.10***	$37,000		Bldg Length * # Instruments		
421	Allowance for Misc Items	10%				$387,167.30	$38,717				
422	Subtotal						$425,884				
423											
424	CONVEYING SYSTEMS:										
425	Monorail Hoist (3 Ton)	1	EA			*$3,451.15*	$3,451		*14MH*		
426	Hoist Rail	194	LF	59.02	m	*$34.86*	$6,750		*14MR*		
427	Allowance for Misc Items	5%				$10,201.35	$510				
428	Subtotal						$10,711				
429											
430	MECHANICAL:										
431	Pipe										
432	Air Scour Pipe-BAW (12-inch , Exposed , Steel , None , None)	282	LF	86.04	m	*$210.27*	$59,354				
433	Filter Influent Header Pipe-FIH (36-inch , Buried , Stee , Cement Mortar , Fusion Bonded Epoxy)	0	LF	0.00	m	*$696.66*	$0				
434	Filter Influent Pipe-FIH (30-inch , Encased , Steel , Cement Mortar , Fusion Bonded Epoxy)	0	LF	0.00	m	*$580.55*	$0				
435	Filter Effluent Pipe-FE (24-inch , Exposed , Steel , Cement Mortar , Paint)	66	LF	20.00	m	*$464.44*	$30,471				
436	Filter Effluent Pipe-FE (24-inch , Encased , Steel , Cement Mortar , Fusion Bonded Epoxy)	66	LF	20.00	m	*$464.44*	$30,471				
437	Filter Control Valve Pipe-FCV (16-inch , Exposed , Steel , None , None)	43	LF	13.00	m	*$280.36*	$11,962				
438	Filter Effluent Header Pipe-FEH (36-inch , Encased , Steel , Cement Mortar , Fusion Bonded Epoxy)	80	LF	24.28	m	*$696.66*	$55,501				
439	Filter to Waste-FTW (24-inch , Exposed , Steel , Cement Mortar , Paint)	43	LF	13.21	m	*$464.44*	$20,129				
440	Filter to Waste-FTW (24-inch , Encased , Steel , Cement Mortar , Fusion Bonded Epoxy)	188	LF	57.40	m	*$464.44*	$87,470				
441	Backwash Supply Pipe-BWS (42-inch , Exposed , Steel , Cement Mortar , Paint)	205	LF	62.59	m	*$812.77*	$166,898				
442	Backwash Supply Pipe-BWS (42-inch , Encased , Steel , Cement Mortar , Fusion Bonded Epoxy)	48	LF	14.63	m	*$812.77*	$39,013				
443	Backwash Waste Pipe-BWW (42-inch , Encased , Steel , Cement Mortar , Fusion Bonded Epoxy)	10	LF	3.05	m	*$812.77*	$8,128				
444	Elbows										
445	Air Scour Pipe-BAW (12-inch , Steel)	16	EA			*$1,398.54*	$22,377				

	B	C	D	E	F	G	H	I	J	K	L
446	Filter Influent Header Pipe-FIH (36-inch , Steel)	0	EA			*$4,195.63*	$0				
447	Filter Influent Pipe-FIH (30-inch , Steel)	0	EA			*$3,496.36*	$0				
448	Filter Effluent Pipe-FE (24-inch , Steel)	4	EA			*$2,797.09*	$11,188				
449	Filter Effluent Pipe-FE (24-inch , Steel)	4	EA			*$2,797.09*	$11,188				
450	Filter Control Valve Pipe-FCV (16-inch , Steel)	0	EA			*$1,864.72*	$0				
451	Filter Effluent Header Pipe-FEH (36-inch , Steel)	0	EA			*$4,195.63*	$0				
452	Filter to Waste-FTW (24-inch , Steel)	6	EA			*$2,797.09*	$16,783				
453	Filter to Waste-FTW (24-inch , Steel)	0	EA			*$2,797.09*	$0				
454	Backwash Supply Pipe-BWS (42-inch , Steel)	2	EA			*$4,894.90*	$9,790				
455	Backwash Supply Pipe-BWS (42-inch , Steel)	2	EA			*$4,894.90*	$9,790				
456	Backwash Waste Pipe-BWW (42-inch , Steel)	0	EA			*$4,894.90*	$0				
457	Tees										
458	Air Scour Pipe-BAW (12-inch , Steel)	4	EA			*$3,186.41*	$12,746				
459	Filter Influent Header Pipe-FIH (36-inch , Steel)	0	EA			*$9,559.23*	$0				
460	Filter Influent Pipe-FIH (30-inch , Steel)	0	EA			*$7,966.03*	$0				
461	Filter Effluent Pipe-FE (24-inch , Steel)	4	EA			*$6,372.82*	$25,491				
462	Filter Effluent Pipe-FE (24-inch , Steel)	0	EA			*$6,372.82*	$0				
463	Filter Control Valve Pipe-FCV (16-inch , Steel)	0	EA			*$4,248.55*	$0				
464	Filter Effluent Header Pipe-FEH (36-inch , Steel)	0	EA			*$9,559.23*	$0				
465	Filter to Waste-FTW (24-inch , Steel)	0	EA			*$6,372.82*	$0				
466	Filter to Waste-FTW (24-inch , Steel)	2	EA			*$6,372.82*	$12,746				
467	Backwash Supply Pipe-BWS (42-inch , Steel)	6	EA			*$11,152.44*	$66,915				
468	Backwash Supply Pipe-BWS (42-inch , Steel)	0	EA			*$11,152.44*	$0				
469	Backwash Waste Pipe-BWW (42-inch , Steel)	0	EA			*$11,152.44*	$0				
470	Crosses										
471	Air Scour Pipe-BAW (12-inch , Steel)	2	EA			*$4,248.55*	$8,497				
472	Filter Influent Header Pipe-FIH (36-inch , Steel)	0	EA			*$12,745.64*	$0				
473	Filter Influent Pipe-FIH (30-inch , Steel)	0	EA			*$10,621.37*	$0				
474	Filter Effluent Pipe-FE (24-inch , Steel)	0	EA			*$8,497.09*	$0				
475	Filter Effluent Pipe-FE (24-inch , Steel)	0	EA			*$8,497.09*	$0				
476	Filter Control Valve Pipe-FCV (16-inch , Steel)	0	EA			*$5,664.73*	$0				
477	Filter Effluent Header Pipe-FEH (36-inch , Steel)	2	EA			*$12,745.64*	$25,491				
478	Filter to Waste-FTW (24-inch , Steel)	0	EA			*$8,497.09*	$0				
479	Filter to Waste-FTW (24-inch , Steel)	0	EA			*$8,497.09*	$0				
480	Backwash Supply Pipe-BWS (42-inch , Steel)	0	EA			*$14,869.91*	$0				
481	Backwash Supply Pipe-BWS (42-inch , Steel)	0	EA			*$14,869.91*	$0				
482	Backwash Waste Pipe-BWW (42-inch , Steel)	0	EA			*$14,869.91*	$0				
483	Valves										
484	Air Scour Pipe-BAW (12-inch ,V500 - BFV)	4	EA			*$10,228.60*	$40,914				
485	Filter Influent Header Pipe-FIH (36-inch ,V500 - BFV)	0	EA			*$30,685.79*	$0				
486	Filter Influent Pipe-FIH (30-inch ,V500 - BFV)	4	EA			*$25,571.49*	$102,286				
487	Filter Effluent Pipe-FE (24-inch ,V500 - BFV)	4	EA			*$20,457.20*	$81,829				
488	Filter Effluent Pipe-FE (24-inch ,V500 - BFV)	0	EA			*$20,457.20*	$0				
489	Filter Control Valve Pipe-FCV (16-inch ,V500 - BFV)	4	EA			*$13,638.13*	$54,553				
490	Filter Effluent Header Pipe-FEH (36-inch ,V500 - BFV)	0	EA			*$30,685.79*	$0				
491	Filter to Waste-FTW (24-inch ,V500 - BFV)	4	EA			*$20,457.20*	$81,829				
492	Filter to Waste-FTW (24-inch ,V500 - BFV)	0	EA			*$20,457.20*	$0				
493	Backwash Supply Pipe-BWS (42-inch ,V500 - BFV)	4	EA			*$35,800.09*	$143,200				
494	Backwash Supply Pipe-BWS (42-inch ,V500 - BFV)	0	EA			*$35,800.09*	$0				
495	Backwash Waste Pipe-BWW (42-inch ,V500 - BFV)	4	EA			*$35,800.09*	$143,200				
496	Allowance for Misc Items	5%				$1,390,208.02	$69,510				
497	Subtotal						$1,459,718				
498											
499	ELECTRICAL:										
500	MCC's										
501	Sections	4	EA			*$7,187.15*	$28,749				
502	AFD's										
503	Air Scour Blowers (81 hp each)	-	EA			*$16,315.75*	$0				
504	Switchgear										
505	Units	-	EA			*$33,060.88*	$0				
506	Electrical Conduit & Wire	0	LF	0.00	m	*$10.10*	$0		Bldg Length * # Motors		
507	Allowance for Misc Items	5%				$28,748.59	$1,437				
508	Subtotal						$30,186				
509											
510	**USER DEFINED ESTIMATE ITEMS**	**QUANT (ENGLISH)**	**UNIT (ENGLISH)**	**QUANT (METRIC)**	**UNIT (METRIC)**	**$/UNIT**	**TOTAL COST**				
511	Item 1 Description	0.00		0.00		0.00	$0				
512	Item 2 Description	0.00		0.00		0.00	$0				
513	Item 3 Description	0.00		0.00		0.00	$0				
514	Item 4 Description	0.00		0.00		0.00	$0				
515	Item 5 Description	0.00		0.00		0.00	$0				
516	Item 6 Description	0.00		0.00		0.00	$0				
517	Item 7 Description	0.00		0.00		0.00	$0				
518	Item 8 Description	0.00		0.00		0.00	$0				
519	Item 9 Description	0.00		0.00		0.00	$0				
520	Item 10 Description	0.00		0.00		0.00	$0				
521	Item 11 Description	0.00		0.00		0.00	$0				
522	Item 12 Description	0.00		0.00		0.00	$0				
523	Item 13 Description	0.00		0.00		0.00	$0				
524	Item 14 Description	0.00		0.00		0.00	$0				
525	Item 15 Description	0.00		0.00		0.00	$0				
526	Subtotal						$0				
527											
528	Subtotal						$7,848,434.20				
529											
530	ALLOWANCES:		**User Over-write**								
531	Finishes Allowance	2%		$8,530,907	$170,618.13						
532	Mechanical Allowance	2%		$8,530,906.74	$170,618.13						
533	I&C Allowance	2%		$8,530,906.74	$170,618.13						
534	Electrical Allowance	2%		$8,530,906.74	$170,618.13						
535						Facility Cost Name					
536	Facility Cost	**21,280,000**	**GPD**	**$0.40**	**$8,530,907**	FLCFC01					
537	Facility Cost with Standard Additional Project Costs Added	**21,280,000**	**GPD**	**$0.51**	**$10,919,561**	FLCFC02					
538	Facility Cost with Standard Additional Project Costs & Contractor Markups Added	**21,280,000**	**GPD**	**$0.81**	**$17,209,261**	FLCFC03					
539	Facility Cost with Standard Additional Project Costs, Contractor Markups & Escalation Added	**21,280,000**	**GPD**	**$0.81**	**$17,209,261**	FLCFC04					
540	Facility Cost, Contractor Markups, Escalation Added & Location Adjustment Factor Added (excluding ALL Additional Project Costs)	**21,280,000**	**GPD**	**$0.63**	**$13,444,735**	FLCFC05					
541	Facility Cost with Standard Additional Project Costs, Contractor Markups, Escalation Added & Location Adjustment Factor Added	**21,280,000**	**GPD**	**$0.81**	**$17,209,261**	FLCFC06					

Appendix C

Assessing Net Environmental Benefit Analysis Using an Ecological Currency

The objective of a net environmental benefit analysis (NEBA) is to determine the net environmental value that the proposed action would yield. This is accomplished by determining the value of the ecological service flows over time from the subject ecosystem *with* the action relative to the value of the ecological service flows over time from the subject ecosystem *without* the action.

The use of ecological metrics for valuing environmental benefits in a NEBA was first introduced for the purpose of scaling mitigation to offset environmental effects. This method is called the Habitat Equivalency Analysis (HEA) approach, and it was developed by the U.S. Fish and Wildlife Service and the National Oceanic and Atmospheric Administration[1] to determine compensation to the public for injuries to natural resources[2] resulting from the discharge of oil, release of hazardous substances, or physical effects from vessels. The statutes stipulate that recoveries for natural resource injuries be provided via "restoring, rehabilitating, replacing, or acquiring the equivalent of" natural resources. The HEA methodology is intended to scale the natural resource replacement projects that compensate the public for resource service losses. That is, the determination of how much ecological restoration is enough is fundamentally tied to both the level of scientific knowledge related to ecosystem function and services and the relative values that the public places on those services. This is important, as scientific and human preference weights are often needed to ensure that the environment and the public are to be made whole by resource-based compensation[3]. Under natural resource damages, the resource-based compensation must be just sufficient to offset the resource loss.

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[1] National Oceanic and Atmospheric Administration (NOAA) and U.S. Department of Commerce. *Habitat Equivalency Analysis: An Overview*. Damage Assessment and Restoration Program, 1995 (revised 2006). http://www.darrp.noaa.gov/northwest/cbay/pdf/dbhy-a.pdf

National Oceanic and Atmospheric Administration (NOAA). *Scaling Compensatory Restoration Actions: Guidance Document for Natural Resource Damage Assessment under the Oil Pollution Act of 1990*. Damage Assessment and Restoration Program, 1997.

Oil Pollution Act. *33 U.S.C.,* Sections 2701–2761, 1990.

Unsworth, R. E. and Bishop, R. Assessing Natural Resource Damages Using Environmental Annuities. Elsevier Science, *Ecological Economies* **1993**, *11* (1994), 35–41.

[2] From the Oil Pollution Act regulations:

> Natural Resources means land, fish, wildlife, biota, air, water, ground water, drinking water supplies, and other resources belonging to, managed by, held in trust by, appertaining to, or otherwise controlled by the United States (including the resources of the Exclusive Economic Zone), any State or local government or Indian Tribe…

[3] NOAA, 1997, defines primary restoration as:

> …any action, including natural recovery, that returns injured natural resources and services to baseline. This may include actions to restore, replace, rehabilitate, or acquire the equivalent of injured natural resources or services.

In HEA, changes in ecological services are measured as percentage changes from a baseline or reference condition. HEA begins by identifying the various habitat types that are relevant to the site, and the acreage of each habitat. The major service flow from the habitat type or ecosystem layer site is identified, and some structural or functional indicators are then developed of the ability of the habitat to provide that service flow. A baseline or reference habitat is specified. Suppose this baseline habitat is defined to provide 100% of the service flows from a habitat. Habitats at issue are then compared to the reference habitat using the indicator(s) of service flows, and the service flows under alternative actions computed as a percentage difference relative to the reference area. Note that, if the reference area is an ideal habitat, the flow of services from the habitats being evaluated are always less than or equal to 100%, but quality differences of an evaluated habitat relative to a reference habitat could generate more than 100% of services. Furthermore, because this model examines service flows over time, it is critical that the appropriate reference habitat be provided for each year.

The units of comparison are called "ecological units." One acre of habitat operating at 100% service flows generates one ecological unit of services. Taking into account the acreage and the percentage differences in amount of services, the evaluated habitats provide a certain number of ecological units called "service acre years" or SAYs, each year. For example, 20 acres of forested wetland habitat operating at 80% of reference services in a given year provides 16 forested wetland habitat SAYs. In this way, degraded ecosystems produce smaller quantities of ecosystem services than their fully functioning counterparts and thus have a lower value to society.

With one additional step, this ecological currency provide a relatively straightforward means of tracking changes in ecosystem services and thus the value of the for inclusion in a BCA approach toward TBL accounting. The SAYs for all future years are discounted to calculate the NPV of the flow in ecosystem services over time. In this way, temporary gains or losses in ecosystem services have less weight in the analysis than permanent effects. Similarly, effects that are delayed until some future year receive less weight than any immediate changes in ecosystem services. This is shown by the following equation:

Discounted Service Acre Years (DSAYs) =

$$\left[\sum_{t=0}^{B} \rho_t \left(b^j - x_t^j\right)\right] * J$$

where t is time in years and the following notation applies :

t = 0, the impact occurs

t = B, the last year of impacts

x_t^j, the percentage of services per acre provided by the impacted habitat in year t

b^j, the baseline percentage of services per acre of the impacted habitat

ρ_t, discount factor where $\rho_t = 1/(1+r)^t$, and r is the discount rate

J, the number of injured acres

In the case where the impact results in a total loss of services $x_t^j = 0$.

The flow of ecological services is discounted using the best available estimate of the public's time rate of preference. NOAA and DOI have adopted a 3% discount rate as a matter of policy. Discounting future service flows is to capture the observed phenomenon that the public prefers to receive the ecological service flow sooner rather than later.

To calculate the lost services from siting facilities, we employ the following general steps:

1. Identify and characterize the affected habitat.
2. Describe the primary ecological services the habitats do or could provide (which are flows).
3. Choose or construct the appropriate indicator to measure the changes in primary service flows because of the diversion.
4. Establish the condition of the habitat over time without the action (i.e., in terms of the indicator variables) to provide the reference or baseline.
5. Predict the change in the condition of the habitat over time with the action (i.e., in terms of percentage changes in the indicator variables);
6. Determine the time frame for the analysis (e.g., 2012−2052 or 40 years?).
7. Choose the appropriate discount rate (DOI uses 3%).
8. Quantify the ecological service losses using the equation.

Appendix D

Utility Questionnaire

Note: Please fill out this form for each water reuse plant you own and operate. A reuse plant is defined as the plant or portion of the wastewater treatment plant that provides treatment of secondary effluent to a tertiary level (e.g., filtration) and possibly beyond (e.g., membrane filtration, RO, UVAOP) for beneficial use of reclaimed water.

1. Utility Information:
   a. What is the name of your utility?
   b. Provide narrative description of your water reuse system (wastewater and reuse treatment provided, extent of reuse distribution system, pumping, storage, reclaimed water users). Please describe in less than 200 words.
   c. Enter your utility's website address
2. Wastewater Treatment Plant (WWTP) and reuse plant locations:
   a. What is the name of the WWTP?
   b. In what city is the WWTP located?
   c. In what state is the WWTP located?
   d. What is the zip code of the WWTP?
   e. In what country is the WWTP located?
   f. What is the name of the reuse plant?
   g. Is the reuse plant located on the same site as the WWTP? If yes, skip to the next section; if no, answer the next series of questions.
   h. In what city is the reuse plant located?
   i. In what state is the reuse plant located?
   j. What is the zip code of the reuse plant?
   k. In what country is the reuse plant located?
3. WWTP:
   a. Description:
      i. Beginning with raw wastewater entering the WWTP, list the liquid treatment processes in sequential order, separated by a comma, e.g., screening, grit removal, primary clarifiers, biological reactors, secondary clarifiers, chlorine disinfection, dechlorination
      ii. Is nitrification practiced at the WWTP?
      iii. Is dentrification practiced at the WWTP?
      iv. Is biological phosphorus removal practiced at the WWTP?
         v. At what point in the WWTP is water delivered to the reuse plant? (After secondary clarifiers, after disinfection, other: please explain)

b. Will you be reporting values for this survey in English units or metric units?

c. WWTP flow (use last three years' worth of data if possible):

    i. What is the average annual flow (mgd or mld)?

    ii. What is the 99th percentile flow (mgd or mld)?

    iii. What is the 1st percentile flow (mgd or mld)?

    iv. How many years of data are these flows based on?

d. Secondary effluent water quality (if secondary effluent data is unavailable, use WWTP final effluent data):

    i. Where available, provide average, 10th percentile, and 90th percentile for the following parameters:

        1. pH, temperature (C), alkalinity (mg/L $CaCO_3$), TDS (mg/L), TSS (mg/L), TOC (mg/L), BOD (mg/L), COD(mg/L), turbidity (NTU), e. coli (#/100mL), total coliform (#/100mL), fecal coliform (#/100mL), total nitrogen (mg N/L), ammonia nitrogen (mg N/L), nitrate (mg N/L), nitrite (mg N/L), orthophosphate (mg P/L), hardness (mg/L $CaCO_3$), sodium (mg/L), magnesium (mg/L), calcium (mg/L), chloride (mg/L), total trihalomethanes (µg/L), NDMA (ng/L), TKN(mg/L).

            a. If data is unavailable, leave blank.

        2. Does water quality data provided represent secondary effluent or WWTP final effluent?

        3. How many years of data are these values based on?

        4. Indicate the frequency of sample collection for each parameter (daily, weekly, monthly, quarterly, or annually).

4. Reuse Plant

a. Description:

    i. Beginning with the secondary effluent from the WWTP entering your reuse plant, list the liquid treatment processes in sequential order, separated by a comma. For example: rapid mix with coagulant addition, flocculation, inclined plate clarification, granular media filtration, chlorine disinfection. List in-plant pump stations if they are present at your plant.

b. Reuse Plant Flow:

    i. What is the average annual flow (mgd or mld)?

    ii. What is the plant's maximum capacity (mgd or mld)?

    iii. What is the maximum day flow during your maximum flow month (mgd or mld)?

    iv. In what month does that occur?

    v. What is the maximum day flow during your minimum flow month (mgd or mld)?

    vi. In what month does that occur?

    vii. How many years of data are these flows based on?

c. Liquid Treatment Design Criteria.

1. Chemical Addition:

   a. Select which chemicals are added at the treatment plant out of the following (ignore membrane and UV cleaning chemicals); aluminum sulfate, ferric chloride, ferric sulfate, polyaluminum chloride, coagulant polymer, flocculation polymer, filter aid polymer, chlorine gas, sodium hypochlorite, chlorine dioxide, ozone, aqueous ammonia, sodium hydroxide, hydrated lime, carbon dioxide, hydrogen peroxide, antiscalant, sodium bisulfite, sulfuric acid, hydrochloric acid, soda ash, potassium permanganate, other

   b. List where is chemical added in the treatment process (e.g., at chlorine contact basin)?

   c. What is the average chemical dose for each chemical (mg/L)?

2. Coagulation:

   a. Type of coagulant rapid mix (in-pipe, in-line mechanical mixer, in-basin)

3. Flocculation:

   a. Hydraulic residence time at max day flow (minutes)

   b. Flocculator type: horizontal or vertical?

   c. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

4. Sedimentation:

   a. What type of sedimentation is provided: conventional, inclined plate clarification, or solids contact clarifier?

      i. Conventional: hydraulic residence time at max day flow (minutes)

      ii. Inclined plate clarification: individual plate size (sq ft or sq m) and total number of plates

      iii. Solids contact clarifier: Loading rate at max day flow (gpm/sf or m/hr)

   b. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

5. Granular media filtration:

   a. Monomedia or multimedia?

   b. Are the filters continuous backwash, conventional, or traveling bridge type?

   c. What is the filter loading rate at max day flow with all filters in service(gpm/sf or m/hr)?

   d. What is the total media depth (ft or m)?

   e. What is the total number of filters?

   f. What is the filter surface area per filter (sq ft or sq m)?

g. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

6. Disk Filtration:

   a. Are the disks located in manufacturer supplied tanks or concrete tanks?
   b. What is the active filtration area per disk?
   c. How many trains are provided?
   d. What is the total number of disks per train?
   e. What is the filter loading rate at max day flow (gpm/sf or m/hr)?
   f. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

7. Membrane filtration (MF or UF only):

   a. Immersed or pressurized?
   b. Membrane manufacturer (GE, Siemens, Pall, other)
   c. Flux at max day flow (gal/sq ft/day or L/sq m /hr)
   d. Average transmembrane pressure (psi or kpa)
   e. Total number of membrane trains
   f. Total membrane area (sq ft or sq m of membrane area)
   g. Number of strainers provided upstream of membranes
   h. Clean-in-Place frequency (months)
   i. Backwash frequency (minutes)
   j. Average membrane replacement frequency (years)
   k. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

8. Which of the following advanced treatment processes are provided: Reverse Osmosis (RO), UV advanced oxidation (UVAOP), granular activated carbon (GAC), ozone oxidation?

   a. RO:

      i. RO design flux at max day summer flow (gal/sq ft/day or L/sq m/hr)
      ii. Number of RO stages (1, 2, or 3?)
      iii. Number of RO elements per RO vessel
      iv. RO recovery? (percent)
      v. RO feed pressure (psi or kpa)
      vi. RO antiscalant dose (mg/L)
      vii. RO CIP frequency (months)
      viii. Total number of RO trains
      ix. Average membrane replacement frequency (years)

x. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building)?

xi. Where is RO concentrate discharged?

xii. What is the average annual flow of the RO concentrate (mgd or mld)?

xiii. Is a decarbonator used on the RO permeate?

b. UVAOP

i. What is the design parameter for destruction (NDMA, 1-4 dioxane, other)

ii. What is the design log reduction (number of logs)

iii. Is the UVAOP process designed around a UV dose (mJ/cm2) or the electrical energy per order of destruction (EEo)?

1. If UV dose, what is the design UV dose (MJ/cm2)?

2. If EEo, what is the EEo (kwh/1,000 gal/log parameter destruction)?

iv. What is the average UV254 transmittance (percentage)

v. Total number of trains

vi. Total number of lamps per train

vii. Lamp size (watts per lamp)

viii. Hydrogen peroxide dose (mg/L)

ix. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

c. GAC:

i. Is the target effluent organics goal TOC or COD?

ii. What is the target effluent organics goal? (mg/L)

iii. GAC Loading rate at max day flow (gpm/sf or m/hr)

iv. Total media depth (ft or m)

v. Total number of GAC filters

vi. Filter surface area per GAC filter (sq ft or sq m)

vii. Regeneration frequency (months)

viii. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

d. Ozone Oxidation:

i. Average ozone dose (mg/L)

ii. Pipeline contactor or basin contactor?

iii. Hydraulic residence time at max day flow in contactor (minutes)

iv. Sidestream ozone injection or diffuser injection?

v. Number of ozone generators

vi. Size of each ozone generator (lb/ day or K/ day)

9. Disinfection

a. What type of disinfection is provided? (chlorine [free chlorine or monochloramine], UV, ozone)

i. Chlorine Disinfection:

1. What is the average chlorine dose (mg/L)?
2. Pipeline contactor or basin contactor?
3. What is the hydraulic residence time at max day flow in the chlorine contact basin (minutes)?
4. Is sodium hypochlorite or chlorine gas used?

ii. UV Disinfection:

1. What is the average UV dose (mJ/cm2)?
2. Are the UV lamps in open channels or enclosed vessels?
3. What is the average UV254 transmittance (percentage)?
4. What is the total number of UV trains
5. What is the total number of lamps per train
6. What is the lamp size (watts per lamp)
7. Is the treatment process located in a building? If yes, what type (canopy, metal building, block or concrete building, other)?

iii. Ozone Disinfection:

1. Average ozone dose (mg/L)
2. Pipeline contactor or basin contactor?
3. Hydraulic residence time at max day flow in contactor (minutes)
4. Sidestream ozone injection or diffuser injection?
5. Number of ozone generators
6. Size of each ozone generator (lb/day or K/day)

d. Solids Treatment Design Criteria.

i. What type of solids handling treatment processes are provided (i.e., gravity thickener, centrifuge, filter press, drying beds or lagoons, sewer discharge)?

ii. For each solids treatment process provided, indicate

1. the number of units (number)
2. capacity (specify units; e.g., gpm for centrifuge, acres for drying beds, etc.)

e. Site Considerations:

i. How many acres is the site for the reuse plant (acres or hectares)?

ii. What is the total electrical connected load for the plant (kW or hp)?

iii. Does your plant have a standby generator? If yes, what is its capacity (kW)?

f. Reuse Plant Finished Water Quality:

   i. Where available, provide average, 10th percentile, and 90th percentile for the following parameters:

      1. pH, temperature (C), alkalinity (mg/L $CaCO_3$), TDS (mg/L), TSS (mg/L), TOC (mg/L), BOD (mg/L), COD(mg/L), turbidity (NTU), e. coli (#/100mL), total coliform (#/100mL), fecal coliform (#/100mL), total nitrogen (mg N/L), ammonia nitrogen (mg N/L), nitrate (mg N/L), nitrite (mg N/L), orthophosphate (mg P/L), hardness (mg/L $CaCO_3$), sodium (mg/L), magnesium (mg/L), calcium (mg/L), chloride (mg/L), total trihalomethanes (ug/L), NDMA (ng/L), TKN(mg/L). If data is not available, please leave blank.

      2. How many years of data are these values based on?

      3. Indicate the frequency of sample collection for each parameter (daily, weekly, monthly, quarterly, or annually).

g. Reuse Plant Construction Costs: For each major construction contract (>$1M) where treatment processes were added or flow capacity was increased, provide

   i. Year construction started

   ii. Year construction completed

   iii. New treatment plant or retrofit?

   iv. Narrative of scope included (describe using less than 100 words)

   v. Flow capacity increase (mgd or mld)

   vi. Total construction cost (do not include engineering and construction administration costs)

   vii. Currency in which construction cost is reported

   viii. Narrative of any special items for consideration that may have significantly affected cost (e.g., poor soil conditions requiring expensive foundations). Describe in less than 100 words.

h. Reuse Plant Operational and Maintenance Costs: If possible, provide average O&M costs for last 3 years. Only report **costs and quantities associated with the reuse plant**. Do not include costs and quantities associated with the WWTP (from screening through secondary treatment).

   i. Annual power used (not including finished water pumping) (kwh/yr)

   ii. Average electricity cost ($/kwh)

   iii. Annual natural gas used (therms/year or cubic m/year)

   iv. Annual chemical quantity used (gallons) and annual cost ($/year) for each chemical.

   v. Equipment maintenance and replacement costs ($/year)

   vi. Annual Laboratory Costs ($/year).

vii. Annual residuals quantity disposed offsite (wet tons/year or wet m tons/year) and annual residuals offsite disposal cost ($/year).

viii. Annual SCADA and instrument maintenance and replacement costs ($/year)

ix. Total annual plant staff hours (hrs/year) and annual plant labor costs with fringe benefits ($/yr).

x. Number of full-time plant staff employed

xi. Annual vehicle operation and maintenance costs ($/yr).

xii. Miscellaneous costs (all other annual O&M costs not identified previously).

1. Please provide a description of what these miscellaneous costs include.

iii. How many years of data are the costs provided based on?

iv. Average annual flow over time period (mgd or mld).

5. End Uses of Water:

a. Identify each end use of the reclaimed water and the percentage of the total annual flow delivered to each user. Also indicate the percent of total annual flow to each use, as well as if it is potable or nonpotable.

b. How much does your utility charge both commercial/industrial users and residential users for reclaimed water?

i. Flat rate charge in $/connection/month

ii. Use charge in $/1,000 gal or $/kL

c. What is the potable water rate in the area ($/1,000 gal or $/kL)?

d. Relative to the needs of the end users, do you feel that the level of treatment is too low, just right, or too high? If too low or two high, describe why? Describe in less than 100 words.

e. Must the end users incur additional costs, or do they enjoy any cost savings owing to attributes of the reuse water? For example, for landscape or agricultural irrigation applications, can the end user take advantage of nutrients in the reuse water to decrease fertilizer applications? Describe in less than 100 words.

6. Regulations:

a. Do you provide any treatment processes at your reuse plant that are not required to meet your permit? If so please describe the process and explain why it was added using less than 100 words.

b. Are there any upcoming regulations that may impact treatment requirements at your reuse plant? If yes, please explain in less than 100 words.

7. Does your utility have any formal or informal sustainability policy? If yes, which of the following parameters are considered when implementing capital projects or modifying operational procedures: energy utilization, GHG emissions, other air pollutants, creating open space and other community benefits (such as from treatment wetlands)

8. Please provide any additional comments you feel are relevant to the content of this survey.

9. Please e-mail Larry.Schimmoller@ch2m.com the following documents in PDF form:

a. A process flow diagram of the WWTP
b. A process flow diagram of the Reuse Plant
c. Your facility's permit that identifies treatment and water quality requirements for use of the reclaimed water

Appendix E

Scenario Cost Tables

Scenario 1A (GMF) Capital Costs

Facility	**5**	**20**	**70**
Equalization Basin	$80,000	$220,000	$590,000
Raw Water Pump Station	$480,000	$1,110,000	$2,880,000
Inline Rapid Mix	$400,000	$610,000	$1,280,000
Tertiary Filters	$2,210,000	$4,160,000	$9,980,000
Chlorine Contactor	$880,000	$2,690,000	$7,980,000
Backwash Supply Pump Station	$910,000	$1,400,000	$1,620,000
Liquid Chemical: Ferric	$280,000	$290,000	$510,000
Liquid Chemical: Polymer	$220,000	$220,000	$220,000
Liquid Chemical: Cl2	$330,000	$520,000	$1,050,000
Backwash Waste EQ Basin and Pump Station	$700,000	$1,260,000	$1,980,000
Administration Building	$630,000	$1,260,000	$1,890,000
Additional Project Costs			
Overall Sitework	$430,000	$820,000	$1,800,000
Plant Computer System	$140,000	$270,000	$600,000
Yard Electrical	$360,000	$690,000	$1,500,000
Yard Piping	$1,070,000	$2,060,000	$4,500,000
Contractor Markups			
Overhead	$640,000	$1,230,000	$2,690,000
Profit	$970,000	$1,880,000	$4,100,000
Mob/Bonds/Insurance	$320,000	$620,000	$1,350,000
Contingency	$3,310,000	$6,390,000	$13,950,000
Nonconstruction Costs			
Engineering	$1,000,000	$1,940,000	$4,230,000
Services During Construction	$1,000,000	$1,940,000	$4,230,000
Total Project Capital Cost	**$16,360,000**	**$31,580,000**	**$68,930,000**

Scenario 1B (MF) Capital Costs

Facility	5	20	70
Equalization Basin	$80,000	$220,000	$610,000
Raw Water Pump Station	$550,000	$1,310,000	$2,960,000
Immersed MF/UF	$0	$0	$61,290,000
Pressurized MF/UF	$6,090,000	$14,170,000	$0
Break Tank	$100,000	$290,000	$330,000
Liquid Chemical: Ammonia	$310,000	$310,000	$270,000
Microfiltration Waste EQ Basin and Pump Station	$380,000	$680,000	$1,150,000
Liquid Chemical: Cl2	$450,000	$670,000	$820,000
Chlorine Contactor	$860,000	$2,110,000	$7,850,000
Administration Building	$630,000	$1,260,000	$1,890,000
Additional Project Costs			
Overall Sitework	$470,000	$1,050,000	$3,860,000
Plant Computer System	$280,000	$630,000	$2,320,000
Yard Electrical	$570,000	$1,260,000	$4,630,000
Yard Piping	$1,040,000	$2,310,000	$8,490,000
Contractor Markups			
Overhead	$830,000	$1,840,000	$6,750,000
Profit	$1,260,000	$2,810,000	$10,320,000
Mob/Bonds/Insurance	$420,000	$930,000	$3,410,000
Contingency	$4,290,000	$9,550,000	$35,090,000
Nonconstruction Costs			
Engineering	$1,300,000	$2,900,000	$10,640,000
Services During Construction	$1,300,000	$2,900,000	$10,640,000
Total Project Capital Cost	**$21,210,000**	**$47,200,000**	**$173,320,000**

Scenario 1C (MF/RO; Ocean Disposal) Capital Costs

Facility	**5**	**20**	**70**
Equilization Basin	$90,000	$250,000	$780,000
Raw Water Pump Station	$600,000	$1,480,000	$3,400,000
Microfiltration	$6,630,000	$16,530,000	$65,890,000
Break Tank	$110,000	$340,000	$660,000
Reverse Osmosis	$9,920,000	$19,360,000	$52,860,000
RO Concentrate Pump Station	$300,000	$520,000	$800,000
Liquid Chemical: Ammonia	$310,000	$310,000	$530,000
Dry Chemical: Lime	$840,000	$1,900,000	$5,410,000
Recarbonation	$280,000	$520,000	$900,000
Microfiltration Waste EQ Basin and Pump Station	$500,000	$690,000	$1,230,000
Liquid Chemical: Cl2	$450,000	$900,000	$1,810,000
Chlorine Contactor	$310,000	$740,000	$2,840,000
Administration Building	$630,000	$1,260,000	$1,890,000
Additional Project Costs			
Overall Sitework	$1,050,000	$2,240,000	$6,950,000
Plant Computer System	$630,000	$1,340,000	$4,170,000
Yard Electrical	$1,260,000	$2,690,000	$8,340,000
Yard Piping	$2,310,000	$4,930,000	$15,290,000
Contractor Markups			
Overhead	$1,830,000	$3,920,000	$12,160,000
Profit	$2,800,000	$5,990,000	$18,590,000
Mob/Bonds/Insurance	$930,000	$1,980,000	$6,140,000
Contingency	$9,530,000	$20,370,000	$63,190,000
Nonconstruction Costs			
Permitting	$2,890,000	$6,180,000	$19,170,000
Engineering	$2,890,000	$6,180,000	$19,170,000
Total Project Capital Cost	**$47,090,000**	**$100,620,000**	**$312,170,000**

Scenario 2A (GAC) Capital Costs

Facility	**5**	**20**	**70**
Equilization Basin	$80,000	$230,000	$690,000
Raw Water Pump Station	$490,000	$1,140,000	$2,920,000
Inline Rapid Mix	$410,000	$840,000	$1,550,000
Ozone Contactor	$5,050,000	$7,660,000	$15,080,000
Biologically Activated Carbon Filters	$2,920,000	$6,170,000	$14,770,000
In-Plant Filter Pump Station	$480,000	$1,130,000	$2,970,000
Granular Activated Carbon Filters	$3,550,000	$8,530,000	$23,530,000
UV Disinfection	$810,000	$840,000	$2,410,000
In-Plant Backwash Supply Pump Station	$700,000	$960,000	$1,220,000
Lamella Clarifier	$840,000	$2,470,000	$7,250,000
Gravity Thickener	$450,000	$1,010,000	$1,700,000
Flocculation Basin	$930,000	$2,380,000	$6,660,000
Backwash Waste EQ Basin and Pump Station	$790,000	$960,000	$2,240,000
Liquid Chemical: Ferric	$310,000	$370,000	$1,680,000
Liquid Chemical: Polymer	$300,000	$300,000	$360,000
Administration Building	$630,000	$1,260,000	$1,890,000
Centrifuge	$2,790,000	$2,970,000	$3,990,000
Additional Project Costs			
Overall Sitework	$1,290,000	$2,350,000	$5,460,000
Plant Computer System	$430,000	$780,000	$1,820,000
Yard Electrical	$1,080,000	$1,960,000	$4,550,000
Yard Piping	$3,230,000	$5,880,000	$13,640,000
Contractor Markups			
Overhead	$1,930,000	$3,510,000	$8,150,000
Profit	$2,950,000	$5,370,000	$12,450,000
Mob/Bonds/Insurance	$970,000	$1,770,000	$4,110,000
Contingency	$10,020,000	$18,260,000	$42,330,000
Nonconstruction Costs			
Permitting	$3,040,000	$5,540,000	$12,840,000
Engineering	$3,040,000	$5,540,000	$12,840,000
Total Project Capital Cost	**$49,510,000**	**$90,180,000**	**$209,100,000**

Scenario 2B (RO; Ocean Disposal) Capital Costs

Facility	5	20	70
Equilization Basin	$90,000	$250,000	$780,000
Raw Water Pump Station	$600,000	$1,480,000	$4,060,000
Microfiltration	$6,640,000	$16,530,000	$65,890,000
Break Tank	$110,000	$340,000	$660,000
Reverse Osmosis	$9,920,000	$19,360,000	$52,860,000
RO Concentrate Pump Station	$300,000	$520,000	$800,000
Liquid Chemical: Ammonia	$290,000	$310,000	$530,000
Dry Chemical: Lime	$840,000	$1,900,000	$5,410,000
Recarbonation: CO_2	$280,000	$520,000	$900,000
UV Advanced Oxidation Process	$2,790,000	$9,690,000	$23,280,000
Microfiltration Waste EQ Basin and Pump Station	$500,000	$690,000	$1,230,000
Liquid Chemical: Cl2	$300,000	$470,000	$1,050,000
Administration Building	$630,000	$1,260,000	$1,890,000
Additional Project Costs			
Overall Sitework	$1,160,000	$2,670,000	$7,970,000
Plant Computer System	$700,000	$1,600,000	$4,780,000
Yard Electrical	$1,400,000	$3,200,000	$9,560,000
Yard Piping	$2,560,000	$5,860,000	$17,530,000
Contractor Markups			
Overhead	$2,040,000	$4,670,000	$13,940,000
Profit	$2,110,000	$7,130,000	$21,310,000
Mob/Bonds/Insurance	$1,030,000	$2,350,000	$7,030,000
Contingency	$10,590,000	$24,240,000	$72,440,000
Nonconstruction Costs			
Permitting	$3,210,000	$7,350,000	$21,970,000
Engineering	$3,210,000	$7,350,000	$21,970,000
Total Project Capital Cost	**$51,300,000**	**$119,740,000**	**$357,840,000**

Scenario 2B (RO; Mech Evap) Capital Costs

Facility	5	20	70
Equilization Basin	$80,000	$220,000	$610,000
Raw Water Pump Station	$550,000	$1,310,000	$2,960,000
Microfiltration	$6,120,000	$14,220,000	$61,100,000
Break Tank	$100,000	$290,000	$330,000
Reverse Osmosis	$8,080,000	$16,900,000	$51,470,000
Brine Concentrator and Crystallizer for RO Concentrate	$16,930,000	$53,690,000	$156,220,000
Liquid Chemical: Ammonia	$290,000	$310,000	$520,000
Dry Chemical: Lime	$840,000	$1,890,000	$5,410,000
Recarbonation: CO_2	$280,000	$520,000	$900,000
UV Advanced Oxidation Process	$3,440,000	$11,160,000	$23,280,000
Microfiltration Waste EQ Basin and Pump Station	$430,000	$680,000	$1,150,000
Liquid Chemical: Cl2	$430,000	$460,000	$460,000
Administration Building	$630,000	$1,260,000	$1,890,000
Additional Project Costs			
Overall Sitework	$1,060,000	$2,460,000	$7,500,000
Plant Computer System	$640,000	$1,480,000	$4,500,000
Yard Electrical	$1,280,000	$2,950,000	$9,000,000
Yard Piping	$2,340,000	$5,420,000	$16,510,000
Contractor Markups			
Overhead	$1,860,000	$4,310,000	$13,130,000
Profit	$2,850,000	$6,580,000	$20,070,000
Mob/Bonds/Insurance	$940,000	$2,170,000	$6,620,000
Contingency	$9,670,000	$22,380,000	$68,230,000
Nonconstruction Costs			
Permitting	$4,120,000	$10,540,000	$31,630,000
Engineering	$4,120,000	$10,540,000	$31,630,000
Total Project Capital Cost	**$67,080,000**	**$171,740,000**	**$515,120,000**

Scenario 2B (RO; Evap Ponds) Capital Costs

Facility	5	20	70
Equilization Basin	$90,000	$250,000	$780,000
Raw Water Pump Station	$600,000	$1,480,000	$3,400,000
Microfiltration	$6,640,000	$16,530,000	$65,890,000
Break Tank	$110,000	$340,000	$660,000
Reverse Osmosis	$9,920,000	$19,360,000	$52,860,000
RO Concentrate Pump Station	$300,000	$520,000	$800,000
Evaporation Ponds for RO Concentrate	$34,910,000	$160,800,000	$626,590,000
Liquid Chemical: Ammonia	$290,000	$310,000	$530,000
Dry Chemical: Lime	$840,000	$1,900,000	$5,410,000
Recarbonation: CO_2	$280,000	$520,000	$900,000
UV Advanced Oxidation Process	$2,790,000	$9,690,000	$23,280,000
Microfiltration Waste EQ Basin and Pump Station	$500,000	$690,000	$1,230,000
Liquid Chemical: Cl2	$300,000	$470,000	$1,050,000
Administration Building	$630,000	$1,260,000	$1,890,000
Additional Project Costs			
Overall Sitework	$1,160,000	$2,670,000	$7,930,000
Plant Computer System	$700,000	$1,600,000	$4,760,000
Yard Electrical	$1,400,000	$3,200,000	$9,520,000
Yard Piping	$2,560,000	$5,860,000	$17,450,000
Contractor Markups			
Overhead	$2,040,000	$4,670,000	$13,880,000
Profit	$2,110,000	$7,130,000	$21,220,000
Mob/Bonds/Insurance	$1,030,000	$2,350,000	$7,000,000
Contingency	$10,590,000	$24,240,000	$72,140,000
Nonconstruction Costs			
Permitting	$5,650,000	$18,610,000	$65,740,000
Engineering	$5,650,000	$18,610,000	$65,740,000
Total Project Capital Cost	**$91,090,000**	**$303,060,000**	**$1,070,650,000**

Scenario 1A (GMF) Annual O&M Costs

	5 mgd	20 mgd	70 mgd
Power	$57,000	$145,000	$340,000
Chemical	$47,000	$189,000	$660,000
Maintenance & Repair	$187,000	$360,000	$790,000
Labor	$800,000	$1,400,000	$4,900,000
Total O&M Costs	**$1,091,000**	**$2,094,000**	**$6,690,000**

Scenario 1B (MF) Annual O&M Costs

	5 mgd	20 mgd	70 mgd
Power	$76,000	$173,000	$820,000
Chemical	$60,000	$233,000	$820,000
Maintenance & Repair	$276,000	$610,000	$2,250,000
Labor	$800,000	$1,400,000	$4,900,000
MF Replacement (7-year replacement, annualized cost)	$110,000	$400,000	$1,360,000
Total O&M Costs	**$1,322,000**	**$2,816,000**	**$10,150,000**

Scenario 1C (MF/RO; Ocean Disposal) Annual O&M Costs

	5 mgd	20 mgd	70 mgd
Power	$460,000	$1,060,000	$3,340,000
Chemical	$214,000	$800,000	$2,760,000
Maintenance & Repair	$620,000	$1,330,000	$4,160,000
Labor	$800,000	$1,400,000	$4,900,000
MF Replacement (7-year replacement, annualized cost)	$133,000	$460,000	$1,540,000
RO Replacement (5-year replacement, annualized cost)	$82,000	$403,000	$1,339,000
Total O&M Costs	**$2,309,000**	**$5,460,000**	**$18,030,000**

Scenario 2A (GAC; 2 year replacement) Annual O&M Costs

	5 mgd	**20 mgd**	**70 mgd**
Power	$143,000	$350,000	$1,030,000
Chemical	$170,000	$670,000	$2,330,000
GAC	$219,000	$780,000	$2,230,000
Maintenance & Repair	$570,000	$1,030,000	$2,390,000
Labor	$800,000	$1,400,000	$4,900,000
UV Equipment	$7,000	$3,000	$14,000
Total O&M Costs	**$1,909,000**	**$4,233,000**	**$12,894,000**

Scenario 2A (GAC; 8 year replacement) Annual O&M Costs

	5 mgd	**20 mgd**	**70 mgd**
Power	$140,000	$350,000	$1,030,000
Chemical	$170,000	$670,000	$2,330,000
GAC	$55,000	$195,000	$560,000
Maintenance & Repair	$570,000	$1,030,000	$2,390,000
Labor	$800,000	$1,400,000	$4,900,000
UV Equipment	$7,000	$3,000	$14,000
Total O&M Costs	**$1,742,000**	**$3,648,000**	**$11,224,000**

Scenario 2B (RO; Ocean Disposal) Annual O&M Costs

	5 mgd	**20 mgd**	**70 mgd**
Power	$520,000	$1,280,000	$4,370,000
Chemical	$179,000	$680,000	$2,350,000
Maintenance & Repair	$575,000	$1,390,000	$4,230,000
Labor	$800,000	$1,400,000	$4,900,000
UV Equipment Replacement	$81,000	$320,000	$890,000
MF Replacement (7-year replacement, annualized cost)	$133,000	$460,000	$1,540,000
RO Replacement (5-year replacement, annualized cost)	$82,000	$373,000	$1,240,000
Total O&M Costs	**$2,370,000**	**$5,903,000**	**$19,520,0000**

Scenario 2B (RO; Mech Evap) Annual O&M Costs

	5 mgd	20 mgd	70 mgd
Power	$1,670,000	$5,230,000	$17,390,000
Chemical	$266,000	$940,000	$3,260,000
Maintenance & Repair	$880,000	$2,260,000	$6,780,000
Labor	$800,000	$1,400,000	$4,900,000
UV Equipment Replacement	$81,000	$320,000	$890,000
MF Replacement (7-year replacement, annualized cost)	$121,000	$400,000	$1,360,000
RO Replacement (5-year replacement, annualized cost)	$71,000	$315,000	$1,073,000
Total O&M Costs	**$3,889,000**	**$10,865,000**	**$35,653,000**

Scenario 2B (RO; Evap Ponds) Annual O&M Costs

	5 mgd	20 mgd	70 mgd
Power	$720,000	$1,760,000	$4,990,000
Chemical	$204,000	$750,000	$2,620,000
Maintenance & Repair	$1,210,000	$3,970,000	$14,020,000
Labor	$800,000	$1,400,000	$4,900,000
UV Equipment Replacement	$81,000	$320,000	$890,000
MF Replacement (7-year replacement, annualized cost)	$130,000	$460,000	$1,540,000
RO Replacement (5-year replacement, annualized cost)	$82,000	$373,000	$1,237,000
Total O&M Costs	**$3,227,000**	**$9,033,000**	**$30,197,000**

	Power Consumption (MWh/year)		
Scenario	**5 mgd**	**20 mgd**	**70 mgd**
Scenario 1A (GMF)	717	1,818	4,302
Scenario 1B (MF)	949	2,162	10,279
Scenario 1C (MF/RO; Ocean Disposal)	5,713	13,311	41,714
Scenario 2A (GAC)	1,788	4,355	12,842
Scenario 2B (RO; Ocean Disposal)	6,537	16,006	54,686
Scenario 2B (RO; Mech Evap)	20,922	65,377	217,434
Scenario 2B (RO; Evap Ponds)	9,006	22,003	62,419

Scenario 1A (GMF)

Chemical	5 mgd	20 mgd	70 mgd
Ferric Chloride	23.52	94.15	329.49
Liquid Polymer	0.47	1.88	6.59
Sodium Hypochlorite (12.5%)	23.52	94.15	329.49

Scenario 1B (MF)

Chemical	5 mgd	20 mgd	70 mgd
Sodium Hypochlorite (12.5%)	43.68	173.60	607.07
Citric Acid	2.17	7.05	15.18
Sodium Hydroxide	0.12	0.34	10.05
Sodium Bisulfite	0.23	0.64	19.19
Ammonia	12.15	48.56	169.93

Scenario 1C (MF/RO; Ocean Disposal) Chemical Usage

Chemical	5 mgd	20 mgd	70 mgd
Sodium Hypochlorite (12.5%)	47.25	192.83	654.85
Citric Acid	5.75	11.27	22.21
Sodium Hydroxide	2.88	3.12	16.94
Sodium Bisulfite	0.28	0.75	20.24
Scale Inhibitor	18.80	75.20	263.19
Sulfuric Acid	134.30	537.25	1,880.18
Ammonia	14.27	57.12	199.91
Calcium Hydroxide	210.04	840.17	2,940.60
CO_2	45.66	182.65	639.26
STPP	2.50	3.84	14.88
DDBS	0.30	0.46	1.78

Scenario 2A Chemical Usage

Chemical	5 mgd	20 mgd	70 mgd
Ferric Chloride	147.12	588.76	2,060.80
Liquid Polymer	5.18	16.26	57.08
Liquid Oxygen	294.25	1,166.01	4,080.50
GAC (2-year replacement)	80.43	285.89	818.44
GAC (8-year replacement)	20.11	71.47	204.61

Scenario 2B (RO; Mech Evaporation) Chemical Usage

Chemical	5 mgd	20 mgd	70 mgd
Sodium Hypochlorite (12.5%)	43.68	86.40	287.44
Citric Acid	5.15	9.45	20.16
Sodium Hydroxide	18.35	66.68	240.08
Sodium Bisulfite	0.23	0.64	19.19
Scale Inhibitor	15.98	63.93	223.74
Sulfuric Acid	422.37	1,689.41	5,913.16
Ammonia	12.15	48.56	169.93
Calcium Hydroxide	210.04	840.17	2,940.60
CO_2	45.66	182.65	639.26
Hydrogen Peroxide	13.70	54.79	191.78
STPP	0.37	3.00	12.45
DDBS	0.04	0.36	1.49

Scenario 2B (RO; Ocean Disposal & Evap Ponds) Chemical Usage

Chemical	5 mgd	20 mgd	70 mgd
Sodium Hypochlorite (12.5%)	24.42	96.72	334.77
Citric Acid	5.75	11.27	22.21
Sodium Hydroxide	2.88	3.12	16.94
Sodium Bisulfite	0.28	0.75	20.24
Scale Inhibitor	18.80	75.21	263.23
Sulfuric Acid	134.30	537.19	1,880.18
Ammonia	14.27	57.12	199.91
Calcium Hydroxide	210.04	840.17	2,940.60
CO_2	45.66	182.65	639.26
Hydrogen Peroxide	13.70	54.79	191.78
STPP	2.50	3.84	14.88
DDBS	0.30	0.46	1.79

Annual Solids Production and Associated Mileage for Disposal

	5 mgd		20 mgd		70 mgd	
Scenario	**cy/yr**	**Mileage**	**cy/yr**	**Mileage**	**cy/yr**	**Mileage**
Scenario 2A (GAC)	734	36726	2911	14556	10296	51480
Scenario 2B (RO; Mech Evap)	2052	10260	8327	41637	28725	143625
Scenario 2B (RO; Evap Ponds)	3641	18204	14605	73026	51097	255483

GHG Emissions and Environmental/Social Costs

	5 mgd		20 mgd		70 mgd	
	Tons/ year	**$/yr[a]**	**Tons/ year**	**$/yr[a]**	**Tons/ year**	**$/yr[a]**
Scenario 1A (GMF)	459	$12,353	1214	$32,669	3108	$83,641
Scenario 1B (MF)	719	$19,356	1872	$50,378	8238	$221,677
Scenario 1C (MF/RO; Ocean Disposal)	4429	$119,192	11844	$318,725	38445	$1,034,550
Scenario 2A (GAC; 2-year replacement)	1298	$37,504	2879	$86,615	10283	$302,897
Scenario 2B (RO; Ocean Disposal)	4913	$132,212	13398	$360,540	46084	$1,240,120
Scenario 2B (RO; Mech Evap)	13905	$374,186	44228	$1,190,173	147838	$3,978,321
Scenario 2B (RO; Evap Ponds)	6464	$173,935	17219	$463,358	51346	$1,381,721

a. Cost for CO_2e is $26.91 per ton

GHG Emissions and Environmental/Social Costs (95% Confidence Interval)

	5 mgd		20 mgd		70 mgd	
	Tons/ year	**$/yra**	**Tons/ year**	**$/yra**	**Tons/ year**	**$/yra**
Scenario 1A (GMF)	459	$37,817	1214	$100,009	3108	$256,052
Scenario 1B (MF)	719	$59,256	1872	$154,224	8238	$678,622
Scenario 1C (MF/RO; Ocean Disposal)	4429	$364,886	11844	$975,717	38445	$3,167,083
Scenario 2A (GAC; 2-year replacement)	1298	$106,931	2879	$237,147	10283	$847,086
Scenario 2B (RO; Ocean Disposal)	4913	$404,741	13398	$1,103,727	46084	$3,796,400
Scenario 2B (RO; Mech Evap)	13905	$1,145,502	44228	$3,643,494	147838	$12,178,894
Scenario 2B (RO; Evap Ponds)	6464	$532,471	17219	$1,418,485	51346	$4,229,883

a. Cost for CO_2e is $82.39 per ton

Other Air Emissions at 5-mgd Plant Capacity

Scenario	CO_2e (tons/year)	$PM_{2.5}$ (lb/year)	SO_2 (lb/year)	NO_x (lb/year)	NH_3 (lb/year)	CO (lb/year)
Scenario 1A (GMF)	459.06	180	2052	1201	0.3	20
Scenario 1B (MF)	719.30	227	2654	1489	0.5	28
Scenario 1C (MF/RO; Ocean Disposal)	4429.30	1492	17236	9421	2	126
Scenario 2A (GAC; 2-year replacement)	1393.67	486	5568	3245	1	46
Scenario 2B (RO; Ocean Disposal)	4913.10	1651	19164	9296	2	108
Scenario 2B (RO; Mech Evap)	13905.10	5406	63751	27188	2	126
Scenario 2B (RO; Evap Ponds)	6463.60	2294	26775	12402	2	114

Other Air Emissions at 20-mgd Plant Capacity

Scenario	CO_2e (tons/year)	$PM_{2.5}$ (lb/year)	SO_2 (lb/year)	NO_x (lb/year)	NH_3 (lb/year)	CO (lb/year)
Scenario 1A (GMF)	1213.99	450	5080	3321	1	60
Scenario 1B (MF)	1872.10	470	5125	4356	2	104
Scenario 1C (MF/RO; Ocean Disposal)	11844.10	3450	39086	25283	7	438
Scenario 2A (GAC; 2-year replacement)	3218.68	1178	13243	9099	3	172
Scenario 2B (RO; Ocean Disposal)	13398.00	4009	45915	27104	7	399
Scenario 2B (RO; Mech Evap)	44227.90	16821	198158	88015	7	436
Scenario 2B (RO; Evap Ponds)	17218.80	5568	64392	34,715	7	413

Other Air Emissions at 70-mgd Plant Capacity

Scenario	CO_2e (tons/year)	$PM_{2.5}$ (lb/year)	SO_2 (lb/year)	NO_x (lb/year)	NH_3 (lb/year)	CO (lb/year)
Scenario 1A (GMF)	3108.18	1089	12030	9398	3	207
Scenario 1B (MF)	8237.70	2312	25912	18258	6	357
Scenario 1C (MF/RO; Ocean Disposal)	38444.80	12031	136431	87606	25	1500
Scenario 2A (GAC; 2-year replacement)	11255.94	3533	39441	28613	10	580
Scenario 2B (RO; Ocean Disposal)	46084.00	13730	157133	93268	23	1389
Scenario 2B (RO; Mech Evap)	147838.00	56243	662316	295471	26	1515
Scenario 2B (RO; Evap Ponds)	51346.00	16047	184666	104293	24	1396

Other Air Emissions Environmental/Social Costs per pound

	3% Discount Rate	7% Discount Rate
Emission (from electricity generation)	**$/lb**	**$/lb**
SO_2	$18.43	$16.32
NO_x	$2.74	$2.42
$PM_{2.5}$	$68.44	$63.19
Emissions (from mobile sources)	**$/lb**	**$/lb**
NO_x	$3.84	$3.47
$PM_{2.5}$	$189.52	$168.46

Other Air Emissions Social Costs (3% Discount Rate)

	5 mgd	20 mgd	70 mgd
Scenario 1A (GMF)	$54,946	$137,782	$336,493
Scenario 1B (MF)	$69,448	$145,813	$685,824
Scenario 1C (MF/RO; Ocean Disposal)	$453,781	$1,056,481	$3,683,153
Scenario 2A (GAC; 2-year replacement)	$146,864	$357,413	$1,073,425
Scenario 2B (RO; Ocean Disposal)	$498,506	$1,213,003	$4,154,245
Scenario 2B (RO; Mech Evap)	$1,627,398	$5,064,224	$16,934,119
Scenario 2B (RO; Evap Ponds)	$691,619	$1,681,697	$4,850,782

Other Air Emissions Social Costs (7% Discount Rate)

Scenario	5 mgd	20 mgd	70 mgd
Scenario 1A (GMF)	$49,128	$123,198	$300,907
Scenario 1B (MF)	$62,085	$130,399	$613,122
Scenario 1C (MF/RO; Ocean Disposal)	$405,713	$944,650	$3,293,272
Scenario 2A (GAC; 2-year replacement)	$131,242	$319,333	$958,996
Scenario 2B (RO; Ocean Disposal)	$445,529	$1,083,956	$3,712,268
Scenario 2B (RO; Mech Evap)	$1,454,684	$4,526,719	$15,136,712
Scenario 2B (RO); Evap Ponds)	$618,156	$1,502,931	$4,334,930

Appendix F

95th Percentile Environmental Costs and Net Present Values for 7% Discount Rate

NPVs at 7% Discount Rate:

Scenario 1: Nonpotable Reuse for Landscape Irrigation

Flow	Treatment Trains			Difference (1B-1A)	Difference (1C-1A)
	1A (GMF-Based)	1B (MF-Based)	1C (MF+RO-Based)		
Financial NPV (Capital and O&M costs)					
5mgd	$ 25,490,000	$ 31,920,000	$64,800,000	$6,430,000	$ 39,310,000
20mgd	$ 49,070,000	$ 69,570,000	$143,240,000	$20,500,000	$94,170,000
70mgd	$ 128,600,000	$ 253,690,000	$434,680,000	$125,090,000	$306,080,000
Environmental NPV (Monetized GHGs and Other Air Emissions)					
5mgd	$ 1,210,000	$ 1,800,000	$ 10,840,000	$ 590,000	$ 9,630,000
20mgd	$ 3,110,000	$ 4,440,000	$ 27,280,000	$ 1,330,000	$ 24,170,000
70mgd	$ 7,760,000	$ 20,100,000	$ 87,210,000	$ 12,340,000	$ 79,450,000
Total NPV					
5mgd	$ 26,700,000	$ 33,720,000	$75,640,000	$7,020,000	$48,940,000
20mgd	$ 52,180,000	$ 74,010,000	$ 170,520,000	$21,830,000	$118,340,000
70mgd	$ 136,360,000	$ 273,790,000	$ 521,890,000	$137,430,000	$385,530,000

NPVs at 7% Discount Rate:

Scenario 2: Potable Reuse

Flow	Treatment Trains				Difference (2B1-2A)	Difference (2B2-2A)	Difference (2B3-2A)
	2A (GAC-Based)	2B1 (RO-Based w/ Ocean Disposal)	2B2 (RO-Based w/` Mech Evap)	2B3 (RO-Based w/Evap Ponds)			
Financial NPV (Capital and O&M costs)							
5mgd	$ 62,950,000	$70,030,000	$ 98,500,000	$113,850,000	$ 7,080,000	$35,550,000	$ 50,900,000
20mgd	$ 122,390,000	$165,010,000	$261,260,000	$358,490,000	$42,570,000	$138,820,000	$236,050,000
70mgd	$ 315,010,000	$511,760,000	$814,215,000	$1,248,950,000	$196,670,000	$499,125,000	$933,860,000
Environmental NPV (Monetized GHGs and Other Air Emissions)							
5mgd	$ 3,320,000	$ 12,180,000	$ 36,530,000	$ 16,340,000	$ 8,860,000	$ 33,210,000	$13,020,000
20mgd	$ 7,800,000	$ 31,610,000	$ 115,090,000	$ 41,680,000	$ 23,810,000	$ 107,290,000	$33,880,000
70mgd	$ 25,230,000	$ 108,390,000	$ 383,700,000	$ 121,350,000	$ 83,160,000	$ 358,470,000	$96,120,000
Total NPV							
5mgd	$ 66,270,000	$82,210,000	$ 135,030,000	$130,190,000	$ 15,940,000	$ 68,760,000	$63,920,000
20mgd	$ 130,190,000	$ 196,620,000	$376,350,000	$400,170,000	$66,380,000	$246,110,000	$269,930,000
70mgd	$ 340,240,000	$620,150,000	$1,197,915,000	$1,370,300,000	$279,830,000	$857,595,000	$1,029,980,000

NPVs at 3% Discount Rate, 95% Confidence Interval
Scenario 1: Nonpotable Reuse for Landscape Irrigation

Flow	Treatment Trains			Difference (1B-1A)	Difference (1C-1A)
	1A (GMF-Based)	1B (MF-Based)	1C (MF+RO-Based)		
Financial NPV (Capital and O&M costs)					
5mgd	$ 35,050,000	$ 43,640,000	$86,100,000	$8,590,000	$51,050,000
20mgd	$ 67,440,000	$ 94,750,000	$ 92,960,000	$27,310,000	$125,520,000
70mgd	$ 185,250,000	$ 344,600,000	$581,730,000	$159,350,000	$396,480,000
Environmental NPV (Monetized GHGs and Other Air Emissions)					
5mgd	$ 2,830,000	$ 4,260,000	$ 28,680,000	$ 1,430,000	$ 25,850,000
20mgd	$ 7,440,000	$ 10,800,000	$ 76,990,000	$ 3,360,000	$ 69,550,000
70mgd	$ 18,360,000	$ 47,810,000	$ 259,990,000	$ 29,450,000	$ 241,630,000
Total NPV					
5mgd	$ 37,880,000	$ 47,900,000	$114,780,000	$10,020,000	$76,900,000
20mgd	$ 74,880,000	$ 105,550,000	$269,950,000	$30,670,000	$195,070,000
70mgd	$ 203,610,000	$ 392,410,000	$841,720,000	$188,800,000	$638,110,000

NPVs at 3% Discount Rate, 95% Confidence Interval

Scenario 2: Potable Reuse

Flow	Treatment Trains				Difference (2B1-2A)	Difference (2B2-2A)	Difference (2B3-2A)
	2A (GAC-Based)	2B1 (RO-Based w/ Ocean Disposal)	2B2 (RO-Based w/ Mech Evap)	2B3 (RO-Based w/Evap Ponds)			
Financial NPV (Capital and O&M costs)							
5mgd	$ 80,960,000	$92,170,000	$133,430,000	$145,240,000	$11,210,000	$52,470,000	$64,280,000
20mgd	$ 161,140,000	$ 219,925,000	$358,190,000	$449,570,000	$58,695,000	$196,960,000	$288,340,000
70mgd	$ 428,970,000	$ 690,610,000	$1,128,780,000	$1,556,730,000	$261,490,000	$699,660,000	$1,127,610,000
Environmental NPV (Monetized GHGs and Other Air Emissions)							
5mgd	$ 7,790,000	$ 27,630,000	$ 85,430,000	$ 38,490,000	$ 19,840,000	$ 77,640,000	$ 30,700,000
20mgd	$ 18,410,000	$ 72,620,000	$ 274,700,000	$ 100,780,000	$ 54,210,000	$ 256,290,000	$ 82,370,000
70mgd	$ 59,770,000	$ 245,680,000	$ 899,760,000	$ 290,030,000	$ 185,910,000	$ 839,990,000	$ 230,260,000
Total NPV							
5mgd	$ 88,750,000	$119,800,000	$218,860,000	$183,730,000	$31,050,000	$ 130,110,000	$94,980,000
20mgd	$ 179,550,000	$292,545,000	$632,890,000	$550,350,000	$112,905,000	$453,250,000	$370,710,000
70mgd	$ 488,740,000	$936,290,000	$2,028,540,000	$1,846,760,000	$ 447,400,000	$1,539,650,000	$1,357,870,000

Practical Solutions for Water Scarcity




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