The Impacts of Membrane Process Residuals on Wastewater Treatment
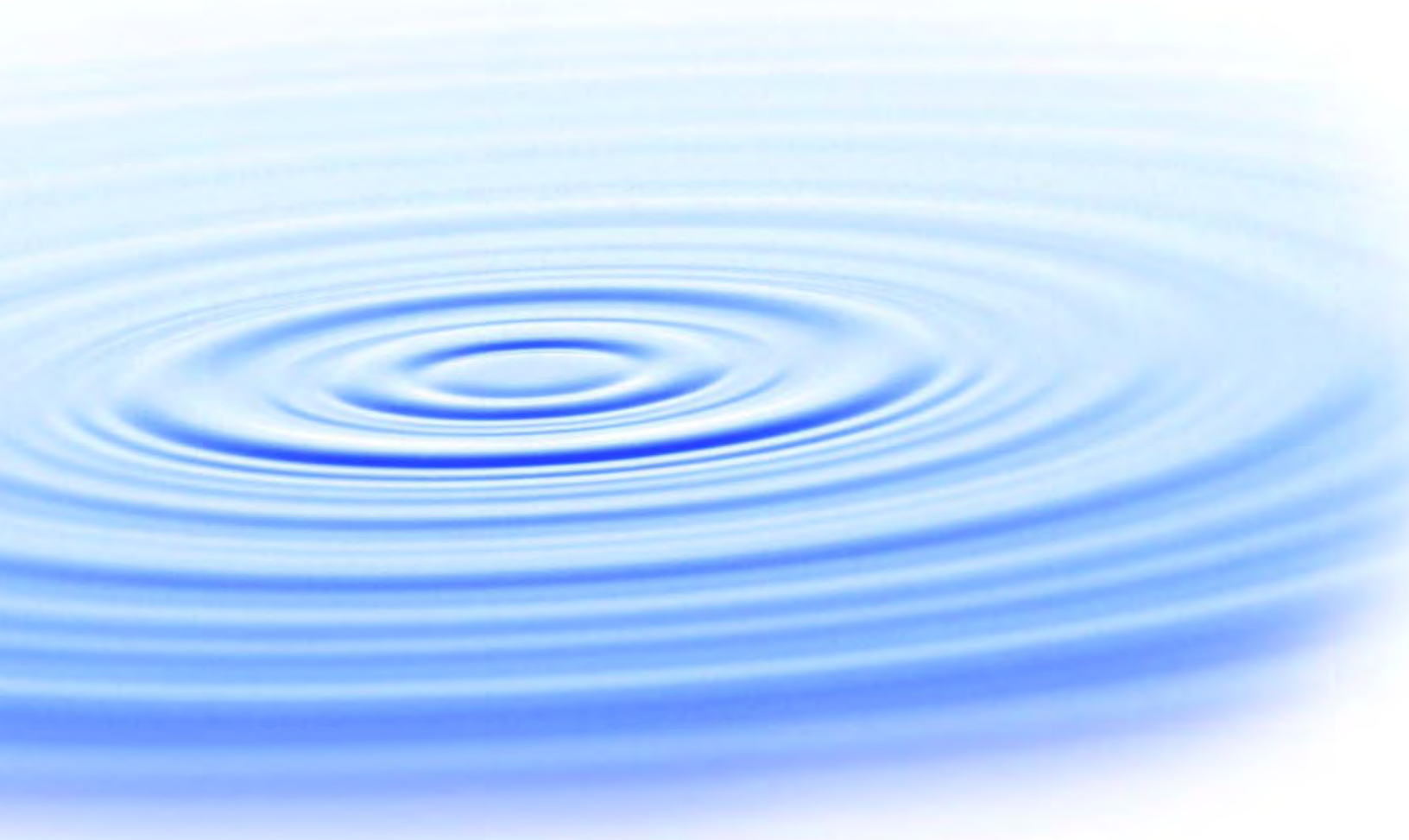
Guidance Manaual

WateReuse Foundation

The Impacts of Membrane Process Residuals on Wastewater Treatment

About the WateReuse Foundation

The mission of the WateReuse 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 U.S. Bureau of Reclamation, the California State Water Resources Control Board, the Southwest Florida Water Management District, and the California Department of Water Resources. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations. The Foundation also conducts research in cooperation with the Global Water Research Coalition.

The Impacts of Membrane Process Residuals on Wastewater Treatment

Guidance Manual

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Disclaimer

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ACRONYMS

AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation
BOD	biological oxygen demand
BOD_5	five-day BOD
COD	chemical oxygen demand
EC	electrical conductivity
EC_{50}	50% effective concentration
EDC	endocrine-disrupting compound
EDR	electrodialysis reversal
EDTA	ethylenediamene tetraacetic acid
EPA	U.S. Environmental Protection Agency
gpd	gallons per day
IPP	Industrial Pretreatment Program
IU	industrial user
LC_{50}	50% lethal concentration
MAHL	maximum allowable headworks loading
MAIL	maximum allowable industrial loading
MBR	membrane bioreactor
M/D	monovalent/divalent cation ratio
MF	microfiltration
mgd	million gallons per day
MLSS	mixed liquor suspended solids
NF	nanofiltration
NOEL	no observable effect level
NPDES	National Pollutant Discharge Elimination System
OUR	oxygen uptake rate
PhAC	pharmaceutically active compound
POC	pollutant of concern
POTW	publicly owned treatment works
ppd	pounds per day
QSAR	quantitative structure–activity relationship
RO	reverse osmosis
SAR	sodium adsorption ratio
SOUR	specific oxygen uptake rate
TDS	total dissolved solids
THM	trihalomethane
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration
WERF	Water Environment Research Foundation
WET	whole effluent toxicity (testing)
WRF	WateReuse Foundation
WTP	water treatment plant
WWTP	wastewater treatment plant
ZLD	zero liquid discharge

FOREWORD

The WateReuse 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.

A Research 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, including the following:

- Defining and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluating methods for managing salinity and desalination
- Economics and marketing of water reuse

The Research Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs 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 RAC and PACs and provide overall management of projects.

The Foundation's primary funding partner is the U.S. Bureau of Reclamation. Other funding partners include the California State Water Resources Control Board, the Southwest Florida Water Management District, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and funding relationships. The Foundation is also a member of the Global Water Research Coalition.

This publication presents the results of a study sponsored by the Foundation. The goal of this research project was to provide practical guidance to utilities concerning the effects of membrane process residuals and, in particular, concentrate from desalination facilities on wastewater treatment (including treatment processes, effluent quality, and water reuse and residuals management options).

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EXECUTIVE SUMMARY

As the use of membrane processes in the treatment of drinking water is rapidly expanding worldwide, their application in water reuse projects expands as well and will be equally important. Membrane technologies that are used to remove inorganic ions (reverse osmosis, nanofiltration, and electrodialysis) produce a residuals stream that is enriched in such ions. This stream, called "concentrate" (also referred to as reject and, in the case of seawater desalination, brine), represents a significant disposal challenge. Concentrate treatment to either harmless by-products or complete destruction has so far been costly, from both a capital and an operating perspective. Thus, the disposal options for concentrate usually involve transport off-site, shifting responsibility for their ultimate disposal to another environmental system or other approaches. According to the literature surveys conducted for this project, the typical method of brine residuals disposal is discharge to wastewater treatment plants (WWTPs) or to the sea or other water body.

The ultimate fates of the constituents in the concentrate depend on their reactivity in the wastewater stream and partitioning onto biomass within the WWTP. Inorganic constituents neither react nor partition. The additional mass loading can have an adverse impact on the performance of a WWTP. An increase in the total dissolved solids (TDS) concentration can affect settling by changing the wastewater density, inhibit the biological treatment process, and increase the aquatic toxicity, which may limit the options for surface discharge or reuse. In addition, the treatment plant's discharge permits (National Pollutant Discharge Elimination System permits in the United States) may include limits for TDS or specific ions, most commonly sodium and/or chloride. Chloride above a certain level can adversely impact the whole effluent toxicity testing results for a WWTP, resulting in exceptions to the permit. Concentrates containing high TDS levels can also aggravate corrosion of the collection system piping and treatment plant process equipment. In these cases, concentrate disposal via ocean or estuarine discharge might not be an option because of the distance from production to disposal (e.g., inland desalination facilities), high cost, or regulatory limits.

The goal of this research project was to provide practical guidance to utilities concerning the effects of membrane process residuals and, in particular, concentrate from desalination facilities on wastewater treatment (including treatment processes, effluent quality, and water reuse and residuals management options). This goal was met by achieving the following objectives:

1. Identify the concentrations at which constituents of concern can adversely impact wastewater treatment or treatment plant facilities or their permits;
2. Develop recommendations for estimating the adverse impacts of membrane process residuals on wastewater treatment and for planning new membrane projects with respect to discharge of residuals to wastewater collection and treatment systems;
3. Develop models for water and wastewater utilities to assess the impacts of residuals disposal not only on current facilities but also on future projects;
4. Develop a guidance manual as a reference source for all of this material; and
5. Make recommendations for future research.

To achieve the stated objectives, the project consisted of four major elements:

1. A literature survey;
2. An Internet survey to determine water and wastewater utility experience with membrane residuals;
3. Development of models to determine the impact of residuals disposal on collection systems and WWTPs; and
4. Development of a guidance manual.

The literature review covered a wide range of topics relevant to the discharge of concentrate to wastewater collection systems and ultimately to WWTPs. Data specific to concentrates in wastewater are scarce, because only a limited number of WWTPs accept such discharges. However, the literature survey does include data that show the cause and effect relationships for corrosion, toxicity to activated sludge, toxicity to anaerobic digestion, poorly settling biomass, partitioning, and aquatic toxicity. Relatively few concentrate streams are currently discharged to wastewater collection systems, and documentation of adverse effects is only beginning. While few specifics are available, the assembled literature review should provide operators some guiding principles to address possible concerns.

Other issues may be of concern as well. For example, the concentrate from highly brackish water could produce a density current that would cause short-circuiting of flow through the WWTP, yet no data were found regarding this effect. The mass balance modeling of a WWTP will be important for understanding the complex pathways by which components of concentrates travel from the headworks of the WWTP to either the biosolids or the treated water. Likewise, the mass balance modeling of the integrated collection system or WWTP is critically important for assessing system-wide impacts. It also provides a basis from which to estimate future impacts as additional desalting facilities are placed on-line and their concentrate is discharged to the sewer.

Two surveys were conducted to obtain information from utilities: one for wastewater utilities receiving membrane residuals, and the other for potable water utilities discharging membrane residuals to a wastewater collection system. Using the Internet-based survey instrument SurveyMonkey (www.surveymonkey.com), survey questions were developed by the project team, with refinements that incorporated feedback from the Project Advisory Committee and partner utilities.

The objectives of the surveys were to learn the following from participating utilities:

1. Their established experience with membrane residuals disposal;
2. Any problems (with residuals disposal, planning, or otherwise) experienced with these discharges and the approaches taken to handle them;
3. The control procedures in place, or that the utilities suggest, for addressing membrane residuals disposal; and
4. Suggestions on future research needs.

From the 30 wastewater utilities that accessed the survey and the 19 who took the time to complete the survey, a limited amount of information was available. The results of the wastewater survey indicate that in general the utilities appear to know less about the membrane discharges into their system than would be expected.

The results of the water utility survey produced some data. The demographic information indicates that respondents have excellent operating experience. However, while 12

respondents accessed the water utilities survey on the Internet, only 8 of them actually answered the survey. Six had been directly involved in discharging membrane residuals to wastewater systems. Five respondents reported participation in membrane pilot studies.

For the most part, communities whose water and wastewater utilities discharged their concentrate to WWTPs generally did not require either testing of the reject concentrate or characterization of the impact of the concentrate discharge on collection systems. Therefore, little or no data exist on concentrate impacts. This is clearly an area where communities must begin to collect data.

This project provides utilities with two types of models for predicting the impacts of membrane concentrate loadings on the collection system and the WWTP. Point source impacts reflect the discharge of concentrates to the wastewater collection system and are evaluated with models developed using Microsoft® Excel. These models can project possible deterioration of the collection system at the point of discharge of concentrates to the system. The impacts of system-wide concentrate discharges are evaluated with an Excel mass balance model. Models for discharges to the collection system are provided to calculate the concentrations of components in discharges of the following:

1. Biomass from a satellite membrane bioreactor WWTP;
2. Reverse osmosis concentrate from a water treatment plant;
3. Backwash water or chemical cleaning solutions; and
4. Concentrate from a satellite reverse osmosis water reclamation plant.

The system-wide mass balance and its features allow almost any water and wastewater treatment system to be modeled. The model is a water mass balance that includes water losses through leaks in the distribution system, water sold outside the wastewater service area, water reuse from both a satellite plant and an effluent reuse facility, and evaporation. The mass balance tracks a number of both conservative and nonconservative pollutants. The conservative pollutants are never destroyed, while the nonconservative pollutants are partially destroyed or converted into another physical form. The model includes many inputs, and this necessitates some front-end time for setup. Once the model is set up, it is very easy to look at impacts to the system that could result from increasing reuse flow, reuse water sent to cooling towers, or membrane treatment at a water plant, power plants, industries, and reuse facilities. Data gathering and input are not trivial efforts. However, attention in setting up the model will significantly increase the utility of the model.

This model is designed to be flexible. It allows future "what if" scenarios to be run to determine whether future projects will produce conditions that could impact system performance and thus require attention. As a planning tool, it enables the utility to look ahead and determine how future projects which incorporate membrane residuals will impact the wastewater collection system (e.g., corrosion) or produce an effluent too high in a particular pollutant.

This guidance manual compiles all the information developed for this project in one central source for a utility. It serves as a resource manual (with the literature survey) as well as provides examples of model runs and suggested data-gathering techniques. Included in this report, as an appendix, is a case study that provides one community's experience with the model (Oklahoma City, OK). The manual walks the user through a description of the model, how to gather data, and how to set up the model runs. It concludes by providing real-time

model runs associated with different input parameters. The guidance manual also illustrates the system impacts from the modeling and discusses their significance.

CHAPTER 1

INTRODUCTION

1.1 PROJECT OBJECTIVES

While the use of membrane processes in the treatment of drinking water is rapidly expanding worldwide, in the long term their applications in wastewater reuse projects will be equally important. Although membranes are highly effective in removing contaminants, the disposal of the membrane process residuals by either conversion to harmless by-products or their complete destruction has so far been cost-prohibitive. Thus, the disposal options for membrane residual streams usually involve transport off-site, which shifts the responsibility for their ultimate disposal to another environmental system. Table 1.1 notes a variety of membrane processes which are available to meet a wide range of contaminant removal objectives.

Table 1.1. Current and Emerging Applications of Membrane Processes[a]

Process(es)	Applications
RO, EDR	TDS reduction
	Desalination of seawater (RO only)
	Desalination of high-silica brackish water
	Removal of inorganic ions
	Fluoride
	Nutrients (nitrogen, phosphorus)
	Radionuclides (RO only)
	Other SDWA-regulated inorganic chemicals (e.g., arsenic)
	Pathogen removal (RO only)
	Synthetic organics removal (RO only)
NF	Hardness removal
	Organics removal
	DBPP
	Synthetic organic chemicals (pesticides)
	Color
	Pathogen removal
MF, UF	Particulate removal
	Suspended solids
	Turbidity
	Pathogens (protozoan cysts and oocysts, bacteria, viruses)
	Protozoan cysts
	Inorganic precipitants, coprecipitants (iron and manganese, arsenic)
	Organic coprecipitants (color and DBPP)

[a]Abbreviations: RO, reverse osmosis; EDR, electrodialysis reversal; NF, nanofiltration; MF, microfiltration; UF, ultrafiltration; TDS, total dissolved solids; SDWA, Safe Drinking Water Act; DBPP, disinfection by-product precursors.

According to the literature survey in Chapter 2, the typical method of brine residuals disposal in the United States is discharge to wastewater treatment plants or to the sea. The ultimate fate of the brine constituents depends on their reactivity in the wastewater stream and partitioning onto biomass within the wastewater treatment plant (WWTP). Inorganic constituents neither react nor partition to a large extent. The additional mass loading can have a severe adverse impact on the performance of the WWTP. An increase in total dissolved solids (TDS) concentration can affect settling by changing the wastewater density, inhibit the biological treatment process, and increase aquatic toxicity, which may limit the options for disposal or reuse. In addition, the WWTP discharge permits (the National Pollutant Discharge Elimination System permit, or NPDES permit, in the United States) may include limits for TDS or specific ions. Brines containing high TDS concentrations can also aggravate corrosion of the collection system piping and treatment plant process equipment. Disposal to the sea might not be an option because of location or regulatory limits.

1.1.1   Types and Character of Membrane Residuals Waste Streams

The character of a concentrate, brine, or high-TDS waste stream depends on the source water quality and the product water recovery of the system. Reverse osmosis (RO) system recovery rates vary greatly depending on the constituents in the source water, but it is generally accepted that brackish water recoveries typically range from 50–80% and seawater recoveries range from 30–50%. The TDS removed from the feed water is concentrated in the brine, with TDS concentrations determined by the percentage of RO recovery and the TDS concentration in the feed water.

It has been demonstrated in a variety of locations that RO treatment of brackish source waters with TDS concentrations in the range of 1500 to 8000 mg/L can produce brine with TDS concentrations ranging from 7500 to 40,000 mg/L of TDS. RO treatment of seawater can result in brine TDS concentrations in the range of 48,000 to 69,000 mg/L. In addition, specific constituents, such as nitrate, radium, radon, arsenic, perchlorate, and heavy metals, that occur in low concentrations in the source water may not be considered problems, but when concentrated in brine they may become harmful, as discussed in the Literature Review (Chapter 2).

Nanofiltration (NF), RO, and electrodialysis reversal (EDR) remove a wide range of constituents from source waters. Typical target water quality parameters are presented in Table 1.2, by source water.

Table 1.2. Typical Water Quality Parameters[a]

Source water	Typical Target Constituents
Surface water	TOC
	DBPP
	Pathogens
	SOCs (e.g., pesticides)
	Taste- and odor-causing chemicals
Fresh Groundwater	Total hardness
	Color
	TOC
Brackish Groundwater	TDS
	Chloride
Seawater	TDS
	Chloride
	Bromide
	Boron
Wastewater Reclamation	SOCs, including emerging contaminants of concern
	Viruses and other pathogens
	Heavy metals

[a]Abbreviations: TOC, total organic carbon; SOCs, synthetic organic chemicals; DBPP, disinfection by-product precursors.

If coagulants, powdered activated carbon, or other chemicals are applied as pretreatment, the characteristics of the microfiltration (MF) and ultrafiltration (UF) residuals become similar to those of the residuals from a conventional water treatment plant (WTP).

Other residuals from membrane processes, which include chemicals used for cleaning, are listed in Table 1.3.

Table 1.3. Typical Characteristics of Chemical Cleaning Solutions and Residuals in Low-Pressure Membrane Systems[a]

Parameter	Typical Value or Attribute
Frequency of Application	Daily to once every 3–4 months
Volume of Waste Produced	Monthly clean-in-place wastes are normally <0.05% of plant feed flow (daily chemically enhanced backwash wastes might be 0.2–0.4% of plant feed flow rate)
Chemicals Commonly Used	Sodium hypochlorite, 500–1000 mg/L as Cl_2 Citric or hydrochloric acid, pH 1–2 Caustic soda, pH 12–13 Surfactant, 0.1% by wt
Characteristics of Spent Cleaning Solution	pH 2–14 Chlorine residual up to 1000 mg/L as Cl_2 Low concentrations of surfactants TSS up to 500 mg/L (neutralization may precipitate additional solids) TOC 10×–30× feed water conc BOD_5 up to 5000–10,000 mg/L if citric acid used

[a] Abbreviations: TSS, total suspended solids; BOD5, 5-day biological oxygen demand.

Because a portion of the active chemical ingredient is consumed during the cleaning process, the resulting waste includes salts from the chemical reactions, "dissolved" organic materials, sediments, and the remaining active ingredient. At some sites, the cleaning chemicals are regenerated and reused to minimize waste quantities. The concentration of chlorine residuals may range from 1–500 mg/L, which may exceed the discharge limits for most sites and result in additional TDS being discharged to the wastewater treatment facility. The pHs of acidic and basic solutions will be outside the allowed range of 5–9 for discharge, and surfactants would occur at low concentrations but still may cause foaming. Mixing acid and alkaline solutions will minimize the need for other neutralization chemicals. Neutralization is also likely to cause precipitation of additional solids, such as calcium carbonate and iron compounds, which increases the suspended solids concentration of the waste stream. Before mixing the two solutions, any residual chlorine should be removed with an appropriate dechlorinating agent to prevent release of chlorine gas when the stream is mixed with an acid solution. After reducing chlorine residuals and neutralizing the pH, the cleaning wastes should be acceptable for discharge to the wastewater collection system, and possibly to receiving waters. If citric acid is used, the 5-day biological oxygen demand (BOD_5) of the spent cleaning solution is likely to be very high, which may preclude discharge to receiving water. Very limited data are available on the characteristics of chemical cleaning wastewaters; therefore, one of the aspects of this study was to examine the contribution of the cleaning wastewater to the brine solution being discharged to the collection system.

Other types of industrial wastes, such as cooling tower and boiler blowdown, can also contribute TDS in quantities that cause adverse impacts to WWTPs and receiving streams.

1.1.2 Disposal Alternatives for Membrane Residuals

Discharge to the sanitary wastewater collection system is a low-cost disposal method with few restrictions for membrane solids. However, the wastewater collection system capacity and WWTP capacity must be considered, and while the WWTP effluent quality will change, it must still comply with the discharge permit. These capacity and quality criteria may limit the amount of NF, RO, or EDR residuals that can be discharged to the wastewater collection system. While discharge costs for this alternative are low, the portion of the plant capacity utilized by the discharge should also be considered as a disposal cost. A permit is typically not required for this discharge alternative, but this requirement may vary by state.

Membrane systems generate three types of wastes for disposal, and these are summarized in Table 1.4: backwash or bleed-off discharges containing raw water solids, pathogens, algae, and possibly chemical residues; solids and sludge produced by concentrating the solids removed from the raw water; and spent cleaning solutions that usually contain high concentrations of chemicals like total organic carbon (TOC) or iron-containing compounds as well as some of the raw water.

Table 1.4. MF and UF Residuals and Applicable Regulations[a]

Residual	Typical Contaminants	Typical Level	Regulation	Representative Limits
BW and Bleed-Off Discharges	Raw water and precipitated solids, algae, pathogens, possible chemical residues	TSS, 5–200 mg/L Cysts, 7×–50× raw conc Acids and bases, pH <6 or >9 Chlorine, >5 mg/L	Clean Water Act SDWA (if recycled at WTP)	pH, 6–9 TSS, 30 mg/L + raw TSS Chlorine, <0.2 mg/L BOD_5, 30 mg/L TSS and cyst removal, 90% Recycle flow, <10% of WTP flow
Solids and Sludge	Raw water and precipitated solids, algae, pathogens	TSS, 500–2000 mg/L for settled BW solids Cysts, 15×–200× raw conc	Clean Water Act RCRA	pH, 6–9 TSS, 30 mg/L + raw TSS BOD_5, 30 mg/L No free liquid (>20% solids after dewatering) Pass TCLP (Possible use as landfill cover or for sod farming)
Spent Cleaning Solutions	Residual cleaning chemicals, TOC, BOD_5, dissolved solids	TSS, <500 mg/L Acids and bases, pH <6 or >9 Chlorine, >5 mg/L TOC, <100 mg/L BOD_5, 5000–10,000 mg/L (if citric acid used) Surfactants, low concentrations	Clean Water Act and EPA and local industrial pretreatment and wastewater collection system use rules	pH, 6–9 TSS, <400 or 500 mg/L BOD_5, <400 or 500 mg/L Chlorine, <10 mg/L Nothing that will harm or interfere with wastewater collection systems, the WWTP, or its operation

[a]Abbreviations: BW, backwash; RCRA, Resource Conservation and Recovery Act; SDWA, Safe Drinking Water Act.

Given the myriad chemical and biological constituents in concentrate streams, a number of adverse impacts from concentrate streams have been identified:

- Inhibition of biological processes by salt
- Toxicity to topsoil and plants
- Monovalent inhibition of flocculation and settling of coagulated solids, impact on whole effluent toxicity (WET)
- WWTP effluent quality and toxicity
- Impacts of salt to WWTP treatment equipment and appurtenances
- Impacts of salt to wastewater collection system and pumping stations
- Density impacts from mixing brine and wastewater
- Trihalomethane formation
- Reduced ability to reuse treated effluent
- Corrosive impacts to collection systems
- Impacts to WWTP operations

As illustrated in the Literature Review (Chapter 2) and the Utility Survey (Chapter 3), an increase in TDS in the WWTP influent can have a major impact on the collection system, the treatment plant, and the receiving stream. Some states, including California, Arizona, New Mexico, Texas, Oklahoma, Missouri, Illinois, and Florida, have developed water quality standards that address the control of inorganic constituents in concentrate or high-TDS streams based on various parameters (TDS, chloride, sulfate, salinity, and conductivity). Other states are considering establishing water quality standards for these pollutants.

The ultimate environmental sink for TDS (the WWTP) becomes an even more acute problem when considering the disposal of concentrate streams from wastewater reuse projects. In these applications, the TDS concentration is increased by all human activities that result in wastewater discharges, both domestic and industrial. Some communities that aggressively practice reuse are now faced with deciding whether to find a creative solution to remove TDS from the water component of the environment or to abandon more aggressive programs to increase wastewater reuse and fall back to less sustainable programs of increased extractions from fresh water sources. In many cases, environmental laws may dictate the final course of action.

The accumulation of commonly regulated metals in reuse water should already be adequately controlled through local and federal industrial pretreatment programs. Therefore, accepting return water from industrial users needs to be carefully evaluated before design and construction of new facilities at publicly owned treatment works (POTWs). Case studies can provide insight into how different communities have addressed the issue of accepting return waters.

Other constituents of concentrate streams in addition to inorganics can also have adverse impacts on wastewater treatment processes. For instance, nonbiodegradable chemical oxygen demand (COD) can cause acute toxicity and interfere with disinfection by altering the wastewater's transmittance of UV light. Chlorine compounds can react with COD to form chlorinated by-products that contribute to toxicity and are regulated by water quality standards, and partial oxidation of nonbiodegradable COD can produce BOD in the effluent.

The ultimate fate of substances of concern, such as endocrine-disrupting compounds (EDCs) and pharmaceutically active compounds (PhACs), is another area of emerging interest. These compounds are found in secondary wastewater effluents, albeit at very low concentrations. Nevertheless, methods of wastewater reuse that include RO would concentrate these chemicals further. If the concentrate is discharged to a WWTP, these chemicals are unlikely to have a negative impact on treatment processes. However, their ultimate fate depends on the extent of biomass production.

Both water and wastewater industries need to become more informed on the impacts and disposal alternatives available for high-TDS wastewater streams. This project seeks to determine the impacts of high-TDS streams on wastewater facilities and to identify successful control strategies that have already been implemented.

1.1.3   Project Goal and Objectives

The goal of this research project was to provide practical guidance to utilities concerning the effects of membrane process residuals on wastewater treatment (including treatment processes, effluent quality, and water reuse and residuals management options). This goal was met by achieving the following objectives:

1. Identify the concentrations at which constituents of concern can adversely impact wastewater treatment or treatment plant facilities
2. Develop recommendations for estimating the adverse impacts of membrane process residuals on wastewater treatment and for planning new membrane projects with respect to discharging residuals to wastewater collection and treatment systems
3. Develop models for water and wastewater utilities to assess the impacts of residuals disposal not only on current facilities but also on future projects
4. Prepare a guidance manual as a reference source for all of this material
5. Compile recommendations for future research

1.2   OVERVIEW OF THE LITERATURE SEARCH

The Literature Review (Chapter 2) covers a wide range of topics relevant to the discharge of concentrate to wastewater collection systems and ultimately to WWTPs. Data specific to concentrates in wastewater are scarce, because only a limited number of WWTPs currently accept discharges of membrane wastes. However, the Literature Review does include data that show the cause and effect relationships for corrosion, toxicity to activated sludge, toxicity to anaerobic digestion, poorly settling biomass, partitioning, and aquatic toxicity. Relatively few concentrate streams are currently discharged to wastewater collection systems, and documentation of adverse effects is only beginning. While few specifics are available, the Literature Review provides operators with some guiding principles to address possible concerns.

There are other issues which may arise. For example, the concentrate from highly brackish water could produce a density current that would cause short-circuiting of flow through the WWTP, yet no data were found regarding this effect. The mass balance modeling of a WWTP is important for understanding the complex pathways by which components of concentrates travel from the headworks of the WWTP to either the biosolids or the treated water. Likewise, the mass balance modeling of the integrated collection system or WWTP is critically important to assessing system-wide impacts. It also provides a basis from which to estimate future impacts as additional membrane facilities are put in place.

1.3   OVERVIEW OF THE UTILITY SURVEY

Two surveys were conducted to obtain information from utilities: one for wastewater utilities receiving membrane residuals, and the other for potable water utilities discharging membrane residuals to a wastewater collection system. The Internet-based survey instrument SurveyMonkey (www.surveymonkey.com) was used. Survey questions were developed by the project team, with refinements incorporating feedback from the Project Advisory Committee and partner utilities.

The objectives of the surveys were to learn the following:

1. Their established experience with membrane residuals disposal
2. Any problems (with residuals disposal, planning, or otherwise) they have experienced with these discharges and the approaches taken to handle them
3. Control procedures in place, or that they suggest, for addressing membrane residuals disposal
4. Their suggestions for future research needs

Survey participants were recruited using two databases: one provided by the WateReuse Foundation from its project "National Database of Water Reuse Facilities," and a listing of membrane installations kindly provided by US Filter. Recruiting for participation was via e-mailed letters. Letters were sent to individuals for whom e-mail addresses were listed in the databases and to those whose e-mail addresses could be procured after a brief Google search or telephone call.

The letters were sent in two batches: a group of 251 letters using the WateReuse database, and 245 e-mail letters using addresses gleaned from the US Filter database and other databases. Thus, a total of 491 letters were e-mailed.

The wastewater utilities survey addressed four sources of membrane residuals:

1. Treatment at a wastewater utility (as a component of tertiary treatment, for example)
2. Biological treatment resulting in residuals discharges to a wastewater system (i.e., satellite systems)
3. Potable water treatment systems
4. Industry membrane users (with a focus on the Significant Industrial Users treatment system, with membrane residuals flow rates greater than 25,000 gal/day [gpd]).

Characteristics of the respondents are summarized in Table 1.5. Thirty responders accessed the wastewater utility survey on the Internet. Some, however, made only a cursory examination of the survey, without answering questions. Nineteen participants actually completed the survey.

Table 1.5. Wastewater Utility Survey: Basic Characteristics of Respondents and Their Facilities

Characteristic	Result
No. of individuals accessing survey	30
No. of actual respondents	19
No. with pretreatment experience	11
No. who have worked on membrane residuals discharges	5
No. of utilities reporting plant flow rate (in mgd) of:	
<0.5	1
1–5	5
6–10	4
11–20	5
21–100	2
>100	1

[a]Abbreviation: mgd, million gallons per day.

The results of the wastewater survey indicate that, in general, the utilities appear to know less about the membrane discharges into their system than would be expected.

The results of the water utility survey produced some data. Demographic information indicates that respondents have excellent operating experience. However, while 12 respondents accessed the water utilities survey on the Internet, only 8 of them actually answered the survey. Four of these participants had more than 10 years of water treatment experience, while the other four had between 3 and 10 years. Seven have worked at least 3 years on pretreatment issues. Six had been directly involved in discharging membrane residuals to wastewater systems. Five respondents reported participation in membrane pilot studies, and one reported being a water plant operator.

Two of the six respondents who completed the survey were employed at the same large utility; thus, information was obtained for only five water utilities.

1.4 OVERVIEW OF FINDINGS ON IMPACTS

Membrane residuals have an impact on not only the wastewater collection system but also on the WWTP. Both the Literature Review (Chapter 2) and the results of the utility surveys (Chapter 3) indicate a variety of impacts.

The operation of membrane systems appears to result in a range of adverse impacts caused by spent backwash, chemical cleaning, and concentrate streams, including the following:

- Corrosion by sulfides and chloride
- Deflocculation by various cations
- Inhibition of biological treatment by salts, metals, and specific organic chemicals
- Partitioning of metals and organic chemicals to biomass
- Inhibition of anaerobic digestion by salts, metals, and specific organic chemicals
- Effluent toxicity of salts, metals, and specific organic chemicals

Concentrates from high-pressure membrane treatment of groundwater may contain sulfate and hydrogen sulfide that under some circumstances could increase corrosion of concrete pipe and components of the WWTP infrastructure. The intermittent discharges of spent cleaning solutions may contain significant amounts of degradable organic compounds, such as citric acid, which will increase the BOD. The discharges of excess biomass from satellite installations of membrane bioreactors (MBRs) could also intensify anaerobic conditions and possibly accelerate sulfide corrosion. Chlorides are also a well-known agent of concrete corrosion.

It has been shown that an unfavorable ratio of monovalent to divalent cations may hamper the settling of biological floc in secondary clarifiers and dewatering of waste activated sludge. An increase in the NaCl concentration in the feed to the activated sludge process has been shown to decrease settleability, but the concentrations of NaCl must be relatively high (up to 5000 mg/L).

The Clean Water Act amendments of 1987, which authorized establishment and enforcement of pretreatment standards, led to many studies of the possible adverse impacts of chemicals on the Priority Pollutant List to the activated sludge process. Many studies of inhibitory effects were conducted in the early 1980s, and some pollutants continue to be evaluated. In fact, heavy metals have been implicated as more likely causes of inhibition than organic chemicals. The Literature Review (Chapter 2) further highlights many of these inhibitory impacts, including those on anaerobic digestion.

Aquatic toxicity caused by effluent discharged from a WWTP may also be an issue, but the determination of such effects is more complex. Small contributions of concentrates to the wastewater flow may or may not have an impact on effluent toxicity, since each type of concentrate, backwash, and chemical cleaning solution will have unique chemical characteristics with its own potential effects.

In summary, data specific to concentrates in wastewater that show cause and effect relationships for corrosion, toxicity to activated sludge and effects on anaerobic digestion, decreased settling of biomass, partitioning, and aquatic toxicity are mostly lacking. Relatively few concentrate streams are currently discharged to wastewater collection systems, and documentation of negative effects is only beginning to be assembled.

1.5 OVERVIEW OF SEWER LINE DISCHARGE AND MASS BALANCE MODELS

This guidance manual provides a utility with two types of models for predicting the impacts of membrane concentrate loadings on the collection system and the WWTP. Point source impacts reflect the discharge of concentrates to the wastewater collection system which are evaluated with mass balance-based models that are provided in Excel. The impacts of system-wide concentrate discharges are also evaluated with an Excel mass balance model. Mass balance models for the discharge to the collection system are provided to calculate the concentrations of components in discharges of (1) biomass from a satellite MBR WWTP, (2) RO concentrate from a WTP, (3) backwash or chemical cleaning solutions, and (4) concentrate from a satellite RO water reclamation plant. The mass balance model for the wastewater treatment plant tracks the concentrate constituents from the headworks to the secondary effluent, inclusive of diversion by solids handling.

The system-wide mass balance and its features allow almost any water and wastewater treatment system to be modeled. The model is a water mass balance that includes water losses through leaks in the distribution system, water sold outside the wastewater service area, water reuse from both a satellite plant and an effluent reuse facility, and evaporation. The mass balance tracks a number of both conservative and nonconservative pollutants. The conservative pollutants are never destroyed, while the nonconservative pollutants are partially destroyed or converted into another physical form. The model includes many inputs, which necessitates some front-end time for setup. Once the model is set up, it is very easy to look at impacts to the system from increasing reuse flow: the reuse water sent to cooling towers, and membrane treatment at the water plant, power plants, industries, and reuse facilities. Attention paid while setting up the model will significantly increase the utility of the model.

This model is designed to be flexible, in order to allow future "what if" scenarios to be run to determine if future projects will produce conditions that could impact system performance and thus require attention. As a planning tool, it enables the utility to look ahead and determine how future projects will impact the wastewater collection system (e.g., corrosion) or produce an effluent too high in a particular pollutant.

1.6   ORGANIZATION OF THE GUIDANCE MANUAL

1.6.1   Who Should Use This Manual

This guidance manual was developed to help utilities identify the potential impacts of membrane discharges to their collection systems and WWTPs. The Literature Review will be useful to other researchers as they review impacts that have been recorded to date. As previously noted, however, the amount of data available is limited, owing to the small number of membrane facilities in operation in the United States. The number of installations is increasing, and it is expected that within the next five years significantly more membrane facilities will be in place.

Utility operators should find the two types of mass balance models very useful. The sewer line discharge model will be particularly useful in forecasting potential damage to the collection system by specific point source discharges. The system-wide model should be very helpful in predicting the increase in solids throughout the system. This is particularly important in areas with a high TDS concentration in the wastewater effluent. Increases of solids from additional discharges of membrane concentrates could affect the suitability of the wastewater for reuse in industrial applications or irrigation.

1.6.2   Decision Tree To Guide the Reader on Model Use

The following flowchart (Figure 1.1) may help the reader better understand how to develop model input and how to use the model included in this guidance manual.
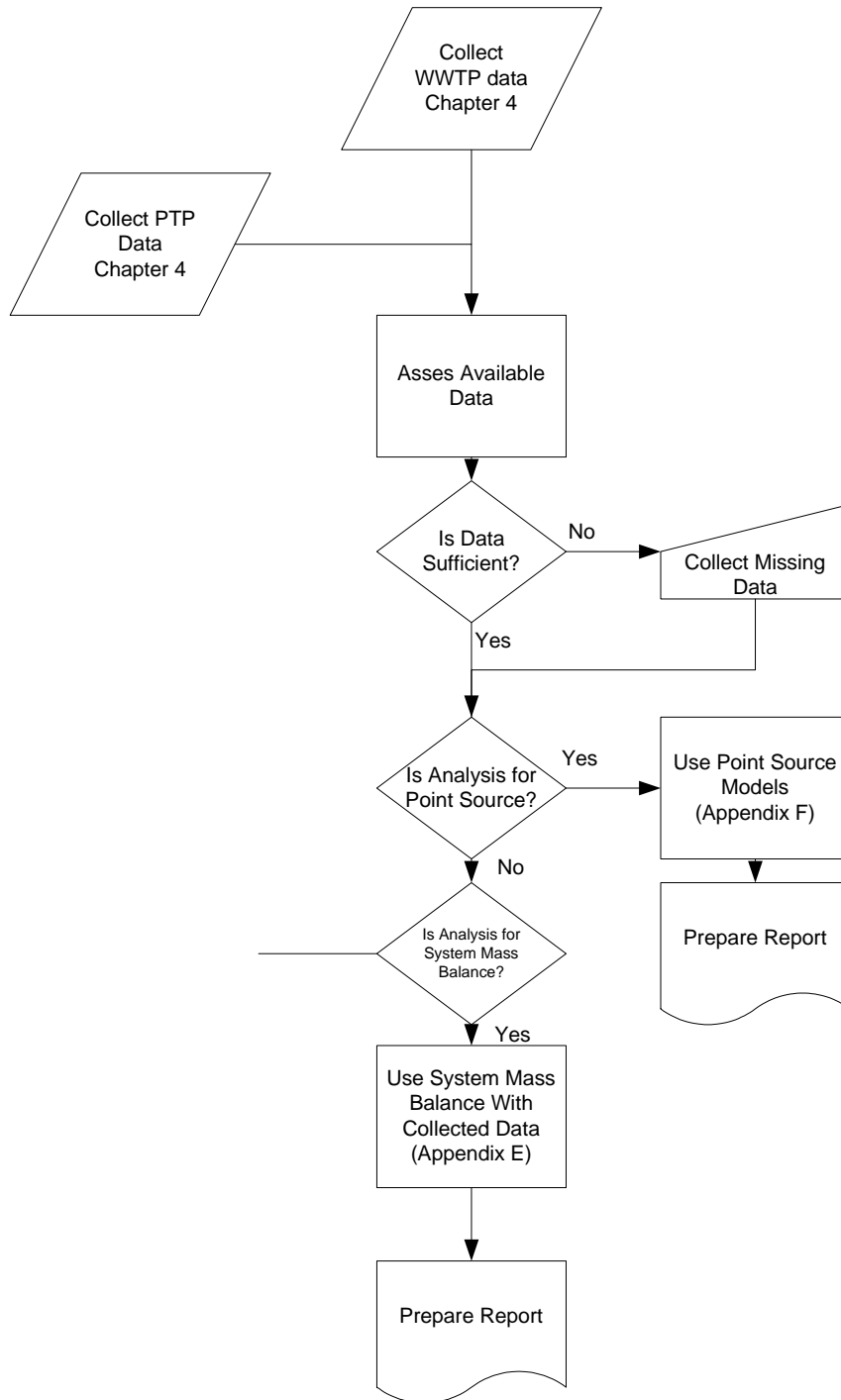
Figure 1.1. Decision tree for model usage.

CHAPTER 2

LITERATURE REVIEW OF CONCENTRATE DISPOSAL TO WWTPs AND COLLECTION SYSTEMS

2.1 SURVEYS OF MEMBRANE FACILITIES

Many surveys of membrane treatment facilities have been financed by grants from the American Water Works Association Research Foundation (AwwaRF), the U.S. Bureau of Reclamation, the Water Environment Research Foundation (WERF), the WateReuse Foundation (WRF), and the St. John's River Water Management District (Mickley et al., 1993; Zander, 2000; Mickley, 2001, 2002; Reardon et al., 2005; Adham et al., 2005; Bryck et al., 2005). With the notable exception of one survey that dealt with wastewater treatment applications (Reardon et al., 2005), the surveys dealt mainly with membrane treatment of drinking water. This is because most applications of membranes to date are for water treatment rather than for wastewater reclamation.

Summary statistics from several surveys provide information on the various types of membrane facilities and their distribution among states. Mickley (2005) reported 431 membrane facilities at water treatment plants as of 2003 with treatment capacities of greater than 0.025 mgd in 25 states. Another 50 plants were under construction as of 2005. Florida has the largest number of plants, followed by Texas and California. Of the 431 membrane facilities, 234 are designed for desalination; these include NF, RO membrane, and EDR systems. In the desalination plant category, 203 of the 234 membrane facilities are used to treat brackish water rather than seawater at inland locations in 17 states. The inland location limits options for concentrate disposal, because the salt content of the concentrate can be significantly higher than that of fresh water levels.

The number of MF and UF installations at WTPs over the last 10 years has increased more rapidly than the number of NF and RO installations. Adham et al. (2005) report 213 installations in North America and 450 worldwide as of 2003. Mickley (2005) reported 197 installations in North America as of 2003, which agrees closely with the number reported by Adham et al. In comparison, in 1996 there were only nine facilities in North America. The median hydraulic capacity of the North American plants has increased from 0.2 mgd in 1996 to 2 mgd in 2003, and the cumulative hydraulic capacity now exceeds 600 mgd.

Categorization of concentrate disposal options is an important element of most surveys. The term "concentrate" is used broadly to include all waste streams generated in membrane separation and the chemical cleaning of membranes. The cross-flow designs of NF and RO systems produce a continuous stream of concentrate and waste chemical cleaning solutions at a typical interval of 6 months. The dead-end designs of most MF and UF systems produce intermittent backwash streams of water and waste chemical cleaning solutions as frequently as once every month in wastewater treatment applications (Reardon et al., 2005).

Of the 203 inland high-pressure membrane plants noted by Mickley (2005), the most common method of concentrate disposal (97 plants in 17 states) is discharge to surface waters. The second most prevalent method is discharge to the wastewater collection system (51 plants), followed by deep well injection (26 plants), land application (20 plants), and evaporation ponds (9 plants). Mickley (2005) noted that the disposal option to a WWTP is used less frequently as the concentrate volume and concentration of salts increase because the negative effects on biological treatment plant operations become more serious.

The residual disposal practices (Reardon et al., 2005) are listed by type of membrane process in Table 2.1 and are based on survey results from Zander (2000). Discharge to the wastewater collection system is a more common option for low-pressure than for high-pressure membranes. The waste cleaning solution is also discharged to the wastewater collection system, either separately or mixed with concentrate. As indicated, 80% of the MF and UF concentrate streams are discharged to wastewater collection systems, in contrast to 37% for NF and 18% for RO. Many of the high-pressure membrane systems in the Zander survey were used for treatment of brackish groundwater near the ocean (e.g., in Florida); thus, disposal to an estuary or the ocean was possible. The reported percentage of high-pressure membrane plants that discharge to the collection system is in general agreement with other surveys. On a percentage basis, the survey of high-pressure membrane plants as of 2003 indicated that about 25% of the systems discharge to the collection system (Mickley, 2005). Van der Bruggen et al. (2003) indicated that, based on data from a 1995 survey by Mickley, 23% of high-pressure membrane plants discharged to the wastewater collection system. Guidance to drinking water utility managers on cost-effective ways to handle, treat, and dispose of the residuals from high-pressure membranes has been proposed (AWWA Membrane Residuals Management Subcommittee, 2004). However, the high concentrations of dissolved solids and large volumes of concentrate are noted as extremely challenging constraints given the current options.

Table 2.1. Disposal Methods for Membrane Process Residuals in Drinking Water Treatment[a]

Disposal Method	% of Plants Using Indicated Membrane Type				
	MF	UF	NF	RO	Total
Wastewater Collection System	47	33	37	18	24
Surface Water	19	17	13	51	38
Ocean Discharge			13	11	8
Deep-Well Injection			37	11	11
Land Application	34	50		9	19

[a]Based on data reported by Reardon et al. (2005), which were based on survey results reported by Zander (2000). Of the surveyed plants, 21% used MF, 6% used UF, 8% used NF, 45% used RO; 80% of the plants surveyed used one of these membrane treatment methods.

A smaller amount of survey data is available on the use of membranes in wastewater treatment. In a worldwide survey, Reardon et al. (2005) identified 120 full-scale membrane facilities with a total treatment capacity of 290 mgd. The facilities are relatively small, with 97% of them having a hydraulic capacity less than 5 mgd. However, the number of larger facilities using membrane systems is increasing, as evidenced by the new Orange County, CA, replenishment system plant, which has a capacity of 70 mgd. MBRs account for the greatest number of installations (62), followed by RO (31) and tertiary filter applications of MF and UF (27). Nearly all of the of RO and tertiary filter facilities are designed for water reclamation, whereas this is true for only about 40% of the MBR installations.

Any mass balance on a membrane separation process will show that because the mass of rejected material is conserved, its disposal only shifts the material to another compartment of the environment. Mickley (2005) explained that salts in the concentrate discharged to the wastewater collection system increase the salt concentration of receiving waters, salts discharged to evaporation ponds and eventually to landfills become a potential point source, and salts injected into deep wells can degrade the quality of groundwater.

A holistic approach to membrane separation leads to the inescapable conclusion that an alternative is needed to the traditional options for concentrate disposal, as listed in Table 2.1. Although still considered very costly, a promising alternative is zero liquid discharge (ZLD) (Ahmed et al., 2003; Mickley, 2005), whereby salts are separated from residual water and marketed. ZLD shifts the focus from disposal to sustainability. The terms "management of concentrates" introduced by Mickley (2005) and "beneficial use" (Ahuja and Howe, 2005) emphasize a more positive solution to the disposal problem (Reardon et al., 2005). Beneficial use is less costly than ZLD, whereby concentrates are used for irrigation of salt-tolerant crops, saline aquaculture, salt marsh development, and energy from solar gradient ponds (Van der Bruggen et al., 2003; Reardon et al., 2005; Ahuja and Howe, 2005). Despite the growing interest in these disposal alternatives, much more research is needed to demonstrate their technical and economic feasibilities.

2.2 CONCENTRATE CHARACTERISTICS

2.2.1 Mass Balances

Mass balances on flow rates and concentrations through membrane systems are essential to understanding the impacts of concentrate discharge to wastewater treatment plants. Mass balance equations have been reported in various textbooks to describe continuous generation of a concentrate stream in cross-flow membrane operations that are used in high-pressure membrane systems.

The mass balance on flow rate is given by:

$$Q_f = Q_p + Q_c \tag{2-1}$$

where the flow rates of the feed, permeate, and concentrate streams are Q_f, Q_p, and Q_c, respectively. The water recovery factor, R, is defined by

$$R = \frac{Q_p}{Q_f} \tag{2-2}$$

Substituting for Q_p from eq 2-1 into eq 2-2 gives the concentrate/feed flow ratio:

$$\frac{Q_c}{Q_f} = (1-R) \tag{2-3}$$

The mass balance on a constituent within the water is:

$$Q_f C_f = Q_p C_p + C_c Q_c \tag{2-4}$$

where the concentrations in the feed, permeate, and concentrate streams are given by C_f, C_p, and C_c, respectively. Rejection of constituents is defined by:

$$r = \frac{C_f - C_p}{C_f} = 1 - \frac{C_p}{C_f} \tag{2-5}$$

Equation 2-4 can be rearranged to give:

$$\frac{C_c}{C_f} \frac{Q_c}{Q_f} = 1 - \left(\frac{Q_p}{Q_f} \frac{C_p}{C_f} \right) \tag{2-6}$$

Substitution of eq 2-2 and 2-5 into eq 2-6 results, after simplification, in the concentrate/feed concentration ratio:

$$\frac{C_c}{C_f} = \frac{1 - [R(1-r)]}{(1-R)} \tag{2-7}$$

The above equation was also reported by van der Bruggen et al. (2003).

As shown in Figure 2.1., Q_c/Q_f declines linearly with increasing water recovery, which means less concentrate for disposal. The effects of water recovery and rejection efficiency on C_c/C_f are also shown in Figure 2.1. C_c/C_f increases nonlinearly with water recovery and asymptotically approaches infinity as R approaches 1. The effect of rejection efficiency is relatively small over the range of practical interest, here bracketed by r values of 0.7 and 1.0. For a water recovery of 90% ($R = 0.9$), C_c/C_f would be 7.3 if the rejection was 70% ($r = 0.7$) and 10 if the rejection was 100% ($r = 1$). As an example, the concentration of salt in the concentrate with $R = 0.9$ is 10,000 mg/L if the salt concentration in the feed to the membrane is 1000 mg/L and the rejection is 100%.

Mass balance equations for intermittent generation of backwash water as characteristic of dead-end filtration in low-pressure membranes are not often reported. The beginning point is:

$$C_{bw} = \frac{Q_f C_f T_{fr}}{V_{bw}} \tag{2-8}$$

where C_{bw} is the concentration of particles and/or bacteria in the backwash stream, Q_f is the feed flow rate to membrane filtration, C_f is the feed concentration of particles and bacteria, T_{fr} is the filtration run time, and V_{bw} is the volume of backwash water generated at the end of each filtration run.

V_{bw} is given by:

$$V_{bw} = Q_{bw}T_{bw}$$ (2-9)

where T_{bw} is the backwash cycle time. The ratio of the concentration in the backwash stream to the feed stream is described by:

$$\frac{C_{bw}}{C_f} = \frac{Q_f T_{fr}}{Q_{BW}T_{bw}}$$ (2-10)
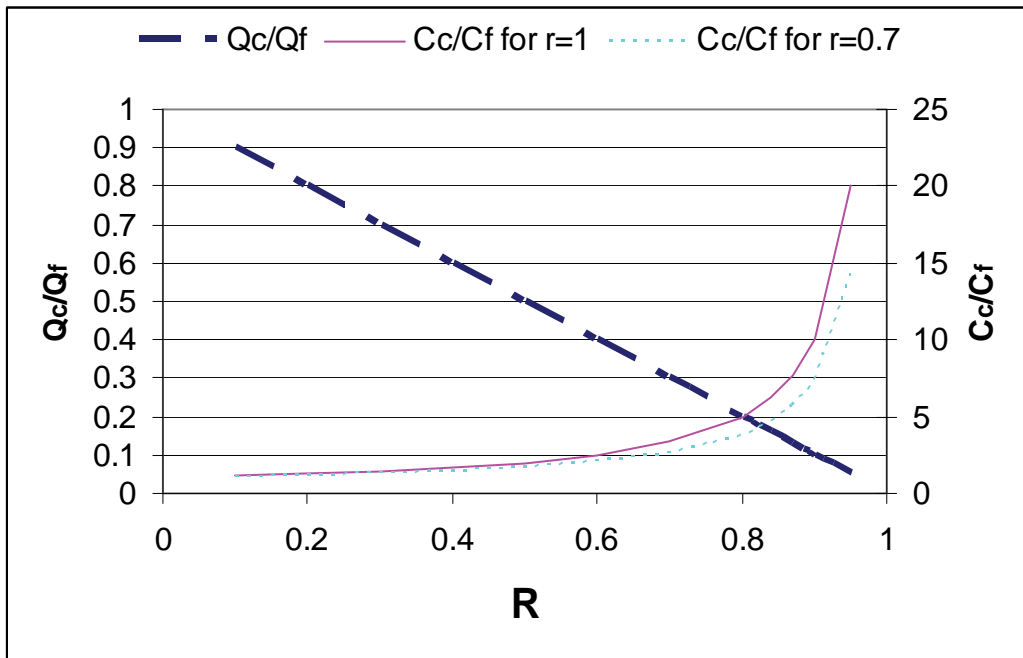
Figure 2.1. Influence of water recovery on flow rate and concentration of constituents (at 70 and 100% rejection) in a concentrate stream, expressed as a fraction of the feed stream value.

The total backwash volume per day is frequently expressed as a percentage of the feed flow rate to obtain a measure that is equivalent to the percentage of recovery in cross-flow operation. On this basis, the recoveries range from 90% to 98% (Chellam and Jacangelo, 1998), and the corresponding values of Q_{bw}/Q_f in eq 2-10 would be 0.1 to 0.02. Using a typical T_{fr} of 30 min and typical t_{bw} of 3 min (Chellam and Jacangelo, 1998), C_{bw}/C_f from eq 2-10 is 30. As an example, if the concentration of particles in the feed is 50 mg/L, the concentration of particles in the backwash water would be 1500 mg/L.

2.3 CONSTITUENTS OF CONCENTRATE AND BACKWASH STREAMS

Constituents of the concentrate and backwash streams are the same as those in the feed stream which are subsequently rejected by a membrane. They may be naturally present or may be added to the water by human activity (i.e., anthropogenic chemicals). The concentration of any constituent can be calculated using eq 2-7 for concentrate streams from high-pressure membranes or eq 2-10 for backwash streams from low-pressure membranes.

The most common objective of high-pressure membrane treatment is desalination. At present, survey data indicate that the vast majority of feed waters to desalination processes are brackish water rather than seawater. Although now outdated, the survey conducted in 1992 by Mickley et al. (1993) identified 140 high-pressure membrane installations, of which 128 were installed to treat brackish groundwaters, while 5 of the remaining 12 plants were used to treat brackish surface water and 7 to treat seawater. Since 1992, only three additional seawater desalination membrane plants have been installed, and the largest of these (2 mgd, in Tampa Bay, FL) would still be considered small (Mickley, 2005). The total number of desalination plants, on the other hand, has increased from 140 in 1992 to 234 in 2005. These statistics emphasize the need to address concentrate disposal from brackish water desalination systems, particularly inland, where discharge to a WWTP may be the most convenient disposal option (Mickley, 2005).

Mickley (2000) identified nine major inorganic ions in concentrates from nine RO systems for brackish groundwater desalination. The range of concentrations of each major ion and the corresponding range of the sums of the ion concentrations for the nine field studies are listed in Table 2.2. The concentrations varied widely. While not shown, the fractional composition also varied widely, and this would affect WET, as will be discussed later. The variability in concentrations of each ion and in fractional composition indicate that groundwater chemistry is site-specific, and therefore the negative effects of the concentrate on WWTP operation will also be site-specific. The broad categories of negative effects are infrastructure corrosion, lowered treatment efficiency, and toxicity both to aquatic organisms in receiving waters and to crops irrigated with the effluent.

In addition to the inorganic ions listed in Table 2.2, radium, radon, and arsenic may be naturally present, along with anthropogenic chemicals, such as nitrate, perchlorate, and heavy metals. The concentrations of all of these chemicals are low in groundwater compared to the ions that characterize brackish waters. Nevertheless, as shown in Figure 2.1, the 10- to 20-fold increase in the concentration of these chemicals in the concentrate stream could be of concern for the wastewater collection system.

The TDS concentration, which represents the summation of all of the inorganic ion concentrations by weight (in milligrams per liter), is a common regulatory parameter for discharge permits (Mickley, 2005). However, this parameter is not sufficient to identify the specific ions that increase corrosion, decrease treatment efficiency, and/or produce a toxic response in the effluent (Mickley, 2000).

Table 2.2. Major Inorganic Ions in Concentrate from RO Facilities Treating Brackish Groundwaters[a]

Inorganic Ion	Range of Conc, mg/L
Sr^+	14–160
F^-	1.4–8.6
HCO_3^-	42–366
Ca^{2+}	250–1000
SO_4^{2-}	810–2800
Mg^{2+}	210–990
K^+	8.9–150
Cl^-	273–14,000
Na^+	130–7000
Total	3652–26,029

[a]As reported by Mickley (2000).

High-pressure membranes can also be used for other purposes besides desalination. Although there have been relatively few such applications, their number is very likely to increase (AWWA Membrane Technology Research Committee, 2005). Softening of fresh water (both surface and groundwaters) is common in Florida and produces high concentrations of calcium and magnesium. Removal of natural organic matter, the precursor to disinfection by-products, is another possible objective of high-pressure membrane treatment of surface water and some groundwaters. For either objective, the anthropogenic chemicals will add to the composition of the concentrate stream. Examples include copper sulfate or other chemicals that are used to treat algal blooms in impounded surface waters, organic anthropogenic chemicals such as pesticides and herbicides from agricultural runoff, and emerging chemicals of concern, such as PhACs and personal care products. As with naturally occurring chemicals, the rejection of all these anthropogenic chemicals by high-pressure membranes will increase their concentrations in the concentrate stream by a factor of 10 to 20 (Figure 2.1).

EDCs, PhACs, personal care products, surfactants, X-ray contrast media, preservatives (e.g., organotins), and pesticides are a major reason for using NF and RO in wastewater reclamation (Daughton and Ternes, 1999; Salveson et al., 2000; Drewes et al., 2002; Andersen et al., 2003; Khan et al., 2004; Daughton, 2005; Reardon et al., 2005; Gagne et al., 2006). Their presence in the concentrate stream from a satellite wastewater reclamation facility may have negative consequences, although very little is currently known about their impacts. Recycling the concentrate stream within the reclamation plant may render these chemicals somewhat easier to remove. Partitioning to biomass or passage through the treatment plant into the receiving water are other possible fates for these by-products (Andersen et al., 2003; D'Ascenzo et al., 2003; Gagne et al., 2006).

Concentrate from satellite wastewater reclamation plants may also be discharged to a central WWTP. While negative impacts on treatment processes and/or on current discharge permits at the central facility are unlikely, the ultimate fate(s) of anthropogenic chemicals is still a concern. The concern over anthropogenic chemicals points to the major limitation of membrane technology: membranes provide excellent separation, but chemicals are not destroyed or altered. If both recalcitrant naturally occurring and anthropogenic chemicals are conserved in the concentrate stream, they will simply be transferred from one water body to another, and this is not environmentally sustainable. The ideal goal would be to develop methods for concentrate management rather than disposal that would involve the destruction

or solidification of constituents, although the costs would be high (Reardon et al., 2005; Mickley, 2005).

An example of the composition of brine from RO treatment of a mixture of municipal and textile wastes in Belgium is given in Table 2.3 (Van Hege et al., 2004). The surrogate measures of organic constituents were COD, which ranged from 151 to 218 mg/L, and light absorbance at 455 nm, which ranged from 0.143 to 0.243 cm^{-1} (i.e., light absorbance in a 1-cm-cell path length). Specific anthropogenic chemicals are unknown from these general measures.

Table 2.3. Chemical Characterization of RO Brine from Treatment of Municipal Wastewater Containing Significant Textile Wastes[a]

Parameter (units)	Sample 1	Sample 2	Sample 3
pH	8.74	7.91	8.05
EC (µS/cm)	5060	5290	3990
Cl^- (mg/L)	777	804	595
ClO_3^--Cl (mg/L)	3.03	3.39	1.16
Ca^{2+} (mg/L)	126	109	208
Mg^{2+} (mg/L)	40.2	23.9	32.3
Active chlorine (mg/L)	<0.01	<0.01	0.07
COD (mg/L of O_2)	151	218	171
TAN (mg/L of N)	31.0	35.4	37.6
Absorbance, 455 nm (cm^{-1})	0.1463	0.2433	0.1340

[a]As reported by Van Hege et al. (2004).

Backwash from low-pressure membranes contains particles and microbes. According to one survey, 14% of low-pressure membrane facilities currently recycle backwash streams (AWWA Residuals Management Research Subcommittee, 2003). However, recycling of backwash streams has undergone close scrutiny because of concern about buildup of microbial contaminants, such as *Cryptosporidium parvum* oocysts and *Giardia lamblia* cysts (Tobiason et al., 2003). The 1996 amendments to the Safe Drinking Water Act mandated that the U.S. Environmental Protection Agency (EPA) address recycling of backwash water, which led to promulgation of the Backwash Recycle Rule in 2001. This rule requires that all recycle streams from granular medium filters be returned to the head of the plant and that all plans for recycling be approved by the state regulatory agency. At present, the only treatment used for membrane recycling is sedimentation; however, with sedimentation, less than 1-log removal (90%) of *Cryptosporidium* oocysts can be achieved (Cornwell and MacPhee, 2001). Backwash streams from low-pressure membranes are not regulated by the Backwash Recycle Rule unless they are commingled with other backwash streams. However, these streams are no less problematic (AWWA Residuals Management Research Subcommittee, 2003; LeGouellec et al., 2004).

2.4 CHEMICAL ADDITIVES TO MEMBRANE SYSTEMS

Chemical additives originate from intermittent cleaning of membrane surfaces and from dosing the membrane feed stream. Chemicals that are added to the feed stream (Table 2.4) include organic biocides, chlorine, copper sulfate, powdered activated carbon, ferric chloride, polyelectrolytes, and antiscalants, such as polyacrylic acid, sodium tripolyphosphate, and trisodium phosphate, all of which will turn up in the concentrate stream. The remaining chemicals listed in Table 2.4 are generated intermittently and appear in waste streams that must also be disposed. Our literature search did not reveal data on specific compositions of waste cleaning solutions.

A fraction of an active chemical ingredient is consumed during the cleaning. The resulting waste includes salts from the chemical reactions, organic constituents removed from the membrane surface, and the residual active ingredient. In some membrane plants, the active ingredient is refreshed and the cleaning chemicals are reused in order to minimize the waste to be disposed (Reardon et al., 2005).

In addition to generating waste that must be disposed, the use of chemical cleaning solutions gives rise to several other concerns. Because of their strong acidic or basic nature, they may produce waste streams outside of the typical pH range of 5–9 that is acceptable for discharge, and they may contain surfactants. Although they may be present at low concentrations, surfactants may cause foaming.

Table 2.4. Chemical Additives Used with Membrane Processes[a]

Acrolein	Hydrochloric acid	Sodium hydroxide
Biocides	Organopolyphosphonates	Sodium meta bisulfite
Caustic soda	Polyacrylic acid	Sodium tripolyphosphate
Chlorine	Polyelectrolytes	Sodium hexametaphosphate
Citric acid	Powdered activated carbon	Sodium dodecylbenzene sulfonate
Copper sulfate	Proprietary cleaning compounds	Sulfuric acid
EDTA	Propylene glycol	Sulfur dioxide
Ferric chloride	Sodium bisulfite	Trisodium phosphate
Glycerin	Sodium dodecyl sulfate	

[a]As reported by the California Coastal Commission (1993) and Van der Bruggen et al. (2003).

Chlorine residuals may range from 1–500 mg/L and may exceed the local pretreatment limits for most sites and result in additional TDS being discharged to the wastewater treatment facility. Dechlorinating agents may be added to prevent the release of chlorine gas if an acidic cleaning solution is used. If both acidic and basic solutions are used, they may be mixed to minimize the need for neutralization chemicals. However, neutralization is also likely to produce precipitates such as calcium carbonate and iron salts, which increase the suspended solids concentration of the waste. If citric acid is used, the BOD_5 of the spent cleaning solution is likely to be very high.

The frequency of using chemical cleaning solutions varies depending on the local conditions. A recent survey of low-pressure membrane facilities for which 54 responses were received (Adham et al., 2005) found that the number of chemical cleanings ranged from 0.2–50/year, and averaged 4/year. There is a trade-off between the costs associated with chemical cleaning and the capital costs of membrane units. Operating the membranes at lower flux reduces the frequency of chemical cleaning but results in larger capital costs because a larger number of membrane units are needed for the same daily water production rate.

The quantities and constituents of waste cleaning solutions for low-pressure membranes are summarized in Table 2.5. Chlorine, surfactants, acids (citric or hydrochloric), and caustic soda are commonly used in cleaning solutions. The residual stream contains bacteria, organic chemicals, and inorganic solids. Biodegradable and nonbiodegradable organic constituents can produce a highly turbid waste stream. Citric acid, which is biodegradable, could produce a residual stream with a BOD_5 in the range of 5000 to 10,000 mg/L (Reardon et al., 2005). Residuals from cleaning membranes in wastewater systems in areas with high TDS concentrations in the drinking water supply may also contain high concentrations of TDS in the residuals.

Table 2.5. Typical Characteristics of Chemical Cleaning Solutions and Residuals

Characteristic	Typical Value or Attribute
Frequency of application	Daily to once every 3–4 months
Volume of waste produced	Monthly clean-in-place wastes normally <0.05% of plant feed flow (daily chemically enhanced BW wastes might be 0.2–0.4% of plant feed flow rate)
Chemicals commonly used	Sodium hypochlorite, 500–1000 mg/L as Cl_2 Citric or hydrochloric acid, pH 1–2 Caustic soda, pH 12–13 Surfactant, 0.1% by weight
Characteristics of spent cleaning solution	pH 2–14 Chlorine residual up to 1000 mg/L as Cl_2 Low conc of surfactants TSS up to 500 mg/L (neutralization may precipitate additional solids) TOC 10×–30× feed water conc BOD_5 up to 5000–10,000 mg/L if citric acid used

2.4.1   Regulatory Implications of Backwash and Chemical Cleaning Wastes

A summary of the categories of constituents in backwash water and chemical cleaning waste streams and the applicable regulations pertaining to their disposal is presented in Table 2.6. A few case studies will be presented in a later section.

Table 2.6. MF and UF Residuals and Applicable Regulations

Residual	Typical Contaminants	Typical Level	Regulation[a]	Representative Limits
Backwash Bleed-Off Discharges	Raw water, precipitated solids, algae, pathogens, possible chemical residues	TSS, 5–200 mg/L Cysts, 7×–50× raw conc Acids and bases, pH <6 or >9 Chlorine, >5 mg/L	Clean Water Act SDWA	pH, 6–9 TSS, 30 mg/L + raw TSS Chlorine, <0.2 mg/L BOD_5, 30 mg/L TSS and cyst removal, 90% recycled at WTP and recycle flow <10% of WTP flow
Solids and Sludge	Raw water, precipitated solids, algae, pathogens	TSS, 500–2000 mg/L for settled BW solids Cysts, 15×–200× raw conc	Clean Water Act RCRA	pH, 6–9 TSS, 30 mg/L + raw TSS BOD_5, 30 mg/L No free liquid (>20% solids after dewatering) Pass TCLP (Possible use as landfill cover or for sod farming)
Spent Cleaning Solutions	Residual cleaning chemicals, TOC, BOD_5, dissolved solids	TSS, <500 mg/L Acids and bases, pH <6 or >9 Chlorine, >5 mg/L TOC, <100 mg/L BOD_5, 5000–10,000 mg/L (if citric acid used) Surfactants, low concentrations	Clean Water Act, EPA & local industrial pretreatment and wastewater collection system use rules	pH, 6–9 TSS, <400 or 500 mg/L BOD_5, <400 or 500 mg/L Chlorine, <10 mg/L Nothing that will harm or interfere with wastewater collection systems, the WWTP, or its operation

[a]Abbreviations: SDWA, Safe Drinking Water Act; RCRA, Resource Conservation and Recovery Act.

2.5 REGULATIONS

2.5.1 Federal Regulations

As indicated in Table 2.6, the Clean Water Act and the Safe Drinking Water Act regulations can impact the disposal of concentrate, backwash water, and waste chemical cleaning solutions. The Clean Water Act regulates all discharges to surface waters and wetlands, disposal of sludge, and discharges to wastewater collection systems through NPDES permits. Although discharge of concentrate to a POTW does not require an NPDES permit, the concentrate must meet local pretreatment requirements established under the EPA National Pretreatment Program (40 CFR 403). Solid residuals may be governed by 40 CFR 503 sewage sludge disposal regulations, because secondary effluent contains small amounts of biological solids.

2.5.2 Wastewater Collection System Discharge Permits

The 1987 amendments to the Clean Water Act required POTWs to set pretreatment standards for each significant local source. Concentrate, backwash water, and waste chemical cleaning solutions are not included among the 35 industrial categories subject to the uniform categorical standards for concentrations of specific pollutants that are technology based and applicable nationwide.

The EPA Local Ordinance Development Document (U.S. EPA, 2004b) is an outgrowth of the pretreatment standards and is intended to complement the categorical standards. Each POTW must set local limits based on site-specific conditions that include the efficiency of the treatment process, history of compliance with the NPDES permit, the water quality standards applicable to the receiving water, and biosolids handling.

The EPA has developed guidelines for establishing local ordinances that begin with the concepts of maximum allowable headworks loading (MAHL) and the maximum allowable industrial loading (MAIL). The MAIL is that portion of the MAHL that is contributed by industrial users (IUs) and is thus considered readily controllable. A water treatment plant or a WWTP that discharges concentrate, backwash water, and/or waste chemical cleaning solutions into the wastewater collection system falls under the category of an IU. A MAIL can be a uniform concentration that applies to all IUs, an individual waste load allocation, or a combination of the two.

The first step in establishing a MAHL is to identify the pollutants of concern (POCs). The general criteria for defining a POC include deleterious effects in the collection system, interference with treatment in violation of the NPDES permits, interference with biosolids handling, jeopardy to workers, and operating problems. At a minimum, the EPA recommends that each WWTP screen for the pollutants listed in Table 2.7.

Table 2.7. Potential POCs for IUs

Arsenic	Silver
Cadmium	Zinc
Chromium	Molybdenum
Cyanide	Selenium
Lead	BOD_5
Mercury	TSS
Nickel	Ammonia

In addition, the EPA recommends examination of POCs that can limit biosolids disposal to the land. This list includes arsenic, cadmium, lead, mercury, molybdenum, nickel, selenium, and zinc (Table 2.7) as well as copper.

Experience with regulation of membrane concentrates, backwash water, and waste chemical cleaning agents is still very limited. Thus, broad guidelines for POCs have not yet been established (Mickley, 2001). The permit limits for discharge of concentrate from membrane systems at water treatment plants to the wastewater collection system can vary widely (Zander, 2000). For instance, local limits for some constituents may be more restrictive than those established by the EPA. In particular, the limits may focus on the corrosiveness of RO brines, pHs above or below neutral, unacceptably high concentrations of TDS, and heavy metals. Some states, including California, Arizona, New Mexico, Texas, Oklahoma, Missouri, Illinois, and Florida, have developed water quality standards that control inorganic constituents in membrane brine streams by limiting constituents such as TDS, chloride, sulfate, salinity, and conductivity.

Disposal fees are based on the volume and chemical characteristics of the concentrate, backwash water, or waste chemical cleaning solution (Zander, 2000). Disposal to the wastewater collection system is often far less costly than other options; however, at least one study found the burden to the environment imposed by discharge to the wastewater collection system to be greater than that imposed by other methods of disposal. Disposal fees are highly variable, depending on the impacts of concentrate on the treatment capacity and hydraulic capacity as well as on the potential for damage to components of the treatment plant.

2.5.3   Limits for Agricultural Reuse

The discharge of concentrate and perhaps, to a lesser extent, backwash water and waste chemical cleaning solutions from membrane desalination plants to the wastewater collection system could restrict the suitability of the reclaimed wastewater for agricultural use. Typical water quality requirements for agricultural irrigation are listed in Table 2.8 (which is based on the data reported by Reardon et al., 2005). High TDS concentrations can decrease soil permeability and productivity. Excessive concentrations of sodium, bicarbonate, and carbonate ions contribute to loss of soil permeability and add specific ions that are toxic to certain crops. The sodium adsorption ratio (SAR) is a common way to quantify the loss in soil permeability:

$$SAR = \frac{[Na+]}{\sqrt{([Ca^{2+}]+[Mg^{2+}])/2}}$$
(2-11)

where the ion concentrations for Na, Ca, and Mg are expressed in milliequivalents per liter. A common surrogate for SAR is electrical conductivity (EC), which is measured in microSiemens per centimeter (Table 2.8). Natural waters in the western United States often have high SAR values. Thus, depending upon local conditions, the addition of sodium by discharging concentrate to a WWTP may limit irrigation with reclaimed water to more salt-resistant crops.

Table 2.8. Guidelines for Interpretation of Water Quality for Irrigation[a]

Potential Irrigation Problem and Parameter Monitored, Units	Degree of Restriction on Use		
	None	Slight to Moderate	Severe
Salinity[b]			
EC_w, dS/m	<0.7	0.7–3.0	>3.0
TDS, mg/L	<450	450–2000	>2000
Infiltration,[c] dS/m, when EC_W for SAR is:			
0–3	>0.7	0.7–0.2	<0.2
3–6	>1.2	1.2–0.3	<0.3
6–12	>1.9	1.9–0.5	<0.5
12–20	>2.9	2.9–1.3	<1.3
20–40	>5.0	5.0–2.9	<2.9
Specific Ion Toxicity[d]			
Na^+			
Surface Irrigation, SAR	<3	3–9	>9
Sprinkler Irrigation, meq/L	<3	>3	
Cl^-			
Surface Irrigation, meq/L	<4	4–10	>10
Sprinkler Irrigation, meq/L	<3	>3	
B, mg/L	<0.7	0.7–3.0	>3.0
Miscellaneous Effects[e]			
NO_3^-N, mg/L	<5	5–30	>30
$HCO_3^{-[f]}$, meq/L	<1.5	1.5–8.5	>8.5
pH	Normal range is 6.5–8.4		

[a]As reported by Reardon et al. (2005).
[b]Affects crop water availability.
[c]Affects infiltration rate of water into the soil; evaluate using EC_w and SAR together.
[d]Affects sensitive crops.
[e]Affects susceptible crops.
[f]Overhead sprinkling only.

A listing of specific metals, their recommended concentration limits, and a brief description of their negative effects on crops is given in Table 2.9 (based on data reported by U.S. EPA, 2004a).

The limits for many of these metals are very high (>1 mg/L), but for some (arsenic, beryllium, cadmium, chromium, cobalt, copper, molybdenum, and selenium) the limits are in the range of 0.1 mg/L or lower. Determination of whether metals added by discharging concentrate to a municipal WWTP might cause these recommended limits to be exceeded would require analysis by mass balance calculations for each specific application.

Table 2.9. Recommended Limits for Constituents in Reclaimed Water for Irrigation

Constituent	Limit, mg/L, for: Short-Term Use	Long-Term Use	Remarks
Aluminum	5.0	20	Can cause nonproductiveness in acid soils, but soils of pH 5.5–8.0 will precipitate the ion and eliminate toxicity
Arsenic	0.10	2.0	Toxicity to plants, ranging from 12 mg/L for Sudan grass to <0.05 mg/L for rice
Beryllium	0.10	0.5	Toxicity to plants, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans
Boron	0.75	2.0	Essential to plant growth, with optimum yields obtained at a few tenths mg/L in nutrient solutions; toxic to many sensitive plants (e.g., citrus) at 1 mg/L; usually sufficient quantities in reclaimed water to correct soil deficiencies; most grasses are relatively tolerant at 2.0–10 mg/L
Cadmium	0.01	0.05	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in nutrient solution; conservative limits recommended
Chromium	0.1	1.0	Not generally recognized as an essential growth element; conservative limits recommended due to lack of knowledge on toxicity to plants
Cobalt	0.05	5.0	Toxic to tomato plants at 0.1 mg/L in nutrient solution; tends to be inactivated by neutral and alkaline soils
Copper	0.2	5.0	Toxic to a number of plants at 0.1–1.0 mg/L in nutrient solution
Fluoride	1.0	15.0	Inactivated by neutral and alkaline soils
Iron	5.0	20.0	Not toxic to plants in aerated soils but can contribute to soil acidification and loss of essential phosphorous and molybdenum
Lead	5.0	10.0	Can inhibit plant cell growth at very high concentrations
Lithium	2.5	2.5	Tolerated by most crops at concentrations up to 5 mg/L; mobile in soil; toxic to citrus at low doses; recommended limit is 0.075 mg/L
Manganese	0.2	10.0	Toxic to a number of crops at a few tenths to a few mg/L in acidic soils
Molybdenum	0.01	0.05	Nontoxic to plants at normal concentrations in soil and water; can be toxic to livestock if forage is grown in soils with high levels of available molybdenum
Nickel	0.2	2.0	Toxic to a number of plants at 0.5–1.0 mg/L; reduced toxicity at neutral or alkaline pH.
Selenium	0.02	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low levels of selenium
Tin, Tungsten, Titanium			Effectively excluded by plants; specific tolerance levels unknown
Vanadium	0.1	1.0	Toxic to many plants at relatively low concentrations
Zinc	2.0	10.0	Toxic to many plants at widely varying concentrations; reduced toxicity at increased pH (6 or above) and in fine-textured or organic soils
pH	6.0		Most effects on plant growth are indirect (e.g., pH effects on heavy metal toxicity, described above)
TDS	500–2000		Below 500 mg/L, no detrimental effects are usually noticed. Between 500–1000 mg/L, TDS in irrigation water can affect sensitive plants. At 1000–2000 mg/L, TDS levels can affect many crops, and careful management practices should be followed. Above 2000 mg/L, water can be used regularly only for tolerant plants on permeable soils.
Free Cl Residual	<1		Concentrations >5 mg/L cause severe damage to most plants. Some sensitive plants may be damaged at levels as low as 0.05 mg/L.

2.6 MASS BALANCE MODEL FOR ESTABLISHING DISCHARGE LIMITS

A mass balance-based method was proposed two decades ago (Anthony and Breimhurst, 1981) for calculating maximum allowable concentrations of chemicals on the EPA's Priority Pollutant List at the headworks of a WWTP. In today's regulatory framework, the same procedure could be used to produce an MAHL for any POC found in the concentrate, backwash water, or waste chemical cleaning solutions from membrane plants. The original approach considered limiting priority pollutants in the influent based on the following criteria: inhibition of secondary biological treatment efficiency (including nitrification), inhibition of sludge digestion, sludge disposal criteria, effluent limitations (both acute toxicity and ambient quality), and health and structural hazards. A few example mass balances are provided to illustrate the method.

A mass balance around the primary treatment process gives:

$$\overline{C}_{in} = \frac{\overline{C}_{prim}}{1 - \dfrac{R_{prim}}{100}} \tag{2-12}$$

where $\overline{C}_{prim}$ is the maximum allowable primary effluent concentration of a specific chemical to prevent inhibition of secondary treatment, $\overline{R}_{prim}$ is the removal efficiency of primary treatment for this chemical, and $\overline{C}_{in}$ is the resulting concentration limit at the headworks. A mass balance between the headworks and the unstabilized sludge gives the following equation:

$$\overline{C}_{in} = \overline{C}_s \frac{100}{R_s} \frac{Q_s}{Q_{in}} \tag{2-13}$$

where $\overline{C}_s$ is the maximum allowable undigested sludge concentration to prevent inhibition of sludge digestion, Q_{in} is the flow rate into the plant, Q_s is the flow rate of sludge to the digester, and R_s is the percentage of the chemical removed in the undigested sludge (obtained from the uptake by suspended solids removed in primary clarification and waste biomass from the biological treatment process). Similarly, a mass balance can be written between the undigested and the digested sludge:

$$\overline{C}_d = \overline{C}_s \left(1 - \frac{R_d}{100}\right) \frac{Q_s}{Q_d} \tag{2-14}$$

where $\overline{C}_d$ is the maximum allowable digested sludge concentration for safe disposal and Q_d is the flow rate of digested sludge. Substituting eq 2-13 into eq 2-14 and rearranging gives the limiting concentration at the headworks based on the criterion of safe disposal of digested sludge:

$$\overline{C}_{in} = \overline{C}_d \frac{100}{R_s} \frac{Q_d}{Q_s} \frac{1}{\left(1 - \frac{R_d}{100}\right)}$$

(2-15)

To calculate the limiting influent concentration, data must be provided on the limiting concentration for each deleterious effect and the removal efficiency by each treatment process; this calculation also depends on partitioning of chemicals between solids and water. Sample results for a set of these values and the flow rate balance for a typical secondary WWTP are presented in Table 2.10 (based on data reported by Anthony and Breimhurst, 1981). For each metal, biosolids disposal controls the maximum influent concentration. In fact, the heavy metal content of stabilized biosolids typically ranges from 0.5–2% on a dry weight basis (Gu and Wong, 2004). According to one source, a high metal content is estimated to restrict application to agricultural lands (Lombardi and Garcia, 2002).

Table 2.10. Limiting Influent Concentrations for Six Metals[a]

Metal	Limiting Influent Conc, mg/L				
	Inhibition to Secondary Treatment	Inhibition to Digestion	Digested Sludge Disposal	Acute Toxicity (Effluent)	Maximum Influent Conc
Cd	2.1	0.63	0.09	3.3	0.09
Cr	12.5	1.1	0.45	40	0.50
Cu	1.3	0.42	0.38	2.5	0.4
Pb	3.8	2.8	1.1	50	1.0
Ni	2.1	0.28	0.34	14	0.30
Zn	4.0	2.4	0.97	33	1.0

[a]Based on data reported by Anthony and Breimhurst (1981).

2.7 EXPERIENCE WITH DISPOSAL OF CONCENTRATE TO WWTPs

Concentrate streams from treatment of highly brackish groundwater supplies on four Seminole Tribe reservations of Florida were proposed to be discharged to the respective WWTP (Kile and Ajy, 2005); however, because of concerns about the impacts on the WWTPs for biological treatment, it was decided to discharge the concentrate to percolation ponds. The TDS limit in effluent for land application, however, is 700 mg/L. The TDS of the concentrates was 1185 mg/L at the Immokalee Reservation and 3060 mg/L at the Big Cypress Reservation. In both cases, the concentrate was blended with secondary effluent to reduce TDS concentrations to about 700 mg/L. At the Brighton Reservation, the TDS of the concentrate stream was 2530 mg/L, and the distance to the WWTP was considered too long for blending with effluent to be economical. Instead, the concentrate was diluted with water from a nearby canal. At the Hollywood Reservation, the TDS of the blended concentrate and secondary effluent exceeds 700 mg/L, and the reservation lacks adequate land area for a percolation pond. This problem has not yet been resolved, because the Seminole Tribe Reservations of Florida organization does not have the right of eminent domain for locating a discharge pipe off the reservation land.

A 2-year study by the St. John's River Water Management District (Florida) led to preparation of the Demineralization Concentrate Management Plan (Reiss et al., 2002). The RO plant was assumed to generate a concentrate with a TDS of 5000 mg/L. The TDS concentration of the wastewater at the WWTP that received the concentrate was 250 mg/L, and the permit limit for discharge to the receiving water was 500 mg/L. Using eq 2-7, the volume of concentrate would be limited to 5.5% of the volume of the wastewater to meet the discharge permit limit.

Treatment of brackish water for drinking in Dunedin, FL, produces about 3000 m^3/day (0.8 mgd) of concentrate that is discharged to the WWTP. The dilution ratio of concentrate with municipal wastewater is 3.8:1, which increases the TDS concentration of the wastewater from 300 mg/L to nearly 800 mg/L. A fraction of the effluent is used for residential irrigation water (Abdessemed and Nezzal, 2002; Kety et al., 2002). However, the remaining effluent that is discharged to the receiving water has occasionally failed the aquatic toxicity test because of high TDS concentrations.

Irrigation with blends of concentrate and municipal wastewater will depend on local conditions. The case histories presented above indicate TDS values approaching 1000 mg/L. Tables 2.8 and 2.9 include general guidance regarding water quality for irrigation, but the salt tolerance of crops varies widely. While golf course grasses and citrus trees are relatively salt tolerant, they cannot grow if the TDS concentration in irrigation water exceeds 1000 mg/L. Other crops, such as olives, almonds, and pistachios, may be able to thrive even if the TDS concentration in irrigation water reaches 4500 mg/L (URS, 2002). The use of membrane concentrates and of secondary effluent from WWTPs that receive membrane concentrate for land irrigation was included in an AwwaRF survey of membrane installations (Zander, 2000). The chemical cleaning waste from one MF plant was used for irrigation after neutralizing its pH. The concentrates from one UF plant and four RO plants were used for irrigation. Two NF plants discharge concentrate to a WWTP, the secondary effluent from which is used for irrigation. Reports from the Middle East and the United Kingdom raise concerns that the salt concentration in the concentrate may limit the opportunities for irrigation (Squire, 2000; Ahmed et al., 2001).

Discharge of concentrate from a small wastewater reclamation plant to a "brine line" for delivery to a larger treatment plant has been proposed (Reardon et al., 2005). This includes the present operation of the Santa Ana River Interceptor project in Orange County, CA (Energy & Environmental Solutions et al., 1994; Orange County Water District, 1995) and a proposed brine line from the Phoenix and Tucson, AZ, areas to the Gulf of California (U.S. Bureau of Reclamation, 2000). The Santa Ana River Interceptor project was constructed in the 1970s to export salt from the upper portions of the Santa Ana watershed to the ocean, but it was never fully utilized for this purpose. Instead, the interceptor is now used to collect and desalinate concentrate, agricultural runoff, and wastewater from domestic and industrial users in Riverside to two WWTPs operated by the Orange County Water District. Effluent from these WWTPs is discharged to the ocean. A 400-km (250-mi) pipeline from Tucson would connect with a 108-km (67-mi) pipeline from Phoenix. Pipe diameters would range from 76 to 152 cm (30 to 60 in.). Despite the large size of the piping, the estimated cost of the pipeline would be less than the cost of evaporation ponds (U.S. Bureau of Reclamation, 2000).

2.8 NEGATIVE IMPACTS ON WWTPs

2.8.1 Impacts on the Wastewater Collection System and Headworks

Concentrates from high-pressure membrane treatment of groundwater may contain sulfate and hydrogen sulfide that, under some circumstances, could increase corrosion of concrete pipe and components of the WWTP infrastructure. Sulfate can increase concrete corrosion either by direct (Lea, 1998) or indirect (Morton et al., 1991) attack.

In a direct attack, sulfates react with free calcium hydroxide in set concrete to form calcium sulfate (gypsum) and with hydrated calcium aluminates to form calcium sulfoaluminate (Lea, 1998). The reaction products more than double the volume of the crystal, thus causing the concrete to soften. Even though the solubility of calcium sulfate is low, it can react with concrete to form calcium sulfoaluminate. The ACI 318 Building Code (ACI 2002) includes the ranges of sulfate concentrations associated with the following levels of corrosion: negligible, <150 mg/L; moderate, 150 to 1500 mg/L; severe, 1500 to 10,000 mg/L; and very severe, >10,000 mg/L.

In an indirect attack, the anaerobic conditions in the wastewater collection system line convert sulfate to sulfide, of which hydrogen sulfide is the dominant species. Hydrogen sulfide then volatilizes and reaches the wastewater collection system crown, where oxygen in the air above the wastewater flow reoxidizes sulfide to produce acid, which causes cement pipe crown corrosion (Morton et al., 1991). This process is catalyzed by sulfur-oxidizing bacteria. Crown corrosion is described in detail in guidance manuals for the wastewater conveyance and treatment industry (U.S. EPA, 1985, 2004a, 2004b).

The problem of sulfide corrosion in wastewater collection systems was investigated extensively in the early 1990s in response to a mandate of the 1987 Clean Water Act amendments. Several case history reports are available (Chwirka and Satchell, 1990; Wizgall et al., 1990; Morton et al., 1991). One of these reports showed the presence of sulfate concentrations ranging from 30–80 mg/L in Sacramento, CA, 150–200 mg/L in Omaha, NE, and 115–140 mg/L in Lakeland, FL (Wizgall et al., 1990). The concentrations are only noted as being more than sufficient to produce corrosion by anaerobic formation of sulfide.

The Pomeroy–Parkhurst model is an empirical method that has been widely used for calculating sulfide generation rates in wastewater collection systems and the resulting corrosion rates (Pomeroy and Parkhurst, 1977). Sulfide generation is driven in this model by the BOD and by a sulfide generation constant that is related empirically to the concentration of sulfate in the wastewater collection system. However, the data used to generate the model were collected before the industrial pretreatment program was implemented and may have ignored the inhibitory effect of the relatively high concentrations of metals in the wastewater collection system on sulfide generation (Morton et al., 1991). Other deficiencies have been noted by Witzgall et al. (1990). Nevertheless, the Pomeroy–Parkhurst model notes the important role of BOD. For instance, intermittent discharges of spent cleaning solutions may contain significant amounts of degradable organic compounds, such as citric acid (Table 2.5), which will increase the BOD. The discharge of excess biomass from satellite installations of MBRs will intensify anaerobic conditions and possibly accelerate sulfide corrosion in the wastewater collection system.

While specific correlations of the concrete corrosion rate to sulfate concentration in the wastewater collection system are not available, increasing the sulfate concentration could

under the proper conditions lead to increased corrosion. More sulfate can allow more H_2S to be produced. Two examples of sulfate concentrations projected in NF and RO concentrates from treatment of Florida groundwater and seawater are provided. The average sulfate concentration in the Biscayne Aquifer, the raw water source for Boca Raton, was reported to be 17 mg/L (Suratt et al., 2000). With a projected recovery rate of NF and 100% rejection of sulfate, the sulfate concentration in the concentrate according to eq 2-7 would be about 160 mg/L. In Hollywood, FL, the projected sulfate concentrations in the concentrate from treatment of two groundwater source waters were 3306 mg/L from brackish Floridan groundwater and 1448 mg/L from Biscayne fresh water (Bloetscher and Meeroff, 2005).

The mass balance needed to determine the maximum allowable fraction of concentrate based on corrosion prevention is:

$$Q_c C_c + Q_{ww} C_{ww} = Q_T C_{Max} \tag{2-16}$$

where Q_{ww} is the municipal wastewater flow rate, C_{ww} is the typical concentration of sulfate added to water by domestic use, Q_T is the total flow rate to the headworks, and C_{Max} is the maximum allowable concentration of sulfate. The equation can be arranged to give:

$$\frac{Q_c}{Q_T} = \frac{C_{Max}}{\left[C_c - C_{ww}\right] + C_{ww}} \tag{2-17}$$

Using the most restrictive estimate of sulfate by the ACI to prevent cement corrosion by direct attack (150 mg/L), the highest concentration of sulfate for concentrate from treatment of the brackish Floridan aquifer (C_c = 3306 mg/L) and a typical C_{ww} of 50 mg/L (Mickley et al., 1993), the percentage of concentrate stream would be limited to about 4.5%. For moderate corrosion by direct attack, the ACI recommendation is a C_{Max} of 1500 mg/L and, thus, the allowable percentage increases to 45%. However, the indirect attack mechanism through sulfide generation would probably impose a much lower C_{Max} value if sufficient BOD were present to produce sulfate.

Sulfides can also be present in groundwaters treated by high-pressure membranes. However, the groundwater chemistry controls the release of sulfides. Groundwaters that are rich in iron, for example, rarely contain sulfide, because the sulfide is precipitated by iron. Conversely, groundwaters with high concentrations of H_2S typically have low iron concentrations because sulfides precipitate iron. For instance, the groundwater supply for Boca Raton, FL, was reported to contain 0.25–0.5 mg/L of hydrogen sulfide, and the concentration of dissolved iron (presumably as oxidizable Fe^{2+}) was 0.15 mg/L (Suratt et al., 2000). In Venice, FL, the concentrate from RO treatment of groundwater was reported to contain from 1.5–2.5 mg/L of total sulfides (Pangasa et al., 2001). Local wastewater collection ordinances often limit discharge to 1 mg/L of sulfide; however, the local limit in Venice was 0.04 mg/L. The sulfide content of concentrates from water treatment may also be limited because chlorine is added ahead of membrane units, thus oxidizing sulfide (Pangasa et al., 2001).

Chloride is another well-known agent of concrete corrosion (Energy & Environmental Solutions et al., 1994; Squire, 2000; Kobylinski et al., 2002; McIntyre et al., 2002). For example, chloride at concentrations above 1000 mg/L may cause deterioration of concrete walls and corrosion of metal surfaces. Equation 2-17 shows that 1000 mg/L of chloride would be reached when the concentrate flow rate is about 5% of the wastewater flow rate if the chloride concentration in the feed water to the membrane facility for treatment of highly

brackish water is 2500 mg/L (Bloetscher and Meeroff, 2005), the membrane recovery is 0.85, and the addition by domestic chlorides is 200 mg/L (Mickley et al., 1993).

2.8.2 Deflocculation of Activated Sludge by Cations

An unfavorable monovalent/divalent cation ratio (M/D) may adversely affect the settling of biological floc in the secondary clarifier and dewatering of waste activated sludge (Higgins and Novak, 1996; Murthy et al., 1998; Novak et al., 1998, 2003; Bott and Love, 2002; Moon et al., 2003). Activated sludge has been proposed as an ion exchange medium (Higgins and Novak, 1996; Murthy et al., 1998). In this model, the exchange of monovalent ions for divalent ions in the floc matrix was proposed to weaken the biopolymer bonds, thus releasing soluble proteins and causing deterioration of settling and dewatering properties. Field observations at WWTPs have shown that to avoid such problems, the M/D ratio should be less than 2 (Higgins and Novak, 1996). However, the effect is not the same for all monovalent ions. A bench-scale study of industrial waste treatment showed that the effluent TSS from the activated sludge unit increased as the concentration of sodium was increased, and the M/D ratio correspondingly increased from 2.8 to 5.4 (Novak et al., 1998). The corresponding range of sodium concentrations was 460 to 1150 mg/L. Floc strength also decreased as the M/D ratio increased. In contrast, an increase in potassium instead of sodium caused poor settling only when the M/D ratio reached 2.6 (potassium concentration of 573 mg/L), and floc strength seemed to improve at all M/D ratios. The explanation offered was that potassium is a more critical cation for bacterial metabolism than sodium. The extent to which concentrate from membrane treatment of brackish water shifts the M/D ratio of blended wastewater depends on the M/D ratio of the concentrate versus that of municipal wastewater and the percentage of concentrate.

An increased salt (NaCl) concentration in the feed to the activated sludge process decreases settleability, although this effect is noted only at concentrations that are unusually high for municipal wastes (but may occur in seafood processing) (Moon et al., 2003). In a bench-scale study at NaCl concentrations much lower than those in seawater but still higher than expected in municipal wastewater, even with the addition of concentrate the sludge volume index increased by about 10% when the NaCl concentration was increased to 5000 mg/L (Uygur and Kargi, 2004).

2.8.3 NaCl Inhibition of the Activated Sludge Process

A number of bench-scale studies have examined inhibition of various biological treatment processes and configurations (Table 2.11). The results show that biodegradation is not inhibited significantly by NaCl concentrations of up to 5000 mg/L, which is far higher than would be found at a municipal WWTP that receives concentrate from membrane treatment of brackish water. Even at the hypersaline concentrations (150,000 mg/L) generated in chemical manufacturing and oil and gas production, biological treatment is possible with cultivation of halophilic organisms. For example, more than 99.5% removal of phenol was achieved in a sequencing batch reactor that utilized halophilic organisms and at removal rates similar to those in contained WWTPs (Woolard and Irvine, 1994). Use of a pilot-scale digester to treat high-salinity wastewater from a seafood processing factory provided good methanogenic activity; toxicity assays showed the importance of antagonistic effects of other cations on the toxicity exerted by sodium (Omil et al., 1995).

2.8.4 Other Causes of Inhibition to the Activated Sludge Process

The Clean Water Act amendments of 1987, which authorized establishment and enforcement of pretreatment standards, led to many studies of possible adverse impacts of chemicals from the Priority Pollutant List on the activated sludge process. Many studies of inhibitory effects were conducted in the early 1980s, but the effects of specific metals on the Priority Pollutant List chemicals continue to be reported (Mittal and Ratra, 2000; Lajoie et al., 2003; Karvelas et al., 2003).

As discussed above in Section 2.5.2, Wastewater Collection System Discharge Permits, the categorical pretreatment standards for 35 types of industries, were established to prevent inhibition of biological treatment, land disposal of biosolids, and toxicity to aquatic life in receiving streams. The concern over constituents of concentrates, backwash water, and chemical cleaning solutions has not yet led to establishment of guidelines for POCs or to experimental studies on inhibition of the activated sludge process. This section, therefore, is intended mainly to provide background data from the literature that are unrelated to concentrate discharge, only to show available correlation techniques and data for estimated partitioning and toxicity in the activated sludge and anaerobic digestion processes.

Table 2.11. Inhibition of Biological Treatment Processes by Salt

Biological Treatment Process	Salt Concentration Producing Inhibitory Effect	Citation
Nitrification	50% reduction in nitrification rate at 6000 mg/L of NaCl	Campos et al. (2002)
Nitrification–Denitrification	20% decrease in nitrification rate at 50,000 mg/L No inhibition at 20,000 mg/L	Dincer and Kargi (2001) Dahl et al. (1997)
Activated Sludge	Some inhibition at 10,000 mg/L (synthetic waste)	Dincer and Kargi (2001)
Anaerobic–Anoxic–Aerobic	Reductions in removal: 10% for COD, 5% for total N, 12% for P at 50,000 mg/L (synthetic waste)	Panswad and Anan (1999)
Sequencing Batch Reactor	Reductions in removal: 10% for COD, 10% for total N, 25% for P at 10,000 mg/L (synthetic waste)	Uygur and Kargi (2004)
Thermophilic Digestion	Methanogens were completely inhibited in anaerobic sequencing batch reactors at 10,000 mg/L of Na if previously acclimated to 0 mg/L of Na	Chen et al. (2003)
Anaerobic Digestion	50% inhibition of methanization of volatile fatty acid mixtures at 3000 mg/L of Na; adaptation occurred over 40 days, however	Feijoo et al. (1995)
Rotating Biological Contactor	5% inhibition of COD removal at 20,000 mg/L (synthetic wastewater)	Kargi and Dincer (1999)

Industrial customers that use reclaimed water from membranes for cooling towers are the most likely sources of concentrate that could contain constituents from the Priority Pollutant List, as well as emerging organic chemicals of concern such as estrogens, EDCs, and PhACs. Other potential sources are power plants that use membranes to reclaim municipal wastewater for cooling and satellite municipal WWTPs that use membranes for water reclamation. Assuming that the concentrations of priority pollutants entering these facilities meet the pretreatment limits, they will nevertheless increase in the membrane concentrate by a factor of 8 to 10 at typical recovery values. Obviously, these concentrations will decrease again by dilution in the wastewater collection system, but local ordinances will most likely apply to the concentrate stream.

A review of the literature from the early 1980s produced a range of threshold concentrations for inhibitory effects on the activated sludge and nitrification processes listed in Table 2.12 (based on data reported by Anthony and Breimhurst, 1981). The constituents are organic and inorganic chemicals on the Priority Pollutant List. Single entries of threshold values for metals most likely indicate that only one study was available. Entries showing a range of concentrations indicate that order-of-magnitude differences in threshold concentrations are not uncommon. The range for metal inhibition may reflect synergistic effects among metals, because most of the data were collected from pilot- and full-scale WWTPs that treat wastewater containing more than one metal. In addition, complexing agents such as ethylenediamene tetraacetic acid (EDTA) can reduce metal toxicity.

Table 2.12. Concentrations of Priority Pollutants Inhibitory to Activated Sludge and Nitrification Processes, from an Earlier Literature Review[a]

Priority Pollutant	Threshold Inhibitory Conc, mg/L	
	Activated Sludge	**Nitrification**[b]
Arsenic	0.1	
Benzene	100–500	
Benzidene	500	
Cadmium	1–10	
2-Chlorophenol	20–200	
Chromium(VI)	1–10	0.25
Chromium(III)	15–50	
Copper	1.0	
Cynanide	0.5–1.0	0.05–0.5
Cyanide	0.1–5.0	0.34–0.5
2,4-Dichlorophenol	64	
2,4-Dimethylphenol	40–200	
Lead	1.0–5.0	0.5
Mercury	0.1–1	
Naphthalene	500	
Nickel	1–2.5	0.25–0.5
Nitrobenzene	30–500	
Pentachlorophenol	50	
Phenol	50–200	4–10
Silver	0.25–5	
Toluene	200	
Zinc	0.3–5	0.08–0.5

[a]Based on data reported by Anthony and Breimhurst (1981).
[b]Blank entries indicate that no data were provided in Anthony and Breimhurst (1981).

Threshold concentrations for a wide range of inorganic and organic chemicals that produce inhibitory effects in the activated sludge process are provided in Table 2.13 (based on data reported in U.S. EPA, 1986).

Table 2.13. Inhibition Threshold Concentrations of Inorganic and Organic Chemicals in the Activated Sludge Process

Class and Chemical	Reported Minimum Inhibitory Conc, mg/L	Reported Inhibitory Conc Range, mg/L	Type of Inhibition Study[a]	Reference(s)[b]
Metals and Nonmetal Inorganics				
Cadmium	1	1–10	U	1, 3
Chromium (total)	1	1–100	P	2
Chromium(III)	10	10–50	U	1, 3
Chromium(VI)	1	1–10	U	1, 3
Copper	1	1	P	1, 2, 3
Lead	0.1	0.1–5.0	U	1
Lead	0.1	10–100	L	2
Nickel	1	1.0–2.5	U	1, 3
Nickel	1	5	P	2
Zinc	0.08	0.08–5	U	1
Zinc	0.3	5–10	P	2
Arsenic	0.1	0.1	U	1, 2, 3
Mercury	0.1	0.1–1	U	1, 3
Mercury	0.1	2.5 as Hg(II)	L	2
Silver	0.25	0.25–5	U	1, 3
Cyanide	0.1	0.1–5	U	1, 2, 3
Cyanide	0.1	5	F	2
Ammonia	480	480	U	4
Iodine	10	10	U	4
Sulfide	25	25–30	U	4
Organics				
Anthracene	500	500	L	2
Benzene	100	100–500	U	1
Benzene	100	125–500	L	2
2-Chlorophenol	5	5	U	3
2-Chlorophenol	5	20–200	U	1
1,2-Dichlorobenzene	5	5	U	3
1,3-Dichlorobenzene	5	5	U	3
1,4-Dichlorobenzene	5	5	U	3
2,4-Dichlorophenol	64	64	U	1
2,4-Dimethylphenol	50	40–200	U	1
2,4-Dinitrotoluene	5	5	U	3
1,2-Diphenylhydrazine	5	5	U	3
Ethylbenzene	200	200	U	1
Hexachlorobenzene	5	5	U	3

(Continues)

Table 2.13. *(continued)*

Class and Chemical	Reported Minimum Inhibitory Conc, mg/L	Reported Inhibitory Conc Range, mg/L	Type of Inhibition Study[a]	Reference(s)[b]
Organics				
Naphthalene	500	500	L	2
Naphthalene	500	500	U	3
Naphthalene	500	500	U	1
Nitrobenzene	30	30–500	U	1
Nitrobenzene	30	500	L	2
Nitrobenzene	30	500	U	3
Pentachlorophenol	0.95	0.95	U	3
Pentachlorophenol	0.95	50	U	1
Pentachlorophenol	0.95	75–150	L	2
Phenanthrene	500	500	L	2
Phenanthrene	500	500	U	3
Phenol	50	50–200	U	1
Phenol	50	200	U	3
Phenol	50	200	U	2
Toluene	200	200	U	1
2,4,6-Trichlorophenol	50	50–100	L	2
Surfactants	100	100–500	U	4

[a]Inhibition study types: U, unknown; P, pilot plant; F, full scale; L, laboratory.

[b]Data were obtained from four references, as follows: 1, Anthony and Breimhurst (1981); 2, Jenkins and Associates (1984); 3, Russell et al. (1984); 4, U.S. EPA (1986).

Since the work in the 1980s on the toxicity of organic chemicals on the Priority Pollutant List, more advanced research methods have been developed for measuring the inhibition of microbial activity in the activated sludge process (Sun et al., 1994; Hall et al., 1996; Ren and Frymier, 2003, 2004; Urase and Kikuta, 2005). The EC_{50} is the effective concentration that produces a 50% decline in microbial activity. More recent research has included development of correlations to predict EC_{50} values from quantitative structure–activity relationship (QSAR) models (Sun et al., 1994; Hall et al., 1996; Ren and Frymier, 2004) and from one bioassay technique to another (Ren and Frymier, 2003). The EC_{50} values of 50 organic chemicals, including 17 from the Priority Pollutant List, based on reductions of the oxygen uptake rate (OUR) of activated sludge cultures, were correlated with molecular connectivity indices to produce a QSAR model with Microsoft® Excel (Sun et al., 1994). The EC_{50} values ranged widely, from 14 mg/L for 1,4-dichlorobenzene to 48,619 mg/L for acetone. In another study, 50% bioluminescence repression of a genetically modified pseudomonad achieved by mating these organisms with activated sludge organisms was used as the measure of the EC_{50} (Ren and Frymier, 2003). The lowest EC_{50} of 79 organic chemicals, of which many were the same as those evaluated by Sun et al. (1994), was 4-chlorobenzaldehyde at 46 mg/L. In another comparison, the EC_{50} for benzene was 200 mg/L, whereas 1000 mg/L was reported in the OUR test conducted by Sun et al. (1994). All of these EC_{50} values are several orders of magnitude higher than levels expected in municipal WWTPs with or without discharge of concentrate to the wastewater collection system.

Nitrifying organisms are known to be more sensitive to toxic chemicals than the heterotrophs in conventional activated sludge treatment processes. The bioluminescence EC_{50} values described above were compared with results from a *Nitrosomonas* assay test, which is specific to nitrification inhibition (Ren and Frymier, 2004). The lowest EC_{50} for the *Nitrosomonas* assay among 22 organic chemicals was 0.7 mg/L for chlorobenzene. The EC_{50} of benzene based on the bioluminescence test with genetically modified *Pseudomonas* organisms was much higher (104 mg/L). Nevertheless, the *Nitrosomonas* EC_{50} values for most of the 22 organic chemicals were greater than 20 mg/L, which again suggests that the toxic effects of those organic chemicals in municipal wastewater treatment will be very limited even if membrane concentrate is being discharged to the WWTP.

The effects of 8- and 10-component mixtures of organic chemicals on the OUR inhibition were investigated by Hall et al. (1996). Various mixtures were prepared from a list of 63 organic chemicals, many of which were the same as those used in a previous study by the same research group (Sun et al., 1994). Toxicity was found to be simply additive, so that the EC_{50} of component *i* in an *n*-component mixture was $EC_{50,single/n}$. The lowest total concentration of 10 components that caused 50% inhibition was about 6 mg/L. Most 10-component mixtures achieved 50% inhibition at a total concentration higher than 100 mg/L. These total inhibitory concentrations are still much higher than what is found in most municipal wastewaters. The toxicity from organic chemicals discharged in concentrate would be unlikely to have a significant additive effect.

A recent study of metal inhibition involved adding a single metal to activated sludge samples and measuring the concentration that produced a 50% decrease in bioluminescence and in the specific (per unit biomass) OUR (the SOUR) (Lajoie et al., 2003; Kelly et al., 2004). The results are given in Table 2.14 together with inhibitory concentrations from a much earlier study. Mixtures of metals may have produced synergistic inhibitory effects, which would account for the lower limits of inhibitory concentrations compared to those in the controlled laboratory study. Another early report (Kao et al., 1982) of a 13-day laboratory-scale batch activated sludge reactor (which was fed twice daily) showed no effect on the SOUR with addition of 2 mg/L of cadmium. This finding agrees with the EC_{50} data in Table 2.14. However, a recent study indicated that increasing the cadmium concentration to 5 mg/L caused inhibition of 33% for carbonaceous BOD removal, 61% for denitrification, 76% for anaerobic release of phosphorus, 64% for anoxic uptake of P, and 90% for aerobic uptake of P (Tsai et al., 2006).

Table 2.14. Comparison of EC_{50} Values for Four Metals versus Inhibitory Concentrations from an Earlier Literature Review[a]

Metal	EC_{50}, mg/L		Inhibitory Conc, mg/L
	Bioluminescence	**SOUR**	
Cadmium	15	39	1–10
Copper	63	15	1
Nickel	>100	76	1–2.5
Zinc	16–19	41–58	0.3–5

[a]Results from two recent studies (EC_{50} and SOUR data from Lajoie et al., 2003 and EC_{50} data from Kelley et al., 2004) were compared with those of an earlier study (inhibitory concentrations reported by Anthony and Breimhurst, 1981).

The inhibition of metals specifically on nitrification can be stronger than on conventional activated sludge. As an example, the toxicity limits given in Table 2.13 for arsenic and chromium (VI) for the activated sludge process (o.1 and 0.1 and 1 - 10 mg/L, respectively) were compared to those from a study of fixed film nitrification (Beg et al., 1982).

The nitrification rate was reduced by about 50% at arsenic and chromium concentrations of 50 mg/L and 292 mg/L, respectively. These inhibitory limits are much higher than those reported in Table 2.14 for activated sludge, even though this process is more resistant to inhibition than nitrification.

Fluoride inhibition of nitrification in a fixed film reactor has also been reported (Beg et al., 1982; Collins et al., 1988). Collins et al. (1988) reported about 50% inhibition at a fluoride concentration of 992 mg/L, and this agrees closely with the 1218 mg/L concentration reported by Beg et al. (1982) . Fluoride could be present in concentrates from some groundwaters that may be treated by NF or RO membranes (Mickley, 2000) and in concentrates from NF or RO membranes in satellite water reclamation plants, given that about 1 mg/L of fluoride is added in drinking water treatment. However, the fluoride concentrations would be far below the values that have been noted to cause inhibition to nitrification.

2.8.5 Partitioning to Biomass

The mass balance modeling approach (see *Mass Balance Model To Establish Discharge Limits* section) requires knowledge of the partitioning of constituents between water and biomass in order to determine the inhibition limit for the anaerobic digestion process and for land disposal of the digested biosolids (Anthony and Breimhurst, 1981). In addition, partitioning determines the concentration of constituents that pass through the activated sludge process and are discharged into the receiving water, thereby possibly contributing to effluent toxicity.

The partition coefficient for various solid phases of interest in wastewater treatment (activated sludge biomass, waste activated sludge, or stabilized biosolids) and water is most often expressed as:

$$K_d = \frac{C_{i,s}}{C_{i,w}} \qquad (2\text{-}18)$$

where $C_{i,s}$ is the concentration of component i in the solid phase in units of micrograms per kilogram, $C_{i,w}$ is the concentration of component i in the water phase, in units of micrograms per liter, and K_d is the partition coefficient, in units of liters per kilogram or, less typically, in liters per gram (Weber and DiGiano, 1996; Schwarzenbach et al., 2003). Equation 2-19 is a linear sorption isotherm relationship:

$$C_{i,s} = K_d C_{i,w} \qquad (2\text{-}19)$$

A mass balance accounts for equilibrium partitioning of component i in a flowthrough reactor, such as an activated sludge basin:

$$C_{i,in} Q - C_{i,out} Q = W K_d C_{i,out} Q \qquad (2\text{-}20)$$

where $C_{i,in}$ is the feed concentration, Q is the flow rate, $C_{i,out}$ is the exit concentration, and W is the biomass concentration. Thus, the exit concentration is given by:

$$C_{i,out} = \frac{C_{i,in}}{1 + W K_d} \qquad (2\text{-}21)$$

An alternative form of eq 2-20 gives the solid-phase concentration from the feed and exit concentrations, which may be used to calculate the accumulation of chemicals onto biomass or digester solids from water-phase measurements.

$$C_{i,s} = \frac{C_{i,in} - C_{i,out}}{W} \qquad (2\text{-}22)$$

Because of the experimental difficulty of measurement of K_d, correlations are often produced between K_d and more accessible data for the octanol/water partition coefficient:

$$K_{o/w} = \frac{C_{i,o}}{C_{i,w}} \qquad (2\text{-}23)$$

where $C_{i,o}$ and $C_{i,w}$ are the equilibrium concentrations of component i that exist when octanol and water are in contact. The *Handbook of Environmental Data on Organic Chemicals* (Verschueren, 1996) provides a Microsoft® Excel compendium of K_{ow} values and K_d values for soil, sediment, and biomass, wherein the concentrations of chemicals on the solid phase are expressed per unit weight of organic carbon present in these solids rather than per unit weight of the solids (Verschueren, 1996; Weber and DiGiano, 1996; Schwarzenbach et al., 2003). Other correlations have been produced between K_{ow} and water solubility to facilitate predictions of environmental partition coefficients for new chemicals of concern in broad classes (Chu and Chan, 2000; Schwarzenbach et al., 2003). Nevertheless, correlations must be applied cautiously, because the chemical compositions of solid and water phases differ at each wastewater treatment plant, and these affect the K_d value for any specific metal or organic chemical (Seth et al., 1999; Wei et al., 1999). Moreover, K_d values have been shown to increase with decreasing suspended solids concentrations in samples (Karvelas et al., 2003; Nguyen et al., 2005).

Log K_d values in units of liters per gram were taken from various sources for partitioning of metals to biomass in the activated sludge process and are listed in Table 2.15. The diversity among data sources indicates the differences in composition of solid and water phases and also in methods of determining the concentrations in each phase from environmental samples. Log K_d values reported for organic chemicals on the Priority Pollutant List when converted from units of liters per kilogram to liters per gram range from about −1 to 3 (Weber and DiGiano, 1996; Verschueren, 1996; Burkhard, 2000; Schwarzenbach et al., 2003). Those for metals given in most reports listed in Table 2.15 are toward the low end of this range.

The concern over partitioning of toxic organic chemicals to biomass resulted in a study by an EPA research laboratory in the 1980s which involved spiking 22 of the chemicals on the Priority Pollutant List into a pilot plant activated sludge system (Petrasek et al., 1983). Instead of K_d values, the total concentration of each organic chemical in the primary sludge and the waste activated sludge (in milligrams per liter) was reported. Nevertheless, weak positive correlations were still determined between this measure of the solid-phase concentration and log K_{ow} values. In the decades following this study, research has led to a theoretical basis for a linear correlation between log K_d and log K_{ow} for organic chemical partitioning, and explanations have been offered for variations in these correlations among different solid phases (Verschueren, 1996; Seth et al., 1999; Burkhard, 2000).

K_d values of nine organic chemicals on the Priority Pollutant List were determined for primary sludge, activated sludge biomass, and digested sludge in a follow-up EPA research laboratory study (Dobbs et al., 1989). A good linear correlation was developed between log

K_d and log K_{ow}. The log K_d (in liters per gram) ranged from 2 for methylene chloride to 4.4 for dieldrin. The differences in K_d among the three solids were not substantial.

More contemporary research on organic partitioning in activated sludge has focused on the emerging chemical contaminants of concern. In particular, partitioning coefficients have been reported for estrogens, EDCs, and PhACs (Urase and Kikuta, 2005). A study of partitioning of 15 estrogens, EDCs, and PhACs between activated sludge biomass and water gave log K_d (in liters per gram) values that ranged from −2 to 0.25. A reasonably strong positive linear relationship was found between log K_d and log K_{ow}.

Table 2.15. Partitioning Coefficients for Heavy Metals on Activated Sludge

Metal	Log K_d, L/g	Reference
Copper	0.2–3.0[a]	Karvelas et al. (2003)
	0.54	Kelly et al. (2004)
	1.14	Parker et al. (1994a)
	1.25	Petrasek and Kugelman (1983)
	0.85	Nelson et al. (1981)
Lead	0.8–3.8[a]	Karvelas et al. (2003)
	1.3	Petrasek and Kugelman (1983)
Zinc	1.0–3.2[a]	Karvelas et al. (2003)
	−0.5	Kelly et al. (2004)
	0.79	Parker et al. (1994a)
	0.8	Petrasek and Kugelman (1983)
	0.04	Nelson et al. (1981)
Cadmium	0.5–4.0[a]	Karvelas et al. (2003)
	0.23	Kelly et al. (2004)
	1.3	Parker et al. (1994a)
	0.24	Petrasek and Kugelman (1983)
	0.33	Nelson et al. (1981)
Nickel	−0.59 to −1.84[a]	Karvelas et al. (2003)
	−0.60 to +0.64	Arican et al. (2002)
	−1	Kelly et al. (2004)
	0.59	Parker et al. (1994a)
	0.59	Petrasek and Kugelman (1983)
Chromium	0.2–3.5[a]	Karvelas et al. (2003)
	0.86	Petrasek and Kugelman (1983)
Arsenic	0.2	Petrasek and Kugelman (1983)

[a] K_d increases with a decreasing solids concentration.

The log K_d values are either below or toward the lower the end of those for chemicals on the Priority Pollutant List. While biodegradation accounted for some of the loss of the emerging contaminants from the water phase, partitioning to the biomass was more important. In contrast to this finding, a field study of estrogen fate in a WWTP indicated significant biodegradation in the nitrifying and denitrifying tanks while also indicating a strong role for partitioning (Holbrook et al., 2002; Andersen et al., 2003).

2.8.6 Inhibition of Anaerobic Digestion

A literature search of toxicity to anaerobic digestion by chemicals on EPA's Priority Pollutant List was conducted very early in the Federal program to establish pretreatment standards for industries (Anthony and Breimhurst, 1981). The threshold inhibitory concentrations of metals and organic chemicals from this early attempt are listed in Table 2.16. Much has been

reported since the early 1980s on alternative toxicity tests (Madsen and Rasmussen, 1996; Codina et al., 1998). The results of these tests indicate that EC_{50} values can vary widely, depending upon the assessment method.

Heavy metals have been implicated as a more likely cause of inhibition of anaerobic digestion than organic chemicals. In fact, anaerobic digestion has frequently been reported to be an effective process for biodegradation of toxic chemicals (Parker et al., 1994b). The EC_{50} based on methanogenic activity in sludges taken from operating digesters was 125 mg/L for cadmium, 50 mg/L for copper, 50 mg/L for zinc, 50 mg/L for chromium(VI), and 250 mg/L for nickel (Codina et al., 1998); lower EC_{50} values were obtained with the Microtox test (41, 0.6, 15, 48, and 171 mg/L, respectively). Codina et al. (1998) stated that their values agreed with other reports, all of which were published later than those listed in Table 2.16. In broad categories, the highest toxicities were observed for copper, chromium, and zinc, intermediate toxicity was seen for cadmium and nickel, and the lowest toxicity was for lead.

As indicated in Table 2.16, the toxicity of cadmium(III) is considerably lower than that for cadmium(VI). In a later study, the EC_{50} of chromium(III) to anaerobic digestion was 1140 mg/L (Alkan et al., 1996) for steady feed and 500 mg/L for shock loading, which is 10 to 20 times higher than the 50-mg/L value for chromium(VI) (Codina et al., 1998) when introduced in a shock load.

Table 2.16. Inhibition of Anaerobic Digestion by Selected Metals and Organic Chemicals on the EPA Priority Pollutant List[a]

Chemical	Threshold Inhibitory Conc, mg/L
Metals	
Arsenic	1.6 (soluble)
Cadmium	0.02 (soluble), <20 (total)
Chromium(VI)	5–50 (soluble), 110 (total)
Chromium(III)	50–500 (soluble), 130 (total)
Copper	1–10 (soluble), 40 (total)
Lead	340 (total)
Mercury	13–65 (soluble)
Nickel	10 (total)
Zinc	400 (total)
Organic Chemicals	
Acrylonitrile	5
Benzidene	5
Carbon tetrachloride	10–20
Chloroform	10–16
	48
Hexachlorocyclohexane	
Pentachlorophenol	0.4
Trichloroethylene	20

[a]Based on data reported by Anthony and Breimhurst (1981).

The toxicity of 24 organic chemicals on the Priority Pollutant List to anaerobic digestion was reported only 2 years after the data summarized in Table 2.16 were originally published (Johnson and Young, 1983). Only 7 of these 24 chemicals produced an EC_{50} (based on 50% reduction in gas production) at concentrations of 100 mg/L; all of the other values were much higher. Obviously, 100 mg/L is far higher than the concentrations typically found in municipal wastewater treatment. Moreover, the inhibitory effects were reversible, which

further lessened the concern about the treatability of these compounds. Partitioning decreases the aqueous-phase concentration, which in turn may explain why the EC_{50} values were very high.

Some organic chemicals have been found to be inhibitory at concentrations lower than 100 mg/L. This has led to development of methods for screening the potential toxicity of organic chemicals (Madsen and Rasmussen, 1996). Gas production has been shown to be reduced by surfactants; for example, the EC_{50} values for the two surfactants alkyl dimethylbenzylammonium chloride and sodium alkyl ether sulfate were 6.7 mg/L and 11 mg/L, respectively. These concentrations are still much higher than expected in municipal wastewater. The surfactants from chemicals used for cleaning membranes would be unlikely to be present at these concentrations.

Long ester chains of phthalic acid esters are less susceptible to biodegradation under anaerobic conditions and may even inhibit methanogenesis (Alatriste-Mondragon et al., 2003). Di(2-ethylhexyl) phthalate was sorbed onto the waste activated sludge fed to a bench-scale digester for a period of 12 weeks. Biodegradation of di-*n*-butyl phthalate, a short-chain ester, was inhibited, but the inhibition was completely reversed after di(2-ethylhexyl) phthalate addition was discontinued; gas production and other performance indicators were not impaired.

Chlorophenols and nitrophenols have been shown to inhibit sulfate-reducing bacteria and methanogenic reactions (Uberoi and Bhattacharya, 1997). The indicator of inhibition was the reduction in the rate of proprionate utilization by sulfate-reducing bacteria and the rate of acetate utilization by methanogens. The trichlorophenols and pentachlorophenol produced far greater toxicity than either di- or monochlorophenols; significant inhibition of degradation was found at 2 mg/L of trichlorophenol and 0.5 mg/L of pentachlorophenol

Sodium inhibition of methanogens may be a more relevant concern of concentrate discharge to wastewater collection systems than organic chemicals from wastewater reclamation or heavy metals from industrial reuse. In batch experiments, methanogenic activity as measured by methane gas production decreased by nearly 44% at an acclimation concentration of 12,000 mg/L (as Na), although the organics removal efficiency and methane production did not vary appreciably at different acclimation concentrations (Chen et al., 2003). Introduction of sodium at 2- to 3-week intervals of continuous operation of the flowthrough anaerobic reactor caused deterioration in methanogenic activity at 16,000 mg/L as Na. In another study (Feijoo et al., 1995), the sodium concentrations producing 50% inhibition ranged from 3000–16,000 mg/L, with the higher value obtained from the digesters that treated high-salinity wastewaters. Based on these data, a conservative estimate of the maximum allowable sodium concentration to prevent significant inhibition would be 2000 mg/L. The allowable fraction of concentrate in the flowthrough at a WWTP can be calculated using eq 2-17. Assuming that the maximal increment of sodium by domestic usage is about 100 mg/L, the sodium concentration in the finished water is about 10 mg/L, and the sodium in the concentrate stream is 4000 mg/L (about 500 mg/L in the raw water). The fractional contribution of the concentrate stream to the total wastewater flow is:

$$\frac{Q_c}{Q_T} = \frac{C_{Max}}{\left[C_c - C_{ww} \right] + C_{ww}} = \frac{2,000}{(5,000 - 110) + 110} = 0.5$$

$$(2\text{-}24)$$

2.8.7 Effluent Toxicity

WET testing is a common requirement in NPDES discharge permits of municipal wastewater facilities that discharge effluent to surface water and also in the setting of pretreatment standards. For concentrate, the limiting concentration value (the 50% lethal concentration, or LC_{50}) is typically determined by an acute toxicity test based on the percentage of dilution that results in 50% lethality (Mickley, 2000). A variety of ecotoxicity tests are available that use algae, invertebrates, and vertebrates as test organisms (Burgess et al., 2000). Chronic toxicity tests are used to measure the impairment in the ability of the test organism to reproduce, and results are reported as no observable effect levels (NOELs) and lowest observable effect levels (Bervoets et al., 1996). Failure to meet the WET triggers a toxicity identification evaluation to pinpoint the specific agent responsible for the failure to meet the permit limit (U.S. EPA Office of Wastewater Management, 1999; Mickley, 2000). Toxicity data for lethality or reproductive impairment of specific aquatic organisms as well as surrogate tests, such as reduction in bioluminescence (e.g., the Microtox assay), are abundant in the published literature (Ren and Frymier, 2003). The duration for measuring the lethality response and the type of test organism used can vary widely. Prediction of the toxic response from a chemical structure is also important, because of concern over the production of new organic chemicals. For example, the log K_{ow} value and the molecular connectivity index have been used in QSAR modeling to develop a linear correlation with acute toxicity data (Wei et al., 1999).

The wide ranges of LC_{50} and NOEL values of specific heavy metals as determined in acute and chronic testing with aquatic organisms are presented in Table 2.17 (Bervoets et al., 1996). Conditions such as pH, temperature, and water hardness can affect the values. For comparison, the toxicity test results for calcium chloride in the discharge of an industrial waste versus that from a river system are also included. While the concentrations of $CaCl_2$ that produce a toxic effect are several orders of magnitude higher than those of heavy metals, they may still be of concern (especially the NOEL), depending on the percentage of concentrate in the discharge.

Table 2.17. Ranges of Aquatic Toxicities for Three Heavy Metals and Calcium Chloride[a]

Endpoint	Cd, µg/L	Zn, µg/L	Pb, µg/L	$CaCl_2$, g/L
LC_{50} (24 h)	0.9–5,300	6713[b]		1.84–3.53
LC_{50} (48 h)	3.6–1,1880	68–799	450–4,440	0.46–3.01
NOEL	0.3–1.0	74[b]		0.47[b]

[a]As reported by Bervoets et al. (1996).
[b]Only one value was reported.

The failure of some concentrates from groundwater treatment to meet the WET test in Florida led to an investigation of the major ion toxicity principle (Mickley, 2000). This principle was of concern because of discharge of concentrate to saltwater environments. However, it may also be important for discharge to fresh water environments, although no reports are available. In simple terms, a water that contains the ionic species in the same proportion as seawater, regardless of the salinity level, is said to be balanced for aquatic life. Aquatic toxicity can occur at low TDS concentrations when ions are not balanced, i.e., not present in the same proportion as in seawater. The term adopted to describe this situation is "major ion toxicity." Mickley (2000) identified the 10 most common seawater ions in order of

descending weight fraction as Cl^-, Na^+, SO_4^{2-}, Mg^{2+}, Ca^{2+}, K^+, HCO_3^-, Br^-, $B_4O_7^-$, and Sr^{2+}. Fluoride (F^-) is not considered a major ion. Major ion toxicity was implicated in nine concentrates from groundwater treatment in Florida. The imbalance in several concentrates was attributable to Ca^{2+}, and it likely contributed to the toxicity of other concentrates. Fluoride was the major imbalanced ion in two concentrates and likely contributed to toxicity in two others. The F^- concentration in Florida groundwater is not as high as in several other states: it is estimated to exceed 1 mg/L in 12% of Florida groundwaters and in about the same percentage in Texas, whereas it exceeds 1 mg/L in 26% of Illinois and 36% of Arizona groundwaters. Thus, major ion toxicity by fluoride could be important in other areas of the country.

A summary of literature values for the LC_{50}s of selected heavy metals, mostly from 96-h exposure studies, is presented in Table 2.18 and shows the variability that was noted earlier. For instance, the report by Kwok and Leung (2005) showed that toxicity decreases with increasing salinity and increases with rising temperature.

Table 2.18. Aquatic Toxicity Data[a] from Various Sources for Heavy Metals

Metal	96-h LC_{50} (unless noted otherwise)	Reference
Copper	0.025–1.8[b]	Kwok and Leung (2005)
	0.074[c]	Arambasic et al. (1995)
Lead	55.5[c]	Arambasic et al. (1995)
	0.450–4.4[c]	Bervoets et al. (1996)
Zinc	0.74[c]	Arambasic et al. (1995)
	6.7[d]	Bervoets et al. (1996)
	1.35[d]	Wu and Chen (2004)
Chromium (+6)	1.0–3.95	Murphy (1981)
	0.29[c]	Diamantino et al. (2000)
	0.34–0.77[c]	Mount and Hockett (2000)
Arsenic	0.011–0.0275	Forget et al. (1998)
Cadmium	0.0036–1.88[c]	Bervoets et al. (1996)
	0.017–0.048	Forget et al. (1998)
	1.07[e]	Wu and Chen (2004)
Nickel	3.62[f]	Herkovits et al. (2000)
Molybdenum	>2000[g]	Reid (2002)
	2848[c]	Diamantino et al. (2000)
Tributyltin	0.00015–0.031[b]	Kwok and Leung (2005)

[a]*Daphnia* was used as the test organism, unless otherwise indicated.
[b]Intertidal copepod (*Tigiopus* sp.); toxicity decreases with salinity and increases with temperature.
[c]48-h LC_{50}.
[d]24-h LC_{50}.
[e]White shrimp.
[f]*Bufo arenarum* embryos.

[g]Juvenile Kokanee salmon.

A few examples of aquatic toxicity for specific organic chemicals that are not on EPA's Priority Pollutant List are presented in Table 2.19. The pesticides and herbicides in this table have LC_{50} values in the same range as those of several of the heavy metals listed in Table 2.18.

The Clean Water Act includes water quality criteria for priority pollutants in the form of criteria for maximum and continuous concentrations for each chemical to protect fresh water, saltwater and human health [the EPA 305(a) Criteria for Priority Toxic Pollutants] that are in part based on aquatic toxicity measurements, such as those listed in Table 2.19. A future list of chemicals could possibly contain some of today's emerging chemicals of concern. For example, LC_{50} values are not available for PhACs in wastewater effluents. However, new sensitive biochemical measures of cellular activity suggest that oxidative stress increases in aquatic biota exposed to PhACs, because the enzyme systems are not equipped to metabolize these chemicals completely (Gagne et al., 2006).

Table 2.19. Examples of Aquatic Toxicity Data for Organic Chemicals

Organic chemical	LC_{50}, mg/L	Reference
Phenol	9.4	Arambasic et al. (1995)
Atrazine	0.121–0.153[a]	Forget et al. (1998)
	9.9–11.7[b]	Phyu et al. (2005)
Carbofuran	0.017–0.059[a]	Forget et al. (1998)
Dichlorvos	0.0092–0.046[a]	Forget et al. (1998)
Malathion	0.011–0.028[a]	Forget et al. (1998)
Metsulfuron	0.62[c]	Wei et al. (1999)
Chlorsulfuron	0.41[c]	Wei et al. (1999)
Bensulfuron methyl	0.17[c]	Wei et al. (1999)

[a]*Tigriopus brevicornis.*
[b]Freshwater shrimp (*P. australiensis*).
[c]*Chlorella pyrenoidsosa*; LC_{50}s of degradation products are 1–2 orders of magnitude higher.

The aquatic toxicity data presented in this section cannot be used alone for trying to understand the impact of concentrate discharge to wastewater collection systems. As noted in the section Mass Balance Model To Establish Discharge Limits, a method is needed to account for attenuation and partitioning within the WWTP as the fractional contribution of concentrate to the wastewater flow, in order to set discharge limits. Each type of concentrate, backwash water, and chemical cleaning solution will have unique chemical characteristics that will further define local limits.

2.9   SUMMARY

This literature review covers a wide range of topics relevant to the discharge of concentrate to wastewater collection systems. Data specific to concentrates in wastewater that can be used to show cause and effect relationships for corrosion, toxicity to the activated sludge process and anaerobic digestion, decreased biomass settling, partitioning, and aquatic toxicity are mostly lacking. Data that are available, for example, for toxicity both within the treatment processes and in receiving waters have not been obtained directly from field sites where concentrate is discharged to wastewater collection systems. Relatively few concentrate streams are currently discharged to wastewater collection systems, and documentation for any negative effects is only beginning to be assembled. While the specifics are not available, this literature review

should provide guiding principles to address each possible concern. Other issues may arise as well. For example, the concentrate from highly brackish water could produce a density current that would cause short-circuiting through the WWTP, yet no data were found regarding this effect. Mass balance modeling will be important to understanding the complex pathways by which components of concentrates travel from the headworks of a WWTP to either the biosolids or the treated water.

CHAPTER 3

UTILITY SURVEYS

3.1 SURVEY DEVELOPMENT AND APPROACH

The project team developed two surveys: one for wastewater utilities that receive flow containing membrane residuals, and the other targeting potable water utilities that discharge membrane residuals to wastewater systems. The Internet-based SurveyMonkey (www.SurveyMonkey.com) was used as the survey instrument. Survey questions were developed by the Project Team, with incorporated feedback from the Project Advisory Committee and partner utilities. Hard copies of the survey are included in Appendix B for wastewater utilities and in Appendix C for water utilities. Figure 3.1 illustrates the SurveyMonkey.com home page that facilitated the survey.
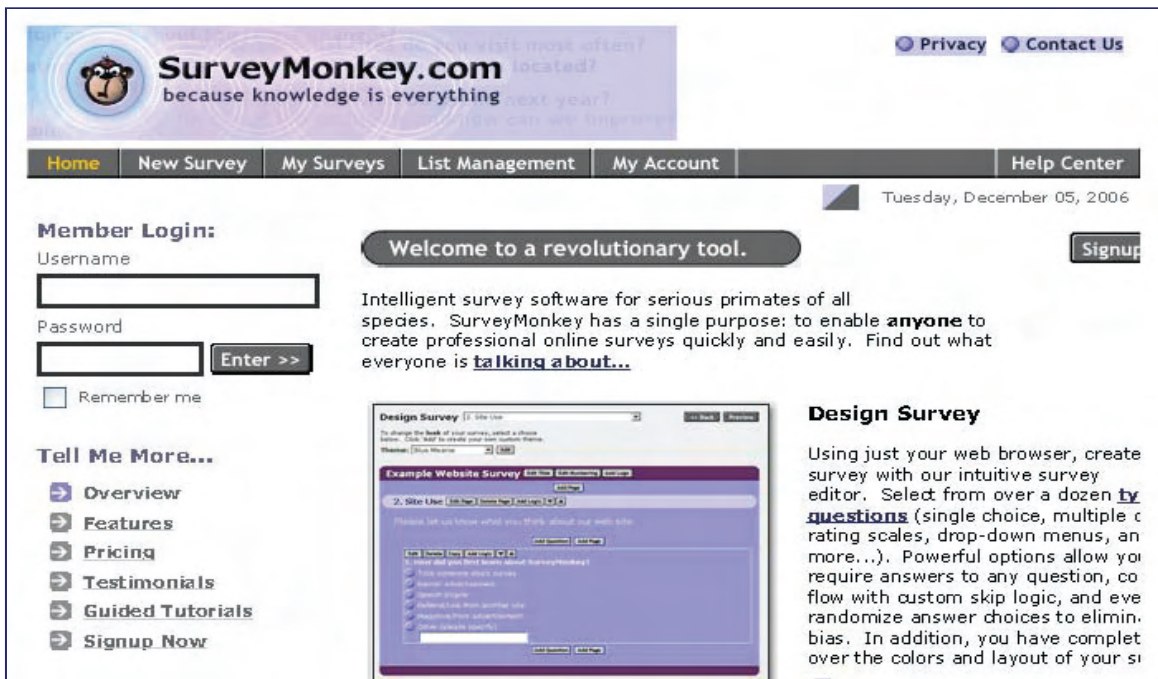
Figure 3.1. SurveyMonkey.com home page.

The objectives of the surveys were to learn the following from participating utilities:

1. Their experience with disposal of membrane residuals
2. Problems (with residuals disposal, planning, or otherwise) experienced with these discharges and approaches taken to handle them
3. Control procedures in place, or suggested, for dealing with disposal of membrane residuals
4. Suggestions for future research

Survey participants were recruited using information found in two databases: one provided by the WateReuse Foundation from its project "National Database of Water Reuse Facilities" and the other a listing of membrane installations that was provided by US Filter. Recruiting was done via e-mailed letters. Letters were sent to individuals for whom e-mail addresses were listed in the databases and to those whose e-mail addresses could be procured after a brief Google search or telephone call. (Early in the process, it was determined that phone calls were approximately twice as efficient as Google searches in producing up-to-date e-mail addresses. Telephone calling produced an average of 10 e-mail addresses per hour, while Google searches averaged 5.)

A total of 496 letters were e-mailed: 251 letters from contacts in the WateReuse database and 245 e-mail letters to addresses from both the US Filter and the WateReuse databases.

3.2   WASTEWATER UTILITIES SURVEY

The wastewater utilities survey addressed four sources of membrane residuals:

1. Treatment at a wastewater utility (as a component of tertiary treatment, for example)
2. Biological treatment producing residuals discharge to a wastewater system (i.e., satellite systems)
3. Potable water treatment systems
4. Membrane uses categorized by industry (with a focus on Significant Industrial Users discharging membrane residuals at flow rates above 25,000 gpd)

Characteristics of the respondents are summarized in Table 3.1. Thirty responders accessed the wastewater utility survey on the Internet. Some, however, made only a cursory examination of the survey, without answering questions; 19 participants actually completed the survey.

Table 3.1. Basic Characteristics of Respondents and Their Facilities from the Wastewater Utility Survey

Characteristic	Result
No. of individuals accessing the survey	30
No. of actual respondents	19
No. with pretreatment experience	11
No. who had worked on membrane residuals discharges	5
Reported plant flow rates (mgd)	
<0.5	1
1–5	5
6–10	4
11–20	5
21–100	2
>100	1

Preliminary questions regarding survey respondents' experience shed light on the extent to which the appropriate population was reached. Seventeen of the 19 respondents had more than 10 years of experience with wastewater treatment; the remaining 2 had at least 2 years. Regarding direct experience with pretreatment issues and use ordinances and permitting, 12 had more than 3 years and 7 had less than 1 year of experience. Five respondents had direct experience with membrane discharges.
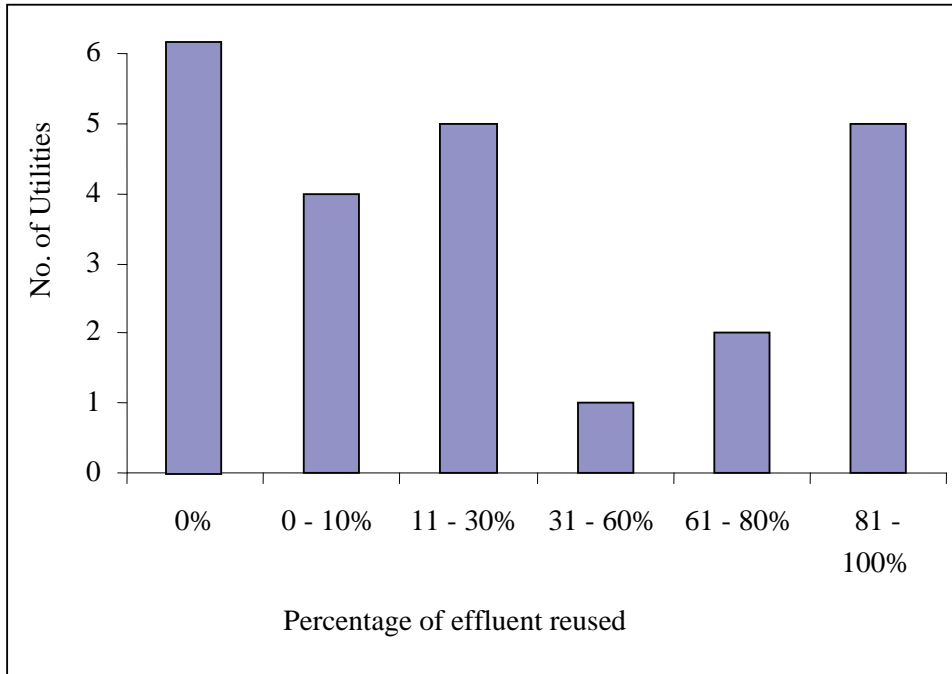
Figure 3.2. Utilities reporting effluent reuse.

The extent of wastewater reuse by responding utilities is shown in Figure 3.2, and the breakdown of use categories is shown in Figure 3.3. Most of the reporting utilities utilize the reclaimed water for irrigation. Each of the survey respondents gave one of the following answers in the "other" category:

- Indirect potable reuse
- Constructed wetlands
- Saltwater barrier
- Irrigation of farm crops
- ASR storage, reuse only
- Toilet-flushing water
- Fire suppression, dust control, vehicle washing, street and sidewalk washing
- Fire protection
- Geyser steam field injection
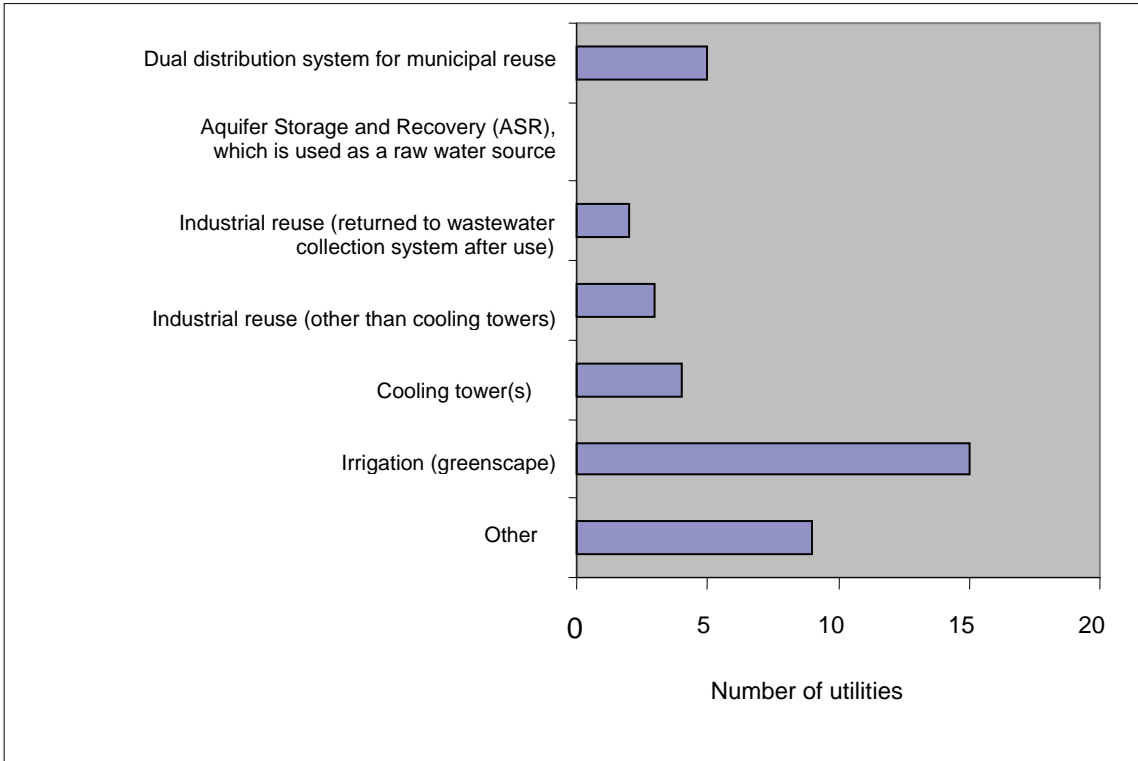
Figure 3.3. Reuse categories reported.

3.2.1   Treatment at a Wastewater Plant

Five survey respondents reported treating municipal wastewater using membranes of the types shown in Figure 3.4. While Figure 3.4 shows eight responses, survey results indicate 10 membrane systems being used by five respondents (some utilities have more than one system that uses a given type of membrane). The flow rates for these 10 systems are listed in Table 3.2. While the survey was not structured for delineating treatment trains, it is certain that some reporting utilities use membranes in series (e.g., UF followed by RO).
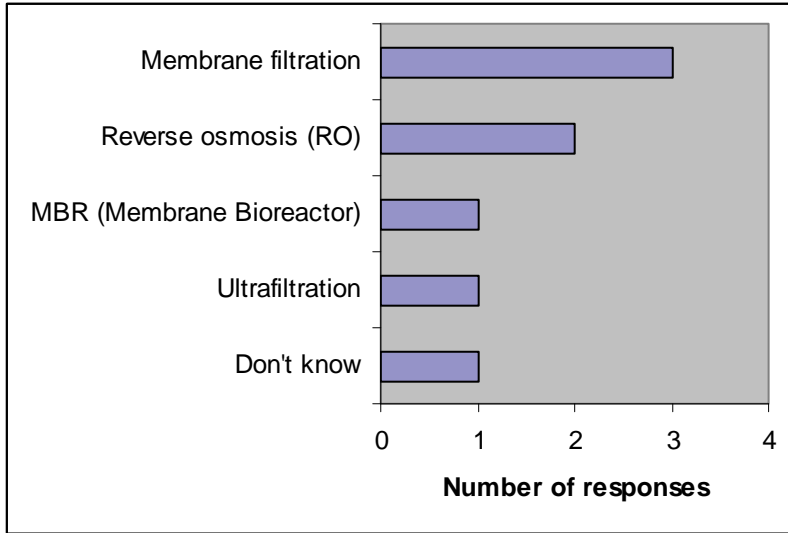
Figure 3.4. Types of membranes used by five reporting wastewater utilities.

Table 3.2. Flow Rates for the 10 Membrane Systems

Flow rate range, mgd	No. of systems in the range
<0.5	4
0.5–1	1
1–3	4
7–10	1

One goal of the survey was to identify the methods used by wastewater utilities to evaluate the acceptability of membrane residuals discharged to their systems. The survey questions addressing this issue and the responses are presented in Figure 3.5.
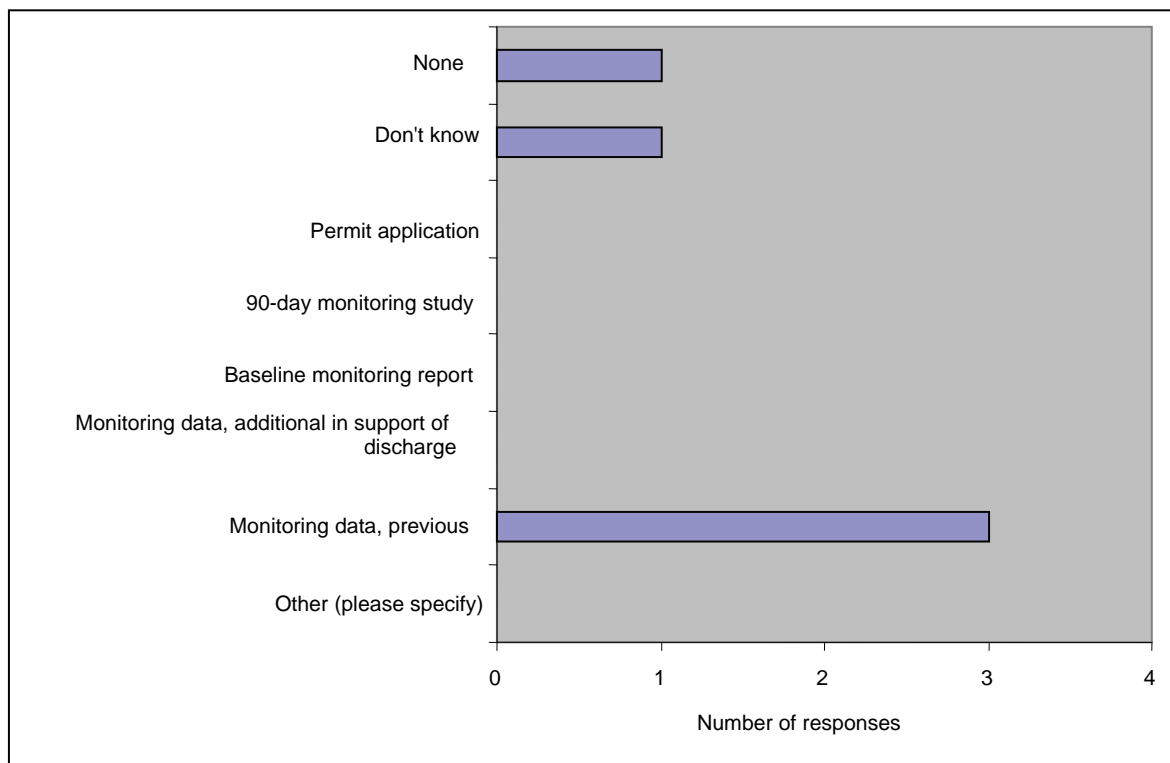
Figure 3.5. Methods of evaluating acceptability of membrane residuals by wastewater utilities.

Although the number of results is limited, the data in Figure 3.5 suggest that many utilities evaluate information from other membrane installations treating municipal wastewater.

The responses shown in Figure 3.5, and other survey questions presenting options, were considered very useful by both the utility personnel reviewing the survey and those taking the survey. Many wastewater utilities have doubts about the advisability of accepting membrane residuals, because of lack of experience and unfamiliarity with the methods of evaluating them. These queries point to approaches that they can add to their evaluation and regulatory arsenals.

Three of the five wastewater utilities indicated that they have no parameters for monitoring the discharges of membrane residuals produced by treating their municipal wastewater. One utility that uses MF (as part of an MBR), UF, and RO membranes indicated using data on TDS, pH, and fecal and total coliforms for this purpose. Although the survey was not structured for determining which parameters apply to each type of membrane, it can be inferred that monitoring these constituents applies to a system that employs UF followed by RO. Another utility reported regulation of membrane residuals pertaining to "polymers" as well as turbidity and TSS.

The survey included the following listing of potential adverse impacts from discharge of membrane residuals:

- None known
- POTW effluent quality problems

- POTW effluent toxicity problems
- Salt impacts to the collection system and pumping stations (e.g., corrosion)
- Density impacts due to mixing high-TDS discharges with wastewater
- Salt impacts on treatment plant equipment (e.g., corrosion)
- Uptake of salts by biomass
- Inhibition of biomass flocculation and settling
- Formation of disinfection by-products during wastewater disinfection
- Metals buildup in biosolids, impacting beneficial reuse
- Salt buildup in residuals, impacting beneficial reuse (e.g., salt toxicity to plants)
- Increase in wastewater treatment costs
- Reduced ability to reuse treated effluent
- Other (please specify)

When presented with this list of potential problems, three wastewater utilities indicated no known problems. The utility referred to above (which utilizes RO, UF, and MBR systems) reported problems with inhibition of flocculation and settling of biomass and stated that "return flows overwork membranes." Another utility which utilizes MF and RO systems indicated a problem with "restriction on polymer use at the POTW" resulting from membrane residuals. One utility indicated that membrane return flows were reducing the capacity of some plant processes (presumably by increasing the hydraulic loading) when they evaluated membrane projects. Thus, while chemical constituents are an important factor, the effects on hydraulic loads must also be considered.

Four of the five responding utilities indicated no problems with corrosion in the collection system resulting from discharges of membrane residuals. The fifth utility did not respond to this question.

All five reporting wastewater utilities indicated they use cleaning solutions which include caustic, citric acid, Memclean, high-pressure reuse water, sulfuric acid, and sodium hypochlorite. Four of the five utilities reported that they discharge cleaning solutions back to the wastewater plant. Two utilities indicated that the discharge of these residuals is regulated in some manner, but they did not indicate how. The fifth reported that its membrane cleaning solutions are treated and retained on-site but did not indicate the final disposal method.

3.2.2 Other Wastewater Facilities Discharging Membrane Residuals to the Systems Surveyed

None of the 14 responding utilities indicated receiving membrane residuals from other wastewater treatment facilities, including satellite MBR systems.

3.2.3 Wastewater Utilities Receiving Membrane Discharges from Potable Water Utilities

Six wastewater utilities reported receiving membrane residuals from potable water plants, three of which are public and three which are private utilities. The types of membranes used are listed in Figure 3.6.

Three respondents reported that the membrane systems are used to treat brackish groundwater; one indicated treating reclaimed water, and the remaining two utilities reported data which could not be interpreted.

Most potable water production facilities in this category are relatively small, but their number is greater than those in other survey categories. Between 23 and 27 facilities discharging membrane residuals from potable water production treat less than 0.5 mgd. One utility reported two facilities treating 0.5–1.0 mgd; another reported having one facility treating 3–5 mgd and plants treating between 10–50 mgd.
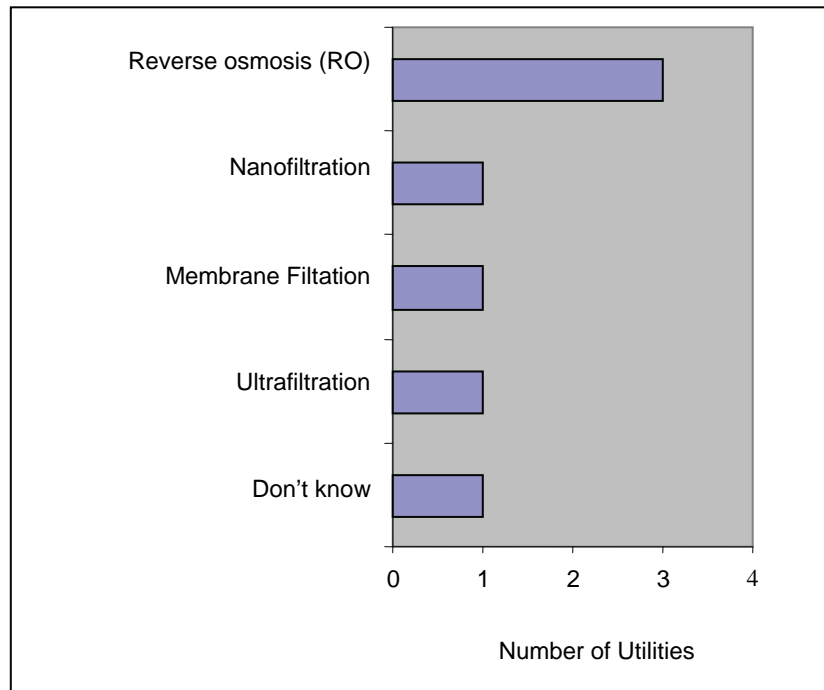
Figure 3.6. Membrane use for potable water production reported by wastewater utilities accepting residuals.

Five of the six wastewater utilities in this category reported assessing the acceptability of membrane discharges from potable water production using the methods summarized in Figure 3.7. Five utilities reported requiring discharge permits (although only four noted that they required actual permit applications). One utility reported having given written authorization for a discharge of this type.
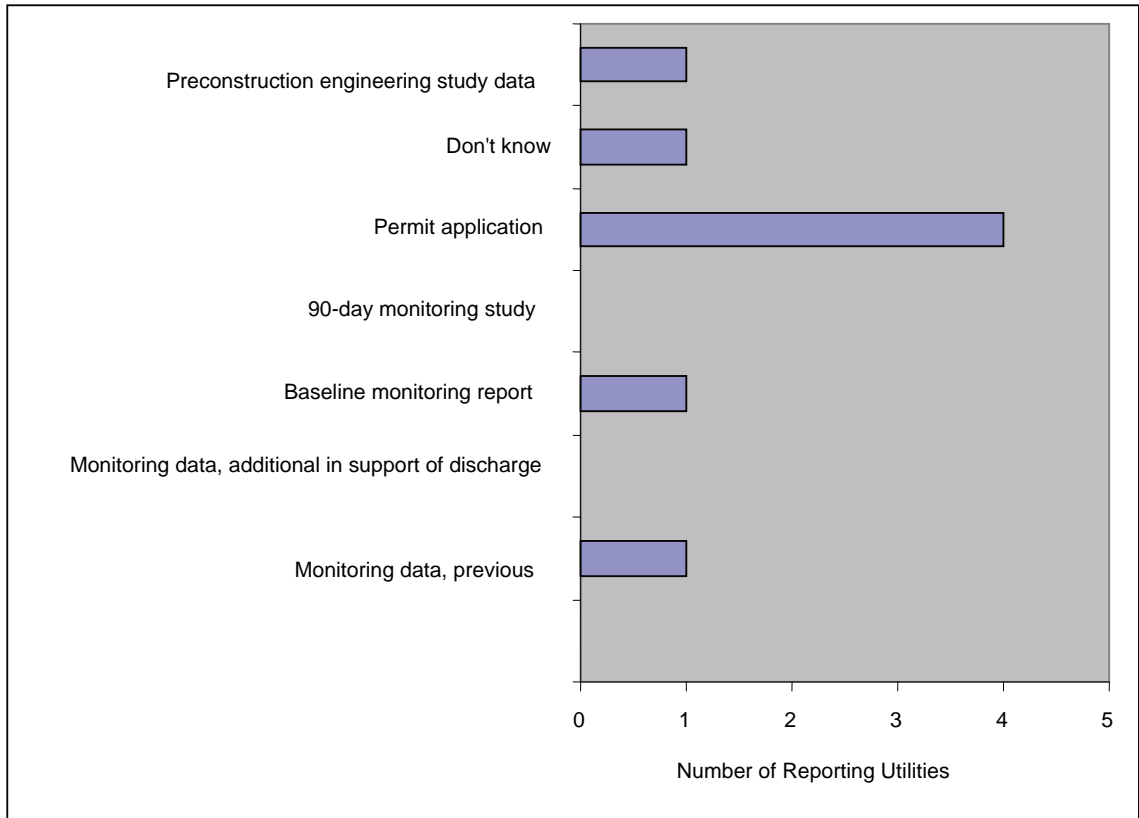
Figure 3.7. Methods of evaluating membrane residuals from potable water production.

Three utilities reported they impose the following terms and conditions in their arrangements with potable water facilities:

1. "Meet all source control limits for water quality."
2. "A standard Industrial Waste Discharge permit is issued which includes the Local Limits requirement."
3. "Comply with local limits; continuous monitoring for: flow, pH, and temperature, with set points for alarms. Monthly sampling, and monitor conductivity, TDS, and chlorides. Lift station and valving so that the discharge can be directed between two POTWs."

Participating utilities imposed the conditions for accepting the membrane residuals at the frequencies shown in Figure 3.8.
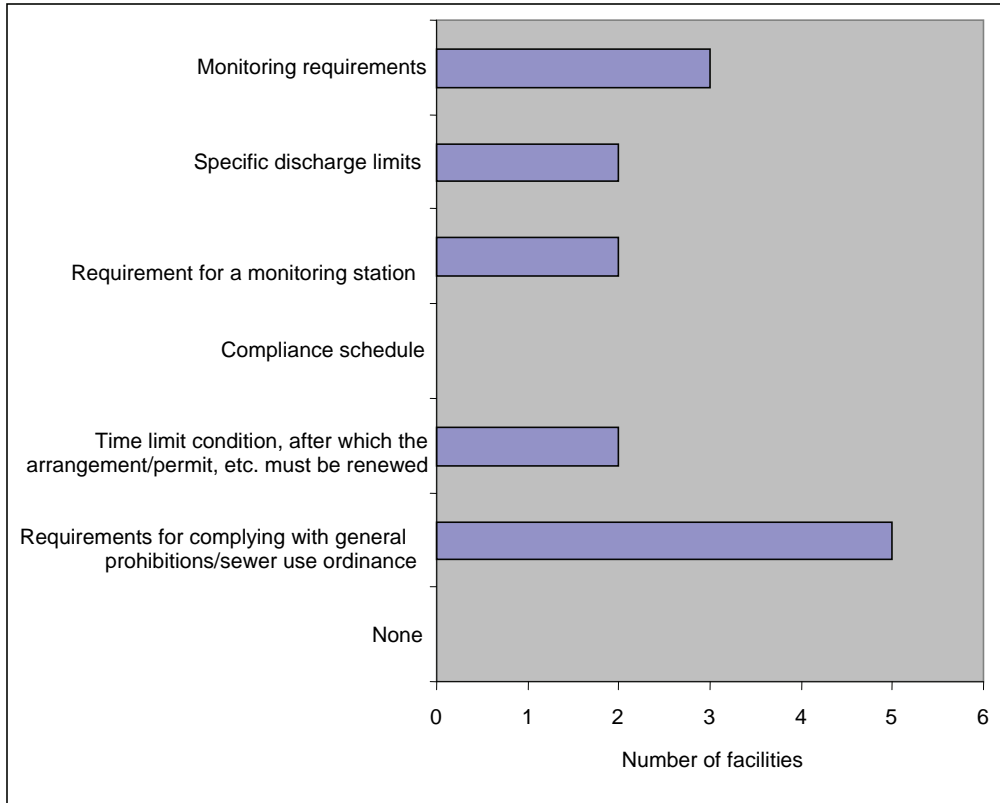
Figure 3.8. Conditions for accepting membrane residuals from potable water facilities.

Two utilities specifically regulate TDS in the membrane discharges, four regulate pH and heavy metals (the specific metals were not noted), and one utility regulates anions as a condition of accepting the discharge.

Negative impacts of membrane residuals on their wastewater systems, as reported by these utilities, are indicated in Figure 3.9. One utility reported problems with corrosion of submerged carbon steel surfaces in the collection system near the point of discharge.
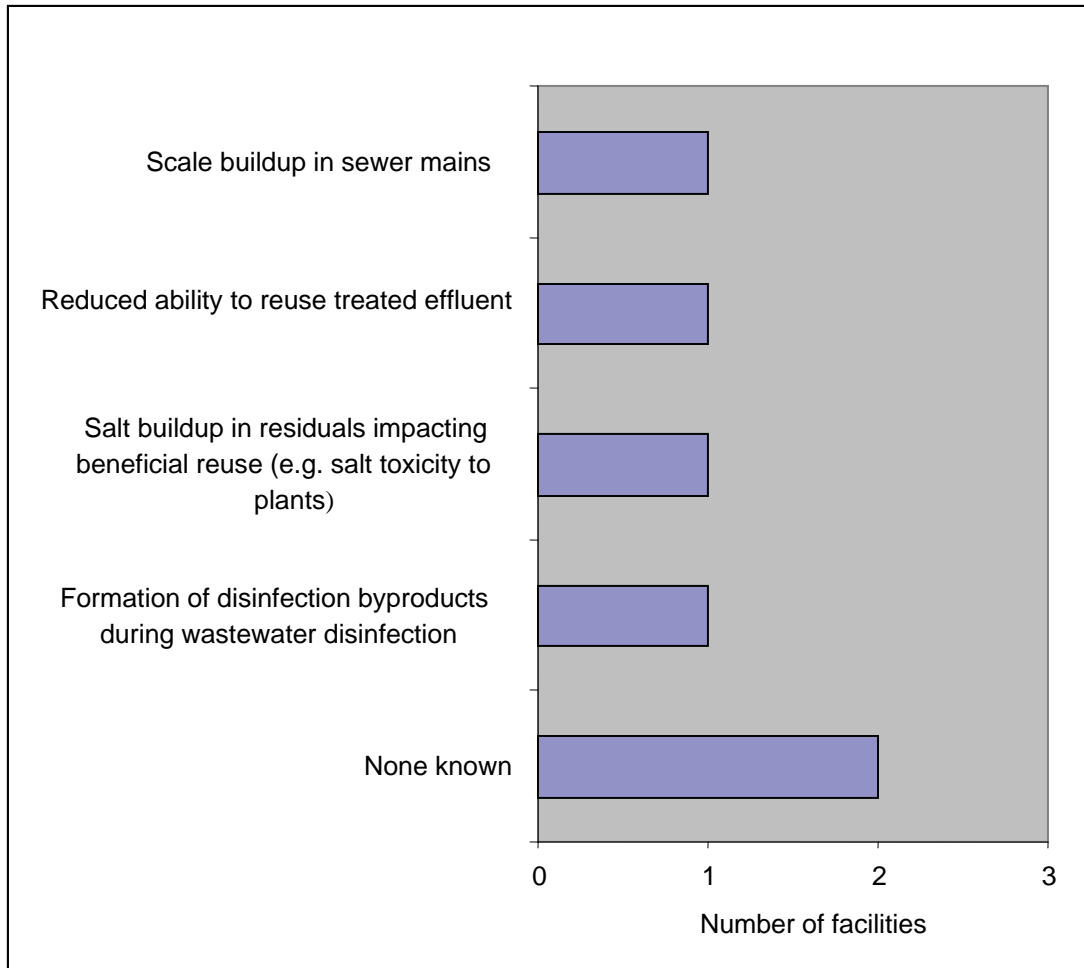
Figure 3.9. Negative impacts of membrane residuals from potable water facilities as reported by four wastewater utilities.

Three of the four reporting utilities regulate discharge of the membrane-cleaning residuals through a permitting or authorization process. The fourth indicated the cleaning solutions are disposed of by deep well injection. The cleaning solutions include caustic, hydrochloric (muriatic) acid, sulfuric acid, sodium hypochlorite, and proprietary products.

3.2.4   Industry Sources of Membrane Residuals

This survey component was confined to discharges greater than 20,000 gpd; however, discharges less than 20,000 gpd can also be important. For example, home water treatment systems that discharge ion exchange regenerant or reject from RO treatment can be problematic if there are a large number of home installations.

Only two wastewater utilities indicated receiving membrane residuals from industry at flow rates greater than 20,000 gpd. One of these utilities receives membrane residuals from 10 or 11 membrane systems (the exact number was not reported), all treating less than 0.5 mgd. These residuals result from "industrial reuse"; survey data indicate the use of more than one membrane system at some industry sites. The other utility receives membrane residuals from four to five electronics firms (wafer fabrication), all treating less than 0.5 mgd, as well as from two power plants treating 0.5–1 mgd.

Known types of membranes employed by these industries include UF and RO; some types were not known. These membranes are used to treat municipal water, for in-plant reuse in one case and reclaimed water in another. The survey was not structured to determine exactly which membrane systems are used for treating a particular input water. It can be inferred from the results that RO is used for treating municipal water for the wafer fabrication facility noted above.

In all cases, a permit application was required for allowing these industrial discharges. All discharge permits issued stipulated the need for compliance with local wastewater collection system use ordinances. Both utilities reported pH and metals as being regulated for some membrane discharges; one utility also regulated "micropollutants," and the other regulated "toxic organics".

The sole problem reported for these discharges was related to color from a red dye. Regarding cleaning solutions, one utility indicated that these are in use but gave no information about their types or disposal methods.

3.3   WATER UTILITIES SURVEY

3.3.1   Survey Results

Demographic information indicates that respondents have excellent utility-operating experience. However, while 12 potential respondents accessed the water utilities survey on the Internet, only 8 of them actually began the survey. Four of these participants had more than 10 years of experience, the other four had between 3 and 10 years. Seven had at least 3 years of involvement with pretreatment, and six had worked directly on discharging membrane residuals to wastewater systems. Five respondents reported participation in membrane pilot studies, and one held the position of water plant operator.

Six of the eight respondents who began the survey continued after entering this demographic information. However, two of these six were employed at the same large utility, and review of the results confirmed that they had provided duplicate information. Hence, the information from a total of only five utilities was useful.

The water production capacities of the five utilities completing the survey are indicated in Figure 3.10. Raw water sources are river or stream (two utilities), natural lake (two utilities), and secondary effluent (one utility).
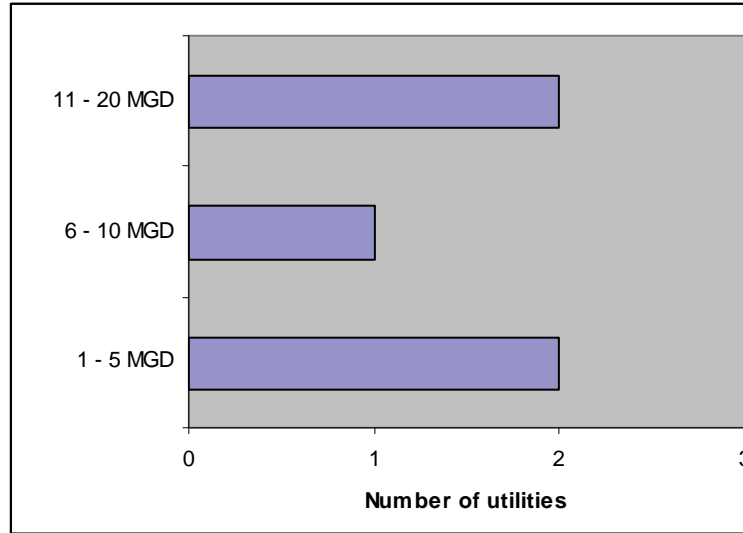
Figure 3.10. Production capabilities of the five water utility respondents.

All respondents use MF. One also uses RO following MF (as a component of a groundwater recharge system).

The purposes of the membrane facilities are summarized in Figure 3.11. The utility producing water for subsurface injection uses membranes for ammonia reduction and for TOC removal and is required to meet all applicable drinking water standards as well as the California Draft Recharge Criteria.
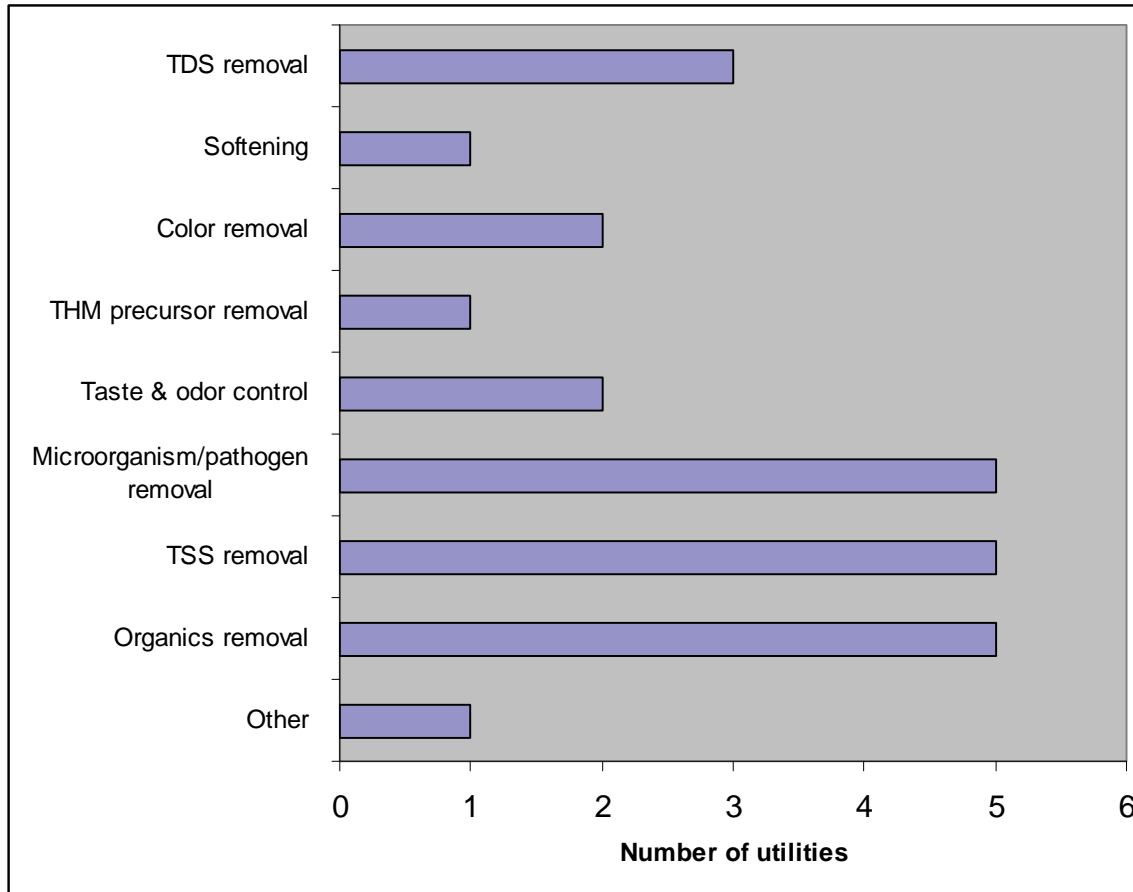
Figure 3.11. Purpose(s) of membrane facilities.

Three systems discharge all residuals (reject streams and cleaning solutions) to a municipal wastewater system. Information necessary for approval of the discharges included pilot plant study results (one utility), previous monitoring (one utility), and approval by state agencies (two utilities). One wastewater utility was granted a discharge permit, another received written authorization, and the third was subject to no formal requirements. One utility indicated that provisions for accepting its discharge included the general requirement to meet the terms of the wastewater utility's collection system use ordinance.

Cleaning agents reported included caustic, sulfuric acid, sodium hypochlorite, proprietary cleaning agents, and citric acid.

One utility was required to neutralize and to monitor the pH of its membrane-cleaning agents prior to discharge. Residuals of the remaining utilities required no additional treatment. In no case was any follow-up monitoring required after the discharge began.

3.3.2 Survey Analysis

On the whole, the findings from the water utility surveys were disappointing. There were far fewer responses than might be expected, particularly in light of the number of water plants known to be using membrane processes. The outreach effort was as thorough as the research team and the WRF Project Advisory Committee could devise. In the future, it may be useful to offer utilities an incentive to participate in such research. This might produce a more robust response.

CHAPTER 4

TDS DATA COLLECTION NEEDS

4.1 BACKGROUND

When considering a system mass balance, TDS levels are the major issue confronting utilities as they consider the impact of membrane discharges into their system. This section discusses what TDS is, how it is measured, and how it fits into a community's wastewater regulatory framework. Based on these factors, the importance it plays in a community's mass loading of solids into a WWTP and ultimately into the receiving stream can be determined and evaluated.

4.2 DEFINITION OF TDS

TDS can be defined as the sum of the anions and cations in the wastewater. From an analytical standpoint, it is the solids dried to a constant weight at 103–105 °C. The analytical methods for TDS tests are given in 40 CFR 136, EPA Test Method 160.3. Results of the TDS test provide aggregated information on the solids content of the sample. Specific ion analysis can be conducted to determine the ions that contribute to the TDS.

One concern associated with TDS is interference. As the analytical method includes drying the wastewater, any material that can be dried, whether volatile, biological, or mineral, will be measured as part of the TDS test. Generally, it is assumed that final effluent samples analyzed for TDS will not contain biological or volatile material, since such materials have been removed during treatment. To gain an understanding of the impact of the volatile TDS, biological materials, and sugars, the wastewater sample will need to be not only dried but also volatilized. This can be done by placing the sample in a muffle furnace and using a procedure similar to the volatile suspended solids test (EPA Test Method 160.4). The remaining inert material is the actual mineral content that is of most interest to the utility and its impact on the WWTP.

Another method for determining the dissolved solids content is to analyze the sample for specific ions, such as sulfate, chloride, and sodium. Testing procedures for inorganic pollutants are presented in 40 CFR part 136 and in Table 4.1 below. The individual ions can be used to develop an ionic balance of the solution and to establish the particular ion species in the wastewater.

Table 4.1. Testing Procedures for Individual Ion Species

Pollutant	EPA Test Method(s)	Pollutant	EPA Test Method(s)
Chloride	325.1/325.2	Sodium	273.1/273.3
Fluoride	340.2	Calcium	215.1
Bromide	320.1	Magnesium	242.1
Sulfate	375.2/375.3/375.4	Iron	236.1
		Manganese	243.1
TDS	160.3		
Hardness	130.1/130.2		

4.3 TRENDING OF DATA

One of the key sources of TDS data is the local water treatment facility and the corresponding raw water supply. Figure 4.1 shows information from the water supply for Phoenix, AZ, one of the study partners. The data indicate that the TDS concentration in the water can change throughout the calendar year. Other water utilities may use a combination of surface and groundwater sources with different TDS contents, which will impact the TDS of the water discharged from the treatment facility.
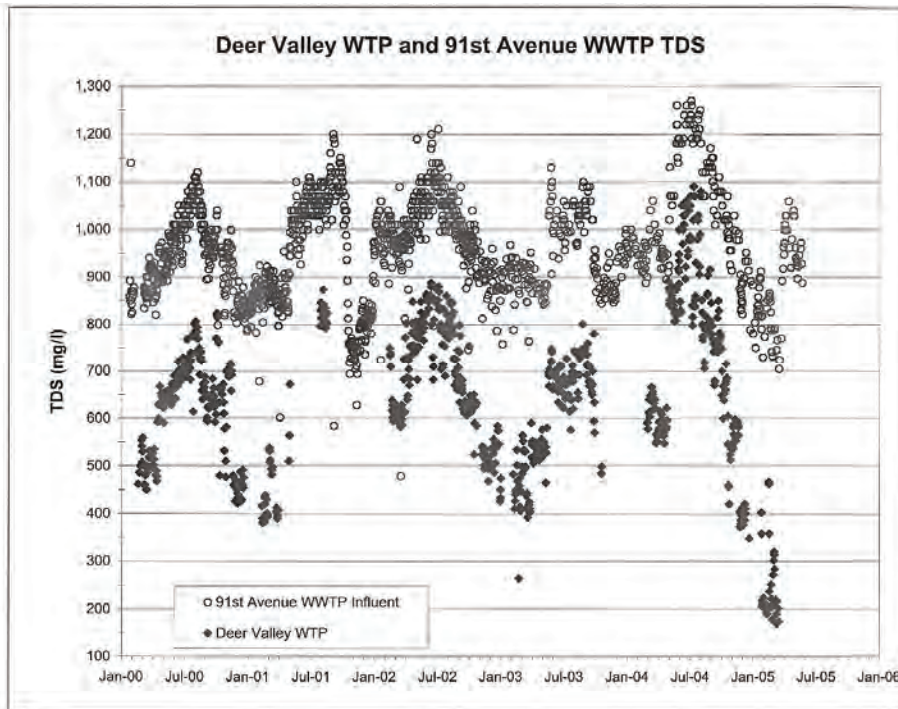
Figure 4.1. Comparison of raw water and TDS at WWTP.

Water treatment facilities that use membranes often have changes in TDS because of seasonal fluctuations in raw water quality, such as in Phoenix. As the total water demand changes, the amount of membrane residuals that may need to be discharged will probably increase, especially during periods of high demand.

Brine production is likely to increase during the summer irrigation season, which is also the time when cooling water by local industrial and commercial users increases. This may cause a number of issues at the WWTP, depending on the overall water consumption.

Membrane discharges from water treatment facilities to WWTPs can be divided into three cases:

- Case 1: The WTP and WWTP serve the same area.

- Case 2: A small WTP in the wastewater service area also receives water from other water plants; the WWTP is larger than the WTP.

- Case 3: The water plant is much larger than the WWTP.

4.3.1 Case 1. WTP and WWTP Serve the Same Area

In Case 1, the two facilities are hydraulically balanced, as shown in Figure 4.2. Assuming minimal water loss in the distribution system and little evaporation, the water produced at the water plant will eventually return to the WWTP. If the residuals are also returned to the WWTP, the wastewater entering the WWTP will essentially be receiving the source water plus the pollutants from domestic, commercial, and industrial uses. The salt content of the wastewater is the same as that of the source water. As shown in Figure 4.2, the TDS concentration of 800 mg/L in the WWTP effluent equals that of the source water. Domestic, commercial, and industrial users contribute TDS to the wastewater. The TDS contribution is highly variable, and for this illustration it has been assumed that no TDS has been added to the wastewater.

A variation of Case 1 is that some water is lost from the distribution system through leaks, use for irrigation, and by evaporation from cooling towers and swamp coolers. Typical return rates range from 60–90%. Assuming a return of 80%, the TDS balance is shown in Figure 4.3.
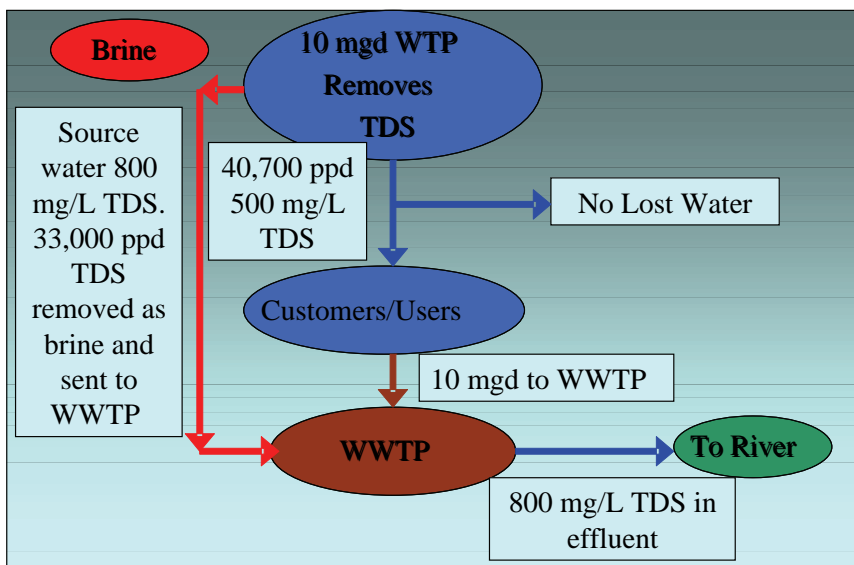
Figure 4.2. Case 1 mass balance.
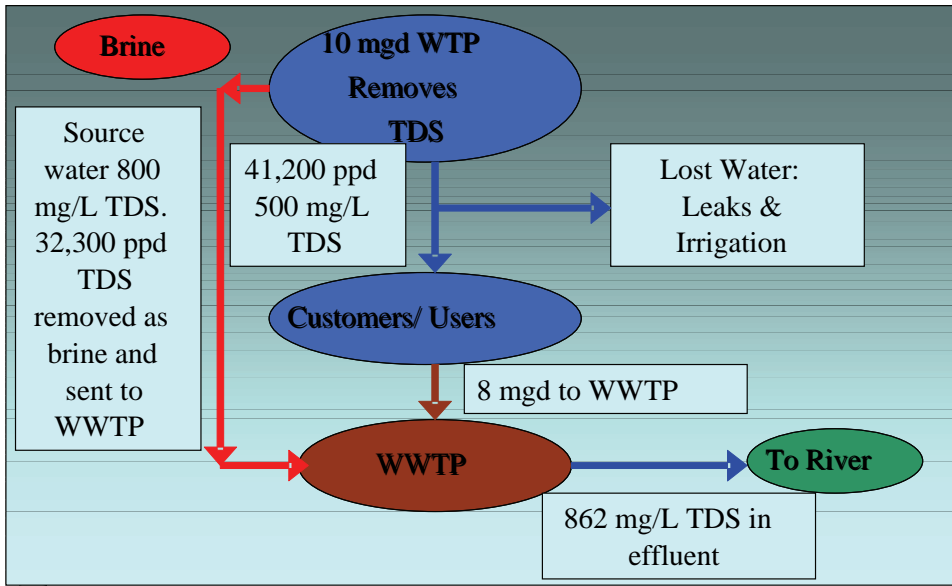
Figure 4.3. Case 1 mass balance with water loss included.

With water losses, less water will reach the WWTP. During dry weather, less wastewater is available for blending with the brine, and thus the TDS concentration in the WWTP effluent increases. The loss of 20% of the produced water increases the TDS concentration in the WWTP effluent from 800–862 mg/L. The membrane recovery rate in this example is 80%, and the TDS rejection rate is 95%. (Note: These values for membrane performance are for illustrative purposes only. Actual performance depends on many site-specific factors and may differ significantly.)

4.3.2   Case 2. Small Water Plant, Large WWTP

In Case 2, the contribution of residuals from the WTP is considerably less than that described for Case 1 and is not considered further.

4.3.3   Case 3. Large Water Plant, Small Wastewater Plant

Case 3 presents the worst case. In this case, the water plant sells water to customers outside the WWTP service area, but the residuals are concentrated in one sidestream and returned to the local WWTP for disposal, as shown in Figure 4.4. The membrane performance characteristics are the same as for Case 1, but the outcome is significantly different.
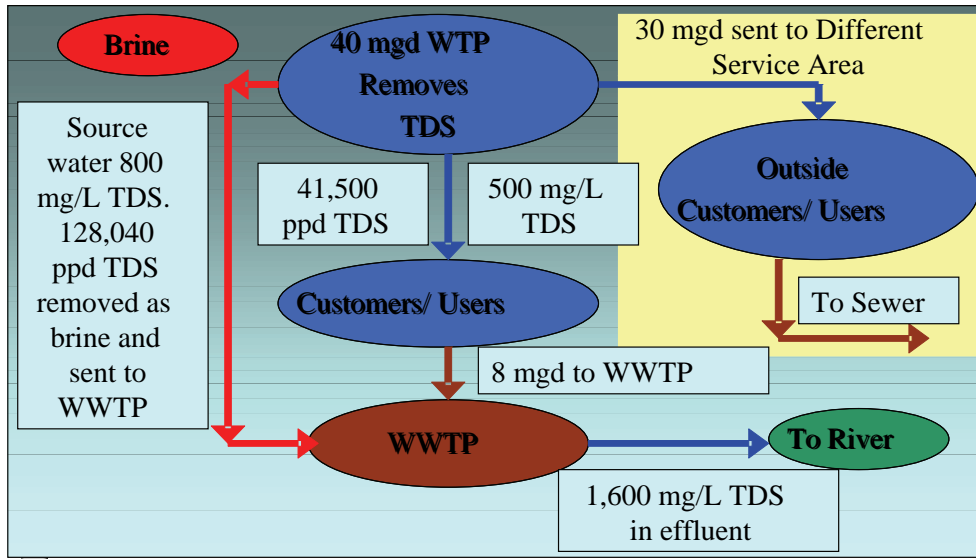
Figure 4.4. Case 3 mass balance with water sold to others.

There are two major impacts to the WWTP: one is the TDS mass load and the higher TDS concentration of 1600 mg/L, rather than the 862 mg/L for Case 1, which may have adverse impacts on receiving stream quality because of acute toxicity from salt and high concentrations of sulfate, chloride, and TDS.

The second impact is the hydraulic load. The WWTP receives a regular dry weather flow of 8 mgd. The brine stream adds 4 mgd, increasing the plant flow to 12 mgd, which uses up clarifier and pipe capacities and may necessitate expansion of the hydraulic capacity or rerating of the WWTP, with loss of treatment capacity.

Wastewater facilities may also need to determine trends for TDS and mineral data in order to comply with local water quality standards. While the EPA has not developed water quality standards for TDS or mineral pollutants, many states have developed standards, as shown in Table 4.2.

Table 4.2. State Water Quality Standards for Salt Compounds (as of 2006)[a]

State	Salt Compound			Other Compounds
	TDS	Sulfate	Chloride	
Alabama				
Alaska	●	●	●	●
Arizona	●[c]			
Arkansas	●	●	●	
California	●			
Colorado		●[b]	●[b]	●
Connecticut				●
Delaware				
Florida				●
Georgia				
Hawaii				●
Idaho				
Iowa			●[b]	
Illinois	●			
Indiana	●			
Kansas			●	
Kentucky		●	●	
Louisiana	●			
Maine				
Maryland				
Massachusetts				
Michigan				
Minnesota			●	
Mississippi				
Missouri		●	●	
Montana				
Nebraska				
Nevada	●			
New Hampshire			●	
New Jersey	●[b]	●[b]	●[b]	
New Mexico				
New York		●	●	
North Carolina				
North Dakota		●	●	●
Ohio				
Oklahoma	●	●	●	
Oregon	●			
Pennsylvania				
Rhode Island				
South Carolina				
South Dakota				
Tennessee				
Texas	●	●	●	
Utah	●	●	●	
Vermont				
Virginia	●[b]	●[b]	●	
Washington			●	
West Virginia			●	
Wisconsin			●	
Wyoming			●	●

[a]For updates, see http://www.epa.gov/waterscience/standards/wqslibrary/index.html.
[b]Receiving stream is public drinking water supply.
[c]Specific receiving streams.

4.4 SEASONAL ISSUES

Seasonal changes can have an impact on the TDS concentrations in the flow received at the WWTP. The seasonal changes are generally caused by changes in the TDS concentration in the raw or potable drinking water supply. The impacts of TDS concentrations from different water supplies and the impacts of storage on TDS concentration are shown graphically in Figure 4.5.
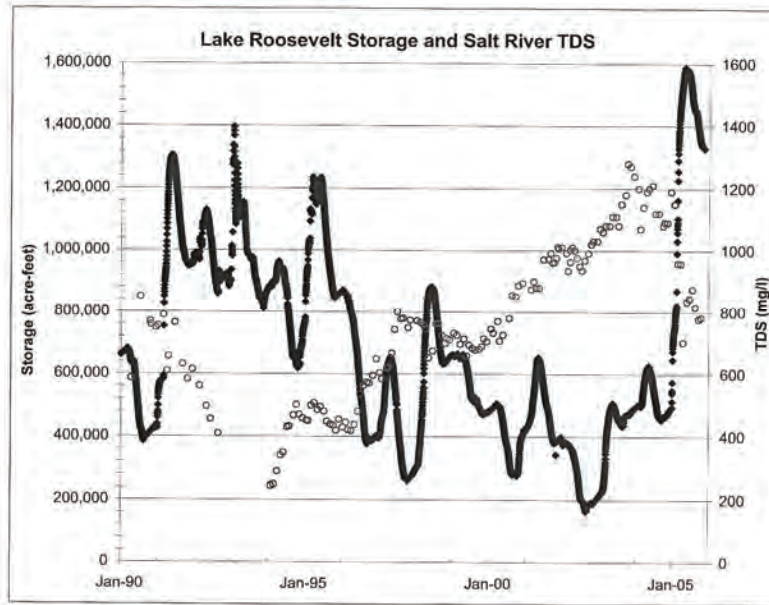
Courtesy of City of Phoenix

Figure 4.5. Impacts of reservoir storage on TDS concentration.

4.5 WATER PURCHASED FROM OTHER UTILITIES

During periods of peak demand, utilities may buy water from another water utility outside of both their water and wastewater service areas. The quantities bought and sold may vary seasonally and can have a considerable impact on TDS concentrations.

4.6 TDS CONTRIBUTIONS FROM DOMESTIC SOURCES

The contributions of TDS from domestic sources to the wastewater can be determined by comparing the TDS concentrations in finished potable water with the TDS concentration from home water softener use plus the basic TDS increase in finished potable water with the TDS concentrations in wastewater. Since a large portion of TDS in domestic wastewater is attributable to the use of home water softeners, some utilities have developed programs to replace older styles of home water softeners with newer updated models.

4.7   TDS AND SALTS IN DOMESTIC WASTEWATER

Figures 4.6 and 4.7 show the increase of TDS across the 91st Avenue and 23rd Avenue WTPs operated by the City of Phoenix. As indicated in the figures, there is a minor increase of TDS across both treatment plants.
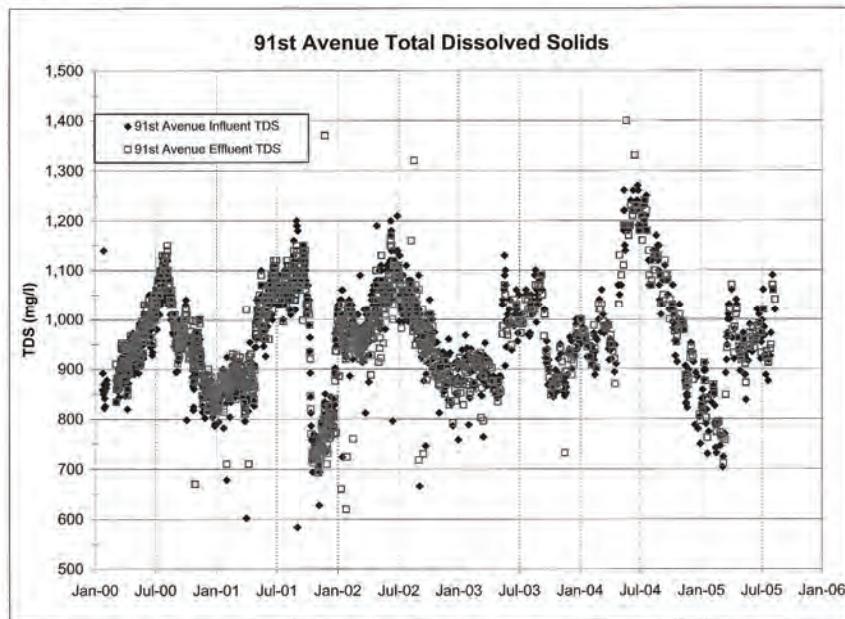
Figure 4.6. TDS in 91st Avenue WWTP effluent.
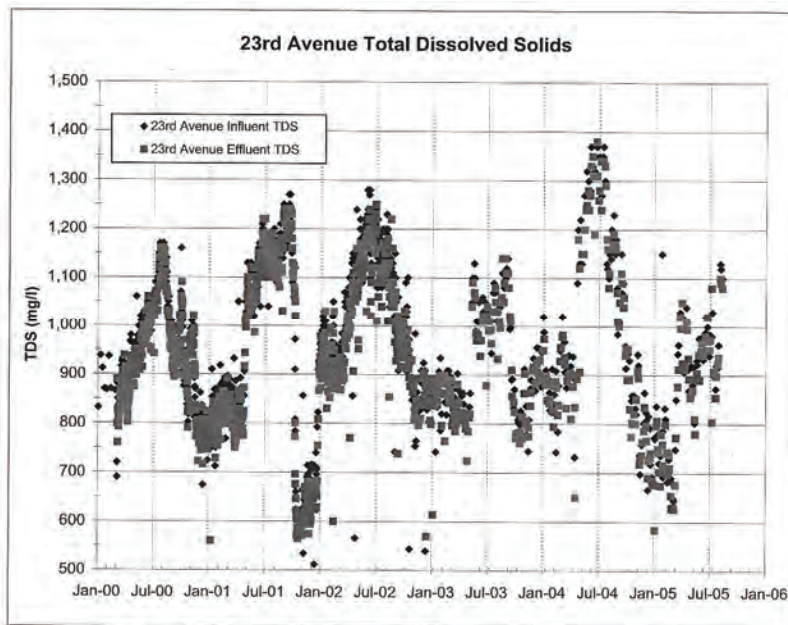
Figure 4.7. TDS in 23rd Avenue WWTP effluent.

Other utilities have also collected data on various salt compounds. Oklahoma City regularly collects chloride data from its North Canadian facility, as illustrated in Figure 4.8.
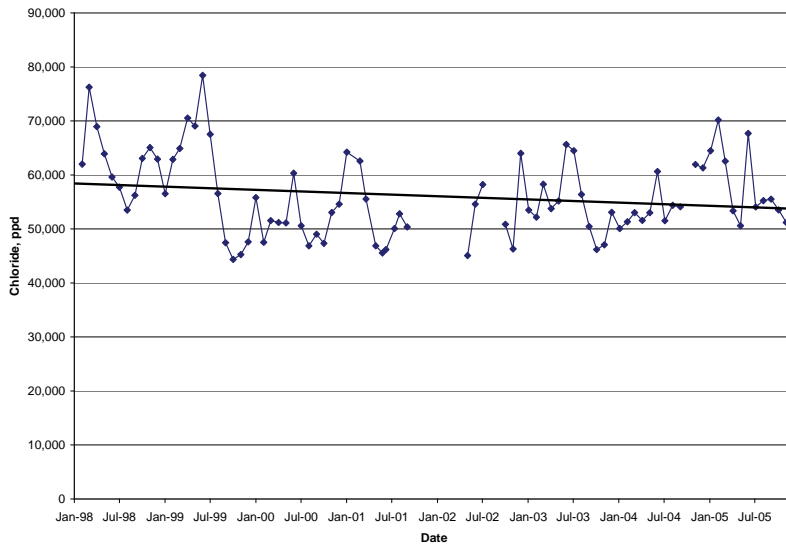
Figure 4.8. Chloride in North Canadian WWTP effluent.

The North Canadian plant has historically used ferrous chloride for odor control, which resulted in over 70,000 pounds per day (ppd) being discharged. Optimization of the use of this chemical resulted in a decrease in the amount used on a yearly basis. In 2002, the North Canadian plant began receiving a high-TDS solution from a local power generating station, which has resulted in an increase of chloride discharged from the treatment plant.

4.8   DEVELOPMENT OF TECHNICAL JUSTIFICATION FOR REGULATING TDS AND SALTS

When does a utility need to establish local limits for TDS? This is a difficult question with which utilities are faced, and implementation of local limits can often be problematic because of local conditions.

When considering establishment of a limit for TDS, utilities need to include an evaluation of the impacts on current customers, should TDS concentrations be reduced. The following list of questions can be used to identify whether a limit is needed:

- Will a TDS limit protect the ultimate uses of the WWTP?
- Where is the largest source of TDS?
- What are the State policies regarding TDS and how do they impact a specific utility?
- Is the TDS concentration in the water supply higher than allowable by State water quality standards?
- Can new water sources with lower TDS concentrations be developed?
- Is it more economical to lower the TDS concentration in potable water or to remove the TDS at the "end of pipe"?

- Is it less expensive to import water with a lower TDS concentration than to treat raw water to remove TDS?
- Does the utility already have a limit for TDS and specific ions or does it want to avoid having a limit imposed?

4.8.1 Development of Discharge Limits

With the MAHL method, local limits are based on the most stringent of three possible criteria: receiving water quality, biosolids quality, and inhibition of the treatment process. The EPA has established criteria for the discharge of effluent and beneficial use of biosolids. These criteria can be used to develop discharge limits. In addition, pollutant loads that could upset, interfere with, or inhibit treatment plant performance must be considered in the evaluation of TDS loadings.

4.8.1.1 Treatment Plant Removal Efficiencies

Removal efficiencies of WWTPs are determined using site-specific sampling data. In the event that the pollutant concentrations in the plant influent or effluent are below detection limits, literature values or EPA values should be used. These "default" values are based on the results of surveys of numerous POTWs throughout the United States as published by the EPA.

4.8.1.2 Domestic Contribution

The concentration of all POCs in the domestic component of the WWTP influent should be determined by sampling the collection system in representative sections of the service area as local limits are being developed. Some adjustments must be made to the conventional pollutant strength values to account for infiltration and inflow, which lowers the overall system-wide waste strength.

4.8.1.3 Protection of Water Quality

The EPA has established water quality standards for many pollutants.

4.8.1.4 Disposal of Biosolids

The biosolids generated at WWTPs are regulated by 40 CFR Part 503, Standards for the Use and Disposal of Sewage Sludge. With TDS, such factors as cation exchange capacity need to be examined. A review of data indicates that salt can leach from biosolids onto soils.

4.8.1.5 NPDES Permits

Discharge permits specify the maximum allowable concentrations of specific constituents in the final effluent.

4.8.1.6 Process Inhibition

The wastewater treatment processes most susceptible to upset are those that rely on biological activity. The inhibitory values used to develop the local limits are provided in Chapter 2.

4.8.2 Final Allowable Industrial Limits

Local limits for POCs can be derived using either the uniform allocation or the contributory flow method.

4.8.2.1 Uniform Allocation

The uniform allocation method distributes the MIHL among all permitted industries in the service area on a flow-weighted basis. Concentration-based limits for the uniform allocation method are calculated as follows (assuming a flow-proportional distribution):

$$LL_{IND} = MILH / (Q_{IND})(8.34) \tag{4-1}$$

where LL_{IND} is the calculated industrial local limit (in milligrams per liter), Q_{IND} is the flow attributable to industrial sources (in million gallons per day), and 8.34 is the unit conversion factor.

4.8.2.2 Contributor Allocation

The contributor allocation method results in MIHLs being applied to the specific IUs that discharge the specific POCs. The MIHL is distributed among only the IUs that contribute the pollutant on either a mass- or a flow-weighted basis. Concentration-based limits are calculated as follows (assuming a flow-proportional distribution):

$$LL_{IND} = MILHcontrib (Q_{INDcontrib})(8.34) \tag{4-2}$$

where LL_{IND} is the calculated industrial local limit (in milligrams per liter), $Q_{INDcontrib}$ is the flow attributable to contributing industrial sources (in million gallons per day), and 8.34 is the unit conversion factor.

4.9 SYSTEM-WIDE MASS AND WATER BALANCE

In order to determine the TDS load (in pounds per day) being discharged to a wastewater treatment facility, a mass balance of the various sources that discharge to the facility needs to be completed. TDS and salt data (with measured flow) need to be collected from industrial, commercial, and domestic sources. This process is similar to those outlined by the EPA in their Local Limits Development Guidance. To collect these data, the wastewater utility needs a sampling plan to define the following:

- When are samples collected? For instance, how long after a storm event? Are all IUs to be sampled?
- Who is responsible for collection of the sample, the wastewater utility staff or commercial or industrial staff?
- Where will the sample be collected? While this may be well defined for IUs that are already permitted by the utility as part of the Industrial Pretreatment Program (IPP), the domestic locations are not always that well defined. If sampling is to be complete, the utility may wish to collect samples from locations that have previously been established to sample domestic wastewater sampling stations.
- Who will pay for and collect the sampling data? In some cases, if permit limits are to be established, this cost may be borne by the IUs; however, for commercial and domestic sites, the wastewater utility may need to bear the cost of this analysis. What analytical and sampling protocols are to be used? Wastewater utilities with Industrial Pretreatment Programs (IPPs) may have already established similar protocols that could be used.
- What type of sampling equipment should be used? The best approach would be to install a composite sampler that collects a flow-weighted sample.

- When should the study take place and for how long? Since TDS concentrations can vary seasonally, sampling should be conducted over a period of at least 1 year to establish a historical baseline.

The data collection is geared towards completing the mass balance for the entire water and wastewater systems. In addition to samples from the collection system, monitoring stations will need to be established within the treatment plant to determine the quantity of salts added by the wastewater utility as part of treatment.

The mass balance enables the wastewater utility to access changes in the water supply, addition of reuse water (end-of-pipe or satellite), new industries coming to town, or impacts from reducing the domestic salt contribution. In addition, the results from the mass balance can be used in developing a long-term control policy for salts. This may require working with various users of the collection system to establish best management practices.

Results of the mass balance can also be useful in assessing and developing actual permit limits if needed. The mass balance will help to identify the major sources of salt in the system. It can also be used to identify if the establishment of limits is the correct approach for controlling the discharge of salt to the wastewater collection system.

CHAPTER 5

SYSTEM-WIDE MASS BALANCE MODEL

5.1 INTRODUCTION

This chapter provides a detailed description of the system-wide mass balance and its features that allow almost any water or wastewater treatment system to be modeled within the context of the community's overall water and wastewater systems. The model is a water mass balance that includes water losses through leaks in the distribution system, water sold outside the wastewater service area, water reclaimed from both a satellite plant and an effluent reclamation facility, and evaporation. The model was developed in Microsoft® Excel, and the workbook consists of a number of spreadsheets.

The mass balance tracks a number of conservative and nonconservative pollutants. The conservative pollutants are never destroyed; the nonconservative pollutants are partially destroyed or converted into another physical form. The model includes many inputs which will require some time to set up. Once the model is set up, it is very easy to evaluate alternative impacts to the system from increasing reclaimed flow, reclamation water sent to cooling towers, and membrane treatment at the water plant, power plants, industries, and reclamation facilities. Attention to setting up the model will significantly increase the utility of the model for users.

The model is designed with flexibility to allow modeling "what if" scenarios that are run to determine whether future projects will produce conditions that will impact a system's performance. As a planning tool it enables the utility to determine how future projects will impact the wastewater collection system (e.g., corrosion) or whether they will produce an effluent too high in a particular pollutant.

5.1.1 Mass Balance Model Requirements

A diagram of the overall system mass balance is provided in Figure 5.1. The eight areas of the overall mass balance are color coded. Each area represents a separate mass balance unto itself. Because the spreadsheets contain a lot of information, tables have been developed to pull selected information into a summary table for easy access and for printing as a record of the run. Users can include additional tables if needed for a specific "what if" run.

The model will require data from the water and wastewater utilities. Most of the water plant data should be available in quarterly or annual reports prepared for the regulatory authority. The membrane performance information, including rejection of specific pollutants, may be the most difficult to find. The water sales information (critical) is needed to determine how much water is sold or transferred out of the WWTP watershed; finished water imported from another utility must be accounted for in the system, and internal water sales and lost water information are needed as well. Water lost is a planning value and is often based on field observations and data analysis. Information on water sold to power plants and industries for use in membrane treatment systems or as feed water for boilers and cooling towers is generally available in water utility billing records.

For WWTPs, the best source of data is the IPP records. As part of their NPDES permit renewal, the EPA requires utilities that have IPPs to review their local limits. The data to be collected and the procedures to follow can be found in the EPA's IPP manual.

The Local Limits Report will contain the following:

- A summary of industrial flows
- WWTP influent and effluent data to calculate pollutant removals across the facility
- Literature values of removal efficiencies for pollutants of concern
- A summary of permit limits, water quality standards, and residuals standards
- A survey of pollutants to identify the pollutants of concern
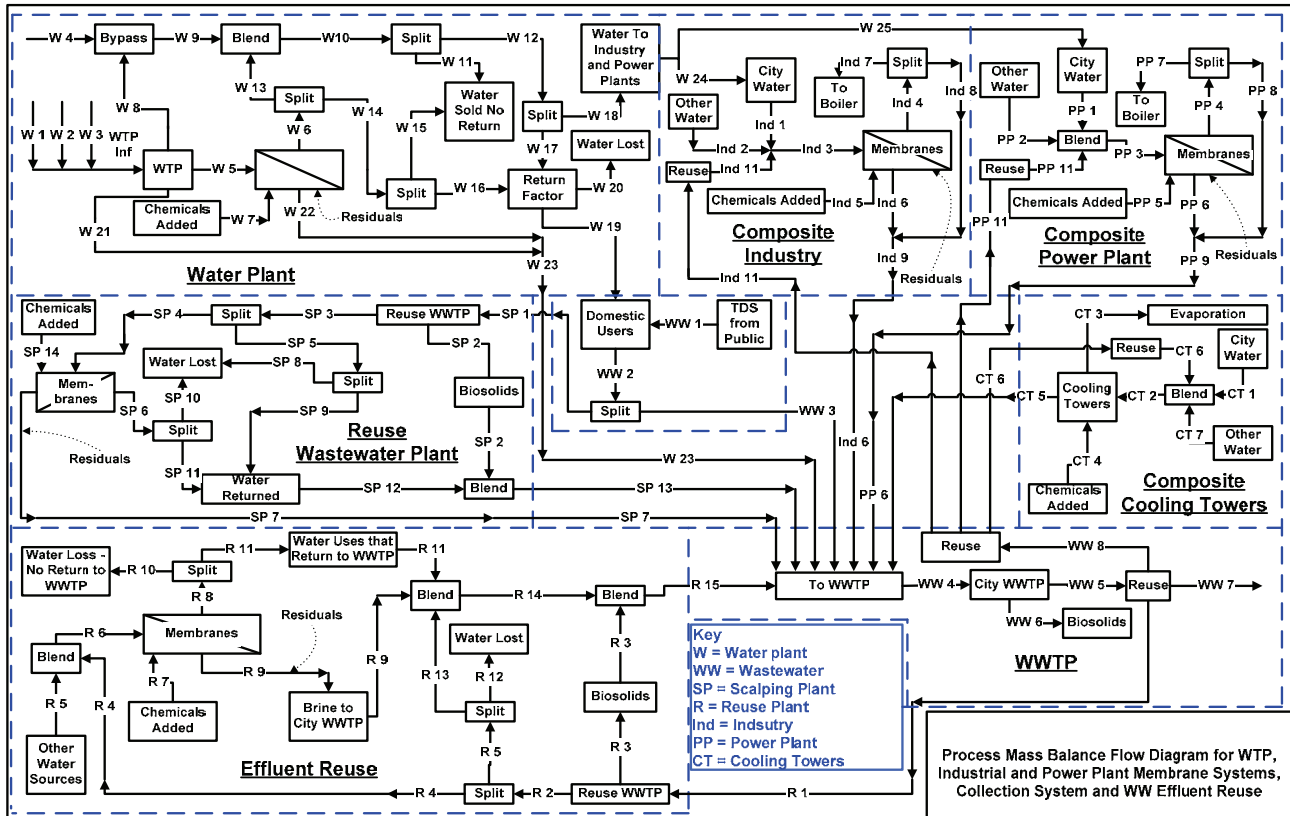- Solids production out of the WWTP

Figure 5.1. Overall mass balance schematic.

The IPP annual reports are also a source of information on industries that have discontinued their operations, industries that have been expanded or downsized, and new industries that have moved into the WWTP service area.

Information can also be obtained from the IPP inspection staff, who are required to visit each industrial site at least once a year and should have files on their operations which should include a recent site water balance identifying industries that operate cooling towers and use membrane treatment systems for treatment of boiler water. IPP staff should also have visited the local power plant. (Note: If the power plant is owned by the City and the City owns or operates the wastewater utility, then the IPP staff may not have inspected the power plant. If this is the case, this inspection will need to be done, as the power plant is potentially a large contributor of salts and dissolved solids.) For information on cooling towers throughout the community, it may be necessary to circulate a questionnaire.

Domestic wastewater data should be available from the sampling conducted for the Local Limits study. The data may be incomplete or missing information on pollutants not commonly regulated, such as chloride, sodium, calcium, sulfate, etc. However, the sampling location will have been identified, and it should be relatively easy to obtain samples for TDS and specific ion analyses.

The pollutants already accounted for in the model are listed in Table 5.1. Additional pollutants can be input to the model or substituted for any pollutant on the list.

Table 5.1. Pollutants Already in the Mass Balance Model

Arsenic	Manganese	Sulfate
Cadmium	Molybdenum	Carbonate
Chromium	Selenium	Bicarbonate
Copper	Strontium	Fluoride
Cyanide	Thallium	Phosphorous
Lead	Tin	Orthophosphate
Mercury	Phenol	Sulfide
Nickel	MBAS	Sulfite
Silver	Calcium	Total Alkalinity
Zinc	Magnesium	BOD
Aluminum	Sodium	COD
Antimony	Potassium	Diazinon
Barium	Silica	TDS
Beryllium	Bromide	TSS
Boron	Chloride	Phosphonates
Iron	Nitrate-Nitrite as N	Polyacrylates

5.1.2 Model Overview

The Microsoft® Excel mass balance model described in Appendix D is extremely versatile and can be used by utilities for assessing the impacts of increased loads of solids or metal ions on their WWTP. The model can handle variables such as stream flow, water quality, reclaimed water flow, chemicals added, and pollutant removal performance. This allows the utility to evaluate the impacts of future projects that add water or wastewater membrane separation systems within their service area or changes in water sources for the WTP, industrial facilities, or power plants.

5.1.3   Microsoft® Excel Setup

The mass balance model is a series of Microsoft® Excel spreadsheets and, consequently, may involve the many quirks and issues particular to the use of Excel in such a modeling effort. It is recommended that a master copy of the model be maintained in a secure location. New evaluations are accomplished by simply opening the master spreadsheet and saving it as new file in a file folder.

To get started, the user opens a new workbook and saves it as a new name, ALWAYS keeping the master workbook intact in another folder. The model includes a circular reference, and when the spreadsheet is opened, it will inform the user that a circular reference has been created and that Excel cannot calculate a formula. Check the box marked OK. Excel will then display a window called Circular Reference. Close this window. Excel will also open the Excel Help window. Close this window also. Unfortunately, every time Excel is started it resets itself and these prompts appear.

Once the workbook is opened, it is necessary to reset the iterative calculations feature. Go to the toolbar and click on Tools. A window will open; select Options. The Options window will open and the window will display a number of tabs. Select the Calculations tab, and a new window will open. The calculations window will have a section labeled Iterations. Check the Iterations box and set the number of iterations to 100. Finally, click on the OK button, and you will now have the iterations feature active in the spreadsheet. If the computer is turned off or Excel is closed, the iteration feature will be turned off and must be reset again to run the model.

Each of the eight mass balance areas in the model is a separate unique system within the whole model. Each mass balance area will be described in detail and critical input parameters will be discussed here.

5.1.4   Water and Wastewater Utility Discharge Scenario

Every community has a utility that produces or sells water to domestic, commercial, and industrial users and a corresponding wastewater utility. However, ownership of the two utilities can vary. Some cities own both the water and wastewater utilities. Sometimes the county may own both utilities, or the county could own either the water or wastewater utility. A private company could even own one or both utilities. If the water utility installs a membrane treatment system, it may remove pollutants from a large volume of water and sell water to other communities not served by the wastewater utility. This situation will concentrate membrane residuals into one wastewater system.

There are three basic cases to examine when considering the modeling effort. The first case, Case 1, is when the water and wastewater service areas and flows are balanced and little or no water is lost. Case 2 is similar to Case 1 but has a significant lost water fraction. Case 3 examines a large water plant selling water outside the wastewater plant service area but discharging brine to the local smaller WWTP. These cases were described in more detail in Chapter 4.

5.2   DATA INPUT

The following sections explain the data input to the mass model for various components of the model. Figures in this section illustrate portions of the data input screen to assist in

orienting the reader to the data entry locations. (Note: Some data input screens are much larger than could be accommodated in this manual and so have been truncated; they should still provide the user a visual orientation for the input screen.)

The mass balance model is built in several modules. Each module is color coded, as shown in Figure 5.1. The Input Data sheet of the mass balance model is also color coded in accordance with the reference module.

5.2.1   Raw and Finished Water Sources

Figure 5.2 illustrates a water plant mass balance schematic. In Figure 5.2, streams W 1 through W 3 represent water into the system. Streams W 1 through W 3 are designated as raw water sources. This allows the user to input data separately if there is more than one water source. For example, if the utility uses water from wells and surface water, data from the wells can be summarized and entered as one of the streams. Similarly, if multiple surface water sources are used, they can be combined into one surface water entry. Stream W 4 is reserved as water bought from another utility, which is why it bypasses treatment. Alternatively, water purchased from another utility can be entered as raw water, if desired.
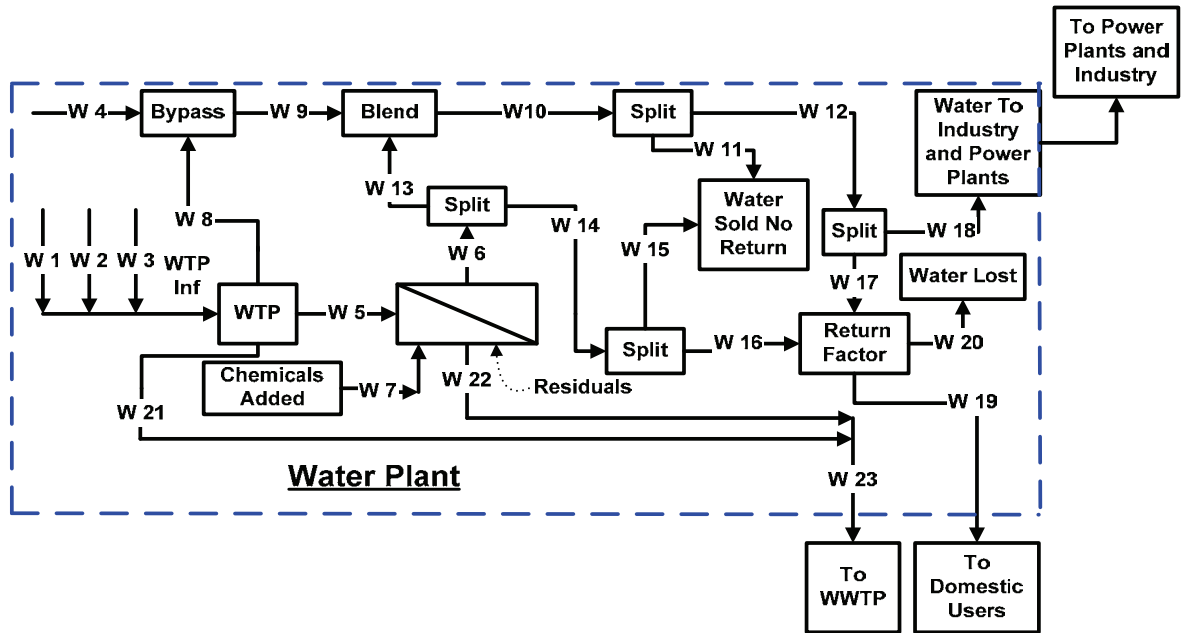
Figure 5.2. Water plant mass balance schematic.

5.2.2   Raw Water Treatment

Streams W 1 through W 3 are combined and enter the WTP. The WTP is meant to be a typical treatment facility. It could be just a filtration facility, or it could be a sedimentation and filtration facility, or it could be a softening plant. This facility is not meant to represent the membrane separation facility.

Begin by collecting information on the WTP. The WTP is the beginning of the whole model and is critical to defining the various water sources and to determining how the quality of

each water supply varies. If the raw water quality varies seasonally, it is recommended that a separate model be developed for each season. Simply save the model under new names such as spring, summer, fall, and winter, or dry weather and wet weather, or any other appropriate names.

Obtain a flow schematic and the raw water quality data for each WTP. The WTP process in the model is very generic. The only important issues are WTP product water quality and residuals production and quality. Mass average the raw waters and product waters to develop an overall removal efficiency for each pollutant. Also, average the residuals volume and quality.

Enter the raw water quality information into the WTP module for each of the raw waters. If raw water from more than three sources is used in the WTPs, mass average the waters in a separate spreadsheet and enter the composite raw water quality as stream W 1, W 2, or W 3. If treated water from another WTP is purchased and blended into the system, enter the purchased water quality into stream W 4 (Figure 5.3).

Treated water from the WTP is split by the user between water to be treated by membranes and water to bypass membrane treatment. If membrane treatment is added to the WTP, membrane performance is set in the Input Data sheet. The water recovery rate and the membrane rejection efficiency for each pollutant are variables that the operator can change. If chemicals are added to the membrane treatment system, the chemical additives must be added as their ionic components. For example, if 100 ppd of pure sulfuric acid is added, enter 98 ppd for sulfate on the Input Data sheet. If 100 ppd of sodium chloride is added, enter 39.3 ppd sodium and 60.3 ppd of chloride into the Input Data sheet. Also enter the flow rate for chemical addition. Usually this flow is negligible; however, if dilute solutions are used, the water volume may be significant. The model assumes that the volume of chemical feed ends up in the brine stream.

8	A	B	C	D	E	F	G	H	I
9	Pollutant Information: Source Waters, Removal Efficiency, Destruction Efficiency								
10		Raw Water	Raw Water	Raw Water	Raw Water	WTP	Membrane	Chemicals	Domestic
11		Source	Source	Source	Source	Removal	Performance	Added	Contribution
12		1	2	3	4	Efficiency	WTP	WTP	
13									
14									
15		W1	W2	W3	W4	% loss H2O	Recovery, %		
16	Flow, mgd	21.31	3	2	1	5	75	0.001	
17	Flow, gpm	14,799	2,083	1,389	694			1	
18	Flow, lb/ day	177,725,400	25,020,000	16,680,000	8,340,000			8,340	

Figure 5.3. Source water input.

The remaining data to be entered for the WTP module deal with flow splits. These flow splits are self-explanatory, such as how much of the product water is sold to users outside the WWTP service area. The splits that require attention are Lost Water, Water Sold No Return, and Water Sold to Industry and Power Plants. Lost Water accounts for leaks in the distribution system and water supplied to households using septic tank systems. The water utility planners should have a value for water lost. The water sold to another utility or transported out of the WWTP service area is very important if membrane separation systems are used. Water is produced and will leave the system while the brine remains behind. Where no membranes are used, the water sold merely transports its proportionate mass of pollutants out of the system. With the use of membranes, pollutants are concentrated. Water sold to

power plants and industries is important because of the evaporation losses, as discussed in a later section.

The calculations are straightforward: removal efficiency for each pollutant and a water loss value are entered, and the contaminants that are removed are concentrated into a sludge stream that is discharged to the WWTP. If the WTP does not discharge sludge to the WWTP, the raw water would be entered as the finished water quality and the removal efficiencies and water loss value across the WTP set to zero.

5.2.3   Membrane Treatment

Stream W 5 is the inlet stream to the membrane system, which can be an MF or UF, or it can be an NF or RO system. It could even be a combination of MF and RO. The data entered into the Input Data sheet of the model define the type of membrane separation system used (Figure 5.4).

8	AA	AB	AC
20			
21	**Flow Split Data for Water Balance**		
22	Flow Split To Membranes, %	75	
23	W 11 Water Sold out of service area	0.01	mgd
24	water Return factor	83	%
25	Membrane Product To blend	75	%
26	W 15 Product Sold out of service area	0.1	%
27	W 18 Water to Ind & power plants	0.1	mgd
28	W 24 Water to Industry	33	%
29	W xx Water to Power Plants	33	%
30	W xx Water to Cooling Towers	34	%
31	W 20 Water Loss factor	0.1	%
32	SP 1 WW to Reuse Plant	0.01	%
33	Reuse WWTP Sludge yield	2000	lbs sludge/ mgd
34	WWTP Sludge Yield	2000	lbs sludge/ mgd
35	SP 5 Reuse H2O direct to Reuse App	50	%
36	SP 9 Reuse App Returned to WWTP	50	%
37	SP 11 Reuse App Returned to WWTP	50	%
38	SP 12 Evaporation Losses	75	%
39	R 1 Flow to Effluent Reuse Plant	10	%
40	R 4 Flow to membrane system	75	%
41	R 12 Water Lost From System	75	%
42	R 10 Water Lost From System	25	%
43	R 18 Evaporative Losses	75	%
44	R 16 Evaporative Losses	75	%
45			
46	Ind 7 Split to Boiler	75	%
47	PP 7 Split to Boiler	75	%
48			
49	Ind 11 Reuse Flow to Industry Membranes	1.674	mgd
50	PP 11 Reuse Flow to PP Membranes	1.674	mgd
51	CT 6 Reuse Flow to Cooling Towers	1.5	mgd

Figure 5.4. Membrane treatment data input.

Data to be entered into the Input Data sheet include individual pollutant removal efficiencies and a system water recovery rate. The model calculates the permeate flow rate and then the concentration of each pollutant in the permeate stream. The pollutant removal efficiency is concentration based, and the concentration of pollutants in the permeate stream equals:

$$[1 - (\text{removal } \%/100)] \times \text{concentration of pollutant in} \tag{5-1}$$

Once the concentration (C) of each pollutant in the permeate is calculated, the mass of each pollutant in the permeate is calculated:

$$\text{Flow (mgd)} \times 8.34 \times \text{C mg/L in permeate} = \text{ppd in permeate} \tag{5-2}$$

The reject stream mass flow is calculated by subtracting the permeate mass flow from the influent flow. The concentrate or brine stream flow is calculated as the influent flow minus the permeate flow. The concentration of each pollutant in the brine stream is calculated by:

$$\text{Brine mass (ppd)}/8.34/\text{flow (mgd)} = \text{brine concentration (mg/L)} \tag{5-3}$$

In most cases, not all of the flow passes through the membrane separation system, and so the membrane bypass flow, stream W 8, must be set on the Input Data sheet. This flow bypasses the membrane system and is eventually blended with the membrane product water.

Many membrane systems require chemical addition to control scale formation or adjust the pH and water quality ahead of the membrane. Stream W 7 allows chemicals to be added to the membrane system and to be combined into the brine stream. The chemicals should be entered into the Input Data sheet as the mass flow (in pounds per day) of each ion. For example, sodium hypochlorite would be added as X ppd sodium and Y ppd chloride. The chemicals added are almost always in liquid form, and so the carrier water added must also be entered into the Input Data sheet. The brine stream, stream W 22, is discharged to the WWTP. If the WTP membrane brine is disposed of in another manner, simply adjust the WTP removal efficiencies to produce the finished water quality. This is necessary because the mass balance determines the interrelationships between water production and brine disposal to WWTP effluent quality.

As noted, the rest of the calculations in the water plant mass balance model are simply flow splits that direct water to various end users, including water lost. The mass balance allows permeate or membrane product water to be sold directly to users. Some of that water may not be returned to the WWTP. This part of the water plant balance is very important in that water may leave the system and never return. When membranes are used to remove TDS, this is very important in that the TDS is being concentrated with water lost from the system. A water loss could be a leaking water distribution system, which is shown as Stream W 20, or it could be water sold out of the system, Streams W 11 and W 15. Water sold to local industries and power plants reenters the mass balance through the industry and power plant modules.

The remaining calculations in this module are simply flow splits that account for the water and mass of pollutants in that stream. Stream W 19 represents the water sent to the domestic users in the utility service area. While the term "domestic user" is used, it really means everyone except the power plant and industrial users, both of whom are called out separately in their respective modules.

5.2.4 Domestic Contribution

The Domestic Contribution Module is an important part of the model. While it is the least complicated from a calculations perspective, it converts the water quality sent to customers into wastewater. The IPP should have data from which the increase in pollutants for domestic, commercial, and industrial uses can be calculated and entered into the model through the Input Data sheet. The schematic of the mass balance for the domestic contribution is shown in Figure 5.5.
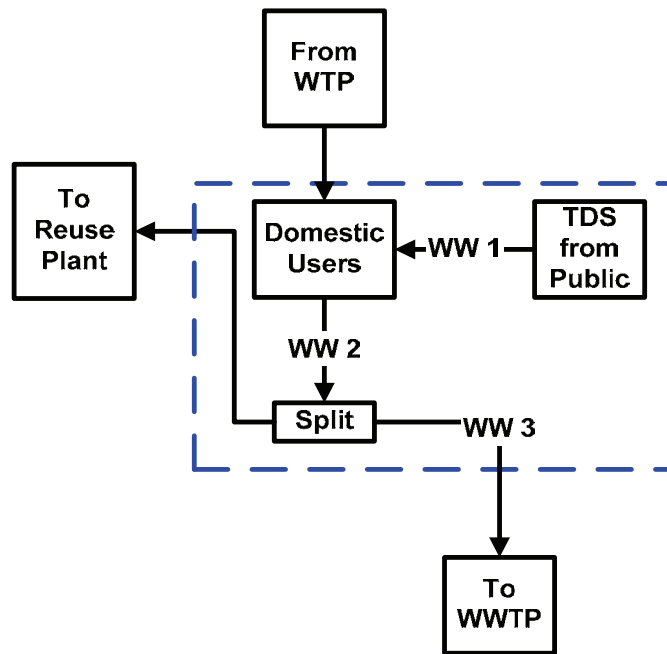

Figure 5.5. Process schematic for the domestic wastewater module.

In the Domestic Contribution Module, the data entered increase the water plant individual pollutant concentrations to those noted in the influent of the WWTP without any reclaimed components added (Figure 5.6). The increase in mass to the system is calculated. This mass addition is very important from a water quality perspective. The mass attributed to the domestic contribution is a very significant mass load, and much of it may be attributed to home water softeners. Any programs to reduce the use of home water softeners would be reflected in the mass balance by lowering the increase in sodium and chloride concentrations from water softeners.

The data input for the domestic contribution (Figure 5.6) is a concentration increase. Historical influent wastewater characteristics are available from the IPP. Product water quality data are available from the WTP quarterly reports. Simply subtract the WTP concentrations from the WWTP influent concentrations to obtain the concentration difference from product water to wastewater. The module also calculates the mass increase from domestic and industrial sources.

8	A	B	C	D	E	F	G	H	I
9	Pollutant Information: Source Waters, Removal Efficiency, Destruction Efficiency								
10		Raw Water	Raw Water	Raw Water	Raw Water	WTP	Membrane	Chemicals	Domestic
11		Source	Source	Source	Source	Removal	Performance	Added	Contribution
12		1	2	3	4	Efficiency	WTP	WTP	
13									
14									
15		W1	W2	W3	W4	% loss H2O	Recovery, %		
16	Flow, mgd	21.31	3	2	1	5	75	0.001	
17	Flow, gpm	14,799	2,083	1,389	694			1	
18	Flow, lb/ day	177,725,400	25,020,000	16,680,000	8,340,000			8,340	
19	Pollutant name input into Cell A22 Updates all other sheets. LOOKUP Function Pulls data from Table into Row 22 Automatically.								
20	Pollutant names in Column A can be changed as needed. Row 22 designated as Quality Control See Mass Balance Check Sheet								
21	Pollutant	mg/L	mg/L	mg/L	mg/L	%	Rejection, %	ppd	mg/L
22	Copper	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
23	Arsenic	0.005	0.006	0.008	0.01	50	90	0.001	0.1
24	Cadmium	0.001	0.001	0.001	0.001	2	90	0.001	0.001
25	Chromium	0.001	0.001	0.001	0.001	2	90	0.001	0.001
26	Copper	0.25	0.2	0.17	0.28	65	90	0.001	0.3
83	% difference	0.94	0.36	-0.14	-2.79			-0.01	-13.45

Figure 5.6. Domestic contribution data entry.

5.2.5 Reclaimed Water or Satellite Plant Membrane

The satellite plant is any reclaimed facility that withdraws wastewater from a collection system upstream from the main utility WWTP. The satellite plant scenario usually involves return of biosolids to the collection system from a secondary treatment facility. The reclaimed water may be treated further with membranes for a higher end-use quality.

The brine from the membrane facility will be returned to the wastewater collection system. A schematic of the facility is shown in Figure 5.7.

The reclaimed water from the satellite plant may be sent out of the system, or some of it may be returned to the wastewater collection system. Reclaimed water that does not return to the wastewater collection system removes a mass of chemicals from the system. However, reclaimed water that returns to the wastewater collection system may undergo evaporation, which will concentrate salts and other dissolved chemicals so that the return water is low in volume but has a high concentration of TDS. The model is flexible enough for the user to model these various scenarios. In the event that there is more than one satellite plant, the flow to the satellite plant module needs to be the sum of the flow of all satellite facilities. Representative values for water loss and evaporation must be developed for input into the model.
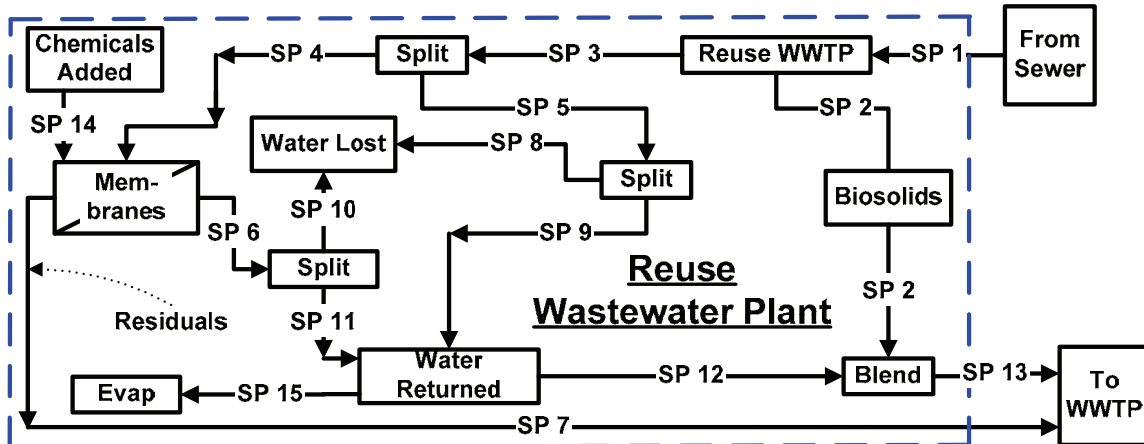
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Figure 5.7. Process schematic for reclaimed wastewater plant or satellite plant module.

The reclaimed WWTP is meant to be a generic secondary treatment facility. On the Input Data sheet there are two pieces of data to input for the reclaimed WWTP performance. The first is WWTP pollutant removal data. Generically, the influent and effluent data will report the removal efficiency of the WWTP. The model concentrates all of the removed material into the sludge stream. The second set of data to enter is the WWTP destruction efficiencies of various pollutants. The destruction efficiency input allows specific pollutants to be destroyed and removed from the mass balance. Most metals and salts will have a destruction efficiency of zero, as these materials are never destroyed. Specific organic compounds are biodegraded, as is BOD, and destroyed (converted to biomass or carbon dioxide). The destruction efficiency feature allows pollutants to be removed from the system and not be returned to the wastewater collection system.

The flow of wastewater sent to the Wastewater Reclaimed Plant Module is set at cell AB 32 (Figure 5.8). It is set as a percentage of flow. This module is meant to be a generic reclaimed module representing all upstream (ahead of the WWTP or satellite plant) reclaimed applications. Because raw wastewater is from the wastewater collection system, the reclaimed facility has a structure similar to the WWTP for modeling the initial wastewater treatment portion of the reclaimed system.

The core Reclaimed WWTP Module is a simple model based upon two sets of inputs: pollutant removal efficiency and pollutant destruction efficiency. The removal efficiency and destruction efficiency are operator-adjustable variables. The operator can enter or change removal or destruction efficiency at columns K and L, respectively, on the Input Data sheet. A removal or destruction efficiency must be entered for every pollutant. It is assumed that the wastewater treatment portion of the module would include biological treatment and effluent polishing, like filtration, enhanced phosphorus removal, and effluent denitrification systems.

Many of the pollutants are conservative; they are never destroyed. They are simply moved from one stream to another. Organic pollutants, BOD, and TSS are nonconservative and can be destroyed. The mass balance model does not include kinetic parameters to adjust pollutant removal based upon operating factors. This module should use data from the WWTP operating data and IPP. Every 5 years, IPPs are required to reevaluate the current local limits,

which involves sampling the WWTP influent and effluent, calculating the overall removal performance, and sampling biosolids quality for the mass balance model.

Conservative pollutant removal efficiencies should be set to 0. The reason these are not hard-lined into the program is that the operator can change the pollutant list.

For nonconservative pollutants, the destruction efficiency is based on overall destruction of a pollutant, which actually occurs in the biosolids stream in this model. The model does not factor in how a pollutant has been removed. It simply calculates the effluent quality based on removal efficiency. The mass that is destroyed is calculated in the biosolids stream.

The rest of the module is similar to the WTP module in that it has a membrane treatment system and various flow splits for water lost, return water, and evaporation. These variables are found in the Input Data sheet in fields AB 35 to AB 38. Refer to the schematic in Figure 5.1 to match the stream numbers with the respective flow splits.

The membrane separation system is defined by the membrane rejection characteristics entered into column M of the Input Data sheet. The membrane separation system could be simply an MF or a UF system removing suspended solids or an NF or an RO system removing many of the soluble pollutants, or even a combination of any of these. MF and UF are often used as pretreatment for NF and RO in wastewater applications. The model does not differentiate between the kinds of systems installed. The only items of importance are the respective overall membrane rejection performance and water recovery efficiency. This simplicity makes the model very user friendly, very flexible, and powerful in that any future membrane system can be built into the scenario to assess impacts to the downstream wastewater facilities. Membrane performance should be entered into column M on the Input Data sheet.

Like the WTP membrane separation systems, the reclaimed water membrane application also includes an entry for chemicals added to improve membrane performance or to reduce scaling and fouling potential. Chemical additives must be broken down into their ionic components for entry into column N on the Input Data sheet.

In column O, any mass lost during evaporation can be entered, for example, if the water lost to evaporation contains sodium and chloride, the mass of sodium and chloride transported to the evaporation site can be entered. If partial evaporation occurs, the pollutants will be concentrated into the remaining volume of water and returned to the system. It is anticipated that the entries for column O usually remain at 0.

The biosolids returned to the collection system contain metals removed across the biological portion of the reclamation facility. This model does not differentiate between soluble and particulate metals. The returned load is the total mass of the metal. If the composition of soluble versus suspended metals changes, the operator must adjust the WWTP removal efficiency accordingly.

In many cases, the reclaimed wastewater plant uses only raw wastewater as make-up water for the system. No additional Other Water source has been built into the mass balance.

If the service area includes more than one upstream reclaimed water system, the model input data must be an average for these facilities. In essence, this module is for a composite reclamation facility, to simplify calculations. Simply mass average the influent concentration

to all the facilities and average rejection and removal efficiencies until a good representation is achieved.

The reclaimed water WWTP will produce biosolids or sludge that is returned to the wastewater collection system. The amount of this material is not calculated. On the Input Data sheet in (cell AB 33), the sludge yield is specified as pounds per million gallons of wastewater treated. For full secondary treatment, the average sludge yield is around 2000 pounds per million gallons of wastewater treated, assuming an average strength or typical wastewater with BOD and TSS concentrations of 200 mg/L each or sludge yield factor that can be adjusted up or down depending upon the typical BOD and TSS concentrations of the wastewater treated.

8	AA	AB	AC
20			
21	**Flow Split Data for Water Balance**		
22	Flow Split To Membranes, %	75	
23	W 11 Water Sold out of service area	0.01	mgd
24	water Return factor	83	%
25	Membrane Product To blend	75	%
26	W 15 Product Sold out of service area	0.1	%
27	W 18 Water to Ind & power plants	0.1	mgd
28	W 24 Water to Industry	33	%
29	W xx Water to Power Plants	33	%
30	W xx Water to Cooling Towers	34	%
31	W 20 Water Loss factor	0.1	%
32	SP 1 WW to Reuse Plant	0.01	%
33	Reuse WWTP Sludge yield	2000	lbs sludge/ mgd
34	WWTP Sludge Yield	2000	lbs sludge/ mgd
35	SP 5 Reuse H2O direct to Reuse App	50	%
36	SP 9 Reuse App Returned to WWTP	50	%
37	SP 11 Reuse App Returned to WWTP	50	%
38	SP 12 Evaporation Losses	75	%
39	R 1 Flow to Effluent Reuse Plant	10	%
40	R 4 Flow to membrane system	75	%
41	R 12 Water Lost From System	75	%
42	R 10 Water Lost From System	25	%
43	R 18 Evaporative Losses	75	%
44	R 16 Evaporative Losses	75	%
45			
46	Ind 7 Split to Boiler	75	%
47	PP 7 Split to Boiler	75	%
48			
49	Ind 11 Reuse Flow to Industry Membranes	1.674	mgd
50	PP 11 Reuse Flow to PP Membranes	1.674	mgd
51	CT 6 Reuse Flow to Cooling Towers	1.5	mgd

8	A	K	L	M
10		Reuse WWTP Removal Efficiency	Reuse WWTP Destruction of Organics	Membrane Performance Reuse WWTP
11				
12				
13				
14				
15		% loss H2O		Recovery, %
16	Flow, mgd	5		75
17	Flow, gpm			
18	Flow, lb/ day			
19	Pollutant name input into Cell A22	Removal		
20	Pollutant names in Column A can l	Efficiency		
21	**Pollutant**	%	%	Rejection, %
22	Copper	#N/A	#N/A	#N/A
23	Arsenic	25	0	90
24	Cadmium	2	0	90
25	Chromium	2	0	90
26	Copper	50	85	90

Figure 5.8. Reclaimed water data entry.

The reclaimed water module also has several flow splits that enable the user to examine various operating scenarios. Stream SP 3 can be sent to the membrane system, or it can be split to have some of it go to the membrane system. The portion of reclaimed water that does not go to the membrane system can be further split to allow some or all of it to be returned to the collection system. At the Water Returned box, the user can specify the expected amount of evaporation. Since evaporation removes water from the system, it concentrates the soluble pollutants in the remaining liquid.

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The reclaimed water from the membrane system can be sent to the Water Lost box, which assumes it is distributed to uses that do not return it to the WWTP. In the Water Returned box, the user can specify the expected amount of evaporation. While the influent volume entered in the Water Returned box is a blend of membrane product water and reclaimed WWTP effluent, it is the loss to evaporation that is important.

The important factors pertaining to the reclaimed wastewater plant are evaporation losses and the return of concentrated pollutants in either the membrane brine or in the biosolids. High evaporation of reclaimed water means more-concentrated soluble material is returned to the collection system and there is a higher concentration of TDS and specific ions in the main WWTP effluent.

5.2.6   Effluent Reclamation

An effluent reclamation facility receives effluent from the WWTP and treats it by advanced treatment processes, such as nitrification and denitrification, to improve its quality, as illustrated in Figure 5.9. It is assumed that conventional sand or cloth medium filtration is used in conjunction with high-level disinfection. Phosphorus precipitation may occur ahead of filtration. The reclaimed WWTP module has operator-adjustable removal efficiencies and destruction of materials in the sludge stream to simulate nearly any treatment scenario. The operator must specify the pounds of sludge produced per million gallons of wastewater treated. This stream will be discharged back to the wastewater collection system. The data needed to run the Effluent Reclaimed Wastewater Plant Module are entered in the Input Data sheet at cells U 16 to Y 80 (Figure 5.10).
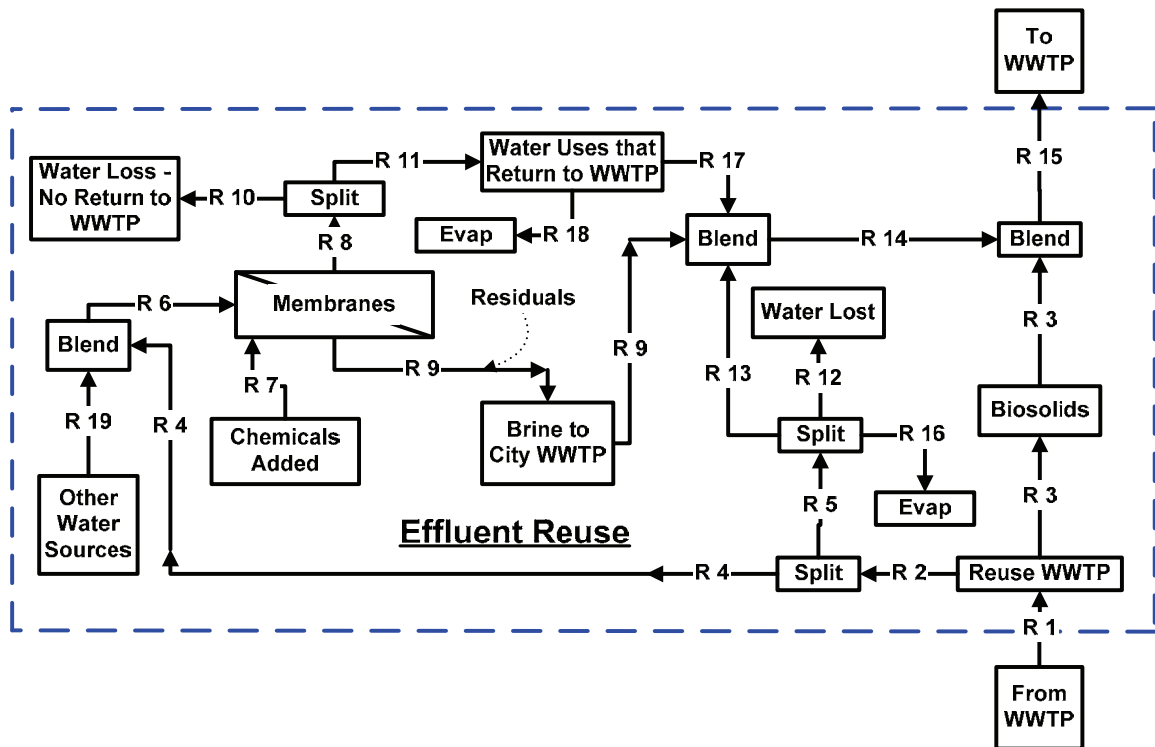

Figure 5.9. Process schematic for the Effluent Reclaimed Wastewater Plant Module.

The Effluent Reclamation Module is similar to the Reclaimed Wastewater Plant Module in many ways. The major difference is in the quality of the influent wastewater to be reclaimed. The influent to the effluent reclaimed module is the WWTP effluent. The effluent reclaimed WWTP is assumed to be nothing more than filtration. The filtration can occur either in the effluent reclaimed facility or in the main WWTP. This interpretation is left to the discretion of the model operator.

The rest of the module is similar to the WTP and Reclaimed Wastewater Plant Modules in that it has a membrane treatment system and various flow splits for water lost, return water, and evaporation. The only major difference is the addition of Other Water as make-up water to the membrane separation system. The volume and quality of Other Water added to the system can be entered in column U of the Input Data sheet. These variables are found in the Input Data sheet in the cell field AB 39 to AB 44 (Figure 5.8). Refer to the schematic in Figure 5.1 to match the stream numbers with the respective flow splits.

The biologically treated product water can be sent to the reclaimed distribution system or to membrane treatment. This flow split is specified at cell AB 40 on the Input Data sheet (Figure 5.8). Reclaimed stream R 5 is split into water that evaporates, water that is lost from the system (used for irrigation or shipped out of the service area), and water returned to the collection system. The flow splits are specified on the Input Data sheet at cells AB 41 and AB 44 (Figure 5.8). Water lost from the system removes the mass of water from the system, while evaporation removes only water and increases the pollutant concentration.

Stream R 4 is sent on to the membrane treatment system. Other Water, Stream R 19, can be added to Stream R 4 ahead of membrane treatment. The volume and quality of the Other Water are entered in column U and to the green cells in rows 16 through 80 on the Input Data sheet (Figure 5.10).

8	A	U	V	W	X	Y
9	Pollutant Information: Source Waters, Removal Efficiency, Destruction Efficiency					
10		Raw Water	Membrane	Chemicals	Effluent	Effluent
11		Source	Performance	Added	Reuse	Reuse
12		to Reuse	Effluent	Effluent	Evaporative	Evaporative
13		Membranes	Reuse WWTP	Reuse WWTP	Losses	Losses
14						
15		R 19	Recovery, %	R 7	R 18	R 16
16	Flow, mgd	2	75	0.001		
17	Flow, gpm	1,389		1		
18	Flow, lb/ day	16,680,000		8,340		
19	Pollutant name input into Cell A22 Updates all other sheets. LOOKUP Function Pulls data from Table into Row 22 Automatically.					
20	Pollutant names in Column A can be changed as needed. Row 22 designated as Quality Control See Mass Balance Check Sheet					
21	Pollutant	mg/L	Rejection, %	ppd	ppd	ppd
22	Copper	0.17	90	0.001	0	0
23	Arsenic	0.008	90	0.001	0	0
24	Cadmium	0.001	90	0.001	0	0
25	Chromium	0.001	90	0.001	0	0
26	Copper	0.17	90	0.001	0	0
80	Free Chlorine	0.01	90	0.001	0	0

Figure 5.10. Effluent reclaimed data entry.

The membrane separation system is defined by the membrane rejection characteristics entered into column M of the Input Data sheet (Figure 5.8). The membrane separation system could be simply an MF or a UF system removing suspended solids, or it could be an NF or RO system removing many of the soluble pollutants or a combination of these. MF and UF are often used as pretreatment for NF and RO. The model does not differentiate between the kinds of systems installed. The only items of importance are the respective membrane

rejection performance and the water recovery efficiency. This simplicity makes the model very user-friendly and powerful in that any future membrane system can be built into the scenario to assess impacts to downstream wastewater facilities. Membrane performance should be entered into column V on the Input Data sheet.

Like the WTP membrane separation systems, the reclaimed membrane application also has an entry for chemicals added to improve membrane performance or reduce scaling or fouling potential. Chemical additives must be broken down into their ionic components for entry into column W on the Input Data sheet (Figure 5.10).

In column X, any mass lost through evaporation can be entered into the system. For example, if the water sent to evaporation contains sodium and chloride, the mass of sodium and chloride transported to the evaporation site can be entered into column O. If partial evaporation occurs, the pollutants will be concentrated into the remaining volume of water and returned to the system. It is anticipated that the entries for column X will usually remain at 0.

Stream R 11 is the water that returns to the wastewater collection system and the amount of this stream that evaporates, both of which can be specified at cell AB 43 of the Input Data sheet. Evaporation removes water from the system without removing any pollutants. Finally, the return water, Streams R 17 and R 13, is combined with brine, R 9, and biosolids, Stream R 3, to form Stream R 15 and returned to the WWTP influent.

5.2.7   Composite Power Plant Module

Power plants are large water users, and their impact on the wastewater quality can be significant. This module addresses only boiler water treatment using membranes. Cooling towers are addressed separately in another module. A schematic of the Power Plant Module is shown in Figure 5.11.
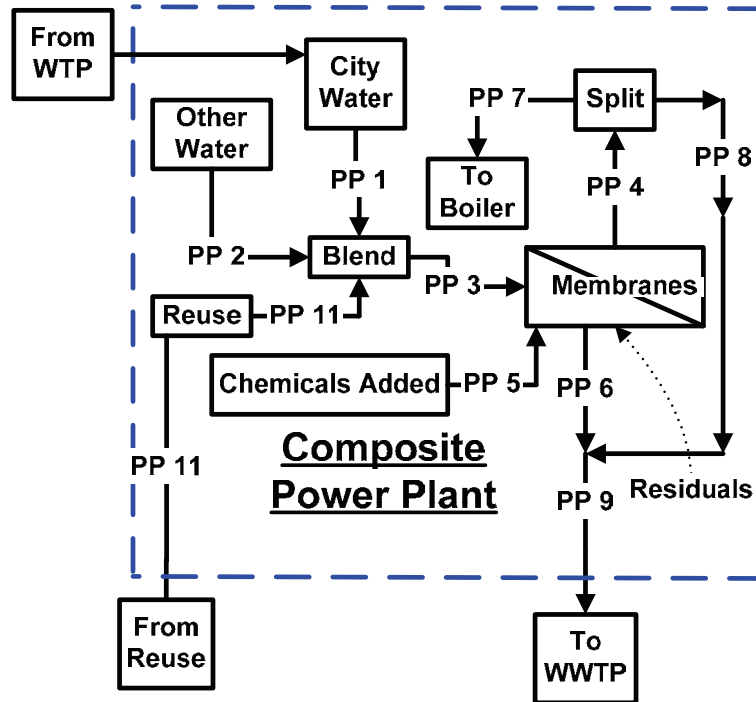
Figure 5.11. Process schematic for the Composite Power Plant Module.

In this module city water, other water, and reclaimed water are used individually or in any combination as feed water to a membrane separation system. Membrane product water is sent to the boiler to produce steam. Steam loss from the system is lost water that results in concentration of the pollutants in the respective waters into wastewater. Furthermore, chemicals can be added for membrane treatment. Any chemicals added to the system can be entered into the Input Data sheet in column BA (Figure 5.12).

The power plant data should be available from the IPP records. If these data are not in the information submitted for IPP permit renewal, IPP staff could visit the sites to collect this information. IPP staff must inspect each industrial site once per year. Another approach would be to send each industrial user a questionnaire regarding membrane applications. These data would then have to be summarized and entered into the Composite Power Plant Module.

Data entry into the Composite Power Plant Module begins on the Power Plant Data Entry sheet. This sheet is set up to allow up to 10 entries of actual plant operating data. The 11th data column is reserved for reclaimed water. The data from the 10 actual facilities are mass averaged into a composite entry for the Input Data sheet. The actual data are also mass averaged to determine membrane rejection and membrane water recovery. These data are also copied into the Input Data sheet.

The Power Plant Data Entry sheet (Figure 5.12) also asks for information about the water source. In row 14 of the Power Plant Data Entry sheet is a cell to enter either 1 for city water or 2 for other water. By specifying the water type, the model develops a composite for city water and a separate composite for other water. The other water is mass averaged into a

composite, and this information is transferred to the Input Data sheet, cells AV 23 to AV 80. If a new water source is being developed for power plants, then an alternate data set can be entered in cells AW 23 to AW 80. The entry in cell AU 14 indicates whether to use the actual data or the alternative data.

The volume of reclaimed water used is specified in cell AB 50 on the Input Data sheet (Figures 5.12 and 5.8). The flow of city water to the power plant is set in cells AB 28 to AB 30 on the Input Data sheet. Cell AB 29 sets the fraction of the city water sold to industrial customers as the flow to the power plant. Cells AB 28, AB 29, and AB 30 must add up to 100.

8	AT	AU	AV	AW	AX	AY	AZ	BA
9	Pollutant Information Power Plant: Source Waters, Removal Efficiency, Destruction Eff							
10		Composite	From Data	Alternate	Membrane	Performance	Alternate	Chemicals
11		Power Plant	Entry Sheet	Composite	Performance	From Data	Membrane	Added
12	For Real Data = 1	Raw Water		Power Plant	Composite	Entry Sheet	Performance	Composite
13	Alt Data = 2	Source		Raw Water	Power Plant			Power Plant
14	Use Real or Alt	1		Source	2			
15		R 16			Recovery, %			R 7
16		0			75	0	75	0.001
17		0						1
18		0						8,340
19	The Purple Color Indicates Data to be Entered			Light Blue = Data pulled from Another Sheet				
20								
21	Pollutant	mg/L	mg/L	mg/L	Rejection, %	Rejection, %	Rejection, %	ppd
22	Copper	0.0014	0.0014	0.25	90	0.0014	90	25
23	Arsenic	0.0050	0.0000	0.0050	90.0	%	90	25
24	Cadmium	0.0010	3.3480	0.0010	90.0	75.0	90	25
25	Chromium	0.0010	2325.0000	0.0010	90.0	0.0	90	25
26	Copper	0.2500	27922320.0000	0.2500	90.0	0.0	90	25
80	Free Chlorine	0.0000	0.0000	0.0100	90.0	0.0	90	25

Figure 5.12. Power plant data entry.

Membrane rejection performance and water recovery performance can be developed from actual data. Membrane rejection efficiency and water recovery efficiency are entered into the Power Plant Data Entry sheet. The mass of pollutants in the membrane permeate or product water stream is calculated and mass averaged into a system composite. A composite membrane rejection and water recovery efficiency is calculated from the individual facility data. The composite membrane rejection efficiency for each pollutant and water recovery efficiency are transferred to the Input Data sheet into cells AY 16 to AY 80. In cells AZ 16 to AZ 80, alternative membrane rejection efficiency and water recovery efficiency can be entered. Cell AX 14 is used to determine whether the actual composite performance data or the alternative input data are to be used (Figure 5.12).

Why allow an alternative data entry? At some time in the future a power plant may change operation, change the membrane process, or tighten up the site water balance and may want to know how such a change impacts WWTP effluent quality. Furthermore, power plants may change water sources, and if a poorer water quality source is developed, it will add more TDS or other pollutants to the system. These become part of the future "what if" scenarios that should be evaluated.

8	AA	AB	AC
20			
21	**Flow Split Data for Water Balance**		
28	W 24 Water to Industry	33	%
29	W xx Water to Power Plants	33	%
30	W xx Water to Cooling Towers	34	%
31	W 20 Water Loss factor	0.1	%
32	SP 1 WW to Reuse Plant	0.01	%
50	PP 11 Reuse Flow to PP Membranes	1.674	mgd
51	CT 6 Reuse Flow to Cooling Towers	1.5	mgd

Figure 5.13. Flow split data for water balance.

The high-purity product water from the membranes will go to the boiler. Stream PP 4 is split; some of it goes to the boiler and the rest to the wastewater collection system. The water to the boiler does not return to the wastewater collection system and represents water lost as steam or water that never returns to the wastewater collection system. The split is controlled at Input Data sheet cell AB 47. Stream PP 8 returns membrane product water to the wastewater collection system. Brine from the membrane separation process is combined with returned membrane product water to the wastewater collection system.

Chemicals used in treating membrane water can be specified on the Input Data sheet. If multiple power plants are present, chemical use from all of the plants must be calculated manually for each facility, and the sum of each pollutant added to the power plants can be entered in column BA of the Input Data sheet.

5.2.8   Composite Industry Module

Industry membrane use is limited to boiler water feed treatment in this mass balance. The number of possible membrane application types in industry are too numerous and complex for consideration in this modeling effort. Many of the membrane applications are used for product or material recovery. Control of pollutants from industrial operations is handled through the IPP.

A schematic of the Composite Industry Module is shown in Figure 5.14. This schematic is the same as the Composite Power Plant Module schematic.
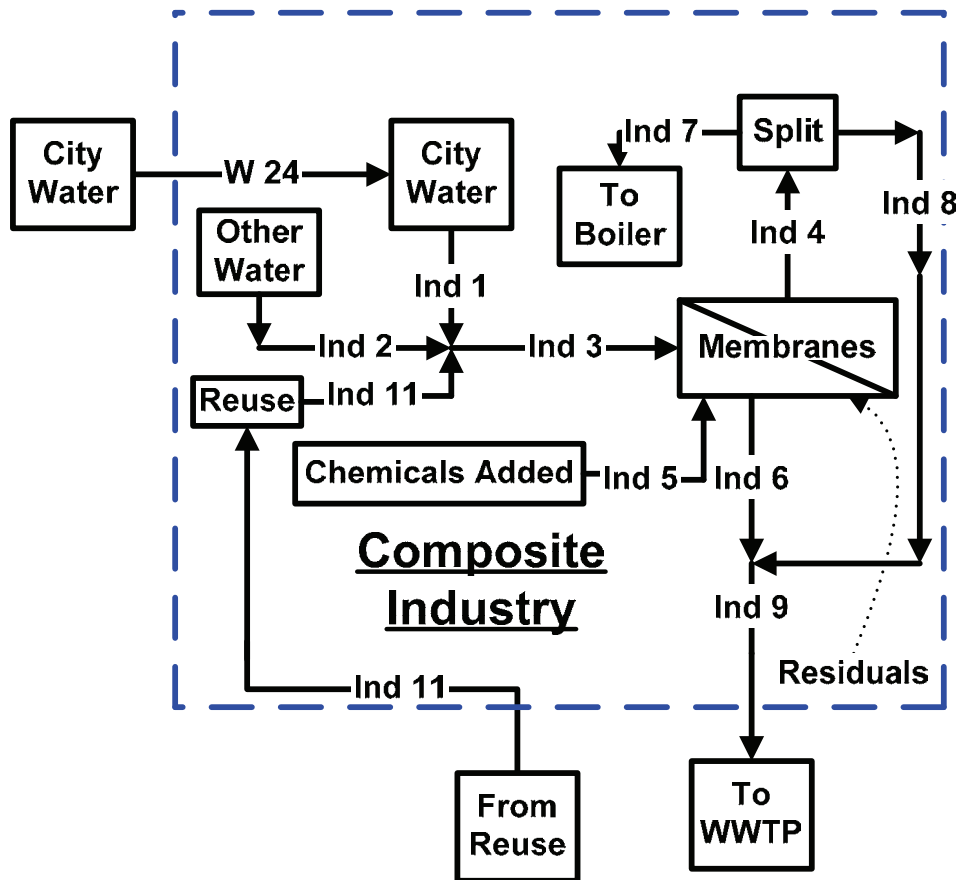
Figure 5.14. Process schematic for the Composite Industry Module.

In this module, city water, other water, and reclaimed water are used individually or in any combination as feed water to a membrane separation system. Membrane product water is sent to the boiler to make steam. Steam loss from the system is lost water that results in concentration of the pollutants in the respective waters into wastewater. Furthermore, chemicals can be added for membrane treatment. Any chemicals added to the system can be entered into the Input Data sheet in column AS (Figure 5.15).

Data entry into the Composite Industry Module begins on the Industry Data Entry sheet. This sheet is set up to allow up to 10 entries of actual plant operating data. The 11th data column is reserved for reclaimed water. The data from the 10 actual facilities are mass averaged into a composite entry on the Input Data sheet. The actual data are also mass averaged to determine membrane rejection and membrane water recovery. These data are also copied into the Input Data sheet.

The Industry Data Entry sheet also asks for information about the water source. Three separate waters or any combination of the three can be used as make-up water for the membrane system. The three waters are city water, WWTP effluent reclaimed water, and other water. In row 5 of the Industry Data Entry sheet there is a cell to enter either 1 for city water or 2 for other water. By specifying the water type, the model develops a composite for city water and a separate composite for other water. The other water is mass averaged into a composite Other Water value, and this information is transferred to the Input Data sheet, cells AN 23 to AN 80. If a new water source is being developed for industries, then an alternate

data set can be entered in cells AO 23 to AO 80. Cell AM 14 is used to select whether to use the actual data or the alternative data. The volume of reclaimed water used is specified in cell AB 49 on the Input Data sheet. The flow of city water to the power plant is set in cells AB 28 to AB 30 on the Input Data sheet. Cell AB 29 sets the fraction of the city water sold to industrial customers as the flow to the power plant. Cells AB 28, AB 29, and AB 30 must add up to 100 (Figure 5.18).

The industrial data should be available through the IPP records. If these data are not in the information submitted for IPP permit renewal, IPP staff could visit the sites to collect this information. IPP staff must inspect each industrial site once per year. Another approach would be to send each industrial user a questionnaire regarding membrane applications. These data would then have to be summarized and entered into the Composite Industry Module.

The mass of pollutants present in the membrane permeate or product water stream is calculated and mass averaged into a system composite. Composite membrane rejection and water recovery efficiency is calculated from the individual facility data. The composite membrane rejection efficiency for each pollutant and water recovery efficiency is transferred to the Input Data sheet into cells AQ 16 to AQ 80. In cells AR 16 to AR 80, alternative membrane rejection efficiency and water recovery efficiency can be entered. Cell AP 14 is used to determine if the actual composite performance data are to be used or if the alternative input data are to be used.

The high-purity product water from the membranes will go to the boiler. Stream IND 4 is split; some of it goes to the boiler and the rest to the wastewater collection system. The water to the boiler does not return to the wastewater collection system and represents water lost as steam or water that never returns to the wastewater collection system. The split is controlled at Input Data sheet cell AB 46. Stream IND 8 returns membrane product water to the wastewater collection system. Brine from the membrane separation process is combined with returned membrane product water to the wastewater collection system.

Chemicals used in treating membrane water can be specified on the Input Data sheet. If multiple industrial plants are present, chemical use from all of the plants must be calculated manually for each facility, and the sum of each pollutant added by the industrial plants is entered in column AS in the Input Data sheet.

Alternative data entry schemes have their place in such a model. At some time in the future, an industry may change its operation, change the membrane process, or tighten up the site water balance, and they may want to know how that would impact WWTP effluent quality. Furthermore, an industry may change water sources, and if a poorer water quality source is developed, it will add more TDS or other pollutants to the system. These become part of the future "what if" scenarios that should be evaluated.

8	AL	AM	AN	AO	AP	AQ	AR	AS
9	Pollutant Information Industry: Source Waters, Removal Efficiency, Destruction Efficiency							
10		Composite	From Data	Alternate	Membrane	Performance	Alternate	Chemicals
11		Industry	Entry Sheet	Composite	Performance	From Data	Membrane	Added
12	For Real Data = 1	Raw Water		Industry	Composite	Entry Sheet	Performance	Composite
13	Alt Data = 2	Source		Raw Water	Industry			Industry
14	Use Real or Alt	1		Source	2			
15		R 16			Recovery, %			R 7
16	Flow, mgd	0			76.0	0	76	0.001
17	Flow, gpm	0						1
18	Flow, lb/ day	0						8,340
19	The Sand Color Indicates Data to be Entered			Light Blue = Data pulled from Another Sheet				
20								
21	Pollutant	mg/L	mg/L	mg/L	Rejection, %	Rejection, %	Rejection, %	ppd
22	Copper	0.0014	0.0014	0.25	90	90	90	25
23	Arsenic	0.0016	0.0000	0.0016	90.0	90.00	90	25
24	Cadmium	0.0010	3.3480	0.0010	90.0	90.00	90	25
25	Chromium	0.0010	2325.0000	0.0010	90.0	90.00	90	25
26	Copper	0.2500	27922320.0000	0.2500	90.0	90.00	90	25
80	Free Chlorine	0.0000	0.0000	0.0100	90.0	90	90	25

Figure 5.15. Industry data entry.

5.2.9 Composite Cooling Tower Module

A schematic of the Composite Cooling Tower Module is shown in Figure 5.16. Three separate waters or any combination of the three can be used as make-up water for the cooling towers. The three waters are city water, WWTP effluent reclaimed water, and other water. The volume of reclaimed water used is specified in cell AB 51 on the Input Data sheet. The flow of city water to the power plant is set in cells AB 28 to AB 30 on the Input Data sheet. Cell AB 30 sets the fraction of the city water sold to industrial customers for use in cooling towers. Cells AB 28, AB 29, and AB 30 must add up to 100 (Figure 5.8).

In this module, city water, other water, and reclaimed water are used individually or in any combination as feed water to a cooling tower system. Water is evaporated to get rid of waste heat. Evaporation increases the concentration of the pollutants in the cooling tower blowdown that becomes wastewater. Furthermore, chemicals can be added for scale and corrosion control. Any chemicals added to the system can be entered into the Input Data sheet in column BG (Figure 5.17).

The cooling tower data should be available through the IPP records. If these data are not in the information submitted for IPP permit renewal, IPP staff could visit the sites to collect this information. IPP staff must inspect each industrial site once per year. Another approach would be to send each industrial user a questionnaire regarding membrane applications. These data would then have to be summarized and entered into the Composite Cooling Tower Module.

Data entry into the Composite Cooling Tower Module begins on the Cooling Tower Data Entry sheet, shown in Figure 5.17. This sheet is set up to allow up to 10 entries of actual plant operating data. The 11th data column is reserved for reclaimed water. The data from the 10 actual facilities is mass averaged into a composite entry for the Input Data sheet. The actual data are also mass averaged to determine cooling tower blowdown and the cycles of concentration. The cycles of concentration value is essentially a concentration factor. These data are also copied into the Input Data sheet.

The Cooling Tower Data Entry sheet also asks for information about the water source. In row 5 of the Cooling Tower Data Entry sheet, there is a cell to enter either 1 for city water or 2 for other water. By specifying the water type, the model develops a composite for city water and a separate composite for other water. The other water is mass averaged into a composite Other Water value, and this information is transferred to the Input Data sheet in cells BD 23 to BD 80. If a new water source is being developed for industries, then an alternate data set can be entered in cells BE 23 to BE 80. Cell BC 14 is used to select whether to use the actual data or the alternative data.
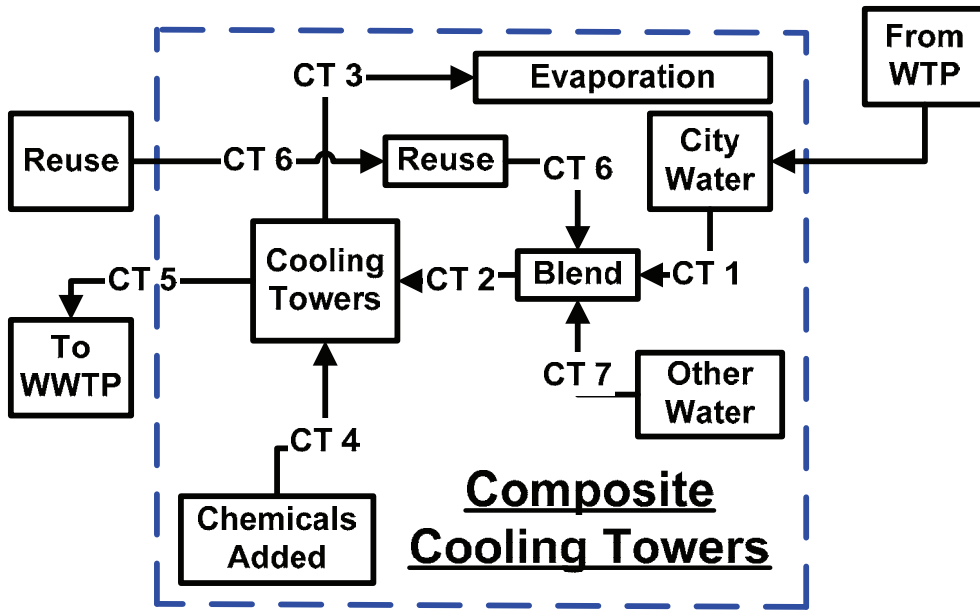
Figure 5.16. Process schematic for the Cooling Tower Module.

8	BB	BC	BD	BE	BF	BG
9	**Pollutant Information CT: Source Waters, Chemicals Added**					
10		Composite	From Data	Alternate	Cycles	Chemicals
11		Cooling Tower	Entry Sheet	Composite	Of	Added
12	For Real Data = 1	Raw Water		CT	Operation	Composite
13	Alt Data = 2	Source		Raw Water		CT
14	Use Real or Alt	1		Source		2
15		CT 7				CT 4
16		0			6.0000	0.001
17		0			0.00	1
18		0			6.00	8,340
19	The Green Color Indicates Data to be Entered			Light Blue = Data pulled from Another Sheet		
20						
21	**Pollutant**	mg/L	mg/L	mg/L		ppd
22	Copper	0.0014	0.0014	0.25		25
23	Arsenic	0.0050	0.0000	0.0050		25
24	Cadmium	0.0010	3.3480	0.0010		25
25	Chromium	0.0010	2325.0000	0.0010		25
26	Copper	0.2500	27922320.0000	0.2500		25
80	Free Chlorine	0.0100	0.8000	0.0100		25

Figure 5.17. Cooling tower data entry.

The Cooling Tower Data Entry sheet allows raw water to be designated as either city water or other water. In the water type box, row 5, enter 1 for city water and 2 for other water. The Cooling Tower Data Entry sheet calculates a composite performance for cooling towers. The data are also separated into city water and other water so that the other water composite characteristics and volume are pulled into the Input Data sheet. The data sheet calculates cycles of concentration for cooling tower operation.

The Input Data sheet allows one to select either the composite other water source for use in the model run or to manually input characteristics of the other water. The Input Data sheet provides further instructions. Similarly, you can select the number of cooling tower cycles of concentration or enter new performance data manually into the Input Data sheet.

Cooling tower performance can be developed from actual data. The mass of pollutants present in the cooling tower blowdown stream is calculated and mass averaged into a system composite. A composite blowdown concentration and cycles of operation are calculated from the individual facility data. The composite cooling tower cycles of operation value is transferred to the Input Data sheet in cell BF 17. In cell BF 16, an alternative cycles of operation value can be entered. Cell BF 14 is used to determine if the actual composite performance data are to be used or if the alternative input data are to be used.

Why allow an alternative data entry? At some time in the future an owner may change cooling tower operation, change chemical use, or tighten up the site water balance, and one would want to know how that impacts WWTP effluent quality. Furthermore, cooling tower systems may change water sources, and if a poorer water quality source is developed, it will add more TDS or other pollutants to the system. These become part of the future "what if" scenarios that should be evaluated.

5.2.10 WWTP Module

The WWTP Module receives flow from all modules, as shown in Figure 5.18. The flow and mass loads from each stream are added together, and then the influent concentration of each pollutant is calculated. The core WWTP module is a simple model based upon two sets of inputs: pollutant removal efficiency and pollutant destruction efficiency. The removal efficiency and destruction efficiency are operator-adjustable variables. The operator can enter or change removal or destruction efficiency at columns P and Q, respectively, on the Input Data sheet (Figure 5.19). A removal or destruction efficiency must be entered for every pollutant. It is assumed that the wastewater treatment portion of the module would include any effluent polishing, like filtration, enhanced phosphorus removal, and effluent denitrification systems.
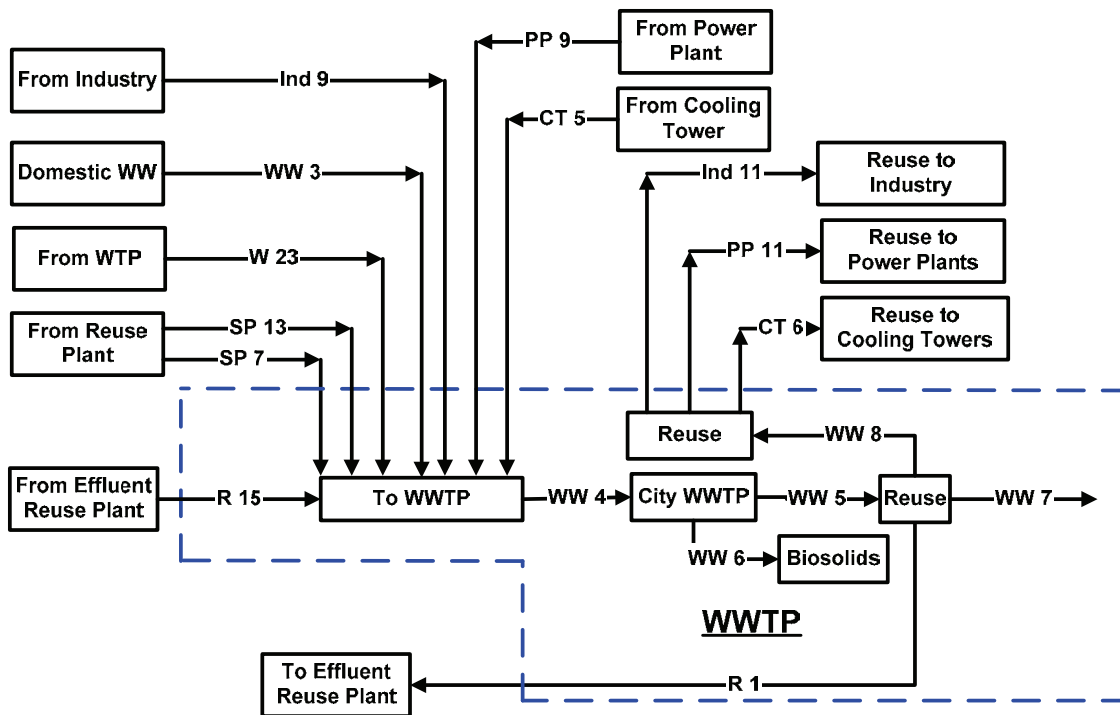
Figure 5.18. Process schematic for the WWTP module.

Treated effluent is sent to four different applications: cooling towers, power plants, industry, and the effluent reclaimed treatment plant. These four reclaimed streams create a circular reference in Microsoft® Excel. The flow to the effluent reclaimed treatment plant has a dummy data entry column to break the circular reference in the event that the model becomes unstable. The effluent reclaimed plant dummy data entry is in columns AM and AN in the WWTP sheet. The effluent reclaimed flow to cooling towers, power plants, and industry can be broken at the Input Data sheet at cells AB 49 to AB 51 (Figure 5.8) by entering 0 into any or all of these three cells.

The satellite plant is an independent module that does not create a circular reference. It simply removes water from the system and concentrates pollutants into a stream that is sent back to a wastewater collection system to be conveyed to the WWTP (Figure 5.15). The Industry, Power Plant, and Cooling Tower modules are also stand-alone systems if the reclaimed flow is set to 0.

Stream WW 7 is the WWTP effluent. This is the effluent stream that must be in compliance with the community's NPDES permit. It is also the water quality of the reclaimed streams for the Industry, Power Plant, Cooling Tower, and Effluent Reclaimed Plant modules. The quality of Stream WW 7 is critical, as it contains the cumulative impact of all chemical additions, evaporation, and water losses from the system.

Many of the pollutants are conservative pollutants; they are never destroyed. They are simply moved from one stream to another. Organic pollutants, BOD, and TSS are nonconservative pollutants, and these materials can be destroyed. This mass balance model does not include kinetic parameters to adjust pollutant removal based upon operating factors. This model uses the WWTP operating data and data collected from the IPP. Every 5 years IPPs are required to

reevaluate the current local limits. Part of this Local Limits evaluation requires staff to sample the WWTP influent and effluent to calculate overall removal performance and to sample biosolids quality. These data are needed for the mass balance model.

Conservative pollutant removal efficiencies should be set to 0. The reason these are not hard-lined into the program is to allow the operator to change the pollutant list.

For nonconservative pollutants, the destruction efficiency is based upon an overall destruction of a pollutant, and this destruction actually occurs in the biosolids stream in this model. The model does not require information on how a pollutant has been removed. It simply calculates an effluent quality based upon a removal efficiency. The mass that is destroyed is calculated in the biosolids stream.

The model also does not calculate sludge production. Sludge production is specified at cell AB 34. Typical sludge production for a WWTP with primary clarifiers and anaerobic digestion is around 2000 ppd solids per mgd of wastewater treated. This sludge yield is also an operator-adjustable variable.

The amount of reclaimed water sent from the WWTP effluent to reclaimed applications is set in cells AB 32, AB 39, AB 49, AB 50, and AB 51 (Figure 5.8).

5.2.11 Returned Reclaimed Water

There are six streams where reclaimed water is returned to the general wastewater collection system. These streams are as follows:

- Reclaimed Wastewater Plant Stream SP 7: brine from the membrane treatment system
- Reclaimed Wastewater Plant Stream SP 13: biosolids and returned reclaimed water from reclaimed applications
- Effluent Reclaimed Stream R 15: contains brine, biosolids, and returned reclaimed water from reclaimed applications
- Composite Industry Stream Ind 9: contains returned reclaimed water from membrane applications and includes water loss from evaporation
- Composite Power Plant Stream PP 9: contains returned reclaimed water from membrane applications and includes water loss from evaporation
- Composite Cooling Towers CT 5: cooling tower blowdown from city water, other water, and reclaimed water

These six streams transport pollutants back into the wastewater collection system. These six streams are also the leftover water returned to the wastewater collection system after irrigation and evaporative losses. Water lost through these applications returns the mass load of pollutants in a lower-volume water stream, thereby concentrating the pollutants in the combined wastewater collection system stream to the WWTP. The net impact is an increase in the pollutant concentrations in Stream WW 7 and an increase in the pollutant concentrations of the reclaimed waters pulled from the WWTP effluent. Only Stream SP 1 is unaffected by the accumulation of pollutants in the WWTP effluent.

There are some reclaimed systems that have no returned reclaimed streams. As far as the mass balance is concerned, this is good. There would be no mass accumulation in the system from the reclaimed streams if the quantity of returned reclaimed water were zero. The model

operator can set the system to have any degree of returned reclaimed water, from 0% to 100%.

5.2.12 Evaporation

Evaporation is the loss of water back to the atmosphere. This change of physical state will leave all dissolved solids behind. Therefore, evaporation is a concentration step. The WTP Module does not include evaporation, nor does the WWTP module, but the Reclaimed, Cooling Tower, Industry, and Power Plant Modules do include evaporation.

The reclaimed modules each allow a specific amount of water to be evaporated from the system. This is an operator-specified value that ranges from 0 to nearly 100%. Complete evaporation can also be duplicated by no water return.

Cooling towers are evaporation systems. The operator controls the cycles of concentration in the Cooling Tower Module. The cycles of concentration can be entered into the cooling tower data entry sheet or it can be specified in Input Data Sheet cell BF 18 (Figure 5.19).

8	BB	BC	BD	BE	BF	BG
9	**Pollutant Information CT: Source Waters, Chemicals Added**					
10		Composite	From Data	Alternate	Cycles	Chemicals
11		Cooling Tower	Entry Sheet	Composite	Of	Added
12	For Real Data = 1	Raw Water		CT	Operation	Composite
13	Alt Data = 2	Source		Raw Water		CT
14	Use Real or Alt	1		Source	2	
15		**CT 7**				**CT 4**
16		0			6.0000	0.001
17		0			0.00	1
18		0			6.00	8,340
19	The Green Color Indicates Data to be Entered			Light Blue = Data pulled from Another Sheet		
20						

Figure 5.19. Evaporation data entry.

Both the Industry and Power Plant Module Streams Ind 7 and PP 7, respectively, show the flow to the boilers. Steam is often lost from the system, and so this split of flow to the boiler versus the WWTP represents water lost to evaporation.

While simple in concept, the amount of evaporation in the system can significantly change the WWTP effluent quality or the quality of water sent for reclamation.

A simple mass balance has been developed on the sheet named "TSS and BOD Impacts to Wastewater Collection System." This sheet is set up to allow the operator to directly assess the impacts of BOD and TSS discharges from a reclaimed facility on the downstream BOD and TSS concentrations. It is known that the biosolids stream returned to the wastewater collection system from an upstream reclaimed application (satellite plant) can significantly change the wastewater collection system BOD and TSS concentrations.

This spreadsheet pulls biosolids stream data from the current model run and displays them in the boxes marked Reclaimed WWTP and Effluent Reclaimed WWTP. Data from the domestic wastewater collection system are pulled into cells C 8, C 10, and C 11. In cells E 8,

E 10, and E 11 the desired domestic wastewater flow and mass loads of BOD and TSS should be entered. In cells F 8, F 10, and F 11 enter the biosolids flow, mass of BOD (in pounds per day), and mass of TSS (in pounds per day). A new flow is calculated, and the resultant concentrations of BOD and TSS are also calculated. The spreadsheet also calculates an increase in the BOD and TSS concentrations for easy reference.

5.2.13 Reports

Nine standard reports have been developed in the mass balance model. These reports are summarized in Table 5.2.

Table 5.2. Standard Mass Balance Model Reports

• Raw Water Summary	• Process Inhibition
• Brine Summary	• Effluent Permit
• Water Quality Comparison	• Effluent Toxicity
• WWTP Influent and Effluent	• Sludge Limits
• MAHL	

The regulatory information needed for these reports is entered into the Input Data sheet in columns AF to AJ (Figure 5.20). Conditional formatting is used in these sheets to indicate if the model output is approaching the permit limit or threshold value. Red indicates that the permit or threshold value has been exceeded. Yellow indicates that the model output is above 70% of the permit or threshold value. The yellow warning is adjustable by the model operator. Typically, cell B 76 is used to set the threshold value.

These reports have been developed for the operator's convenience. These reports can be deleted if desired. Other reports can be developed to replace the current sheets. See the case study in Chapter 7 for a view of these reports.

5.2.14 Importance of Water Balance to Wastewater and Reclaimed Water

The water balance is critical to the mass balance, as water is the medium that moves mass around in the system. Water loss from the system has two impacts. Water is lost, and the dissolved materials in that water are also lost. So, water lost from the system does not increase the concentration of any pollutant until membrane separation systems are added into the mass balance. When dissolved pollutants are concentrated into the brine and the product water leaves the system, the brine is mixed back into the wastewater (minus the lost water), and the resultant pollutant concentration increases.

As previously noted, evaporation directly concentrates pollutants through the loss of water to the atmosphere. Evaporation is a system variable that can radically change the concentration of dissolved material in the WWTP effluent. The accumulation of dissolved materials in the WWTP effluent can cause permit violations and, more importantly, can make the reclaimed water less desirable for many reclaimed water applications.

Considerations for evaporation, water loss, and membrane separation systems are built into the mass balance. Their operation and efficiency are variables to be adjusted to create future "what if" scenarios to determine the impacts to WWTP effluent quality before they happen. It allows the operator to examine the impacts to effluent quality from changes in system

operation, addition of reclaimed projects, increases or decreases in evaporation, and other variables, like new water sources.

5.3   CALCULATION ERROR MESSAGES

As discussed above in Section 5.2.6, Stream R 15 creates a circular reference in Excel. The column Effluent Reclaimed WWTP on the data entry sheet is a dummy column used to break the circular reference. If an incorrect entry is made and the model begins to become unstable, the typical error references of Microsoft® Excel may pop up. These error messages are interpreted as numbers and are transported through the mass balance sheets. If this occurs, delete the values in column AY. Column AY is a copy of column AX. To reestablish the circular reference, copy column AX 16 into AY 16. If the problem is flow related, the model will become unstable. Proceed down the column and copy over values from AX to AY, one at a time, to find the pollutant that has the error.

If the model persists in being unstable, it means that the file has been corrupted or an inadvertent entry has been made into a cell containing a formula. At this point, one has two options. The first option is to troubleshoot the spreadsheet to find the error. This can be a tedious effort. The second option is to open the reference copy of the model and start over. Data entry can be copied over into the new spreadsheet. Note: It is very important to remember to save the new spreadsheet under a new name.

8	AE	AF	AG	AH	AI	AJ
19	Permit Limits and Limiting Conditions					
20			Process	Permit	Effluent	Sludge
21		MAHL	Inhibition	Limits	Toxicity	Limits
22	**Pollutant**	ppd	mg/L	mg/L	mg/L	mg/kg
23	Arsenic	1000	0.5	0.1	0.1	7000
24	Cadmium	200	0.5	0.1	0.1	1000
25	Chromium	200	0.5	0.1	0.1	1000
80	Free Chlorine	100	1	1	1	1000

Figure 5.20. Permit limits and limiting conditions.

CHAPTER 6

EVALUATION OF IMPACTS

6.1 OVERVIEW

The impacts of discharges of concentrate to the wastewater collection system are evaluated with the mass balance-based models created using Microsoft® Excel (see Appendix E). The impacts of system-wide discharges of concentrate are also evaluated in an Excel mass balance model (see Appendix D). The bases of the data input into the model are discussed in Chapter 5. Mass balance models for the discharges to a wastewater collection system are used to calculate the concentration of (1) biomass from a satellite MBR plant, (2) RO concentrate from a WTP, (3) backwash water or chemical cleaning solutions, and (4) concentrate from a satellite RO water reclamation plant. The mass balance model for a WWTP tracks the concentrate constituents from the headworks to secondary effluent, inclusive of diversion by solids handling.

The mass balance models provide a snapshot of stream quality under a specific set of operating conditions or a specific set of reuse projects. The model enables the operator to run future project or operating scenarios and to monitor stream quality for permit compliance or for reuse applications.

6.2 MASS BALANCE MODELS FOR DISCHARGE TO A WASTEWATER COLLECTION SYSTEM

6.2.1 Classification of Concentrate Streams

The concentrate streams are classified broadly as (1) biomass wastage from satellite MBR plants, (2) brine from high-pressure membranes used to treat brackish water or seawater, (3) backwash water and cleaning solutions from low-pressure membranes used to treat fresh water, and (4) concentrate from satellite or regional wastewater reclamation plants discharged to WWTPs.

6.2.2 General Modeling Approach

Different approaches are needed for different types of concentrate to quantify the concentrations of various constituents discharged to the WWTP. These simple mass balance models are intended to identify the process parameters that determine the concentration of each constituent. A review of the scientific literature and common textbooks was used to obtain the values for these process parameters.

The approaches below are intended only to show that rough estimates of concentrations of constituents reaching a WWTP are possible. The challenges that remain are to identify the important constituents of backwash, chemical cleaning, and concentrate streams and to estimate the concentration of each constituent that has negative impacts. For instance, the concentration of constituent A of a concentrate stream may be predicted to be very high, whereas the concentration of constituent B may be relatively low. However, constituent A may have relatively little negative impact on WWTP operations or discharge limits but

constituent B may have a much greater impact. The following are possible negative effects of backwash water, chemical cleaning solutions, and concentrate streams, as discussed in the Literature Review (Chapter 2):

- Corrosion from sulfides and chloride
- Deflocculation by various cations
- Inhibition of biological treatment by salts, metals, and specific organic chemicals
- Partitioning of metals and organic chemicals to biomass
- Inhibition of anaerobic digestion by salts, metals, and specific organic chemicals
- Effluent toxicity of salts, metals, and specific organic chemicals

6.2.3 Model I: Discharge of Biomass Wastage from a Satellite MBR Water Reclamation Plant to a Wastewater Collection System Line

Figure 6.1 is a schematic that describes the mass balance model for Model I.
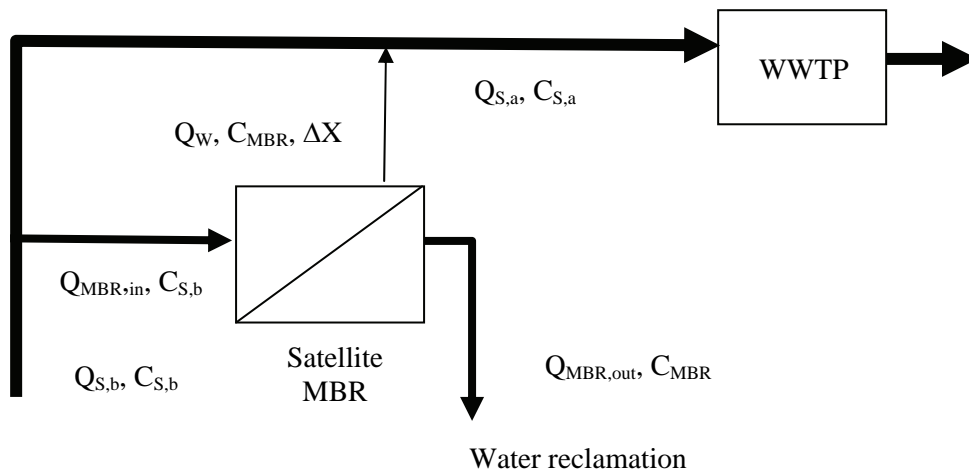
Figure 6.1. Mass balance around a wastewater collection system line with return from a satellite MBR water reclamation plant.

The parameters shown in Figure 6.1 are defined as follows:

$Q_{S,b}$ = flow rate in wastewater collection system line before satellite MBR plant
$C_{S,b}$ = concentration of constituent in wastewater collection system line before satellite MBR plant
$Q_{MBR,in}$ = flow rate to satellite MBR plant
$Q_{MBR,out}$ = flow rate to water reclamation
C_{MBR} = concentration of constituent to water reclamation
Q_W = flow rate of biomass wastage to wastewater collection system line from satellite MBR plant
ΔX = biomass growth in satellite MBR
$Q_{S,a}$ = flow rate in wastewater collection system line after satellite MBR plant
$C_{S,a}$ = concentration of constituent in wastewater collection system line after satellite MBR plant

The derivation of the mass balance model is provided in Appendix E. The equation to calculate the concentration of a chemical constituent in the wastewater collection system after discharge from the MBR plant is:

$$C_{S,a} = \frac{\left\{ f_R \left[f_W + K_D \left(Y_{MLSS} \times BOD_R + SS_{I,S,b} \right) \right] + \left(\frac{1}{f_{MBR}} - 1 \right) \right\} C_{S,b}}{f_W + \frac{1}{f_{MBR}} - 1} \qquad (6\text{-}1)$$

where:

f_R = fraction of constituent remaining in effluent of MBR unit
f_W = fraction of wastewater flow entering MBR returned to collection system ($Q_W/Q_{MBR,in}$)
f_{MBR} = fraction of wastewater flow in collection system entering MBR ($Q_{MBR,in}/Q_{S,b}$)
K_d = linear partitioning coefficient of constituent between water and biomass (in liters per milligram)
BOD_R = BOD removed by MBR (in milligrams per liter)
Y_{MLSS} = yield coefficient of biomass (in milligrams of MLSS per milligrams of BOD_R), where MLSS is the mixed liquor suspended solids
$SS_{I,S,b}$ = inert suspended solids entering MBR unit (in milligrams per liter)
$C_{S,b}$ = concentration of a constituent in collection system before satellite MBR plant (any units)
$C_{S,a}$ = concentration of constituent C in collection system after satellite MBR plant (any units)

To use eq 6-1 to find the concentration of a constituent in the wastewater collection system requires knowledge of the K_d, Y_{MLSS}, BOD_R, SS_I, f_{WR}, f_W, and f_i. Values of K_d can be obtained from the literature for each chemical of interest.

The model assumes that the sorbed constituent would be completely desorbed once the biomass reentered the wastewater collection system. This may be reasonable given that the biomass concentration becomes very low and reequilibration leads to nearly complete desorption.

The same mass balance approach applies for calculation of the suspended solids concentration in the wastewater collection system line after discharge from the MBR plant.

$$SS_{S,a} = \frac{Y_{MLSS} \times BOD_R + SS_{I,S,b} + \left(\frac{1}{f_{MBR}} - 1 \right) SS_{S,b}}{f_W + \frac{1}{f_{MBR}} - 1} \qquad (6\text{-}2)$$

where:

BOD_R = BOD removed by MBR (in milligrams per liter)
Y_{MLSS} = yield coefficient of biomass (in milligrams of MLSS per milligrams of BOD_R)
$SS_{S,a}$ = total suspended solids (SS) in collection system line blending with MBR plant discharge (in milligrams per liter)

$SS_{I,S,b}$ = inert SS in collection system before MBR plant (in milligrams per liter)
$SS_{S,b}$ = total SS in collection system before MBR plant (in milligrams per liter)

6.2.4   Model II: Discharge of RO Concentrate from a WTP to a Wastewater Collection System

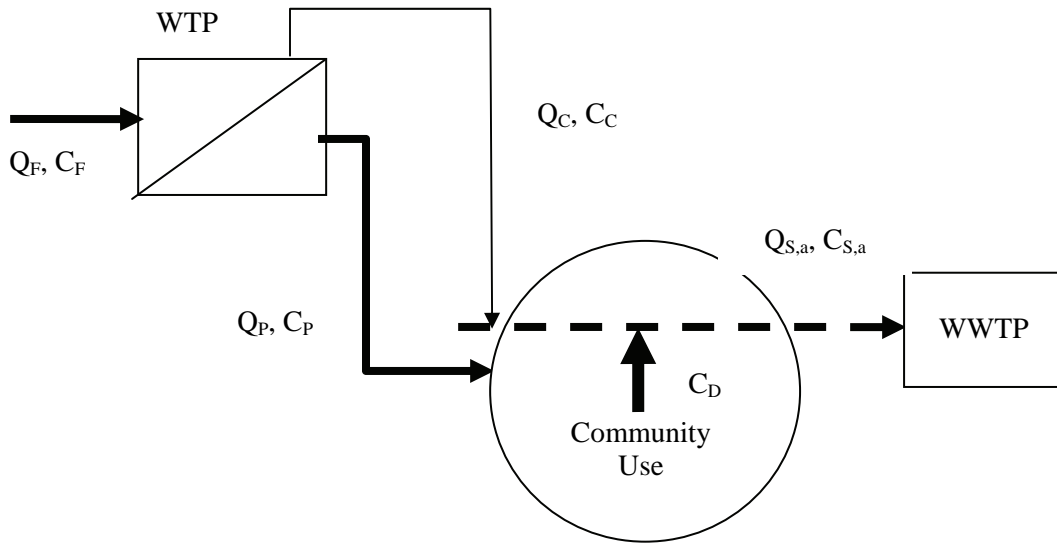Figure 6.2 is a schematic that describes the mass balance for Model II.

Figure 6.2. Mass balance around a wastewater collection system line with discharge of concentrate from a WTP.

The parameters shown in Figure 6.2 are:

Q_F = feed flow to membrane unit
C_F = concentration of constituent in feed flow
Q_C = concentrate stream from membrane unit
C_C = concentration of constituent in concentrate stream
Q_P = permeate stream from membrane unit
C_P = concentration of constituent in permeate stream
C_D = concentration of constituent from domestic flow
$Q_{S,a}$ = flow rate in wastewater collection system after blending with RO concentrate
$C_{S,a}$ = concentration of constituent in wastewater collection system blending with backwash water or chemical cleaning solution

The derivation of the mass balance model is provided in Appendix E. The equation to predict the concentration of a chemical constituent in the wastewater collection system line after discharge of concentrate from the RO plant is:

$$C_{S,a} = C_F + RC_D \qquad (6\text{-}3)$$

The effect of concentrate disposal is dilution of the concentration added by domestic discharges, thus explaining the term RC_D. The concentration in the wastewater collection system without discharge of concentrate is:

$$C_{S,a} = (1-r)C_F + C_D \qquad\qquad (6\text{-}4)$$

where:

r = fraction rejected of a constituent; $r = \dfrac{C_F - C_P}{C_P}$

6.2.5   Model III: Discharge of Backwash Water or Chemical Cleaning Solution to a Wastewater System

Figure 6.3 is a schematic of the mass balance for Model III.
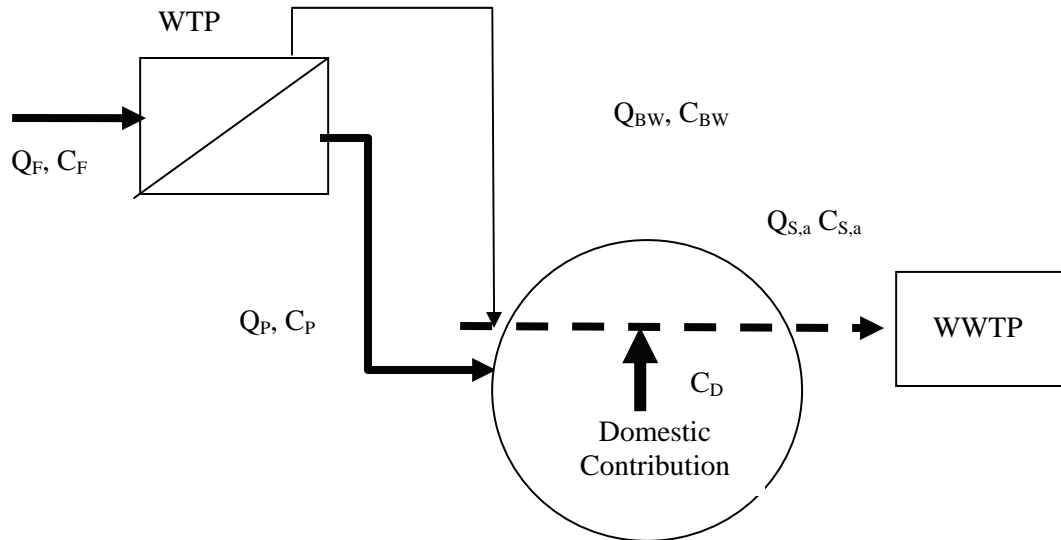
Figure 6.3. Mass balance around a wastewater collection system line receiving discharge of backwash water or chemical cleaning solution.

The parameters shown in Figure 6-3 are:

Q_F =   feed flow rate to membrane unit
C_F =   concentration of constituent in feed flow
Q_{BW} =   backwash water flow from membrane unit
C_W =   concentration of constituent in backwash water stream
Q_P =   permeate stream from membrane unit
C_P =   concentrate of constituent in permeate stream
C_D =   concentration of constituent from domestic use
$Q_{S,a}$ =   flow rate in wastewater collection system line after blending with RO concentrate

6.2.5.1 Continuous Generation of Backwash Water

The derivation of the mass balance for Model III is provided in Appendix E. The equation to calculate the concentration of a constituent in the wastewater collection system after discharge of backwash water or a chemical cleaning solution is:

$$C_{S,a} = \frac{C_F T_{FR}}{T_{BW}} + R(C_P + C_D) \qquad (6\text{-}5)$$

where the additional parameters needing definition are

T_{FR} = filtration run time

T_{BW} = backwashing time

$$R = \text{water recovery} = 1 - \frac{Q_{BW}}{Q_F}$$

6.2.5.2 Intermittent Addition of Backwash Water

The derivation of the mass balance model is provided in Appendix E. The equation to calculate the time-averaged concentration of a constituent in the wastewater collection system after discharge of backwash water or a chemical cleaning solution is:

$$C_S = \frac{f_D C_F T_{FR}}{T_{BW}} + R(C_P + C_D) \qquad (6\text{-}6)$$

where the additional parameter needing definition is:

f_D = fraction of day during which discharge of backwash water occurs

6.2.5.3 Discharge of Chemical Cleaning Solution

The derivation of the mass balance model is provided in Appendix E. A worst-case situation is assumed, in which the chemical cleaning solution is discharged directly without dilution with stored backwash water. The equation to calculate the concentration of a constituent from discharge of the cleaning solution into the wastewater collection system line is:

$$C_{S,a} = \frac{f_{cc} C_{cc} + C_D}{1 + f_{cc}} \qquad (6\text{-}7)$$

where:

C_{cc} = concentration of constituent in chemical cleaning solution
f_{cc} = fraction of permeate flow that is cleaning solution flow (Q_{cc}/Q_P)
C_D = domestic use-generated concentration of a constituent

6.2.6 Model IV: Satellite RO Water Reclamation with Discharge of Concentrate to Wastewater Collection System

Figure 6.4 is a schematic that describes the mass balance for Model IV.
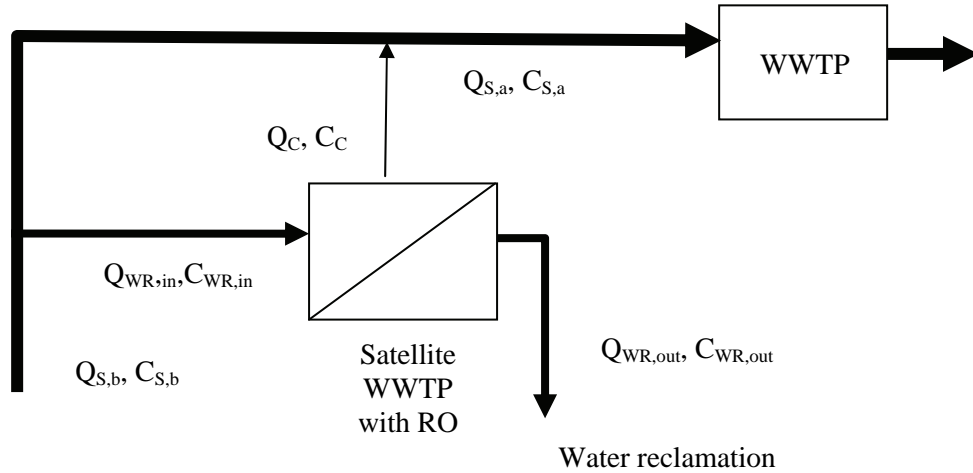
Figure 6.4. Mass balance around a wastewater collection system line receiving discharge of RO concentrate from a satellite water reclamation plant.

The parameters shown in Figure 6.4 are:

$Q_{S,b}$ = flow rate in wastewater collection system line before satellite RO plant
$C_{S,b}$ = concentration of constituent in wastewater collection system line before satellite MBR plant
$Q_{WR,in}$ = flow rate to satellite RO plant from secondary treatment
$C_{WR,in}$ = concentration of constituent after secondary treatment (feed to RO plant)
$Q_{WR,out}$ = permeate flow rate of satellite RO plant to water reclamation
$C_{WR,out}$ = concentration of constituent in permeate of satellite RO plant to water reclamation
Q_C = concentrate stream flow rate from membrane unit
C_C = concentration of constituent in concentrate stream
$Q_{S,a}$ = flow rate in wastewater collection system line after blending with RO concentrate discharge
$C_{S,a}$ = concentration of constituent in wastewater collection system line after blending with RO concentrate discharge

The derivation of the mass balance model is provided in Appendix E. The equation to calculate the concentration of a chemical constituent in the wastewater collection system line after discharge of concentrate from a satellite RO water reclamation plant is:

$$C_{S,a} = \frac{[1 - R(1 - r)]C_{WR,in} + \left(\dfrac{1}{f_{WR}} - 1\right)C_{S,b}}{\dfrac{1}{f_{WR}} - R} \tag{6-8}$$

where the additional parameters needing definition are:

f_{WR} = fraction of wastewater diverted to water reclamation; $f_{WR} = \dfrac{Q_{WR,in}}{Q_{S,b}}$

R = water recovery; $R = \dfrac{Q_{WR,out}}{Q_{WR,in}}$

r = fraction rejected of constituent; $C_{WR,out} = (1 - r)C_{WR,in}$

6.3 HOW TO USE THE MASS BALANCE MODEL FOR WASTEWATER COLLECTION SYSTEM LINE DISCHARGE

A Microsoft® Excel spreadsheet is provided to calculate the increase in concentrations of constituents in the wastewater collection system line in each of the four wastewater collection system discharge models and submodels herein. Examples for each are provided below.

6.3.1 Model 1: Discharge of Biomass Wastage from Satellite MBR Water Reclamation Plant to Wastewater Collection System Line

6.3.1.1 Chemical Constituent

$$C_{S,a} = \frac{\left\{ f_R \left[f_W + K_D \left(Y_{MLSS} \times BOD_R + SS_{I,S,b} \right) \right] + \left(\dfrac{1}{f_{MBR}} - 1 \right) \right\} C_{S,b}}{f_W + \dfrac{1}{f_{MBR}} - 1} \tag{6-9}$$

A key input parameter in this model is the biomass partitioning coefficient, K_d. An explanation of K_d is provided in the Literature Review (Chapter 2). K_d values for a wide variety of organic chemicals and the most environmentally important metals can be obtained from the scientific literature. The *Handbook of Environmental Data on Organic Chemicals* (Verschueren, 1996) includes a large compendium of K_d values for soil, sediment, and biomass wherein the concentrations of chemicals in the solid phase are expressed per unit weight of organic carbon in these solids rather than per unit weight of the solids. Estimating the percentage of organic carbon in the biomass allows the K_d to be expressed per unit weight of biomass. For example, if the K_d value per unit weight of organic carbon is 10 L/g and the biomass is 50% organic carbon, then the K_d per unit weight of biomass is 5 L/g.

Log K_d values reported for organic chemicals on the Priority Pollutant List (in liters per gram) range from about −1 to 3 and, correspondingly, K_d varies from 0.1 to 1000 L/g (Burkhard, 2000; Schwarzenbach et al., 2003; Verschueren, 1996; Weber and DiGiano, 1996). However, experimental K_d values are available for relatively few of the organic chemicals in production. Thus, correlation techniques with other related chemical characteristics have been developed to predict K_d values when data are not available. Examples of these are the octanol/water partition coefficient and water solubility (Chu and Chan, 2000; Schwarzenbach et al., 2003).

Correlations must be applied cautiously, because the chemical compositions of solid and water phases differ from one wastewater treatment plant to another, and this affects the K_d value for any specific metal or organic chemical (Seth et al., 1999; Wei et al., 1999). Many of the log K_d values for metals (Cu, Cd, Cr, Ni, Pb, and Zn) in biomass (Table 2.15 of the Literature Review of Chapter 2) are on the order of 1 and, correspondingly, K_d =10 L/g. However, the range of values in some studies is wide, because K_d values have been shown to increase with decreasing suspended solids concentrations (Karvelas et al., 2003; Nguyen et al., 2005). For this example, a typical reported K_d value of 10 L/g for metals (Table 2.15 of in the Literature Review of Chapter 2) was used.

The input parameter values selected for eq 6-9 are:

K_d = 10 L/g
Y_{MLSS} = 0.65
BOD_R = 200 mg/L
$SS_{I,S,b}$ = 100 mg/L
f_R =   0.9
f_{MBR} = 0.4
f_W = 0.1
$C_{S,b}$ = 100 µg/L

All values of the MBR operating parameters depend upon the characteristics of the specific MBR plant. The biomass yield coefficient (Y_{MLSS}) can be taken from general textbooks on wastewater treatment (e.g., Tchobanoglous et al., 2003). In this example, the biomass produced is based on a BOD_R value of 200 mg/L.

The fraction remaining (f_R) of the metal of interest is 0.9. This is a high value because the ultrafilters and microfilters in MBR treatment do not remove dissolved metals and remove only a fraction of the colloids with which metals may be associated.

The model thus provides the user with the capability to simulate any extent of water reclamation. In this example, the fraction of wastewater flow rate in the collection system line that enters the MBR plant (f_{MBR}) is 0.4, and the fraction of wastewater flow rate entering the MBR in the biomass waste stream (f_W) returned to the collection system line is 0.1.

The concentration of the metal of interest in the wastewater collection system ($C_{S,b}$) may depend on local ordinances that limit the discharge of metals. $C_{S,b}$ was selected as 100 mg/L in this example. Partitioning of the metal to biomass and inert suspended solids is assumed. The concentration of inert suspended solids is 100 mg/L. The units for K_d are converted in the Microsoft® Excel spreadsheet from L/g to L/mg to be consistent with the units for BOD_R and SSI.

Substituting all constants into eq 6-9 gives $C_{S,a}$ = 229 mg/L, which is 2.3 times greater than the concentration in the wastewater collection line without biomass discharge. If the fraction of wastewater used for water reclamation increases to 0.6, the $C_{S,a}$ increases to 369 mg/L, an increase of 3.7 times in concentration. Whether the partitioning of metal to biomass and returning it to the wastewater collection results in toxicity to the activated sludge process or to anaerobic digestion must then be determined by separate mass balance modeling at the WWTP, as described in Section 6.3.

6.3.1.2 Suspended Solids

$$SS_{S,a} = \frac{Y_{MLSS} \times BOD_R + SS_{I,S,b} + \left(\dfrac{1}{f_{MBR}} - 1\right)SS_{S,b}}{f_W + \dfrac{1}{f_{MBR}} - 1} \tag{6-10}$$

The input parameter values selected for eq 6-10 are:

$Y_{MLSS} = 0.65$
$BOD_R = 200$ mg/L
$SS_{I,S,b} = 100$ mg/L
$SS_{S,b} = 200$ mg/L
$f_{MBR} = 0.4$
$f_W = 0.1$

The concentration of suspended solids in the wastewater collection system after discharge from the MBR plant is 331 mg/L, which is 1.7 times greater than that without discharge of biomass. Increasing the fraction of wastewater collection system flow to the MBR plant to 0.6 will increase the suspended solids concentration in the system after biosolids discharge to 474 mg/L, or by a factor of about 2.4.

6.3.2 Wastewater Collection System Line Model II: Discharge of RO Concentrate from a WTP into a Wastewater Collection System

$$C_{S,a} = C_F + RC_D \tag{6-11}$$

A moderately brackish water is presented as an example where the increase in sulfate by discharge of concentrate is of interest. In this example, the sulfate concentration in the feed to RO is 800 mg/L, which is the low end of the range reported by Mickley (2000) for brackish waters. A typical value of the concentration of sulfate added by domestic use is 50 mg/L (Mickley et al., 1993). The parameter values for input to eq 6-11 are:

$C_F = 800$ mg/L
$C_D = 50$ mg/L
$R = 0.8$

Substituting the above parameter values into eq 6-11 shows that $C_{S,a} = 840$ mg/L.

Without the return the concentration:

$$C_{S,a} = (1-r)C_F + C_D \tag{6-12}$$

Assuming a typical rejection of TDS by RO of 0.9 (i.e., 90% rejection) and substituting all input parameter values into eq 6-12 gives $C_{S,a} = 130$ mg/L.

The sulfate concentration is 6.5 times higher than without concentrate discharge. The ACI 318 Building Code (2002) includes the ranges of sulfate concentrations associated with the following levels of corrosion of concrete: negligible, <150 mg/L; moderate, 150 to 1500 mg/L; severe, 1500 to 10,000 mg/L; very severe, >10,000 mg/L. Sulfate concentrations

ranging from 30–80 mg/L in Sacramento, CA, 150–200 mg/L in Omaha, NE, and 115–140 mg/L in Lakeland, FL, have been noted as more than sufficient to produce corrosion by anaerobic formation of sulfide (Wizgall et al., 1990). These citations indicate that corrosion of collection system piping caused by RO concentrate could be a problem. However, even in the absence of the concentrate discharge, the addition of 10% of the sulfate from the feed water in the RO permeate stream (80 mg/L) may be sufficient to increase corrosion.

6.3.3 Model III: Discharge of backwash water or chemical cleaning solution to a wastewater collection system

6.3.3.1 Continuous generation of Backwash Water

$$C_{S,a} = \frac{C_F T_{FR}}{T_{BW}} + R(C_P + C_D) \tag{6-13}$$

Backwash water is typically produced in low-pressure membrane filtration of drinking water. However, a low-pressure membrane system could also be installed in a water reclamation plant for which the same model applies. Continuous generation of backwash water is a worst-case situation that would occur only in a large water treatment plant where many membrane units are operated in parallel so that at least one unit is always being backwashed.

For this example, alum coagulation–flocculation is assumed ahead of the membrane unit. A typical dosage of alum [$Al_2(SO_4)_3 \bullet 18H_2O$] is 50 mg/L, of which about 10% is aluminum. The precipitate that forms is $Al(OH)_3$, which produces a concentrate that is 2.9 times the concentration of aluminum, or about 15 mg/L. A further assumption is that 100% of the SS in the raw water are completely rejected by the membrane. The raw water SS concentration in this example, 50 mg/L, is representative of fairly turbid raw water. Domestic use of water adds typically 200 mg/L of SS. MF and UF are capable of removing 100% of the suspended solids.

The operating characteristics of low-pressure membrane filtration will depend on local conditions. However, a backwashing frequency of 30 min, a backwashing time of 5 min, and water recovery of 90% are typical.

The above assumptions produce the following input parameter values to eq 6-13:

C_F = 50 mg/L of SS + 15 mg/L $Al(OH)_3$ = 65 mg/L
C_D = 200 mg/L of SS
T_{FR} = 30 min
T_{BW} = 5 min
R = 0.9
C_p = 0 mg/L (100% rejection of particles)

Substitution of all parameter values into eq 6-13 gives C_S = 375 mg/L of SS. The SS in the backwash water thus increase the SS concentration in the wastewater collection system by a factor of 1.7.

6.3.3.2 Intermittent Discharge of Backwash Water

$$C_S = \frac{f_D C_F T_{FR}}{T_{BW}} + R(C_P + C_D)$$ (6-14)

The same parameter values are used for this illustration as for the continuous discharge of backwash water. The additional parameter in eq 6-14 is the fraction of a day (f_D) during which backwash flow is generated (the backwashing events are assumed to be uniformly distributed throughout the day).

Assuming $f_D = 0.5$, eq 6-14 gives $C_{S,a} = 278$ mg/L of SS. The SS discharged in the backwash water thus increase the SS in the wastewater collection system by a factor of 1.4. This factor will decrease as f_D becomes smaller.

6.3.3.3 Discharge of Chemical Cleaning Solutions

The concentration of a constituent during the period the cleaning solution is being discharged is:

$$C_{S,a} = \frac{f_{cc} C_{cc} + C_D}{1 + f_{cc}}$$ (6-15)

Citric acid is a typical constituent of chemical cleaning agents. The concern associated with citric acid is its contribution to the BOD_5. The Literature Review in Chapter 2 gives a BOD_5 range of 5000–10,000 mg/L in cleaning solutions (Reardon et al., 2005).

For this example, the fraction of permeate flow generated by the chemical cleaning solution was arbitrarily selected as 0.01 (1% of the flow in the wastewater line). The volume of cleaning solution depends very much on the membrane equipment used in the treatment plant.

The inputs to eq 6-15 are:

$C_{cc} = 5000$ mg/L of BOD_5
$f_{cc} = 0.01$
$C_D = 200$ mg/L of BOD_5

Substitution of the input parameter values into eq 6-15 gives $C_{S,a} = 248$ mg/L of BOD_5.

Thus, the discharge of citric acid in a chemical cleaning solution will temporarily increase the BOD_5 in the wastewater collection system by a factor of 1.2, which could exacerbate corrosion of the line because it creates conditions that lead to sulfide generation. The loading rate to the activated sludge system will also increase. This example does not suggest severe adverse effects, because the BOD_5 increases by only 20%. However, the parameter values needed in eq 6-15 could vary widely depending upon the chemical cleaning procedures used.

6.3.4 Model IV: Satellite RO Water Reclamation with Discharge of Concentrate to a Wastewater Collection System

$$C_{S,a} = \frac{[1-R(1-r)]C_{WR,in} + \left(\frac{1}{f_{WR}}-1\right)C_{S,b}}{\frac{1}{f_{WR}}-R}$$ (6-16)

The constituent of interest in this example is TDS. Ranges of TDS in domestic wastewater are available (e.g., Tchobanoglous et al., 2003 and Reardon et al., 2005). The concentration of TDS entering the RO satellite reclamation plant is the same as in the wastewater collection system (500 mg/L in this example), because TDS are not removed by conventional secondary treatment that precedes RO. Other assumptions in the example include the following: the fraction of wastewater diverted from the collection system for water reclamation (f_{WR}) is 0.5; the fractional rejection by RO is 0.9; the water recovery is 0.8. The input parameter values for eq 6-16 are:

$C_{S,b}$ = 500 mg/L of TDS
$C_{WR,in}$ = 500 mg/L of TDS
r = 0.9
R = 0.8
f_{WR} = 0.5

Substitution of the input parameter values into eq 6-16 gives $C_{S,a}$ = 800 mg/L of TDS.

The TDS increases in the wastewater collection system line by a factor of 1.6.

6.4 MASS BALANCE MODEL FOR WWTPs

6.4.1 Overview

The mass balance model for WWTPs is discussed in detail in Chapter 5. In this section, use of the model to predict impacts is noted. The model tracks the transport and concentration of metals and ions that are never destroyed in a WWTP. Key areas of concern are:

- The WWTP headworks load for regulated materials, such as metals and other compounds regulated by local limits
- Biological process inhibition and toxicity threshold concentrations
- WWTP sludge quality
- WWTP effluent quality for comparison with NPDES permit limits and stream water quality standards
- WWTP effluent quality for common ions that constitute TDS and other specific ions of concern, such as chloride and sulfate, for impact on effluent acute and chronic toxicities
- Localized impacts in the wastewater collection system for corrosion
- Impact on the primary clarifier performance at the WWTP

Most POTWs will have an IPP. The IPP coordinator is responsible for developing technically based local limits. (The procedure is discussed in Chapter 4.) The Local Limits study will be

a source for much of the operating data needed to run the mass balance model. The removal efficiencies needed for the WWTP input parameters will come from the IPP, threshold inhibition values will come from the IPP Local Limits study, and effluent limits for liquid and biosolids will be summarized in the Local Limits study. As part of the Local Limits study, domestic wastewater will be sampled and characterized. The Local Limits study will identify a location or several locations for sampling.

A WTP is required to publish water quality information on a quarterly basis. The data for the WTP may differ from the data for the WWTP. The water plant may have a complete ion balance as well as data on metals and organic contaminants. The WWTP will typically perform a priority pollutant scan but may not have a complete ion balance unless it is involved in reuse projects. The WWTP may not have seasonal data unless a special sampling has been done.

6.4.2 System-Wide Mass Balance Model

The mass balance model tracks pollutants throughout the treatment system and allows various types of treatment technologies to be used, specifically, membrane treatment systems. It allows water to be sold outside the service area, tracks the mass of pollutants transferred outside the system, and keeps track of the materials that eventually reach the WWTP.

As new reclamation projects are added to the wastewater system, the mass balance tracks loss of water from the system and the resulting increase in pollutant concentration. Membranes separate ions from water and concentrate the rejected ions into a brine stream. The brine is usually returned directly to the collection system, and so there is little loss of the dissolved ions. Many membrane separation processes also include chemical addition to minimize scaling and improve membrane performance.

The mass balance provides information on the following impacts to the system:

- Wastewater quality into the WWTP
- Wastewater (reuse) quality out of the WWTP
- Reuse projects
- New water source quality
- A new industry or power plant planning to begin discharge to the wastewater system or using reclaimed water
- Quality of reclaimed water

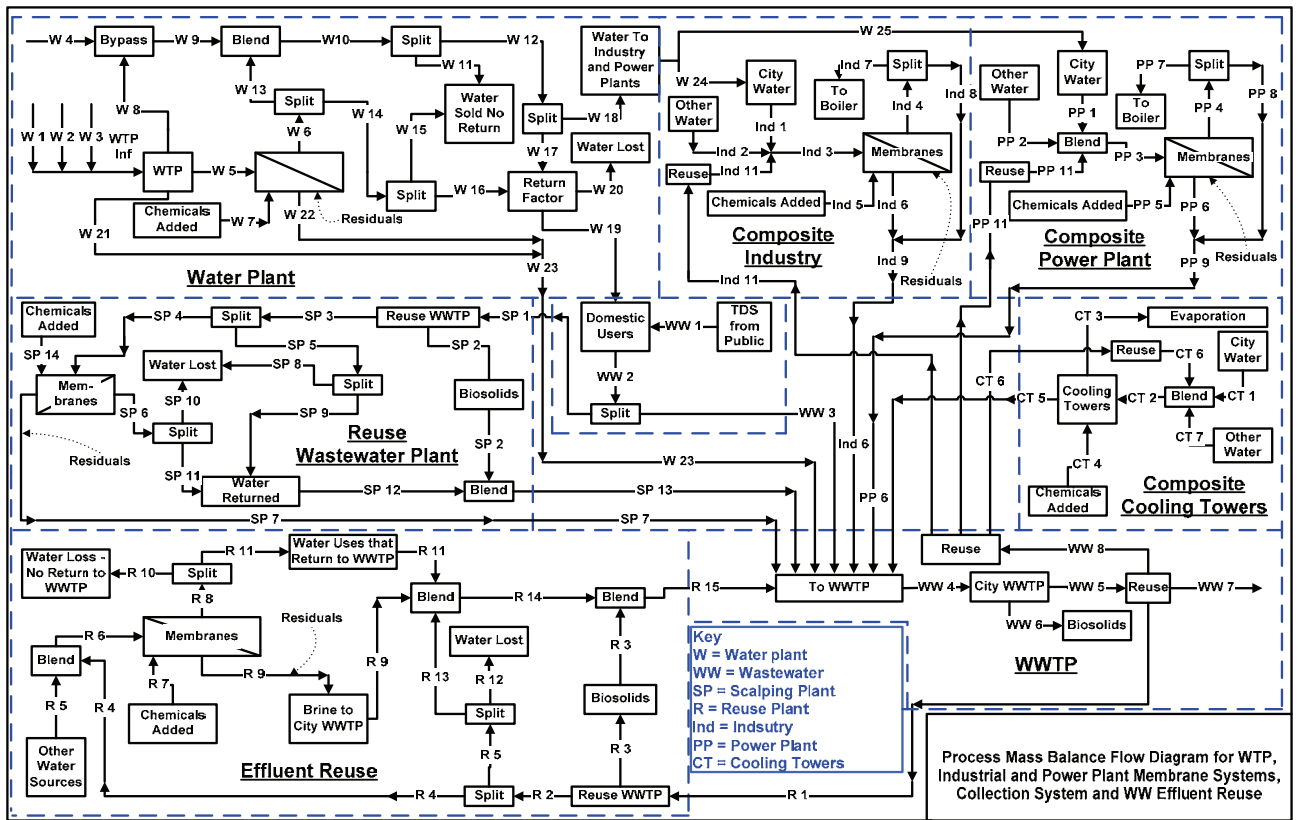The mass balance model contains interactive information on every stream, as illustrated in Figure 6.5.

Figure 6.5. Overall mass balance schematic.

Any variable, such as stream flow, source water quality, reuse stream flow, chemicals added, or pollutant removal performance, can be changed. This allows the utility staff to evaluate the impacts of future projects for reuse, of adding membrane separation systems to treat water or wastewater, or of changes in water sources, industrial facilities, or power plants.

A word of caution: The mass balance model is a Microsoft® Excel spreadsheet and includes the many quirks and issues particular to the use of Excel. It is recommended that a master copy of the model be maintained in a secure location. New evaluations are accomplished by opening the master spreadsheet and saving it into a new file folder with a new name.

Chapter 5 provides a detailed description of how to set up and run the mass balance model. Chapter 7 provides an example of how the model can be used. Based on experience with the project's utility partners, some noted impacts are further explored in this chapter.

6.5 INTERPRETATION OF MASS BALANCE MODELS FOR A WWTP

The reports developed by the mass balance models are described in Chapter 5 and noted in Table 6.1. These can be used for interpreting the results from a model run. They provide a summary of the model conditions in that run. A shortcoming is that they do not carry over information from a previous run. To create a historical profile, it is necessary to copy the results from a given run and use the "paste special" function to copy the model data into a new column. Instructions in the Microsoft® Excel model tell the user how to do this.

Table 6.1. Standard Mass Balance Model Reports

• Raw Water Summary	• Process Inhibition
• Brine Summary	• Effluent Permit
• Water Quality Comparison	• Effluent Toxicity
• WWTP Influent and Effluent	• Sludge Limits
• MAHL	

The model has many variables that can be modified. When using the model, it is important to examine results after every condition change in order to develop a feel for the cause–effect impacts of model parameter changes. Some changes have little impact on WWTP influent quality, but others have a major impact. If numerous changes are made in a single run, it is easy to miss the cause of major changes in the resulting stream quality.

Consider the following situation: There are three possible reuse projects proposed by three different entities. If all three are implemented, the effluent TDS rises to over 2000 mg/L. Does one tell all three entities they cannot implement their project? What if only one of the projects caused the dramatic increase in the effluent TDS concentration? The other two projects could move ahead. Before making a major decision, make sure the factors are known. This will mean running multiple model runs, changing only one parameter at a time. Furthermore, for any request for connection to the system from a user that is denied, the applicant will want a technical reason for the denial. The key is documentation, and the model provides that documentation.

6.5.1 Impacts of TDS and Specific Ions

The impacts of buildup of TDS within a wastewater system have not been very well documented, as noted in Chapter 2. However, as the pressure to reuse more water increases, the potential rise in TDS concentrations in a WWTP effluent must be considered. In the Phoenix, AZ, system the TDS concentration has risen to the point where it causes effluent toxicity, which is a major concern. The threshold toxicity limit is not well defined, and additional testing is needed. The specific ion make-up of the water seems to cause the threshold toxicity to shift, yet it appears that higher bicarbonate concentrations are beneficial whereas higher sodium chloride concentrations are detrimental.

The point where brine enters the collection system also requires scrutiny. The mass balance model discussed earlier in this chapter will help when quantifying the potential impact of such discharges. High TDS concentrations or sulfate and chloride may cause corrosion of concrete pipe. High concentrations of TDS and specific ions may also corrode pumps, metal pipe, and submerged equipment, such as clarifier mechanisms.

The WWTP processes, such as TSS removal in primary clarifiers, may also be inhibited. This may increase the BOD and TSS loads to the secondary treatment system, increasing the oxygen demand. Chloride concentrations over 8000 mg/L will inhibit nitrification.

The model can help to identify such impacts. The specific ion information is part of the model output, and this information can be tracked as various model conditions are changed.

Three factors can significantly change the TDS concentration in the WWTP: influent evaporation, water sold or moved outside of the system, and chemical addition. Evaporation has the biggest overall impact, as it removes water from the system, which increases the

concentration of TDS in the remaining water. If the service area has a large industrial base, cooling towers are likely to have a major impact on the TDS concentration in WWTP influent, since there is not only water evaporation but also that the water is often treated with acidic chemicals and disinfectants. The impact of the chemicals is amplified by evaporation. Using WWTP effluent as cooling tower make-up water will recycle TDS and increase their concentrations.

Water treatment plants using membrane separation systems can also have a large impact on the WWTP influent TDS concentration. If product water is sold outside of the WWTP service area, a disproportionate amount of brine containing TDS will be sent to the WWTP; even though the WTP produces the water used by the population in the service area, it will probably want to discharge brine to the wastewater collection system, as other disposal options are very expensive. Even if the WTP were to discharge brine to the local receiving stream, the TDS would not have gone away, and the WWTP may be faced with the same permit issues. If the WTP discharges to a different watershed, the brine impact to the wastewater utility may be minimal.

The final factor is water loss after membrane treatment in reuse facilities. If high-quality, low-TDS water is not returned to the wastewater system recombined with the brine, the brine becomes concentrated in the WWTP influent.

6.5.2 Conventional Pollutants

The satellite reuse wastewater plant will return biosolids to the collection system; which will have several major impacts to the collection system and main WWTP, and output from the model is provided to assess such impacts.

The biosolids load from the satellite reuse WWTP contains active biomass, which will consume BOD in the wastewater system and will amplify the anaerobic conditions already prevailing in the system. Anaerobic conditions lead to the formation of hydrogen sulfide, which is corrosive to the system piping and other components. Additional information on this subject is available in the EPA Sulfide Control Manual. The American Concrete Pipe Institute has developed a collection system model to predict hydrogen sulfide generation.

If RO membrane systems are used upstream of the WWTP in the wastewater collection system, the background concentration of sulfate will be increased, which will allow more hydrogen sulfide to be produced.

The biosolids returned to the collection system can become partially solubilized in the system, which will increase the soluble BOD concentration passing to secondary treatment.

The biosolids discharged to the wastewater collection system must be treated at the main WWTP. The primary clarifiers at the main WWTP must be designed for the additional load. Biosolids processing will also concentrate all of the sidestream return loads on the secondary processes at the main WWTP.

6.5.3 Metals

Metals will be concentrated in any returned reuse wastewater. The model does not differentiate between metals in the raw wastewater and in the returned reuse water. There is some evidence that the metals in the WWTP effluent may be chelated with soluble organic

material, which makes the metals more soluble and resistant to conventional precipitation. Data should be collected before and after reuse projects have been implemented to determine if the removal effectiveness across the WWTP has changed.

6.5.4   Trends

The model can be used to evaluate trends in wastewater quality. Each model run is based on a specific set of input values. To evaluate a trend, multiple runs must be made and compared. After selecting the parameters to track, the key model variations being studied may be saved. Instructions included in the model describe how to do this.

The data then can be graphed to visually display trends in the results.

6.6   MAHL ISSUES

Reclaimed water plant effluent and return reuse wastewater will contain regulated materials. Reuse will have reduced the volume of wastewater entering the main WWTP. Evaporation will have concentrated the pollutants. Pollutants that were initially close to the MAHL may be concentrated to the point that they exceed MAHL threshold mass loads. While simple concentration of pollutants will not increase the influent mass load, returning the mass in the returned reuse wastewater will increase the mass load to the headworks.

Another consideration is the impact of changing effluent flow and its impacts on the mixing zone used to develop the MAHL. As described in Chapter 5, the model assumes that the removal of a pollutant through the WWTP remains unchanged as wastewater is reused. This may not be the case, and any changes in the WWTP pollutant removal efficiency must be accounted for in the model.

CHAPTER 7

CASE STUDY

7.1 INTRODUCTION

To put the system-wide mass balance model in perspective, an example of model runs was developed for the Oklahoma City WWTP. This example should provide guidance on input data configuration and on output options. Examples of point source examples of impacts are presented in Chapter 6.

7.2 THE OKLAHOMA CITY WWTP

The North Canadian WWTP consists of four secondary treatment facilities with a combined capacity of 80 mgd which were built in three phases and are designed to operate in parallel. The plant essentially has three activated sludge facilities with the recent addition of oxidation ditches. Phase 1, rated at 40 mgd, was placed into operation in 1981; phase 2, rated at 20 mgd, started operation in 1985; phase 3, built in two parts, is also rated at 20 mgd.
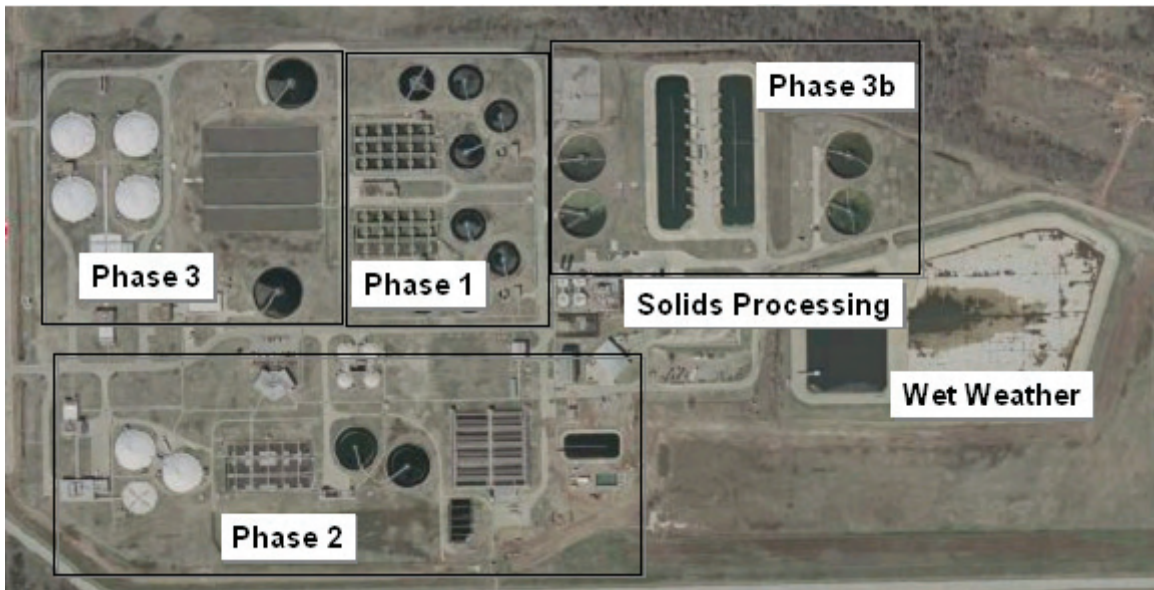
Figure 7.1. North Canadian WWTP.

Redbud Energy, which operates a power-generating facility in the Oklahoma City wastewater service area, uses treated municipal wastewater for nonpotable uses and discharges cooling tower blowdown to the North Canadian WWTP. The wastewater is pumped 10 miles from the North Canadian treatment to the Redbud facility.

7.3 MODEL INPUT DATA

The North Canadian WWTP serves as a good example of the ability of the system-wide mass balance model to predict impacts of solids loading on the total system. While the Oklahoma City plant does not use membrane treatment systems, it does recycle treated effluent to the Redbud power plant, which uses an RO system to treat water for boiler feed and large cooling towers. The blowdown from the cooling towers and all other wastewaters are returned to the North Canadian WWTP, in essence forming a recycle system. Of the recycled water sent to the power plant, 85% is lost to evaporation and the remaining brine is returned to the WWTP. Since the power plant adds chemicals to the cooling towers to reduce scaling, it not only concentrates TDS but also adds more TDS to the return stream.

The information on the domestic concentrations contribution in the spreadsheet is meant to convert drinking water to wastewater. The inputs for increases in the concentrations of pollutants and specific ions can include industrial contributions. (The Industry Module, however, deals only with membrane systems treating municipal or other raw waters for use in the production facility. The Industry Module is not meant to track the contribution of BOD and other pollutants.) Similarly, the Cooling Tower Module can include large cooling towers used at industrial sites. When used in this manner, the mass of pollutants from cooling tower operation should be subtracted from the domestic contribution.

The modeling of the system in Oklahoma City is simplified, because the City's WTP does not use membrane technology. Sale of water outside the service area is not a factor, because the sludge and other waste streams from the water plant are not discharged to the WWTP but flow to a holding pond. Therefore, the water plant operation can be simplified to produce the influent wastewater flow. Operation of the membrane systems of the industrial facilities and the power plants can be adequately simulated through the generic domestic contribution.

The model runs which were used as examples were designed to simulate the impact of a single large-volume reuse customer, the new power plant. Two conditions were compared: (1) before the new power plant started operation and (2) after the new power plant started operation.

In setting up the model, it is important to remember that when a number is divided by zero, an error message is displayed. When this error message is displayed and that cell is used in another calculation, the error message is propagated. Soon, the spreadsheet will be populated with #DIV/0! terms in the cells. To eliminate this problem, do not enter 0 for any flow; instead, use a very small flow value, like 0.000001 mgd. This entry will add a very tiny amount of mass into the model, which should be insignificant considering the plant flow is 50 mgd. For smaller plants, simply make the flow value even smaller.

The input data for the drinking water quality, the domestic contribution, and the WWTP influent concentrations are listed in Table 7.1. A schematic of the Oklahoma City system is shown in Figure 7.2.

Table 7.1. Model Input Data for Drinking Water, Domestic Contribution, and WWTP Influent before Power Plant Startup

Pollutant	Conc in Drinking Water, mg/L	Conc in Domestic Contribution, mg/L	Conc in WWTP Influent, mg/L
Metals and Selected Organics			
Arsenic	0.008	0.03	0.01
Cadmium	0.0001	0.0008	0.038
Chromium	0.001	0.0182	0.0009
Copper	0.005	0.005	0.0192
Cyanide	0	0.01	0.01
Lead	0.0052	0.015	0.01
Mercury	0.00002	0.00025	0.0202
Nickel	0.0002	0.014	0.00027
Silver	0.0007	0.0085	0.0142
Zinc	0.09	0.1	0.0092
Aluminum	0.02	0.08	0.19
Antimony	0.0009	0.004	0.0049
Barium	0.003	0.01	0.013
Beryllium	0.0001	0.0005	0.0006
Boron	0.15	0.15	0.3
Iron	0.01	0.1	0.11
Manganese	0.016	0.025	0.041
Molybdenum	0.001	0.008	0.009
Selenium	0.0005	0.0015	0.002
Strontium	0.02	0.55	0.57
Thallium	0.001	0.004	0.005
Tin	0	0	0
Phenol	0.001	0.069	0.07
MBAS	0	0	0
Specific Ions and Conventional Pollutants			
Calcium	36	1	37.0
Magnesium	14.7	1	15.7
Sodium	60	25	75.0
Potassium	8.3	0.5	8.8
Silica	5	1	6.0
Bromide	0	0	0
Chloride	60	25	85
NO_3+NO_2 as N	7.7	0	7.7
Sulfate	47	18	65
Carbonate	0	0	0
Bicarbonate	200	20	220
Fluoride	1	0	1.0
Phosphorous	0.1	2.8	2.9
Orthophosphate	0	0	0
Sulfide	0	0	0
Sulfite	0	0	0
BOD	1	194	195
COD	2	334	336
Diazinon	0	0.0643	0.06430
TDS	484	100	584
TSS	0	255	255
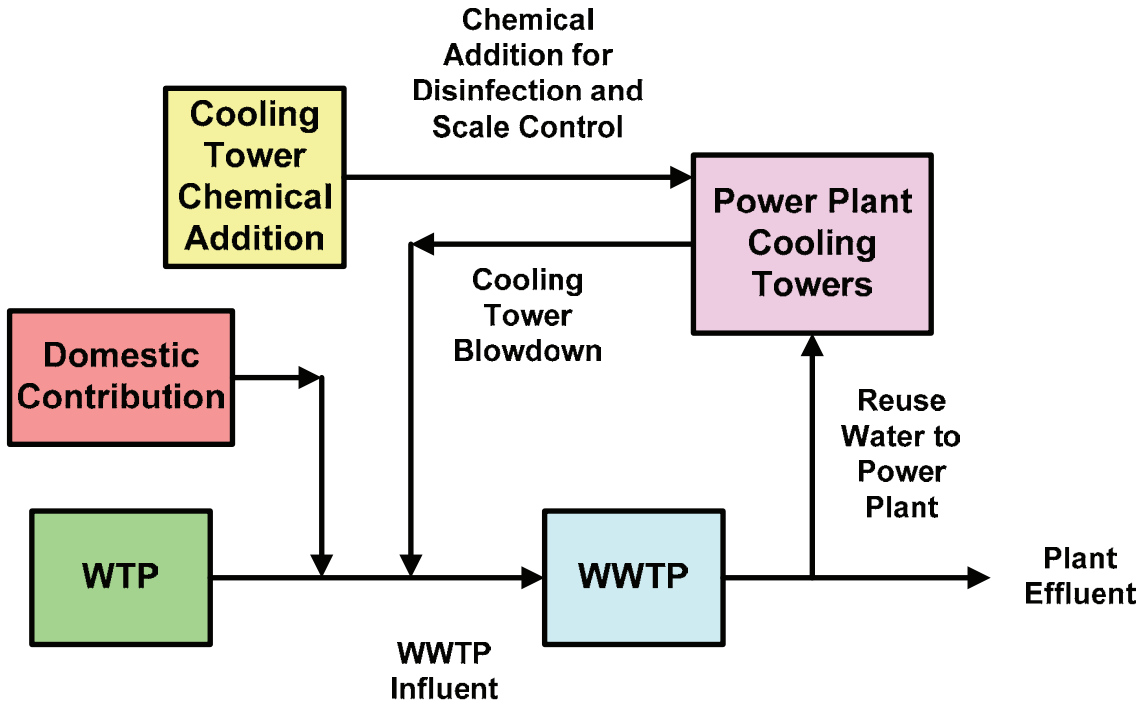
Figure 7.2. Simplified schematic for evaluation of a new reuse application.

The Redbud power plant utilizes 10 mgd of WWTP plant effluent. The power plant operates the cooling towers at an overall seven cycles of concentration. Sulfuric acid and sodium hypochlorite are the primary chemicals added to the cooling towers to control scale and biological growth. Table 7.2 illustrates the data collected for input into the models.

Table 7.2. Cooling Tower Data for Input into Model

Parameter	Value
Flow Data	
Effluent pumped to power plant	10 mgd
Flow returned from power plant	1.429 mgd
Overall cycles of concentration	7
Chemicals Added as Specific Ions	
Sodium	828.21 ppd
Chloride	1262.97 ppd
Sulfate	5403 ppd
TDS	7498.18 ppd

7.4 MODEL RUNS

The model was run under three operating scenarios:

- Run 1: Base case before reuse by power plant
- Run 2: Normal reuse by power plant
- Run 3: Worst-case scenario with high power plant water recycling

These three scenarios demonstrate basic operation of the model. The model run spreadsheets are included in Appendix F.

7.4.1   Model Results

A comparison of the model results is presented in Table 7.3. The concentrations of some metals and organic pollutants rose slightly while others declined slightly. Since there was no net increase in mass from the cooling tower facility, the changes in metal concentrations were based on removal efficiency through the WWTP. The metal concentrations will decrease with high removal efficiencies and increase with low removal efficiencies.

The most important relationship to be determined is whether or not the metals that pass through the WWTP the first time are removed as efficiently under recycling conditions. If they are not, a nonremovable metals fraction will be created. So far at Oklahoma City, the data do not indicate that metals removal is being adversely affected by recycling of the brine back to the headworks of the WWTP.

As expected, TDS and the typical high-concentration ions are accumulating in the system. Calcium, sodium, chloride, and sulfate are increasing in concentration. The TDS rise from water loss is about 20%, from 584 mg/L to 699 mg/L. (The water loss is 8.57 mgd.) The TDS rise from chemicals added for cooling tower water treatment is about 20 mg/L.

Table 7.3. Model Results

Pollutant	Conc in WWTP Influent, mg/L	Conc in WWTP Effluent before Reuse Started, mg/L	Conc in WWTP Effluent after Reuse Started, mg/L
Metals and Selected Organics			
Arsenic	0.01	0.028786	0.028651
Cadmium	0.038	0.000891	0.004481
Chromium	0.0009	0.019005	0.019510
Copper	0.0192	0.005050	0.005469
Cyanide	0.01	0.005050	0.005862
Lead	0.01	0.010201	0.010023
Mercury	0.0202	0.000109	0.000995
Nickel	0.00027	0.01004	0.011754
Silver	0.0142	0.006505	0.014981
Zinc	0.0092	0.067167	0.065371
Aluminum	0.19	0.025262	0.025008
Antimony	0.0049	0.004852	0.008910
Barium	0.013	0.012875	0.022604
Beryllium	0.0006	0.000594	0.054374
Boron	0.3	0.297289	0.290375
Iron	0.11	0.005556	0.005580
Manganese	0.041	0.016579	0.018246
Molybdenum	0.009	0.008911	0.027909
Selenium	0.002	0.001981	0.103836
Strontium	0.57	0.564245	0.550074
Thallium	0.005	0.004951	0.004937
Tin	0	0	0
Phenol	0.07	0.003535	0.003441
MBAS	0	0	0
Specific Ions and Conventional Pollutants			
Calcium	37.0	37.08	44.4
Magnesium	15.7	15.73	18.84
Sodium	75.0	85.13	104.24
Potassium	8.8	8.82	10.6
Silica	6.0	5.46	6.4
Bromide	0	0	0
Chloride	85	85.1	105.4
NO_3+NO_2 as N	7.7	0.078	0.076
Sulfate	65	65.1	92.9
Carbonate	0	0	0
Bicarbonate	220	111	120
Fluoride	1.0	1.002	1.2
Phosphorous	2.9	0.73	0.75
Orthophosphate	0	0	0
Sulfide	0	0	0
Sulfite	0	0	0
BOD	195	19	19.5
COD	336	51	51
Diazinon	0.06430	0.064	0.077
TDS	584	585	721
TSS	255	18	18

A third model run was made to examine a worst-case reuse scenario, in which the power plant utilizes 14.5 mgd with 10 cycles of concentration and produces a 1.45-mgd blowdown flow. Chemical use was estimated to proportionally increase the volume of water pumped to the power plant. The results of this run compared with those under the previous conditions are listed in Table 7.4.

Table 7.4. Comparison of Model Results

Pollutant	Conc before Reuse, mg/L	Conc in WWTP Effluent at Start of Reuse, mg/L	Conc in WWTP Effluent at Maximum Reuse, mg/L
Sodium	85.13	104.24	117
Chloride	85.1	105.4	119
Sulfate	65.1	92.9	111
TDS	585	721	814

The cooling tower blowdown or brine stream will have a high TDS concentration. The blowdown stream quality is shown in Table 7.5.

Table 7.5. Power Plant Waste Streams at Startup and Maximum Reuse Flows

Pollutant	Conc in Waste Stream at 10-mgd Reuse and 7 Cycles, mg/L	Conc in Waste Stream at 14.5-mgd Reuse and 10 Cycles, mg/L
Sodium	798	1271
Chloride	843	1343
Sulfate	1102	1756
TDS	5673	9037

7.4.2   System Impacts

These results demonstrate that reuse will increase the effluent TDS and specific ion concentrations. The increase in the concentrations is linked to the amount of water lost from the system through evaporation. With membranes, system loss of water can be through the sale of high-quality permeate or product water with brine return to the wastewater collection system. While membranes and cooling towers are different systems, their net impacts on a system are the same.

Since the power plant was placed on line, the raw water quality has been improving. This seems to be contradictory, since the power plant has been shown to add TDS and the initial data did show a higher TDS concentration. Oklahoma City obtains water from surface sources which are affected by drought. As the drought eased, the water quality improved and the TDS concentration in the raw water decreased.

When comparing different operating conditions, it must be remembered that the input data may be changed by outside influences, and so it is necessary to use these model results carefully. As in any model, the results are only as good as the input. As noted, with changing water supply quality the impacts of cooling tower blowdown and membrane residuals can be confused with changes in the raw water supply. It is important to look at TDS and specific ion increases over the long-term background to ascertain changes from the long-term baseline of TDS.

7.5   SUMMARY

These runs for the Oklahoma City system show a marked increase in effluent TDS and ion concentrations. Even a 50-mgd modeled plant can experience a 230-mg/L increase in TDS concentration from a reuse project. While Oklahoma City had one big project that increased TDS and ion concentrations, the same result would occur if a number of smaller projects were implemented. It is important to remember that increases in pollutant concentrations are cumulative.

CHAPTER 8

POLICY CONSIDERATIONS

8.1   DEFINING WHEN A PROBLEM MAY EXIST

Of what import might an increase to solids loading to a collection system or WWTP be for a community? The answer lies in part on the results of modeling done by using the work from this project. However, it may also be important if the community raw water supply has a relatively high TDS concentration. Adding more membrane solids would further increase this concentration. The initial loading, combined with the additional loading, could have a significant impact on the collection system or the WWTP.

A review of the literature to compare and contrast a utility system with the findings in other systems may help to reveal similarities between the utility's system and operating data from other systems. This is an important first step which should be taken when beginning to assess the potential impacts of solids loading, both now and in the future.

8.2   COMPLETION OF THE MASS BALANCE MODEL

In order to determine whether or not the potential impact of the solids loading to the system is a function of the raw water supply, industrial usage, or water reuse practices, the system-wide mass balance must be completed. By collecting the data as noted in Chapter 5 (and in the description of the model in Appendix E), the model can be prepared for the appropriate number of runs. Once these runs have been completed, it will be evident from the output data exactly where the particular increase in solids is coming from throughout the system over time.

8.2.1   Evaluation of Alternative Water Sources

If it is determined that an increase in TDS concentration over time is a direct function of the raw water quality, it may be necessary to consider alternative water sources, which might reduce the influent solids concentrations. This is a particular problem in the western United States, such as in Arizona, where surface sources of water supplies may contain high concentrations of solids. The brackish source water could certainly limit the amount of additional solids that can be sent into the WWTP without causing adverse impacts, as described in Chapter 6.

In order to ameliorate such impacts, it might be possible to use an underground water supply or to develop a treatment technology to reduce the solids. These concerns will become more serious as community development increases water use, source waters are depleted, and limits are placed on the amounts of groundwater withdrawn. Such conflicts have been developing over the last decade, and they will continue to increase at an accelerating pace.

Both water and wastewater utilities will have to carefully consider the plans developed for their communities. In the East, where both water and wastewater collection systems are often operated by the same utility, such issues may not be as acute as in the West. In the West, the utilities are more often separate and may actually be competing with one another for the use of reclaimed water. The policy concerns, while not part of this work, must be studied carefully in order to avoid a head-on collision between the utilities and their plans for using membrane technology.

8.2.2   Does the Utility Limit Reuse?

The issue of whether or not a utility may limit water reuse may be a function not only of the quality of the reclaimed water but also of the jurisdiction governing the use of the reclaimed water. The quantity of water available for reuse and also its quality are important considerations. Should the concentration of TDS of the water be high (more than 1000 mg/L), its use may be self-limiting.

The question regarding the type of reuse suitable for the reclaimed water is also a consideration. For example, irrigation tends to be a consumptive use, while use by industry (other than for cooling towers) may not be consumptive. Thus, if water supplies are limited and the reclaimed water can be used in a nonconsumptive way, the potential for limiting consumptive uses may become an obvious policy choice for the operating utility.

On the whole, the uses of reclaimed water will largely be determined by site-specific conditions. It is difficult to develop general characterizations, and a system-wide mass balance model thus becomes an important tool for helping utilities understand the interrelationships between water supply, wastewater treatment, and uses of reclaimed water.

8.3   BRINE DISPOSAL

One of the most difficult problems facing utilities, particularly in land-locked areas, is disposal of the concentrate generated by membrane systems. If the concentrate is disposed of at the WWTP, it is "out of sight, out of mind," because the concentrate is simply flushed into the collection system. While there may be local impacts, as described throughout this work, the problem of concentrate disposal has now become an issue for the WWTP.

For some communities, disposal of brine into a WWTP is not an option. Both WRF and WERF are sponsoring projects to explore alternative methods of brine disposal. One possible alternative for some utilities is to convey the concentrate from the membrane system through a brine line to be pumped to a briny lake, an evaporation pond, or the ocean. For other communities, brine lines are hardly a viable solution.

The system-wide mass balance begins to put into perspective whether or not the membrane concentrate discharged to a system will eventually overtax the WWTP to the point where other disposal methods must be sought. For example, a community could choose to put the concentrate in a separate collection system from the various sources and construct a separate concentrate treatment facility. Such treatment systems are expected to be very costly, and the ongoing research should reveal opportunities for such treatment.

8.4 GENERAL LIMITS AT WWTP HEADWORKS VERSUS LOCAL SITE LIMITS

Another issue is whether the limits on TDS and other pollutants would restrict a community's ability to accept additional concentrate into its system. The impact of the brine discharge can be felt locally in a collection system or at the headworks end of the WWTP. Depending on the characteristics of the concentrate, local impacts may be significant and detrimental to the system. According to utility staff, impacts to collection systems have been noted in Oklahoma City, OK, Phoenix, AZ, and San Antonio, TX. These impacts can be attributed not only to the characteristics of the concentrate but also to the materials from which the wastewater collection systems are constructed. Thus, utilities may be able to mitigate some of the impacts by changing the construction materials of the wastewater collection system, especially in the immediate vicinity of the location of the concentrate discharge.

Conversely, it would be difficult, if not impossible, for a community to mitigate the impact of the concentrate discharge if it increased the TDS concentration at the head of the WWTP beyond the level where it would adversely affect the biological system. The only solution for such a problem at this location would be to limit the amount of membrane discharge into the system by allocating such use among users.

8.5 FURTHER RESEARCH

This project has revealed a variety of opportunities for additional research. Many of the areas of interest are already being studied by a number of organizations, including the WateReuse Foundation.

8.5.1 Grandfather Clause: How To Treat New Facilities while Protecting Existing Industrial and Commercial Customers

One pressing issue facing many utilities is how to ensure availability sufficient for existing industries, commercial customers, and irrigation customers when new facilities are connected and the quantity of water is limited. Obviously, there is no simple answer, but the system-wide mass balance of reclaimed water can help a community to assess when this point may be reached and when limits must be placed on future uses of reclaimed water.

8.5.2 Development of Long-Term Salt Management Policy

Policies regarding long-term salt management are sorely lacking. Communities must begin to consider this issue in order to form a public policy for managing membrane brine.

Part of the responsibility for developing such policies must lie with States, which can compile the pertinent data in centralized databases and track State water quality issues relating to TDS and specific ions.

8.6 DATA COLLECTION

The amount of data that was collected, either from the literature or from utilities who participated in the study, is very limited. It is recommended that the WateReuse Foundation contact the communities in approximately 3–5 years to supplement the data collected in this particular study. This effort could be include an update of the literature survey as well as a collection of data from additional communities that may have added membrane facilities in their treatment systems.

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APPENDIX A

REFERENCE DATABASE HELP FILE

A.1 OVERVIEW

The Reference Database (hereafter "the database") allows one to store reference information and to search and explore this information using several methods. The user interface for this Microsoft Access database has been constructed using standard Access features as well as Visual Basic code written specifically for this application. Familiarity with Access is not required but will give the user greater flexibility in accessing the information in the database.

The application has three windows, the first of which (the Switchboard) simply allows the user to pick one of the other two. One of the other two windows (References) allows the user to go through the database record by record or by using standard Access sort and find commands. It also allows the user to add records. The other form (Search) provides a more convenient way to look for records by keywords, author, title, or journal, is a more powerful search method, and is a means to mark records in order to combine relevant results from various searches.

A.2 SWITCHBOARD FORM

When the database is opened, the Switchboard is the first form to open. It has four buttons which, when clicked, open the References form, the Search form, or the Help form or quit the application.

There is another window open which at the top reads "References: Database". This window should be hidden behind the Switchboard and other forms and is not meant to be used by the casual user. It allows access to the underlying database elements that make up this application. Closing this window will close the application. It can be hidden (by unchecking the "Display Database Window" button under Tools/Startup but has been left visible in order to leave the choice of whether to hide it to the organization implementing this database.

A.3 SEARCH FORM

The Search form allows the user to find a single reference or group of references using various search criteria. After a search, some or all records can be marked by the user. If multiple searches are done, the marked records from all the searches can then be viewed under the Mark Records tab and/or as output to a text file.

Open the search form by clicking the "Search Database" button on the Switchboard. The form may take a while to open as author and keyword information is being consolidated.

There is a row of seven buttons along the top of the form, and there are four tabs just below these buttons. The buttons allow the user to manipulate the marking of multiple records and also allow the user to see details of multiple records. Their function should become obvious in the discussion of the four tabs, below.

A.3.1 Regarding All Tabs

Each tab shows summary information for the individual reference (author, title, and year). Records may not always be present, for example, when there are no matches to a search. One can right click on the column heading to bring up a menu that allows one to sort the columns or copy information. Information in the author and date columns can be edited directly. Do so with caution, however, as there is no "undo" and Access saves a record immediately.

To the left of the author column is a column labeled "Mark". By clicking in the empty box to the left of a particular record, a checkbox will appear to indicate the record is marked. Clicking the box of a marked record will cause it to become unmarked.

To the left of the "Mark" column is an unlabeled column of boxes. Double clicking on one of these boxes will bring up another form with details of that particular record.

Three of the buttons help with marking records. "Clear All" will clear all marks for records in the database, even if the records are not currently being shown. "Mark All Shown" will mark all records currently showing under a particular tab. "Clear All Shown" will clear the mark for records that appear as a result of a search but will not change records that are not showing. Some searches may result in a list of references longer than can be displayed on the Search form. In this case, one uses the scroll bar on the right to see all the records. All of these records are considered showing, even if the scroll bar is needed to actually see them.

Two of the buttons allow the user to see details of multiple records. "Open Marked Records" opens up all records in the database that are marked, regardless of whether they are showing. "Open Shown Records" opens only those records showing under the current tab.

The "Help" button brings up this appendix document. The "Done" button closes the form.

A.3.2 "All Records" Tab

The "All Records" tab shows all records in the database, initially sorted by author.

A.3.3 "Marked Records" Tab

The "Marked Records" tab shows all records that have been marked. This is useful if multiple searches have been used to mark different records.

A.3.4 "Search" Tab

The "Search" tab allows the user to search for words in specific fields or all fields. It also allows searches to be refined or expanded.

Near the top of this tab is a drop-down box that has, by default, the words "New Search" and allows the user to refine or expand a search. To the right of this is a text box where one can enter search terms. To the right of this is a drop-down box that allows one to limit a search to specific database fields.

The user can start with a new search by specifying "New Search" in the first box, entering search terms in the second box, and choosing in which field (or all fields) to look. Clicking on the "Search" button begins the search. By changing "New Search" to "Refine Search," the

search will be performed only on records that are showing, and those that do not match the search criteria will be removed. By specifying "Add to Search," records anywhere in the database that match the search criteria will be added to the existing search results. In this way, "Refine Search" is analogous to using a logical "and," while "Add to Search" is analogous to a logical "or".

Searches under this tab match any part of a word. For example, looking for "Ni" under keywords will bring up records that have "ni" anywhere in any keyword, such as organic or organic matter. To find records with just "Ni" as a keyword, use the Terms tab.

A.3.5 "Terms" Tab

On the upper left of the "Terms" tab is a drop-down box where the user can select "Authors," "Journals," "Titles," or "Keywords". Upon selecting one of these options, a list of existing terms in the database appears below. Upon clicking on a term, all records with that term appear. Clicking on a different term will remove the current records and show only records corresponding to the new term.

A selection from the drop-down box will sometimes cause a delay as the terms are processed. This is especially true when selecting keywords and authors, as the application has to parse the individual authors and keyword phrases from the information within the corresponding field of each record.

A.4 REFERENCES FORM

The References form allows one to explore the database record by record. Limited search capabilities are available via the built-in functionality of Access.

Open the Reference form by clicking the "Look at references one at a time" button on the Switchboard. All records from the database will be opened, but only one is visible at a time. This form is also opened when "Open Marked Records" or "Open Shown Records" buttons are clicked from the search form, but only the corresponding subset of database records will be available. This form is also opened by double clicking on the gray box to the left of the "Mark" column, but only the one record will be available.

A.4.1 Navigation

At the lower left of the form is a set of navigation buttons. These buttons allow the user to go to the first record (|<), go to the previous record (<), go to the next record (>), go to the last record (>|), or add a new record (>*). The text box in the middle of these buttons shows the number of the record you are currently viewing, and text to the right of the button shows the total number of records available. One can type a number in the middle box to go directly to a particular point in the series of records. It should be noted that this number is not the same as the database ID for the reference(s).

A.4.2 Searching and Sorting

To search in a particular field, place the cursor in that field; otherwise, place the cursor in any field. Under the Edit menu, select "Find" and a dialog box will appear. In this box the user can enter the term for which they want to search, specify to search all records or the record they have selected, elect to allow partial matches, and specify in which direction to search. If

a match is found, the first record that matches will be shown. Using the "Find Next" button will take you to subsequent matches in the same record and then to matches in other records.

One can also use the filter functionality of Access, which is available under the Records menu. Please refer to the Help function within Access for instructions on this feature.

The records can also be sorted by any field. Right clicking in a field will bring up a menu that will sort the database based on that field.

A.4.3 Editing Records

Records can be edited directly as they are being viewed. On the left of each record is a tall gray area with a right-pointing triangle. This indicates a saved record. When a record is edited, this triangle becomes a pencil, indicating that what is displayed has not been saved. As long as this pencil is showing, all changes to that record can be undone by pressing the Escape key. Records are saved automatically when the user leaves them by going to another record or closing a window. There is no Save command.

A.4.4 Adding Records

To add records, press the ">*" button at the lower left of the reference form. A blank record will be shown which can be filled out to create a new record. You cannot add the database ID, because this is added automatically. When adding a new record, the pencil will be shown on the right to indicate that the addition can be aborted by pressing the Escape key (sometimes repeatedly).

The Type field is a special field in that the user can select from a list of reference types by clicking on the arrow at the right of the box. The user can also enter a different type if the existing choices are inadequate. The next time the form is closed and opened, the new type will be added to the drop-down list.

The Author and Keywords fields have special formatting requirements. Authors must be separated by a "//" and keywords or keyword phrases must be separated by a "/". There should be no spaces before or after these special characters. There will be no verification of this; however, the search under the Terms tab will not work well for records in which these are not entered correctly.

A.5 OUTPUT

Output is achieved via the Reference form. In most cases it will be most helpful to open this form using the "Open Marked Records" or "Open Shown Records" buttons on the Search form to show the subset of database records that are of interest. This form is also opened by double clicking on the gray box to the left of the Mark column, but only that one record will be available.

At the top of the reference form are four buttons. The "Help" and "Done" buttons perform as they do on the Search form. "Write Multiple Records to Text File on Desktop" will write all the record information for all records to a text file called references.txt, which will be located on the desktop. This file is overwritten and so should be renamed or moved if different outputs need to be saved.

The tab "Copy Current Record to Clipboard" copies the current record to the operating system clipboard. This information can be pasted into another application by using the paste function of that other application.

A.6 CREDIT

Version 1.0 of this program was written by Joe LoBuglio (lolio@lobuglio.org).

A.7 VERSION HISTORY

Version 1.0: Initial release of application with 217 records from a Procite database provided by Francis A. DiGiano, Ph.D., PE, Dept. of Environmental Sciences & Engineering, University of North Carolina, Chapel Hill.

APPENDIX B

WATER UTILITY SURVEY

SurveyMonkey.com
because knowledge is everything

| Home | New Survey | My Surveys | List Management | My Account | | Help Center |

Wednesday, May 24, 2006

Results Summary   Show All Pages and Questions

Export...   View Detail >>

Filter Results
To analyze a subset of your data, you can create one or more filters.

Add Filter...   **Total:** 6
Visible: 6

Share Results
Your results can be shared with others, without giving access to your account.

Configure...   **Status:** Enabled
Reports: Summary and Detail

1. Introduction

1. Please click on the circle below to put a check-mark acknowledging you have read this information.

	Response Percent	Response Total
I have read this information and agree to participate.	100%	6
	Total Respondents	6
	(skipped this question)	0

2. Participant Information

2. Please enter your name (optional; as noted above, we keep all personal information strictly confidential):

View	Total Respondents	3
	(skipped this question)	3

3. Please enter your email address so that we can contact you if any questions arise (optional; as noted above, we keep all personal information strictly confidential):

View	Total Respondents	3
	(skipped this question)	3

4. Please enter your professional title in the space below.

View	Total Respondents	4
	(skipped this question)	2

5. Please enter your mailing address if you would like to receive a hardcopy of the results.

View	Total Respondents	2
	(skipped this question)	4

6. How many years have you been working in the water/wastewater industry?

	Response Percent	Response Total
Less than one year	0%	0
One to three years	0%	0
Three to 10 years	50%	2
More than 10 years	50%	2
Total Respondents		4
(skipped this question)		2

7. How many years have you been working specifically on water treatment processes?

	Response Percent	Response Total
Less than one year	0%	0
One to three years	0%	0
Three to 10 years	50%	2
More than 10 years	50%	2
Total Respondents		4
(skipped this question)		2

8. How many years of experience do you have working on pretreatment issues (Sewer Use Ordinance development, enforcement, permitting, etc.)?

	Response Percent	Response Total
Less than one year	25%	1
One to three years	0%	0
Three to 10 years	25%	1
More than 10 years	50%	2
Total Respondents		4
(skipped this question)		2

9. Which membrane activities have you been involved with? (Check all that apply.)

	Response Percent	Response Total
Pilot studies	75%	3
Evaluation and permitting of membrane residuals (reject and cleaning solutions) discharges	0%	0
Membrane residuals discharges to wastewater systems/POTWs	75%	3
Other (please specify)	0%	0
Total Respondents		4
(skipped this question)		2

3. Information on Your Facility

10. Is your utility public or private?

	Response Percent	Response Total
Public	100%	2
Private	0%	0
Don't know	0%	0
Other (please specify)	0%	0
Total Respondents		2
(skipped this question)		4

11. What is the production flow-rate of your water treatment plant?

	Response Percent	Response Total
0 - 500,000 gpd	0%	0
500,000 gpd - 1 MGD	0%	0
1 - 5 MGD	100%	2
6 - 10 MGD	0%	0
11 - 20 MGD	0%	0
21 -100 MGD	0%	0
> 100 MGD	0%	0
Total Respondents		2
(skipped this question)		4

12. What is the source(s) of water being treated by the membrane system(s)? (Please check all that apply.)

	Response Percent	Response Total
Ocean	0%	0
Groundwater	0%	0
Brackish water	0%	0
River or stream	0%	0
Lake, natural	0%	0
Impoundment	0%	0
[View] Other (please specify)	100%	2
Total Respondents		2
(skipped this question)		4

13. Please write in the year that your membrane system started up:

[View] Total Respondents		2

14. What is the purpose(s) of your membrane facility? (Please check all that apply.)

	Response Percent	Response Total
Organics removal	100%	2
TSS removal	100%	2
Microorganism/pathogen removal	50%	1
Taste & odor control	50%	1
THM precursor removal	50%	1
Color removal	100%	2
Softening	50%	1
TDS removal	100%	2
[View] Other (please specify)	50%	1
Total Respondents		2
(skipped this question)		4

15. What percentage of your water treatment capacity is treated with membranes?

	Response Percent	Response Total
< 10%	0%	0
10-20%	0%	0
21-30%	0%	0
31-40%	0%	0
41-50%	0%	0
51-60%	0%	0
61-70%	0%	0
71-80%	0%	0
> 80%	100%	2
Total Respondents		2
(skipped this question)		4

16. Which type(s) of processes listed below are used at your facility? (Please check all that apply.)

	Response Percent	Response Total
Microfiltration	100%	2
Ultrafiltration	0%	0
Nanofiltration	0%	0
Reverse osmosis	100%	2

	Response Percent	Response Total
EDR, Electrodialysis Reversal	0%	0
Ion exchange	0%	0
Don't know	0%	0
Other (please specify)	0%	0
Total Respondents		**2**
(skipped this question)		**4**

17. What is the average water recovery rate of your membrane facility?

	Response Percent	Response Total
< 50%	0%	0
51-60%	0%	0
61-70%	0%	0
71-80%	0%	0
81-85%	0%	0
> 85%	100%	2
Total Respondents		**2**
(skipped this question)		**4**

4. Information on Discharges

18. Are the residuals from the membrane water treatment processes discharged to a municipal wastewater system?

	Response Percent	Response Total
Yes	100%	2
No	0%	0
Don't know	0%	0
Total Respondents		**2**
(skipped this question)		**4**

5. Untitled Page

19. Please give the name of the wastewater treatment facility the residuals discharge to, if known.

	Response Percent	Response Total
Don't know	0%	0
View Name and location of facility:	100%	2
Total Respondents		**2**
(skipped this question)		**4**

20. What information was required before discharge of membrane residuals to the WWTP was allowed? (Please check all that apply.)

		Response Percent	Response Total
Previous monitoring	▆▆▆▆▆▆	50%	1
Additional monitoring in support of discharge		0%	0
Base-line monitoring report		0%	0
90-day monitoring study		0%	0
Pilot plant data	▆▆▆▆▆▆	50%	1
Permit application		0%	0
None		0%	0
Don't know		0%	0
[View] Other (please specify)	▆▆▆▆▆▆	50%	1
	Total Respondents		2
	(skipped this question)		4

21. Did your facility receive any of the following? (Please check all that apply.)

		Response Percent	Response Total
Discharge permit	▆▆▆▆▆▆	50%	1
Written authorization to discharge		0%	0
Contract		0%	0
Written agreement	▆▆▆▆▆▆	50%	1
No permit nor other authorization was required	▆▆▆▆▆▆	50%	1
Don't know		0%	0
Other (please specify)		0%	0
	Total Respondents		2
	(skipped this question)		4

22. What types of requirements, if any, are stipulated in the permit (or other arrangement) for discharging membrane residuals? (Please check all that apply.)

		Response Percent	Response Total
Requirements for complying with general prohibitions/Sewer Use Ordinance		0%	0
Time limit condition, after which the arrangement/permit must be renewed		0%	0
Compliance, with prohibitions		0%	0
Specific discharge limits (see next question)		0%	0
Monitoring requirements (see next question).		0%	0
[View] Other (please specify)	▆▆▆▆▆▆▆▆▆▆▆	100%	1

	Response Percent	Response Total
EDR, Electrodialysis Reversal	0%	0
Ion exchange	0%	0
Don't know	0%	0
Other (please specify)	0%	0
Total Respondents		**2**
(skipped this question)		**4**

17. What is the average water recovery rate of your membrane facility?

	Response Percent	Response Total
< 50%	0%	0
51-60%	0%	0
61-70%	0%	0
71-80%	0%	0
81-85%	0%	0
> 85%	100%	2
Total Respondents		**2**
(skipped this question)		**4**

4. Information on Discharges

18. Are the residuals from the membrane water treatment processes discharged to a municipal wastewater system?

	Response Percent	Response Total
Yes	100%	2
No	0%	0
Don't know	0%	0
Total Respondents		**2**
(skipped this question)		**4**

5. Untitled Page

19. Please give the name of the wastewater treatment facility the residuals discharge to, if known.

	Response Percent	Response Total
Don't know	0%	0
Name and location of facility:	100%	2
Total Respondents		**2**
(skipped this question)		**4**

26. How far from the WWTP do the membrane residuals enter the wastewater collection system?

	Response Percent	Response Total
< 0.5 miles from the WWTP	50%	1
0.5 - 1 mile	50%	1
1 - 2 miles	0%	0
> 2 miles	0%	0
Don't know	0%	0
Total Respondents		2
(skipped this question)		4

27. (This question is about corrosion other than corrosion typically caused by presence of sulfides.) Near the point of discharge, or downstream from the discharge of membrane residuals to the collection system, has there been to your knowledge corrosion to any of the following? (Please check all that apply.)

	Response Percent	Response Total
Sewer pipe--wetted concrete Manhole	0%	0
Carbon steel submerged metal surfaces	0%	0
Pump impellers	0%	0
Pump body	0%	0
Valves	0%	0
Force main--metal pipe	0%	0
Force main—concrete	0%	0
None known	100%	2
Other (please specify)	0%	0
Total Respondents		2
(skipped this question)		4

7. Untitled Page

28. For your membrane streams (influent feed to the membrane system and effluent/finished water from the membranes), please choose appropriate answers from the pull-down menus. (Standards noted in the pull-down menus are the MCL, Maximum Contaminant Levels or Maximum Contaminant Level Goals, or other standard, as appropriate).

Influent/feed to membrane system

	Would violate standards without further treatment	Below (or within) standards	Never measured	Don't know	Response Total
TDS	100% (1)	0% (0)	0% (0)	0% (0)	1
TSS	0% (0)	100% (1)	0% (0)	0% (0)	1

	Would violate standards without further treatment	Below (or within) standards	Never measured	Don't know	Response Total
Turbidity	**100% (1)**	0% (0)	0% (0)	0% (0)	1
pH	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Total Coliform	**100% (1)**	0% (0)	0% (0)	0% (0)	1
Fecal Coliform	**100% (1)**	0% (0)	0% (0)	0% (0)	1
Cryptosporidium	**100% (1)**	0% (0)	0% (0)	0% (0)	1
Giardia	**100% (1)**	0% (0)	0% (0)	0% (0)	1
TOC	**100% (1)**	0% (0)	0% (0)	0% (0)	1
Hardness	**100% (1)**	0% (0)	0% (0)	0% (0)	1
Color	**100% (1)**	0% (0)	0% (0)	0% (0)	1
Arsenic	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Cadmium	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Chromium	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Copper	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Mercury	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Nickel	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Lead	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Zinc	0% (0)	**100% (1)**	0% (0)	0% (0)	1

Effluent/discharge from membrane system

	Would violate standards without further treatment	Below (or within) standards	Never measured	Don't know	Response Total
TDS	0% (0)	**100% (1)**	0% (0)	0% (0)	1
TSS	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Turbidity	0% (0)	**100% (1)**	0% (0)	0% (0)	1
pH	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Total Coliform	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Fecal Coliform	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Cryptosporidium	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Giardia	0% (0)	**100% (1)**	0% (0)	0% (0)	1
TOC	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Hardness	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Color	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Arsenic	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Cadmium	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Chromium	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Copper	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Mercury	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Nickel	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Lead	0% (0)	**100% (1)**	0% (0)	0% (0)	1
Zinc	0% (0)	**100% (1)**	0% (0)	0% (0)	1

Total Respondents 1

8. Cleaning Waste Questions

29. Does your membrane system(s) undergo a cleaning process?

	Response Percent	Response Total
Yes	100%	2
No	0%	0
Don't know	0%	0
Total Respondents		2
(skipped this question)		4

9. Untitled Page

30. Where is the cleaning waste stream(s) discharged? (Please check all that apply.)

	Response Percent	Response Total
Don't know	0%	0
Receiving stream, ocean	0%	0
Deep well injection	0%	0
Local wastewater treatment system	100%	2
Treated and retained on-site	0%	0
Zero discharge	0%	0
Other (please specify)	0%	0
Total Respondents		2
(skipped this question)		4

31. Are the membrane reject streams and cleaning waste streams regulated by the same authority?

	Response Percent	Response Total
Yes	100%	2
No	0%	0
Don't know	0%	0
Total Respondents		2
(skipped this question)		4

32. What chemicals are used for cleaning? (Please check all that apply.)

	Response Percent	Response Total
Don't know	0%	0

	Response Percent	Response Total
Caustic	100%	2
Hydrochloric (Muriatic) acid	0%	0
Sulfuric acid	50%	1
Sodium hypochlorite	50%	1
Alconox or other soap	0%	0
Proprietary cleaning agents	50%	1
[View] Other (please specify)	100%	2
Total Respondents		2
(skipped this question)		4

33. What is the frequency of membrane cleaning?

	Response Percent	Response Total
Don't know.	0%	0
> 1 x/day	0%	0
1 x/day	0%	0
2x/week	0%	0
1 x/week	0%	0
1 x/2weeks	0%	0
1 x/month	0%	0
1 /quarter	0%	0
[View] Other (please specify)	100%	2
Total Respondents		2
(skipped this question)		4

10. Wrap-Up

34. Are you currently evaluating any future membrane residuals discharges to a wastewater system? If so, we would appreciate your providing some specifics, including water source and flow rates, membrane type, and regulatory approaches you will be following.

	Response Percent	Response Total
No known projects involving membrane residuals are being planned.	100%	1
Total Respondents		1
(skipped this question)		5

35. Please note the types of information or guidance that would be helpful to you when considering discharging membrane residuals to a wastewater system.

Total Respondents		0
(skipped this question)		6

36. Would you please provide contact information on other utilities that would be useful participants in our survey? Thanks.

Total Respondents		0
(skipped this question)		6

37. May we please contact you if necessary for follow-up clarifications? If you would not mind, please provide below an email address or the best telephone number at which you can be reached.

	Response Percent	Response Total
Yes	50%	1
No	0%	0
Email addersss or telephone number	50%	1
Total Respondents		2
(skipped this question)		4

38. Finally, please provide any comments you have on the survey. For example, did you find the survey useful, in and of itself, in pointing to some of the issues regarding membrane residuals discharges to wastewater systems? Suggestions? Observations? Thanks very much for your help!

View **Total Respondents**		2
(skipped this question)		4

APPENDIX C

WASTEWATER UTILITY SURVEY

Design Survey   Show All Pages and Questions

<< Back   Preview

To change the **look** of your survey, select a choice below. Click 'Add' to create your own custom theme.

Theme: Blue Ice   Add

Edit Title
Edit Numbering
Add Logo

Impacts of Membrane Process Residuals Survey: Wastewater Utilities_Meeting

Add Page

1. Introduction   Edit Page | Delete Page | Copy/Move | Add Logic

Thank you for taking the time to help with our survey. The Impacts of Membrane Process Residuals Survey (IMPReS survey) is part of the WateReuse Foundation's (WRF's) (www.watereuse.org) project , "Impacts of Membrane Process Residuals on Wastewater Treament," and we very much appreciate your input.

Water and wastewater processes using membranes are growing in use, and we are contacting you as a representative of a utility which uses membrane systems, or which receives residuals from membrane systems in the community you serve.

Membrane treatment applications have been growing significantly in recent years, and discharge of membrane residuals (reject streams and cleaning wastes) to wastewater systems is an important disposal option. However, membrane process residuals can significantly impact wastewater treatment systems, affecting treatment efficiency and effluent quality, among other effects. Thus, there is great need for improving our understanding of effects of membrane residuals on wastewater treatment systems.

The objectives of this survey are to learn the following from utilities like yours:

1. Your experience with membrane residuals discharges to wastewater systems.
2. Any problems (in collection or treatment systems, with planning, or otherwise) you have experienced with these discharges, and approaches taken to handle them.
3. Control procedures in place, or that you suggest, for addressing membrane residuals discharges.
4. Further research needs.

The survey focuses on four types of membrane applications:
1. Treatment at a wastewater utility (as a component of tertiary treatment, for example),
2. Biological treatment resulting in residuals discharges to your treatment system,
3. Potable water treatment systems, and
4. Industry membrane uses (with focus on Significant Industrial Users of your treatment system, with membrane residuals flow rates greater than 20,000 gpd).

In addition to helping others learn of your experience and concerns, we will use this information to help develop a model predicting effects of membrane discharges on wastewater systems. This model will be publicly available. Another work product that your help will directly contribute to is a Guidance Manual for utilities, aiding planning and addressing membrane residuals discharges to wastewater treatment systems.

One project component involves going beyond this survey to obtain more detailed information from selected utiliities. Thus, with your permission, we may get in touch to ask if you would be willing to provide further information, in a telephone interview, for example. In all events, we shall keep all personally identifiable information strictly confidential, as detailed below.

This project is being conducted for WRF by prime consultant Black & Veatch (http://www.bv.com). The Principal Investigators are:
Barnes Bierck, Consulting Enviornmental Engineer, Chapel Hill, NC

Francis A. DiGiano, University of North Carolina at Chapel Hill
Gary Hunter, Black & Veatch
Ed Kobylinsky, Black & Veatch
Al Rimer, Global Practice Leader, Water Reuse, Black & Veatch

To participate in the survey, you need to:

1. Read the remainder of this document.
2. Click on the link at the bottom of this page, indicating that you have read this document and consent to participate in this survey.
3. Complete the Web survey.

YOUR RIGHTS
As the principal investigators, we assure you that:
1. Your participation in this study is entirely voluntary.
2. You are free to refuse to answer any question at any time.
3. Your participation will be anonymous if you choose not to answer any of the personal identifying information in the beginning of the survey. We would of course appreciate receiving your contact information, for cases where follow-up information would be helpful.
4. All personal identifying information will be kept strictly confidential. Surveymonkey's software has a secure server, and only research team members have access to the survey data. All electronic files with personal identification information will be destroyed after data collection, and hard copies will be kept in a secured locked office space.
5. Upon request, you will be given results of the study after they are formulated.

The survey was designed to be straightforward and easy to complete. If you stop at any point, you will be returned to that point when re-entering the survey. Also, you can move backward and forward through the survey, should it become necessary to go back to add information.

If you have questions about the survey, please contact:

Principal Investigator: Barnes Bierck, P.E, Ph.D.
Environmental Engineering Consultant
Chapel Hill, N.C. 27517
Tel: 919-401-0591, eFax: 815-550-2322
email: sludge1@mindspring.com

Add Question   Add Page

Edit   Delete   Copy/Move   Add Logic

* 1. Please click on the circle below to put a check-mark acknowledging you have read this information.

◯ I have read this information and agree to participate.

Add Question   Add Page

2. Participant Information   Edit Page   Delete Page   Copy/Move   Add Logic

Information about you and your background, including your wastewater/reclamation and pretreatment experience, will provide context for our findings on impacts of membrane process residuals on wastewater treatment. It will also help us contact you for follow-up questions. As noted above, this information, while helpful, is optional. We will keep your personal information strictly confidential.

Add Question   Add Page

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2. Please enter you name in the space below.

Add Question   Add Page

Edit   Delete   Copy/Move
3. Please provide your email address in the space below.

`Add Question` `Add Page`

`Edit` `Delete` `Copy/Move`
4. Please enter your professional title in the space below.

_____

`Add Question` `Add Page`

`Edit` `Delete` `Copy/Move`
5. Please enter your mailing address if you would like to receive a hardcopy of the results.

`Add Question` `Add Page`

`Edit` `Delete` `Copy/Move` `Add Logic`
6. How many years have you been working in the water/wastewater industry?

◡ Less than one year
◡ One to three years
◡ Three to 10 years
◡ More than 10 years

`Add Question` `Add Page`

`Edit` `Delete` `Copy/Move` `Add Logic`
7. How many years have you been working specifically on wastewater treatment processes?

◡ Less than one year
◡ One to three years
◡ Three to 10 years
◡ More than 10 years

`Add Question` `Add Page`

`Edit` `Delete` `Copy/Move` `Add Logic`
8. How many years of experience do you have working on pretreatment issues (Sewer Use Ordinance development, enforcement, permitting, etc.)?

◡ Less than one year
◡ One to three years
◡ Three to 10 years
◡ More than 10 years

`Add Question` `Add Page`

`Edit` `Delete` `Copy/Move` `Add Logic`
9. Which pretreatment activities have you been involved with? (Please check all that apply.)

☐ Sewer Use Ordinance development

☐ Evaluation and permitting of non-municipal discharges to the wastewater system
☐ Membrane residuals discharges (including reject and cleaning wastes) to the wastewater system
☐ Other (please specify) _____

[Add Question] [Add Page]

3. Information on Your Wastewater System [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

This section gathers information on your wastewater system.

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
10. What is the average wastewater flow rate to your WWTP?

○ 0 - 500,000 gpd
○ 500,000 gpd - 1 MGD
○ 1 - 5 MGD
○ 6 - 10 MGD
○ 11 - 20 MGD
○ 21 -100 MGD
○ > 100 MGD

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]
11. At what frequency does your treatment plant monitor your influent for the following parameters? (Please check as appropriate.)

	Not Required	Daily	1x/wk	1x/mo	1x/quarter	1x/year	Don't know
BOD5	☐	☐	☐	☐	☐	☐	☐
COD	☐	☐	☐	☐	☐	☐	☐
TSS	☐	☐	☐	☐	☐	☐	☐
Heavy metals	☐	☐	☐	☐	☐	☐	☐
Toxic organics	☐	☐	☐	☐	☐	☐	☐
TDS	☐	☐	☐	☐	☐	☐	☐
Whole Effluent Toxicity	☐	☐	☐	☐	☐	☐	☐
Ammonia-N	☐	☐	☐	☐	☐	☐	☐
TKN	☐	☐	☐	☐	☐	☐	☐
Nitrate-N	☐	☐	☐	☐	☐	☐	☐
Total-N	☐	☐	☐	☐	☐	☐	☐

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]
12. At what frequency does your treatment plant monitor your effluent for the following parameters? (Please check as appropriate.)

	Not Required	Daily	1x/wk	1x/mo	1x/quarter	1x/year	Don't know
BOD5	☐	☐	☐	☐	☐	☐	☐
COD	☐	☐	☐	☐	☐	☐	☐
TSS	☐	☐	☐	☐	☐	☐	☐
Heavy metals	☐	☐	☐	☐	☐	☐	☐

Toxic organics	☐	☐	☐	☐	☐	☐	☐
TDS	☐	☐	☐	☐	☐	☐	☐
Whole Effluent Toxicity	☐	☐	☐	☐	☐	☐	☐
Ammonia-N	☐	☐	☐	☐	☐	☐	☐
TKN	☐	☐	☐	☐	☐	☐	☐
Nitrate-N	☐	☐	☐	☐	☐	☐	☐
Total-N	☐	☐	☐	☐	☐	☐	☐
Chlorine residual	☐	☐	☐	☐	☐	☐	☐

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

13. Please indicate the parameters for which your wastewater treatment plant has effluent limits (or other requirements). (Note that these parameters are in addition to those listed in the previous questions on monitoring.) (Please check all that apply.)

☐ Conductivity
☐ S04
☐ Chlorine
☐ Sodium
☐ Potassium
☐ Barium
☐ Boron
☐ Selenium
☐ None of the above
☐ Other (please specify)

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

14. What percentage, on average, of your WWTP effluent is used for reuse applications?

○ None
○ 0 - 10%
○ 11 - 30%
○ 31 - 60%
○ 61 - 80%
○ 81 - 100%

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

15. What types of reuse applications is your wastewater effluent used for, if any? (Please check all that apply.)

☐ Don't know
☐ None
☐ Irrigation (greenscape)
☐ Cooling tower(s)
☐ Industrial reuse (other than cooling towers)
☐ Industrial reuse (returned to wastewater collection system after use)
☐ Aquifer Storage and Recovery (ASR), which is used as a raw water source
☐ Dual distribution sysem for municipal reuse
☐ Other (please specify)

4. Membrane Systems at Your Wastewater Facility [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

The next series of questions targets treatment systems using membranes for treating some or all of their wastewater--for tertiary treatment, for example, and/or for producing high-quality effluent for reuse purposes. If your answer to the next question is "No" or "Don't Know" (indicating that your treatment facility does not use membranes), the survey continues with questions covering the next membrane application under consideration. (Note that any discharges of membrane residuals from other wastewater plants to your system, including satellite plants, are addressed in a separate survey section.)

Add Question   Add Page

[Edit] [Delete] [Copy/Move] [Edit Logic]

16. Does your wastewater treatment plant(s) use membranes, residuals from which are routed back into the treatment plant for treatment?

- ○ Yes
- ○ No
- ○ Don't know

Add Question   Add Page

5. Untitled Page [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

Add Question   Add Page

[Edit] [Delete] [Copy/Move] [Add Logic]

17. What type of membrane systems are used? (Please check all that apply.)

- ☐ Don't know
- ☐ Reverse osmosis (RO)
- ☐ Low pressure RO (nanofiltration)
- ☐ Ultrafiltration
- ☐ Membrane filtration
- ☐ MBR (Membrane Bioreactor)
- ☐ None
- ☐ Other (please specify)
  _____

Add Question   Add Page

[Edit] [Delete] [Copy/Move]

18. What is the approximate capacity of the membrane facility or facilities (please check off how many of each size range).

	1 facility	2 facilities	3 facilities	4 -5 facilities	6 – 8 facilities	9 – 10 facilities	> 10 facilities
< 0.5 MGD	☐	☐	☐	☐	☐	☐	☐
0.5 – 1 MGD	☐	☐	☐	☐	☐	☐	☐
1 – 3 MGD	☐	☐	☐	☐	☐	☐	☐
3 – 5 MGD	☐	☐	☐	☐	☐	☐	☐
5 – 7 MGD	☐	☐	☐	☐	☐	☐	☐
7 – 10 MGD	☐	☐	☐	☐	☐	☐	☐
10 – 50 MGD	☐	☐	☐	☐	☐	☐	☐
50 – 100 MGD	☐	☐	☐	☐	☐	☐	☐
> 100 MGD	☐	☐	☐	☐	☐	☐	☐

Add Question | Add Page

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19. What type(s) of information was required to consider discharging these residuals back to the POTW? (Please check all that apply.)

☐ Don't know

☐ None

☐ Monitoring data, previous

☐ Monitoring data, additional in support of discharge

☐ Base-line monitoring report

☐ 90-day monitoring study

☐ Permit application

☐ Other (please specify) _____

Add Question | Add Page

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20. Were any of the following necessary components of allowing this discharge of membrane residuals? (Please check all that apply.)

☐ Discharge permit

☐ Written authorization

☐ Contract

☐ Agreement

☐ Don't know

☐ Other (Please specify)

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

21. Please briefly note the terms of the arrangement allowing the discharge, if applicable.

○ No arrangement with any authorities was necessary.

○ Terms of the arrangement

WateReuse Foundation

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

22. Which of the following conditions, if any, were imposed for this discharge? (Please check all that apply.)

☐ None

☐ Requirements for complying with general prohibitions/Sewer Use Ordinance

☐ Time limit condition, after which the arrangement/permit, etc. must be renewed

☐ Compliance schedule

☐ Requirement for a monitoring station

☐ Specific discharge limits

☐ Monitoring requirements

☐ Don't know

☐ Other (please specify)

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

23. Are any of the following parameters regulated as a component of the arrangement allowing the discharge(s). Please check all that apply.)

☐ No parameters are specified

☐ TDS

☐ pH

☐ Metals

☐ Anions (sulfate, chloride, etc.)

☐ Micropollutants

☐ Toxic organics

☐ Fecal coliform

☐ Total Coliform

☐ Don't know

☐ Other (please specify)

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

24. Which negative impacts resulting from accepting these residuals have you observed, if any? (Please check all that apply.)

☐ None known

☐ POTW effluent quality problems

☐ POTW effluent toxicity problems

☐ Salt impacts to the collection system and pumping stations (e.g. corrosion)

☐ Density impacts due to mixing high TDS discharges with wastewater

☐ Salt impacts on treatment plant equipment (e.g. corrosion)

☐ Upake of salts by biomass

☐ Inhibition of biomass flocculation and settling

☐ Formation of disinfection byproducts during wastewater disinfection

☐ Metals buildup in biosolids impacting beneficial reuse

☐ Salt buildup in residuals impacting beneficial reuse (e.g. salt toxicity to plants) Increase in wastewater treatment costs

☐ Reduced ability to reuse treated effluent

☐ Other (please specify)

Add Question | Add Page

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25. How far from the WWTP do the membrane residuals enter the wastewater collection system? (Please check all that apply if you have more than one source of membrane residuals.)

	1 discharge	2 discharges	3 -4 discharges	> 5 discharges
< 0.5 miles	☐	☐	☐	☐
1 – 2 miles	☐	☐	☐	☐
> 2 miles	☐	☐	☐	☐

Add Question | Add Page

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26. (This question is about corrosion other than corrosion typically caused by presence of sulfides.) Near the point of discharge, or downstream from the discharge of membrane residuals to the collection system, have treatment or collection system staff noticed corrosion to any of the following? (Please check all that apply.)

☐ Sewer pipe--wetted concrete Manhole
☐ Carbon steel submerged metal surfaces
☐ Pump impellers
☐ Pump body
☐ Valves
☐ Force main--metal pipe Force main—concrete
☐ None known
☐ Other (please specify)
_____

Add Question | Add Page

6. Cleaning Waste Questions Edit Page | Delete Page | Copy/Move | Add Logic

Add Question | Add Page

Edit | Delete | Copy/Move | Edit Logic

27. Does your membrane system(s) undergo a cleaning process?

◻ Yes
◻ No
◻ Don't know

Add Question | Add Page

7. Untitled Page Edit Page | Delete Page | Copy/Move | Add Logic

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

28. Where is the cleaning waste stream(s) discharged? (Please check all that apply.)

☐ Don't know
☐ Back to the wastewater treatment plant
☐ Receiving stream, ocean
☐ Deep well injection
☐ Treated and retained on-site
☐ Zero discharge
☐ Other (please specify)
_____

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

29. Are the membrane reject streams and cleaning waste streams regulated by the same authority?

- ◯ Don't know
- ◯ No
- ◯ Yes (Please write in the authority name if yes):
  [   ]

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

30. What chemicals are used for cleaning? (Please check all that apply.)

- ☐ Don't know
- ☐ Caustic
- ☐ Hydrochloric (Muriatic) acid
- ☐ Sulfuric acid
- ☐ Sodium hypochlorite
- ☐ Alconox or other soap
- ☐ Proprietary cleaning agents
- ☐ Other (please specify)
  [   ]

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

31. What is the frequency of membrane cleaning?

- ◯ Don't know
- ◯ > 1 x/day
- ◯ 1 x/day
- ◯ 2x/week
- ◯ 1 x/week
- ◯ 1 x/2weeks
- ◯ 1 x/month 1 /quarter
- ◯ Other (please specify)
  [   ]

Add Question | Add Page

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8. Untitled Page Edit Page | Delete Page | Copy/Move | Add Logic

Add Question | Add Page

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32. Does your wastewater treatment system receive residuals from other membrane systems (including other wastewater facilities, potable water treatment plants, or industry membrane treatment systems with residuals flow rates greater than 20,000 gpd)?

- ◯ Yes
- ◯ No
- ◯ Don't know

Add Question | Add Page

---

9. Membrane Residuals from Other WWTPs Edit Page | Delete Page | Copy/Move | Add Logic

The next series of questions targets membrane residuals from other WWTPs, including sludge solids from MBR--membrane bioreactor--facilities. If your answer to the next question is "No" or "Don't Know" (indicating that you do not receive such residuals), the survey continues with the next membrane application.

Add Question | Add Page

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33. Does your wastewater system receive membrane residuals from other WWTPs? (Please note that these residuals include sludge solids from MBR—membrane bioreactor—facilities.)

- Yes
- No
- Don't Know

Add Question | Add Page

0. Untitled Page Edit Page | Delete Page | Copy/Move | Add Logic

Add Question | Add Page

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34. What type of membrane systems are used? (Please check all that apply.)

- Don't know
- Reverse osmosis (RO)
- Low pressure RO (nanofiltration)
- Ultrafiltration
- Membrane filtration
- MBR (Membrane Bioreactor)
- None
- Other (please specify)

Add Question | Add Page

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35. What is the approximate capacity of the membrane facility or facilities (please check off how many of each size range).

	1 facility	2 facilities	3 facilities	4 -5 facilities	6 – 8 facilities	9 – 10 facilities	> 10 facilities
< 0.5 MGD							
0.5 – 1 MGD							
1 – 3 MGD							
3 – 5 MGD							
5 – 7 MGD							
7 – 10 MGD							
10 – 50 MGD							
50 – 100 MGD							
> 100 MGD							

Add Question | Add Page

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36. What type(s) of information was required to consider discharging these residuals to the POTW? (Please check all that apply.)

- None
- Monitoring data, previous
- Monitoring data, additional in support of discharge
- Base-line monitoring report
- 90-day monitoring study

☐ Permit application
☐ Don't know
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
37. Were any of the following necessary for the facility to be allowed to discharge the membrane residuals? (Please check all that apply.)

☐ Discharge permit
☐ Written authorization
☐ Contract
☐ Agreement
☐ Don't know
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]
38. Please briefly note the terms of the arrangement allowing the discharge.

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
39. Which of the following conditions, if any, were imposed for this discharge? (Please check all that apply.)

☐ None
☐ Requirements for complying with general prohibitions/Sewer Use Ordinance
☐ Time limit condition, after which the arrangement/permit, etc. must be renewed
☐ Compliance schedule
☐ Requirement for a monitoring station
☐ Specific discharge limits
☐ Monitoring requirements
☐ Don't know
☐ Other (please specify)
_____

[Add Question] [Add Page]

40. Are any of the following parameters regulated as a component of the arrangement allowing the discharge(s). (Please check all that apply.)

☐ No parameters are specified
☐ TDS
☐ pH
☐ Metals
☐ Anions (sulfate, chloride, etc.)
☐ Micropollutants
☐ Toxic organics
☐ Fecal coliform
☐ Total Coliform
☐ Don't know
☐ Other (please specify)
   [   ]

41. Which negative impacts resulting from accepting these residuals have you observed, if any? (Please check all that apply.)

☐ None known
☐ POTW effluent quality problems
☐ POTW effluent toxicity problems
☐ Salt impacts to the collection system and pumping stations (e.g. corrosion)
☐ Density impacts due to mixing high TDS discharges with wastewater
☐ Salt impacts on treatment plant equipment (e.g. corrosion)
☐ Upake of salts by biomass
☐ Inhibition of biomass flocculation and settling
☐ Formation of disinfection byproducts during wastewater disinfection
☐ Metals buildup in biosolids impacting beneficial reuse
☐ Salt buildup in residuals impacting beneficial reuse (e.g. salt toxicity to plants) Increase in wastewater treatment costs
☐ Reduced ability to reuse treated effluent
☐ Other (please specify)
   [   ]

42. How far from the WWTP do the membrane residuals enter the wastewater collection system? (Please check all that apply if you have more than one source of membrane residuals.)

	1 discharge	2 discharges	3 -4 discharges	> 5 discharges
< 0.5 miles	☐	☐	☐	☐
1 – 2 miles	☐	☐	☐	☐
> 2 miles	☐	☐	☐	☐

43. (This question is about corrosion other than corrosion typically caused by presence of sulfides.) Near the point of discharge, or downstream from the discharge of membrane residuals to the collection system, have treatment or collection system staff noticed corrosion to any of the following? (Please check all that apply.)

☐ Sewer pipe--wetted concrete Manhole

☐ Carbon steel submerged metal surfaces
☐ Pump impellers
☐ Pump body
☐ Valves
☐ Force main--metal pipe Force main—concrete
☐ None known
☐ Other (please specify)
_____

[Add Question] [Add Page]

11. Cleaning Waste Questions [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Edit Logic]
44. Does the membrane system(s) undergo a cleaning process?
○ Yes
○ No
○ Don't know

[Add Question] [Add Page]

12. Untitled Page [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
45. Where is the cleaning waste stream(s) discharged? (Please check all that apply.)
☐ Don't know
☐ Receiving stream, ocean
☐ Deep well injection
☐ Local wastewater treatment system
☐ Treated and retained on-site
☐ Zero discharge
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
46. Are the membrane reject streams and cleaning waste streams regulated by the same authority?
○ Don't know
○ No
○ Yes. (Please write in the authority name):
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
47. What chemicals are used for cleaning? (Please check all that apply.)
☐ Don't know
☐ Caustic
☐ Hydrochloric (Muriatic) acid
☐ Sulfuric acid
☐ Sodium hypochlorite
☐ Alconox or other soap
☐ Proprietary cleaning agents

☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
48. What is the frequency of membrane cleaning?
○ Don't know.
○ > 1 x/day
○ 1 x/day
○ 2x/week
○ 1 x/week
○ 1 x/2weeks
○ 1 x/month 1 /quarter
○ Other (please specify)
_____

[Add Question] [Add Page]

13. Untitled Page [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Edit Logic]
49. Does your wastewater treatment system receive residuals from other membrane systems (including potable water treatment plants, or industry membrane treatment systems with residuals flow rates greater than 20,000 gpd)?
○ Yes
○ No
○ Don't know

[Add Question] [Add Page]

14. Potable Water Treatment Plant--Membrane Discharges [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

The next group of questions targets membrane residuals from potable water treatment plants. If your answer to the next question is "No" or "Don't Know" (indicating that you do not receive such residuals), the survey continues with the next membrane application.

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Edit Logic]
50. Does your wastewater facility receive membrane residuals from a potable water treatment plant?
○ Yes, from a publicly-owned water treatment utility
○ Yes, from a privately-owned water treatment facility
○ No
○ Don't know

[Add Question] [Add Page]

15. Untitled Page [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
51. What type of membrane systems are used? (Please check all that apply.)
☐ Don't know
☐ Reverse osmosis (RO)
☐ Low pressure RO (nanofiltration)
☐ Ultrafiltration

☐ Membrane filtration
☐ MBR (Membrane Bioreactor)
☐ None
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
52. What is the source of water, which through membrane treatment results in the discharge of residuals to the wastewater system? (Please check all that apply.)

☐ Don't know
☐ Municipal (city) water
☐ Ocean
☐ Groundwater Brackish water
☐ Surface water--River or stream
☐ Surface water--Lake or impoundment
☐ Wastewater (municipal)
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]
53. What is the approximate capacity of the membrane facility or facilities (please check off how many of each size range).

	1 facility	2 facilities	3 facilities	4 -5 facilities	6 – 8 facilities	9 – 10 facilities	> 10 facilities
< 0.5 MGD	☐	☐	☐	☐	☐	☐	☐
0.5 – 1 MGD	☐	☐	☐	☐	☐	☐	☐
1 – 3 MGD	☐	☐	☐	☐	☐	☐	☐
3 – 5 MGD	☐	☐	☐	☐	☐	☐	☐
5 – 7 MGD	☐	☐	☐	☐	☐	☐	☐
7 – 10 MGD	☐	☐	☐	☐	☐	☐	☐
10 – 50 MGD	☐	☐	☐	☐	☐	☐	☐
50 – 100 MGD	☐	☐	☐	☐	☐	☐	☐
> 100 MGD	☐	☐	☐	☐	☐	☐	☐

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
54. What type(s) of information was required to consider discharging these residuals to the POTW? (Please check all that apply.)

☐ Don't know
☐ None
☐ Monitoring data, previous
☐ Monitoring data, additional in support of discharge
☐ Base-line monitoring report
☐ 90-day monitoring study
☐ Permit application
☐ Other (please specify)

[Edit][Delete][Copy/Move][Add Logic]

55. Were any of the following necessary for the facility to be allowed to discharge the membrane residuals? (Please check all that apply.)

☐ Discharge permit

☐ Written authorization

☐ Contract

☐ Agreement

☐ Don't know

☐ Other (please specify)

[Edit][Delete][Copy/Move]

56. Please briefly note the terms of the arrangement allowing the discharge.

[Edit][Delete][Copy/Move][Add Logic]

57. Which of the following conditions, if any, were imposed for this discharge? (Please check all that apply.)

☐ None

☐ Requirements for complying with general prohibitions/Sewer Use Ordinance

☐ Time limit condition, after which the arrangement/permit, etc. must be renewed

☐ Compliance schedule

☐ Requirement for a monitoring station

☐ Specific discharge limits

☐ Monitoring requirements

☐ Don't know

☐ Other (please specify)

[Edit][Delete][Copy/Move][Add Logic]

58. Are any of the following parameters regulated as a component of the arrangement allowing the discharge(s). (Please check all that apply.)

☐ No parameters are specified

☐ TDS

□ pH
□ Metals
□ Anions (sulfate, chloride, etc.)
□ Micropollutants
□ Toxic organics
□ Fecal coliform
□ Total Coliform
□ Don't know
□ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

59. Which negative impacts resulting from accepting these residuals have you observed, if any? (Please check all that apply.)

□ None known
□ POTW effluent quality problems
□ POTW effluent toxicity problems
□ Salt impacts to the collection system and pumping stations (e.g. corrosion)
□ Density impacts due to mixing high TDS discharges with wastewater
□ Salt impacts on treatment plant equipment (e.g. corrosion)
□ Upake of salts by biomass
□ Inhibition of biomass flocculation and settling
□ Formation of disinfection byproducts during wastewater disinfection
□ Metals buildup in biosolids impacting beneficial reuse
□ Salt buildup in residuals impacting beneficial reuse (e.g. salt toxicity to plants)
□ Increase in wastewater treatment costs
□ Reduced ability to reuse treated effluent
□ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]

60. How far from the WWTP do the membrane residuals enter the wastewater collection system? (Please check all that apply if you have more than one source of membrane residuals.)

	1 discharge	2 discharges	3 -4 discharges	> 5 discharges
< 0.5 miles	□	□	□	□
1 – 2 miles	□	□	□	□
> 2 miles	□	□	□	□

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

61. (This question is about corrosion other than corrosion typically caused by presence of sulfides.) Near the point of discharge, or downstream from the discharge of membrane residuals to the collection system, have treatment or collection system staff noticed corrosion to any of the following? (Please check all that apply.)

□ Sewer pipe--wetted concrete Manhole
□ Carbon steel submerged metal surfaces
□ Pump impellers
□ Pump body
□ Valves

Force main--metal pipe Force main—concrete

None known

Other (please specify)

[Add Question] [Add Page]

16. Cleaning waste questions [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Edit Logic]

62. Does the membrane system(s) undergo a cleaning process?

Yes

No

Don't know

[Add Question] [Add Page]

17. Untitled Page [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

63. Where is the cleaning waste stream(s) discharged? (Please check all that apply.)

Don't know

Receiving stream, ocean

Deep well injection

Local wastewater treatment system

Treated and retained on-site

Zero discharge

Other (please specify)

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

64. Are the membrane reject streams and cleaning waste streams regulated by the same authority?

Don't know

No

Yes (Please write in the name of the authority):

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

65. What chemicals are used for cleaning? (Please check all that apply.)

Don't know

Caustic

Hydrochloric (Muriatic) acid

Sulfuric acid

Sodium hypochlorite

Alconox or other soap

Proprietary cleaning agents

Other (please specify)

[Add Question] [Add Page]

Edit | Delete | Copy/Move | Add Logic

66. What is the frequency of membrane cleaning?

- ○ Don't know.
- ○ > 1 x/day
- ○ 1 x/day
- ○ 2x/week
- ○ 1 x/week
- ○ 1 x/2weeks
- ○ 1 x/month 1 /quarter
- ○ Other (please specify)

Add Question | Add Page

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18. Untitled Page Edit Page | Delete Page | Copy/Move | Add Logic

Add Question | Add Page

Edit | Delete | Copy/Move | Edit Logic

67. Does your wastewater treatment system receive residuals from industry membrane treatment systems with residuals flow rates greater than 20,000 gpd)?

- ○ Yes
- ○ No
- ○ Don't know

Add Question | Add Page

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19. Industry Sources of Membrane Residuals Edit Page | Delete Page | Copy/Move | Edit Logic

This series of questions targets membrane residuals from industry, with residuals discharge flow rates greater than 20,000 gpd.

Add Question | Add Page

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68. Please note the type of facility, and SIC code(s) of the industrial source(s).

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

69. What type of membrane systems are used? (Please check all that apply.)

- ☐ Don't know
- ☐ Reverse osmosis (RO)
- ☐ Low pressure RO (nanofiltration)
- ☐ Ultrafiltration

☐ Membrane filtration
☐ MBR (Membrane Bioreactor)
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

70. What is the source of water, which through membrane treatment results in the discharge of residuals to the wastewater system? (Please check all that apply.)

☐ Don't know
☐ Municipal (city) water
☐ Ocean
☐ Groundwater Brackish water
☐ Surface water--River or stream
☐ Surface water--Lake or impoundment
☐ Wastewater (municipal)
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]

71. What is the approximate capacity of the membrane facility or facilities (please check off how many of each size range).

	1 facility	2 facilities	3 facilities	4 -5 facilities	6 – 8 facilities	9 – 10 facilities	> 10 facilities
< 0.5 MGD	☐	☐	☐	☐	☐	☐	☐
0.5 – 1 MGD	☐	☐	☐	☐	☐	☐	☐
1 – 3 MGD	☐	☐	☐	☐	☐	☐	☐
3 – 5 MGD	☐	☐	☐	☐	☐	☐	☐
5 – 7 MGD	☐	☐	☐	☐	☐	☐	☐
7 – 10 MGD	☐	☐	☐	☐	☐	☐	☐
10 – 50 MGD	☐	☐	☐	☐	☐	☐	☐
50 – 100 MGD	☐	☐	☐	☐	☐	☐	☐
> 100 MGD	☐	☐	☐	☐	☐	☐	☐

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

72. What type(s) of information was required to consider discharging these residuals to the POTW? (Please check all that apply.)

☐ Don't know
☐ None
☐ Monitoring data, previous
☐ Monitoring data, additional in support of discharge
☐ Base-line monitoring report
☐ 90-day monitoring study
☐ Permit application
☐ Other (please specify)
_____

Add Question   Add Page

Edit   Delete   Copy/Move   Add Logic

73. Were any of the following necessary for the facility to be allowed to discharge the membrane residuals? (Please check all that apply.)

☐ Discharge permit
☐ Written authorization
☐ Contract
☐ Agreement
☐ Don't know
☐ Other (please specify)
_____

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74. Please briefly note the terms of the arrangement allowing the discharge.

Add Question   Add Page

Edit   Delete   Copy/Move   Add Logic

75. Which of the following conditions, if any, were imposed for this discharge? (Please check all that apply.)

☐ None
☐ Requirements for complying with general prohibitions/Sewer Use Ordinance
☐ Time limit condition, after which the arrangement/permit, etc. must be renewed
☐ Compliance schedule
☐ Requirement for a monitoring station
☐ Specific discharge limits
☐ Monitoring requirements
☐ Don't know
☐ Other (please specify)
_____

Add Question   Add Page

Edit   Delete   Copy/Move   Add Logic

76. Are any of the following parameters regulated as a component of the arrangement allowing the discharge(s). (Please check all that apply.)

☐ No parameters are specified
☐ TDS
☐ pH

☐ Metals
☐ Anions (sulfate, chloride, etc.)
☐ Micropollutants
☐ Toxic organics
☐ Fecal coliform
☐ Total Coliform
☐ Don't know
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]

77. Which negative impacts resulting from accepting these residuals have you observed, if any? (Please check all that apply.)

☐ None known
☐ POTW effluent quality problems
☐ POTW effluent toxicity problems
☐ Salt impacts to the collection system and pumping stations (e.g. corrosion)
☐ Density impacts due to mixing high TDS discharges with wastewater
☐ Salt impacts on treatment plant equipment (e.g. corrosion)
☐ Upake of salts by biomass
☐ Inhibition of biomass flocculation and settling
☐ Formation of disinfection byproducts during wastewater disinfection
☐ Metals buildup in biosolids impacting beneficial reuse
☐ Salt buildup in residuals impacting beneficial reuse (e.g. salt toxicity to plants) Increase in wastewater treatment costs
☐ Reduced ability to reuse treated effluent
☐ Other (please specify)
_____

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]

78. How far from the WWTP do the membrane residuals enter the wastewater collection system? (Please check all that apply if you have more than one source of membrane residuals.)

	1 discharge	2 discharges	3 -4 discharges	> 5 discharges
< 0.5 miles	☐	☐	☐	☐
1 – 2 miles	☐	☐	☐	☐
> 2 miles	☐	☐	☐	☐

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Edit Logic]

79. (This question is about corrosion other than corrosion typically caused by presence of sulfides.) Near the point of discharge, or downstream from the discharge of membrane residuals to the collection system, have treatment or collection system staff noticed corrosion to any of the following? (Please check all that apply.)

☐ Sewer pipe--wetted concrete Manhole
☐ Carbon steel submerged metal surfaces
☐ Pump impellers
☐ Pump body
☐ Valves
☐ Force main--metal pipe Force main—concrete
☐ None known

☐ Other (please specify)

[Add Question] [Add Page]

20. Cleaning Waste Questions [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Edit Logic]
80. Does the membrane system(s) undergo a cleaning process?

○ Yes
○ No
○ Don't know

[Add Question] [Add Page]

21. Untitled Page [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
81. Where is the cleaning waste stream(s) discharged? (Please check all that apply.)

☐ Don't know
☐ Receiving stream, ocean
☐ Deep well injection
☐ Local wastewater treatment system
☐ Treated and retained on-site
☐ Zero discharge
☐ Other (please specify)

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
82. Are the membrane reject streams and cleaning waste streams regulated by the same authority?

○ Don't know
○ No
○ Yes. (Please write in the name of the authority):

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
83. What chemicals are used for cleaning? (Please check all that apply.)

☐ Don't know
☐ Caustic
☐ Hydrochloric (Muriatic) acid
☐ Sulfuric acid
☐ Sodium hypochlorite
☐ Alconox or other soap
☐ Proprietary cleaning agents
☐ Other (please specify)

[Add Question] [Add Page]

Edit | Delete | Copy/Move | Add Logic

84. What is the frequency of membrane cleaning?

- ⌣ Don't know.
- ⌣ > 1 x/day
- ⌣ 1 x/day
- ⌣ 2x/week
- ⌣ 1 x/week
- ⌣ 1 x/2weeks
- ⌣ 1 x/month 1 /quarter
- ⌣ Other (please specify)
  [   ]

Add Question | Add Page

22. Cooling Tower/Boiler Questions Edit Page | Delete Page | Copy/Move | Add Logic

Cooling towers and boilers discharging blowdown to wastewater systems can significantly increase TDS values in wastewater, as do reverse osmosis membrane systems. Thus, these systems to useful to examine. We would appreciate your consulting with Industrial Pretreatment coordinators, as necessary, to obtain answers to the questions below on these systems.

Add Question | Add Page

Edit | Delete | Copy/Move | Edit Logic

85. Are there any cooling towers discharging to your system?

- ⌣ No
- ⌣ Don't know
- ⌣ Yes (please enter how many)
  [   ]

Add Question | Add Page

23. Untitled Page Edit Page | Delete Page | Copy/Move | Add Logic

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

86. How much water (in gpd) is used by the cooling tower(s), on average?

- ⌣ Don't know
- ⌣ Please enter the flow rate in gpd:
  [   ]

Add Question | Add Page

Edit | Delete | Copy/Move | Add Logic

87. What is the typical number of cycles of concentration the towers utilize?

- ⌣ Don't know
- ⌣ Please enter the number of cycles:
  [   ]

Add Question | Add Page

24. Untitled Page Edit Page | Delete Page | Copy/Move | Add Logic

Add Question | Add Page

Edit | Delete | Copy/Move | Edit Logic

88. Do facilities served by your system have boilers that are monitored by your pretreatment team?

- ⌣ No
- ⌣ Don't know

◡ Yes (please note how many):

[Add Question] [Add Page]

25. Untitled Page [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
89. Do any of these boiler facilities use city water directly, without implementing hardness or TDS removal?
◡ Don't know
◡ No
◡ Yes. (Please indicate the number of facilities):

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
90. Do any of the boiler facilities use ion exchange softening or TDS removal?
☐ Don't know
☐ No
☐ Yes. (Please indicate the number of facilities):

[Add Question] [Add Page]

26. Wrap-Up [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

Finally, we ask for information about future plans you may have regarding membrane residuals discharges to your system. We also ask for help in finding other utilities that may participate, and ask for your feedback on this survey.

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
91. Are you currently evaluating any future membrane residuals discharges to your wastewater system? If so, we would appreciate your providing some specifics, including water source and flow rates, membrane type, and regulatory approaches you plan to follow.
◡ No known projects involving membrane residuals are being planned.
◡ We are planning these projects, with the following details:

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]
92. Please note the types of information or guidance that would be helpful to you when considering accepting membrane residuals to your wastewater system.

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]
93. Would you please provide contact information on other utilities that would be useful participants in our survey?

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move] [Add Logic]
94. May we contact you for follow-up clarifications if necessary?

◡ Yes

◡ No

[Add Question] [Add Page]

[Edit] [Delete] [Copy/Move]
95. Finally, please provide any comments you have on the survey. For example, did you find the survey useful, in and of itself, in pointing to some of the issues regarding membrane residuals discharges to wastewater systems? Suggestions? Observations? Thanks very much for your help.

[Add Question] [Add Page]

27. Thank you! [Edit Page] [Delete Page] [Copy/Move] [Add Logic]

Thanks very much for participating in our survey. We look forward to sharing the results!

This project is being conducted for WRF by prime consultant Black & Veatch (http://www.bv.com). The Principal Investigators are:
Barnes Bierck, Consulting Enviornmental Engineer, Chapel Hill, NC
Francis A. DiGiano, University of North Carolina at Chapel Hill
Gary Hunter, Black & Veatch
Ed Kobylinsky, Black & Veatch
Al Rimer, Global Practice Leader, Water Reuse, Black & Veatch

[Add Question] [Add Page]

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APPENDIX D

MASS BALANCE FOR SYSTEM ANALYSIS

All material for the mass balance system analysis can be found on the enclosed CD-ROM. The Mass Balance Model, which is described in Chapters 5 and 6, allows almost any water or wastewater treatment system to be modeled within the context of the community's overall water and wastewater systems. The model is a water mass balance that includes water losses through leaks in the distribution system, water sold outside the wastewater service area, water reclaimed from both a satellite plant and an effluent reclamation facility, and evaporation. The model was developed in Microsoft® Excel, and the workbook consists of a number of spreadsheets. Please insert the accompanying CD-ROM and save the spreadsheet to your hard drive.

APPENDIX E

DERIVATION OF MASS BALANCE MODELS FOR DISCHARGE OF CONCENTRATES, BACKWASH WATER, AND CLEANING SOLUTIONS TO A WASTEWATER COLLECTION SYSTEM

E.1 MODEL I: RETURN OF BIOMASS WASTAGE TO A WASTEWATER COLLECTION SYSTEM LINE FROM A SATELLITE MBR WATER RECLAMATION PLANT
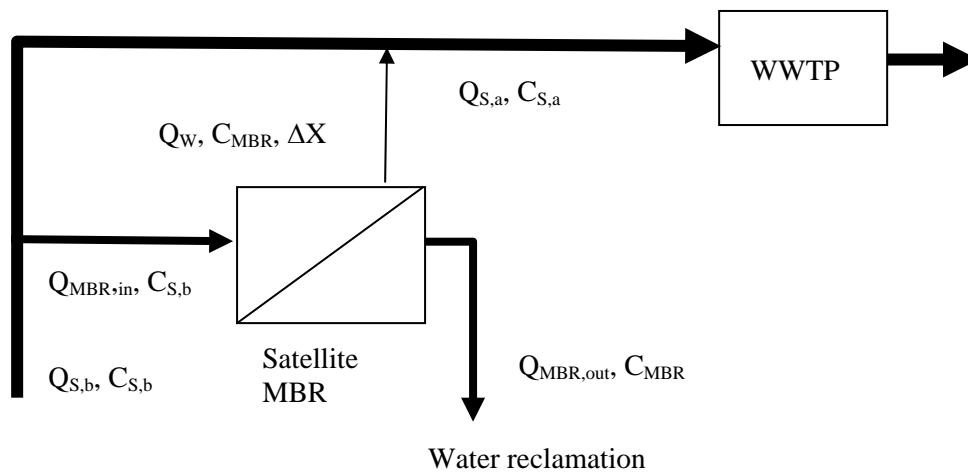

Figure E.1. Model I: mass balance around a wastewater collection system line receiving discharge of biomass from a satellite MBR water reclamation plant.

$Q_{S,b}$ = flow rate in wastewater collection system line before satellite membrane bioreactor (MBR) plant

$C_{S,b}$ = concentration of constituent in wastewater collection system line before satellite MBR plant

$Q_{MBR,in}$ = flow rate to satellite MBR plant

$Q_{MBR,out}$ = flow rate to water reclamation

C_{MBR} = concentration of constituent to water reclamation

Q_W = flow rate of biomass wastage to wastewater collection system line from satellite MBR plant

ΔX = biomass growth in satellite MBR

$Q_{S,a}$ = flow rate in wastewater collection system line after blending with waste discharge from satellite MBR plant

$C_{S,a}$ = concentration of constituent in wastewater collection system line after blending with waste discharge from satellite MBR plant

For constituents partitioning to biomass, linear partitioning is assumed between biomass and secondary effluent:

$$q = K_D C_{MBR,out} \qquad (E-1)$$

where q is the mass of a constituent per unit of biomass, K_d is the linear partitioning coefficient of a constituent between water and biomass, and $C_{MBR,out}$ is the secondary effluent concentration of a constituent produced by the MBR.

The mass rate of discharge of a constituent with wasted biomass is:

$$M = K_D C_{MBR,out} \times \Delta X \qquad (E-2)$$

where M is the mass of a constituent in the biomass per day and ΔX is the biomass growth (mass per day).

The biomass production rate per day is given by:

$$\Delta X = \left[Y_{MLSS} \times BOD_R + SS_{I,S,b} \right] Q_{MBR,in} \qquad (E-3)$$

where Y_{MLSS} is the net yield coefficient [in mg of mixed liquor suspended solids (MLSS)/mg of BOD_R], BOD_R (in milligrams per liter) is the BOD removed, and $SS_{I,S,b}$ is the inert suspended solids (SS) in the wastewater collection system line before the MBR plant and rejected by the membrane. Y_{MLSS} can be obtained from Y_{VSS} (milligrams of volatile suspended solids [VSS] produced per milligram of BOD biodegraded) by the equation $Y_{VSS}/0.75$.

The mass balance on a constituent after addition of the biomass wastage stream is:

$$Q_{S,a} C_{S,a} = Q_W C_{MBR,out} + M + \left(Q_{S,b} - Q_{MBR,in} \right) C_{S,b} \qquad (E-4)$$

where $Q_{S,a}$ is the wastewater flow rate in the wastewater collection system line after the WRP, $C_{S,a}$ is the concentration of a constituent in the wastewater collection system line after return of the biomass wastage stream from the MBR, Q_W is the waste activated sludge flow rate, $C_{MBR,out}$ is the concentration of a constituent leaving in the effluent of the MBR unit, $Q_{S,b}$ is the wastewater flow rate in the wastewater collection system before the WRP, $Q_{MBR,in}$ is the flow rate diverted to the MBR facility for water reclamation, and $C_{S,b}$ is the concentration of a constituent in the wastewater collection system line before discharge of the biomass wastage stream from the MBR.

Solving for $C_{S,a}$ gives:

$$C_{S,a} = \frac{Q_W C_{MBR,out} + M + \left(Q_{S,b} - Q_{MBR,in} \right) C_{S,b}}{Q_{S,a}} \qquad (E-5)$$

To determine flow balance:

$$Q_{S,a} = Q_W + Q_{S,b} - Q_{MBR,in} \qquad (E-6)$$

Substituting for $Q_{S,a}$ in eq E-5 gives:

$$C_{S,a} = \frac{Q_W C_{MBR,out} + M + \left(Q_{S,b} - Q_{MBR,in}\right)C_{S,b}}{Q_W + Q_{S,b} - Q_{MBR,in}} \qquad \text{(E-7)}$$

Substituting eq E-2 and E-3 into E-7 gives:

$$C_{S,a} = \frac{Q_W C_{MBR,out} + K_D\left(Y_{MLSS} \times BOD_R + SS_{I,S,b}\right)C_{MBR,out}Q_{MBR,in} + \left(Q_{S,b} - Q_{MBR,in}\right)C_{S,b}}{Q_W + Q_{S,b} - Q_{MBR,in}} \qquad \text{(E-8)}$$

Dividing through by $Q_{MBR,in}$ and defining the fraction of a constituent that remains after MBR treatment as $C_{MBR,out}/C_{S,b}$:

$$C_{S,a} = \frac{\left\{f_R\left[f_W + K_D\left(Y_{MLSS} \times BOD_R + SS_{I,S,b}\right)\right] + \left(\dfrac{1}{f_{MBR}} - 1\right)\right\}C_{S,b}}{f_W + \dfrac{1}{f_{MBR}} - 1} \qquad \text{(E-9)}$$

where the additional terms needing definition are:
f_R = fraction of constituent remaining in effluent of MBR unit
f_W = fraction of wastewater flow rate entering MBR returned to wastewater collection system line ($Q_W/Q_{MBR,,in}$)
f_{MBR} = fraction of wastewater flow rate in wastewater collection system line entering MBR ($Q_{MBR,,in}/Q_{S,b}$)

For suspended solids, the mass balance on suspended solids after addition of the biomass wastage stream is:

$$Q_{S,a}SS_{S,a} = \Delta X + \left(Q_{S,b} - Q_{MBR,in}\right)SS_{S,b} \qquad \text{(E-4)}$$

where $SS_{S,b}$ is the total SS in the wastewater collection system line before the MBR plant and $SS_{S,a}$ is the total SS, i.e., the sum of the wasted biosolids from the return flow of the MBR plant and the wastewater collection system line flow that did not pass through the MBR plant.

Substituting the biomass production rate per day, ΔX, from eq E-3:

$$Q_{S,a}SS_{S,a} = \left(Y_{MLSS} \times BOD_R + SS_{I,S,b}\right)Q_{MBR,in} + \left(Q_{S,b} - Q_{MBR,in}\right)SS_{S,b} \qquad \text{(E-10)}$$

Substituting for $Q_{S,a}$ from eq E-6 and solving for $SS_{S,a}$:

$$SS_{S,a} = \frac{\left(Y_{MLSS} \times BOD_R + SS_{I,S,b}\right)Q_{MBR,in} + \left(Q_S - Q_{MBR,in}\right)SS_{S,b}}{Q_W + Q_{S,b} - Q_{MBR,in}} \qquad \text{(E-10)}$$

Dividing through by $Q_{MBR,in}$:

$$SS_{S,a} = \frac{Y_{MLSS} \times BOD_R + SS_{I,S,b} + \left(\dfrac{1}{f_{MBR}} - 1\right) SS_{S,b}}{f_W + \dfrac{1}{f_{MBR}} - 1}$$ (E-11)

where:
$SS_{S,a}$ = total SS in wastewater collection system line after blending with MBR plant discharge
$SS_{I,S,b}$ = inert SS in wastewater collection system line before MBR plant
$SS_{S,b}$ = total SS in wastewater collection system line before MBR plant
f_W = fraction of wastewater flow rate entering MBR returned to wastewater collection system line ($Q_W/Q_{MBR,,in}$)
f_{MBR} = fraction of wastewater flow rate in wastewater collection system line entering MBR ($Q_{MBR,,in}/Q_{S,b}$)

E.2 MODEL II: DISCHARGE OF RO CONCENTRATE FROM A WTP TO A WASTEWATER COLLECTION SYSTEM LINE
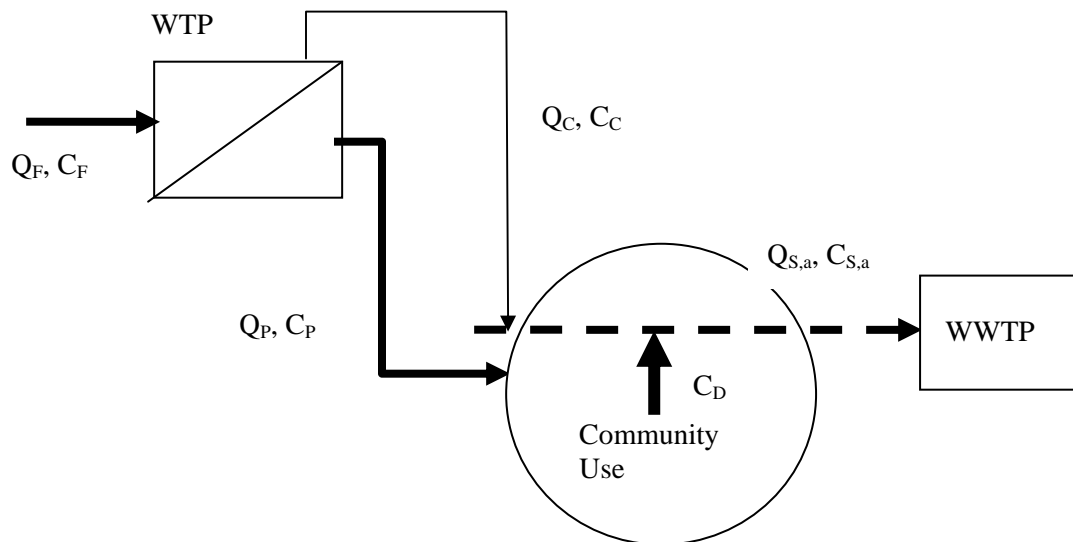

Figure E.2. Model II: discharge of RO concentrate from a WTP to a wastewater collection system line.

The parameters shown in Figure E.2 are:
Q_F = feed flow rate to membrane unit
C_F = concentration of constituent in feed flow
Q_C = concentrate stream flow rate from membrane unit
C_C = concentration of constituent in concentrate stream
Q_P = permeate stream flow rate from membrane unit
C_P = concentration of constituent in permeate stream

C_D = domestic use-generated concentration of constituent
$Q_{S,a}$ = flow rate in wastewater collection system line after blending with RO concentrate discharge
$C_{S,a}$ = concentration of constituent in wastewater collection system line after blending with backwash or chemical cleaning solution discharge

Mass balance around reverse osmosis (RO):

$$Q_F C_F = Q_C C_C + Q_P C_P \qquad \text{(E-12)}$$

To define rejection:

$$C_P = (1-r)C_F \qquad \text{(E-13)}$$

where:
r = fractional rejection of constituent

Defining recovery:

$$R = \frac{Q_P}{Q_F} \qquad \text{(E-14)}$$

such that:

$$\frac{Q_C}{Q_F} = 1 - R \qquad \text{(E-15)}$$

Solving eq E-12 for C_C:

$$C_C = \frac{C_F}{(1-R)} + \left(\frac{R}{1-R}\right)C_P \qquad \text{(E-16)}$$

$$C_C = \frac{[1-R(1-r)]C_F}{1-R} \qquad \text{(E-17)}$$

The mass balance for the wastewater collection system line after addition of concentrate stream:

$$Q_{S,a} C_{S,a} = Q_C C_C + \left(Q_P\right)\left(C_P + C_D\right) \qquad \text{(E-18)}$$

where $Q_{S,,a}$ is the flow rate in the wastewater collection system line after addition of concentrate, $C_{S,a}$ is the concentration of a constituent in the wastewater collection system line after addition of concentrate, and C_D is the contribution from domestic usage of water.

Solve eq E-18 for $C_{S,a}$:

$$C_{S,a} = \frac{Q_C C_C + Q_P (C_P + C_D)}{Q_{S,a}}$$

(E-19)

$$\text{where}: Q_{S,a} = Q_C + Q_P = Q_F$$

(E-20)

Substituting definitions of $Q_{S,,a}$ (eq E-20), C_C (eq E-17), and C_P (eq E-13) into eq E-19:

$$C_{S,a} = (1 - R)\frac{[1 - R(1 - r)]C_F}{1 - R} + R[(1 - r)C_F + C_D]$$

(E-21)

Simplifying eq E-21:

$$C_{S,a} = C_F + RC_D$$

(E-22)

The form of eq E-22 can be rationalized intuitively. If the RO concentrate is returned to the wastewater collection system line, then the mass of the constituent returning to the wastewater collection system line ($C_p Q_p + C_c Q_c$) must equal that entering the water treatment plant, and thus the concentration in the wastewater collection system line would be the same as the feed concentration to the water treatment plant if $C_D = 0$. The concentration added by domestic usage is diluted by the addition of concentrate flow; thus, R is multiplied by C_D.

The concentration in the wastewater collection system line without discharge of concentrate is:

$$C_{S,a} = C_P + C_D = (1 - r)C_F + C_D$$

(E-23)

where:
r = fraction rejected of a constituent
$$r = \frac{C_F - C_P}{C_P}$$

E.3 MODEL III: DISCHARGE OF BACKWASH WATER OR CHEMICAL CLEANING SOLUTION TO A WASTEWATER COLLECTION SYSTEM LINE
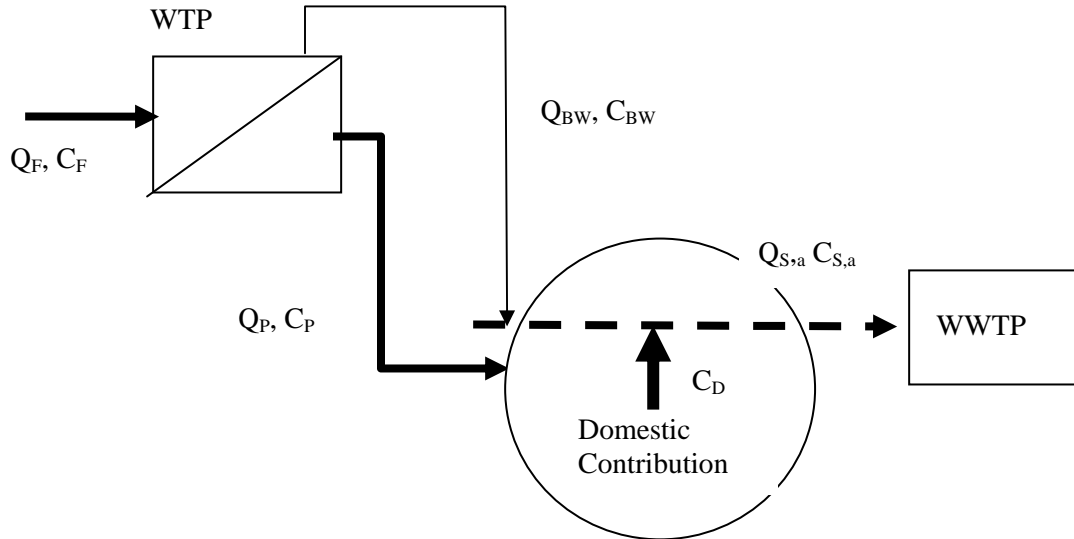

Figure E.3. Model III: mass balance around a wastewater collection system line receiving discharge of backwash water or chemical cleaning solution.

The parameters shown in Figure E.3 are:

Q_F = feed flow rate to membrane unit

C_F = concentration of constituent in feed flow

Q_{BW} = backwash water (BW) flow rate from membrane unit

C_W = concentration of constituent in backwash water stream

Q_P = permeate stream flow rate from membrane unit

C_P = concentrate of constituent in permeate stream

C_D = domestic use-generated concentration of constituent

$Q_{S,a}$ = flow rate in wastewater collection system line after blending with RO concentrate discharge

E.3.1 Continuous Generation of BW

Assume multiple low-pressure units in a WTP that undergo backwashing in sequence through the day.

Define the concentration in the BW stream as:

$$C_{BW} = \frac{Q_F C_F T_{FR}}{V_{BW}} \tag{E-24}$$

where:

C_{BW} = concentration of particles or bacteria in backwash stream
Q_F = feed flow rate to membrane filtration
C_F = feed concentration of particles or bacteria
T_{FR} = filtration run time
V_{BW} = volume of BW generated at end of each filtration run

Mass balance on the wastewater collection system line after addition of the BW stream:

$$Q_{S,a} C_{S,a} = Q_{BW} C_{BW} + Q_P (C_P + C_D)$$ (E-25)

Solve for $C_{S,a}$:

$$C_{S,a} = \frac{Q_{BW} C_{BW} + Q_P (C_P + C_A)}{Q_{S,a}}$$ (E-26)

For dead-end filtration, recovery (R) is defined as water used for BW:

$$R = \frac{Q_P}{Q_F} = \frac{Q_F - Q_{BW}}{Q_F} = 1 - \frac{Q_{BW}}{Q_F}$$ (E-27)

The flow rate in the wastewater collection system line is the wastewater generated after use of the permeate water by the community and with the addition of the BW stream, which is assumed to be equivalent to the feed flow rate to the membrane, i.e., BW derives exclusively from the feed flow rate.

$$Q_{S,a} = Q_P + Q_{BW} = Q_F$$ (E-28)

Substitute Q_F for $Q_{S,a}$ in eq E-26 and substitute eq E-27 into eq E-26:

$$C_{S,a} = (1 - R) C_{BW} + R (C_P + C_D)$$ (E-29)

Substitute the definition of C_{BW} from eq E-24:

$$C_{S,a} = (1 - R) \frac{Q_F C_F T_{FR}}{V_{BW}} + R (C_P + C_D)$$ (E-30)

Rewrite as:

$$C_{S,a} = \frac{Q_{BW}}{Q_F} \frac{Q_F C_F T_{FR}}{V_{BW}} + R (C_P + C_D)$$ (E-31)

Simplify:

$$C_{S,a} = \frac{Q_{BW} C_F T_{FR}}{V_{BW}} + R(C_P + C_D)$$ (E-32)

Define V_{BW}:

$$V_{BW} = Q_{BW} T_{BW}$$ (E-33)

Substitute eq E-33 into eq E-32:

$$C_{S,a} = \frac{C_F T_{FR}}{T_{BW}} + R(C_P + C_D)$$ (E-34)

E.3.2   Intermittent Addition of BW

Start with the concentration increase from continuous addition of BW to the wastewater collection system:

$$C_{S,a} = \frac{C_F T_{FR}}{T_{BW}} + R(C_P + C_D)$$ (E-35)

The time-averaged concentration added by BW is:

$$C_{S,a} = \frac{f_D C_F T_{FR}}{T_{BW}} + R(C_P + C_D)$$ (E-36)

where:
f_D = fraction of the day during which BW discharge occurs

E.3.3   Continuous Generation of Chemical Cleaning Solution

The worst-case situation is chemical cleaning solution discharged directly without dilution with stored BW. The mass balance on a chemical constituent in the cleaning solution is:

$$Q_{S,a} C_{S,a} = Q_{cc} C_{cc} + Q_P C_D$$ (E-37)

where Q_{cc} is the flow rate of chemical cleaning solution, C_{cc} is the concentration of a constituent in the chemical cleaning solution, C_P is the wastewater flow rate, and C_D is the concentration of the constituent added by domestic usage. While C_D will be negligible for many constituents, citric acid is biodegradable and thus adds to the BOD_5 from domestic usage. The flow rate in the wastewater collection system line is the sum of the permeate flow rate and the cleaning solution flow rate:

$$C_{S,a} = \frac{Q_{cc} C_{cc} + Q_P C_D}{Q_P + Q_{cc}}$$ (E-38)

$$C_{S,a} = \frac{f_{cc}C_{cc} + C_D}{1 + f_{cc}} \tag{E-39}$$

where f_{cc} = the fraction of the permeate flow rate that is the cleaning solution flow rate (Q_{cc}/Q_P).

E.4   MODEL IV: SATELLITE RO WATER RECLAMATION WITH DISCHARGE OF CONCENTRATE TO A WASTEWATER COLLECTION SYSTEM LINE
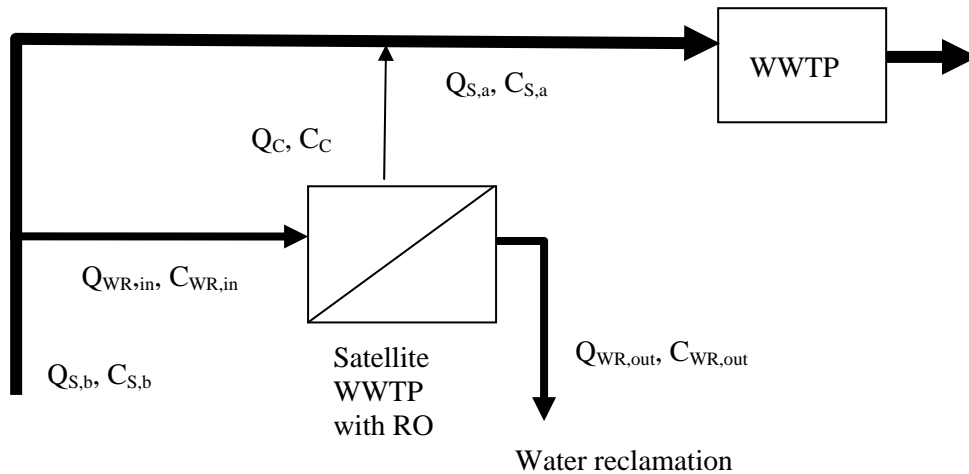

Figure E.4. Model IV: mass balance around a wastewater collection system line receiving discharge of RO concentrate from a satellite water reclamation plant.

The parameters shown in Figure E.4 are:
$Q_{S,b}$ = flow rate in wastewater collection system line before satellite RO plant
$C_{S,b}$ = concentration of constituent in wastewater collection system line before satellite MBR plant
$Q_{WR,in}$ = flow rate to satellite RO plant from secondary treatment
$C_{WR,in}$ = concentration of constituent after secondary treatment (feed to RO plant)
$Q_{WR,out}$ = permeate flow rate of satellite RO plant to water reclamation
$C_{WR,out}$ = concentration of constituent in permeate of satellite RO plant to water reclamation
Q_C = concentrate stream flow rate from membrane unit
C_C = concentration of constituent in concentrate stream
$Q_{S,a}$ = flow rate in wastewater collection system line after blending with RO concentrate discharge
$C_{S,a}$ = concentration of constituent in wastewater collection system line after blending with RO concentrate discharge

Mass balance after discharge of concentrate to the wastewater collection system line:

$$Q_{S,a}C_{S,a} = Q_C C_C + \left(Q_{S,b} - Q_{WR,in}\right)C_{S,b} \tag{E-40}$$

$$C_{S,a} = \frac{Q_C C_C + \left(Q_{S,b} - Q_{WR,in}\right)C_{S,b}}{Q_{S,a}} \tag{E-41}$$

where:

$$Q_{S,a} = Q_C + Q_{S,b} - Q_{WR,in} \qquad \text{(E-42)}$$

Substituting for $Q_{S,a}$ in eq E-41:

$$C_{S,a} = \frac{Q_C C_C + (Q_S - Q_{WR,in})C_{S,b}}{Q_C + Q_{S,b} - Q_{WR,in}} \qquad \text{(E-43)}$$

Mass balance around RO:

$$Q_{WR,in}C_{WR,in} = Q_C C_C + Q_{WR,out}C_{WR,out} \qquad \text{(E-44)}$$

Note: $C_{WR,in}$ = secondary effluent of satellite water reclamation plant

Define rejection:

$$C_{WR,out} = (1-r)C_{WR,in} \qquad \text{(E-45)}$$

Define recovery:

$$R = \frac{Q_{WR,out}}{Q_{WR,in}} \qquad \text{(E-46)}$$

$$\frac{Q_C}{Q_{WR,in}} = 1 - R \qquad \text{(E-47)}$$

Solve RO balance for C_C:

$$C_{Wr,in} = (1-R)C_C + R(1-r)C_{WR,in} \qquad \text{(E-48)}$$

$$C_C = \frac{[1-R(1-r)]C_{WR,in}}{1-R} \qquad \text{(E-49)}$$

Substitute eq E-49 into eq E-43:

$$C_{S,a} = \frac{Q_C \dfrac{[1-R(1-r)]C_{WR,in}}{1-R} + (Q_{S,b} - Q_{WR,in})C_{S,b}}{Q_C + Q_{S,b} - Q_{WR,in}} \qquad \text{(E-50)}$$

Substitute for Q_C from eq E-47 and divide through by $Q_{WR,in}$:

$$C_{S,a} = \frac{[1 - R(1-r)]C_{WR,in} + \left(\dfrac{Q_{S,b}}{Q_{WR,in}} - 1\right)C_{S,b}}{\dfrac{Q_C}{Q_{WR,in}} + \dfrac{Q_{S,b}}{Q_{WR,in}} - 1}$$

(E-51)

Substitute the definition of $Q_C/Q_{WR,in}$ from eq E-47:

$$C_{S,a} = \frac{[1 - R(1-r)]C_{WR,in} + \left(\dfrac{Q_{S,b}}{Q_{WR,in}} - 1\right)C_{S,b}}{\dfrac{Q_{S,b}}{Q_{WR,in}} + R}$$

(E-52)

Define the fraction of wastewater diverted to water reclamation:

$$f_{WR} = \frac{Q_{WR,in}}{Q_{S,ib}}$$

(E-53)

Substitute eq E-53 into eq E-52:

$$C_{S,a} = \frac{[1 - R(1-r)]C_{WR,in} + \left(\dfrac{1}{f_{WR}} - 1\right)C_{S,b}}{\dfrac{1}{f_{WR}} - R}$$

(E-54)

APPENDIX F

CASE STUDY EXAMPLE

All material for the case study example is provided on the enclosed CD-ROM.

Appendix F includes two examples from Oklahoma City, OK. The "Redbud Mass Balance Model" file demonstrates data input for just one end user on the system. Effluent from the North Canadian WWTP is sent to the power plant and the effluent from the power plant comes back to the WWTP influent.

The "All Power Plants Mass Balance Model" file includes a second power plant taking flow from one of the city's smaller WWTPs and taking water from a neighboring community, using the water and discharging back to the main WWTP. It also includes the impact from a new industry that is contemplating moving to town.

Both of these examples demonstrate how data is accumulated and put into the model.

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