Analyzing Alternatives for Sulfate Treatment in Municipal Wastewater

Prepared for:
Minnesota Pollution Control Agency

May 1, 2018

Prepared by:
Bolton & Menk, Inc. and Barr Engineering Company

Certifications

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Abstract

The current revision of Minnesota's surface water quality standard for sulfate may result in some municipal wastewater treatment plants having to reduce the sulfate in their discharge. This two-part study evaluated options for sulfate treatment and examined the implications of those treatment options for typical municipal wastewater treatment plants in Minnesota. The first project activity reviewed and ranked 31 technologies for sulfate removal based on effectiveness, operability/maintainability, cost, complexity of pre- and post-treatment, and waste management requirements. The types of technologies reviewed included chemical precipitation, ion exchange, membrane separation, electrochemical, biological, and evaporative treatment. The technology review indicated that reverse osmosis (RO) and nanofiltration (NF) are the most well-developed and effective alternatives available for sulfate removal at this time, despite the complexity and cost associated with final waste management. The second part of the study examined the implementation of RO for sulfate removal at Minnesota's municipal wastewater treatment plants in greater depth, using six hypothetical case studies covering a range of treatment plant sizes and sulfate treatment goals typical for the state. The case studies considered the technical, operational, and economic issues associated with integration of RO into conventional municipal treatment systems. Sulfate treatment using RO was found to be extremely expensive and operationally complex. The main driver of complexity and costs was membrane waste management, which in this study focused on mechanical evaporation and crystallization. Due to the complexity of the processes, which differ significantly from those currently employed for conventional municipal wastewater treatment, increased staffing levels and operator training would be needed for successful implementation. RO and NF are effective in removing sulfate from wastewater, but waste management challenges remain a barrier to implementation. Across all industries employing RO and NF, additional research and development are needed to create cost-effective, sustainable waste management alternatives.

Executive Summary

1.1 Introduction

The State of Minnesota is currently revising the surface water quality standard of 10 mg/L. A revised water quality standard may result in some municipal wastewater treatment plants (WWTPs) needing to reduce the concentration of sulfate in their discharges. Historically, municipal WWTPs have not been required to treat sulfate to achieve compliance with a NPDES permit. This report presents the results of a study commissioned by the Minnesota Pollution Control Agency through funding from the Minnesota Environment and Natural Resources Trust Fund to assess the current technologies and tools available to municipal WWTPs to reduce sulfate concentrations in their discharges and identifies the challenges of meeting potential sulfate limits in the future.

In Part 1 of the study (2017), a wide range of established and emerging sulfate treatment technologies from the municipal and industrial sectors and source control options were reviewed, screened, and ranked to understand their advantages and disadvantages and to identify potentially feasible technologies currently available for sulfate removal.

Of the technologies reviewed, reverse osmosis (RO) and nanofiltration (NF), both membrane technologies, were identified as the most promising, well-established technologies for sulfate removal. Part 1 also stated that further research and development on cost-effective means for managing the salt-laden, liquid waste generated by these processes is needed. This liquid waste stream is called either concentrate or reject. The process and cost of managing this waste stream became a major part of Part 2.

Part 2 (2018) examines the practical design, implementation considerations, and costs of select treatment technologies for use in removing sulfate in typical municipal WWTPs. Six hypothetical case studies are presented that cover a broad range of sulfate treatment scenarios and treatment plant types.. The case studies include: biological wastewater treatment plant costs, membrane treatment costs, concentrate management costs, and if required, intermediate water treatment with a second stage of membrane treatment for concentrate minimization.

1.2 Technology Summary from Part 1

The screening process used in Part 1 was a three-step process that included:

1. Threshold screening based on the technology's degree of development and commercialization, and ability to achieve a threshold sulfate removal performance;
2. Technology screening based on performance, cost, and other factors; and
3. Screening based on removal performance for other parameters of concern, such as nutrients, chloride, total dissolved solids, and mercury.

The goal of the screening process was to understand the advantages and limitations of each sulfate treatment approach, and to identify the most feasible treatment technologies for reducing sulfate in municipal wastewater effluent using a uniform scoring and ranking methodology.

Of the 31 technologies evaluated, 18 technologies were screened out, and 13 technologies were successful in the first level of screening and were then screened using these second level criteria. Second level assessment is based on: effectiveness, operability/maintainability, relative cost, degree/complexity of pre and post treatment requirements, and management of treatment residuals.

The treatment technologies that received the top ratings were reverse osmosis, and nano-filtration. These technologies scored highest in effectiveness and operability/maintainability, including cold weather performance. They have a high potential for beneficial reuse of the treated wastewater. Both of the membrane technologies will produce a very high quality effluent for a wide variety of water reuse applications. However, the membrane technologies received the lowest overall scores under the residuals management category. Residuals management for membrane processes is a known technical and economic challenge associated with this class of treatment technologies and is an area of active investigation across several industries.

1.3 Summary of Part 2

In Part 2, the two top ranked technologies were used to develop capital and operating and maintenance (O&M) costs for POTW's with flows from 0.5 to 10 MGD. Table ES-1 shows the various flow rates and biological treatment processes considered for evaluation and percentage of influent flow needed to be treated by RO membrane process to achieve the target effluent sulfate level.

Table ES-1 Analysis cases for cost evaluations

Case Number	Flow (MGD)	Type of Biological Treatment	Influent Sulfate (mg/L)	Required Effluent Sulfate (mg/L)	% of Flow Treated by RO to Meet Effluent Target
1	10	Activated Sludge	100	10	93%
2	2.5	Trickling Filter	25	10	63%
3	2.5	Activated Sludge	600	100	89%
4	0.5	Activated Sludge	300	10	99%
5	0.5	Activated Sludge	300	100	74%
6	0.5	Facultative Pond	600	250	68%

Depending on the influent and the required effluent level for sulfate, the percentage that had to be treated by the RO membrane system ranged from 60 to 99 percent. The major disadvantage with the RO treatment process is the difficulty and expense of concentrate disposal. In MN, the only viable concentrate disposal when RO treatment is used at POTW is a mechanical thermal evaporation (MTE) process. MTE is sometimes referred to as a zero liquid discharge (ZLD) process since all the liquid concentrate waste is evaporated and a solid residue remains requiring disposal in a landfill. The MTE process is a very expensive capital and energy intensive process.

Table ES-7 **Estimated costs for biological treatment costs for liquid treatment and biosolids**

Case Study	Biological Liquids Treatment		Biosolids Processing	
	Capital Costs ($)	O&M Costs ($)	Capital Costs ($)	O&M Costs ($)
1	24,578,000	2,651,000	10,054,000	7,006,000
2	18,721,000	631,000	5,714,000	1,810,000
3	22,791,000	903,000	6,052,000	1,940,000
4	10,514,000	569,000	1,946,000	534,000
5	10,497,000	570,000	1,946,000	535,000
6	14,000,000	96,000	N/A	N/A

Table ES-8 presents the sulfate removal costs and the concentrate disposal costs for the six cases. For Cases 1, 3 and 4 concentrate minimization or volume reduction was analyzed by treating RO reject by lime softening or pellet softening and then processing through a secondary RO system and a proprietary VSEP secondary membrane treatment process.

Table ES-8 **Estimated costs for sulfate removal by ro membrane treatment process and concentrate management**

Case Study	Sulfate Removal		Concentrate Treatment	
	Capital Costs ($)	O&M Costs ($)	Capital Costs ($)	O&M Costs ($)
1	33,821,000	1,623,000	(1) 34,000,000 (2) 28,500,000 (3) 65,308,000	(1) 14,033,000 (2) 14,598,000 (3) 6,878,000
2	11,748,000	449,000	16,250,000	3,478,000
3	11,318,000	466,000	(1) 25,250,000 (2) 17,750,000 (3) 38,400,000	(1) 5,979,000 (2) 5,203,000 (3) 2,964,000
4	7,318,000	94,000	(1) 14,600,000 (2) 10,000,000 (3) 17,000,000	(1) 1,841,000 (2) 1,429,000 (3) 948,000
5	7,293,000	133,000	12,000,000	2,094,000
6	5,452,000	88,00	13,000,000	2,479,000

(1) Lime softening is used prior to secondary (concentrate reduction) RO treatment.
(2) Pellet softening is used prior to secondary (concentrate reduction) RO treatment.
(3) A VSEP concentrator process is used treat RO concentrate.

Table ES-9 presents the summary of the total capital costs, total O&M costs and the 20-year present value costs for the six case studies evaluated.

Table ES-9 Summary of the total capital costs, O&M costs and a 20-year present cost for all six case studies

Case Study	Total Capital Costs ($)	Total O&M Costs ($)	20-Year Present Costs ($)
1	(1) 102,453,000 (2) 96,953,000 (3) 133,761,000	(1) 25,313,000 (2) 25,878,000 (3) 18,158,000	(1) 510,751,642 (2) 514,360,382 (3) 426,651,992
2	52,432,688	6,367,243	155,136,318
3	(1) 65,411,000 (2) 57,911,000 (3) 78,561,000	(1) 9,287,000 (2) 8,511,000 (3) 6,272,000	(1) 215,207,205 (2) 195,192,224 (3) 179,730,529
4	(1) 34,378,000 (2) 29,778,000 (3) 36,778,000	(1) 3,039,000 (2) 2,626,000 (3) 2,146,000	(1) 83,388,571 (2) 72,141,495 (3) 71,388,014
5	31,736,000	3,331,000	85,467,866
6	32,452,000	2,662,000	75,397,024

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Part 1: Feasibility Alternative Review

Prepared for
Minnesota Pollution Control Agency

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Acronyms

Acronym	Description
ARROW	Advanced reject recovery of water
BOD	Biochemical oxygen demand
CCD RO	Closed-circuit desalination reverse osmosis
CESR	Cost-effective sulfate removal
CIP	Clean-in-place
CRF	Concentrate reduction facility
ED/EDR	Electrodialysis/electrodialysis reversal
EPWU	El Paso Water Utilities
EWM	Enviro Water Minerals Company
FO	Forward osmosis
GAC	Granulated activated carbon
HERO	High efficiency reverse osmosis
IX	Ion exchange
KBH	Kay Bailey Hutchison Drinking Water Desalination Plant
MDC	Membrane distillation with crystallization
MDH	Minnesota Department of Health
MGD	Million gallons per day
MPCA	Minnesota Pollution Control Agency
NF	Nanofiltration
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and maintenance
RO	Reverse osmosis
SANI	Sulfate reduction, autotrophic denitrification, and nitrification integrated
SBR	Sequencing batch reactor
SDWA	Safe Drinking Water Act
SPARRO	Slurry precipitation and reverse osmosis
SRB	Sulfate-reducing bacteria
TCLP	Toxicity characteristic leaching procedure
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
U of MN	University of Minnesota
UF	Ultrafiltration
UIC	Underground Injection Control
USBR	United States Bureau of Reclamation
UASB	Upflow anaerobic sludge blanket
USEPA	United States Environmental Protection Agency
VSEP	Vibratory shear enhanced processing

WWTP	Wastewater treatment plant
ZDD	Zero discharge desalination
ZLD	Zero-liquid discharge

Abstract

The State of Minnesota is currently revising the surface water quality standard of 10 mg/L sulfate for the protection of wild rice. A revised water quality standard may result in some municipal wastewater treatment plants (WWTPs) needing to reduce the concentration of sulfate in their discharges. Historically, WWTPs have not been required to treat sulfate to achieve compliance. This report presents the results of the first of a two-part study commissioned by the Minnesota Pollution Control Agency through funding from the Minnesota Environment and Natural Resources Trust Fund to assess the current technologies and tools available to WWTPs to reduce sulfate concentrations in their discharges and identifies the challenges of meeting potential sulfate limits in the future. In Part 1 of the study (this report), a wide range of established and emerging sulfate treatment technologies from the municipal and industrial sectors and source control options were reviewed, screened, and ranked to understand their advantages and disadvantages and to identify potentially feasible technologies currently available for sulfate removal. While several potential treatment technologies may be available for municipal WWTPs, several key technical challenges still need to be overcome.

Municipal WWTPs use a combination of physical, biological, and chemical treatment processes for wastewater treatment. Sulfate can be transformed biologically and therefore it is logically of interest to use biological approaches for removal. The typical biological process used for municipal wastewater treatment was evaluated to determine if it could be adapted for sulfate removal. The evaluation identified limitations to this approach resulting from the slow growth of sulfate-reducing bacteria, and the need for more significant development of design and operational strategies to ensure the success of sulfate-reducing bacteria growth before they can be employed to full-scale implementation. Other classes of technologies were also reviewed: chemical precipitation, ion exchange, membrane treatment, electrochemical treatment, and evaporative treatment. Of these, the membrane technologies were identified as promising, well-established technologies for sulfate removal. Further research and development on cost-effective means for managing the salt-laden, liquid waste generated by these processes is needed, however, and this is a widespread challenge in many water treatment applications where these technologies are employed.

Controlling sources of sulfate to municipal wastewater through source reduction was also examined to determine if enough sulfate could be removed upstream of treatment plants to impact the discharge concentration. The primary sources of sulfate and sulfide into a typical municipal wastewater plant include the drinking water supply (reporting to the domestic wastewater), industrial discharges, and the contents of domestic wastewater itself. The sulfate concentration in Minnesota’s drinking water supply varies widely by geographic region, and the presence of industrial dischargers will also vary greatly. Thus, the ability to use source reduction to comply with potential future sulfate limits will be highly site-specific. In some cases, it may be more cost-effective and less technically complex to remove sulfate at the source (e.g., the drinking water supply) rather than at the municipal wastewater treatment plant.

Part 2 of the study examines the practical design, implementation considerations, and costs of select treatment technologies for use in removing sulfate in typical WWTP applications.

Executive Summary

The State of Minnesota is currently in the process of revising the surface water quality standards for sulfate applicable to wild rice. While many states have sulfate water quality standards, Minnesota is unique because it is the only state in the United States that has established a sulfate standard for the protection of wild rice, currently 10 mg/L. When the new water quality standard is implemented, some municipal wastewater treatment plants may be required to remove sulfate to comply with National Pollutant Discharge Elimination System (NPDES) permit limits protective of the surface water quality standard for sulfate applicable to wild rice. The proposed water quality standard is equation-based, site-specific, and has the potential to generate a wide range of protective sulfate concentrations from less than 1 mg/L to greater than 1,000 mg/L. Historically, municipal wastewater systems have not been required to consider sulfate treatment for discharge compliance purposes, so little information is available concerning the applicability of sulfate treatment technologies to municipal wastewater processes for this purpose. This study was designed to address the sulfate treatment requirements associated with a wide range of potential effluent concentration limits.

Sulfur in wastewater is most commonly present as sulfate or sulfide, which originates primarily from drinking water sources, human waste, and industrial discharges. More than 95% of municipalities in Minnesota use groundwater as the source for their drinking water. The concentrations of sulfate in the groundwater vary geographically across the state from less than 10 mg/L to over 500 mg/L. Untreated domestic wastewater constituents typically add another 20 to 50 mg/L of sulfate [Ref. (1)], and some municipalities may have additional industrial contributions. The form of sulfur is dependent on the condition of the wastewater, with sulfate present in oxygen-rich waters and sulfide present in oxygen-depleted water. The environmental conditions that help determine the state of sulfur in wastewater may be readily transformed, either biologically or chemically, by natural and engineered processes. Both sulfate and sulfide provide pathways for the removal of sulfur from wastewater. However, the technologies available to remove sulfate and sulfide from wastewater have mostly been developed and employed in applications other than municipal wastewater treatment, including drinking water treatment, mine water treatment, power generation, and others.

In this study, treatment technologies for sulfate removal were reviewed and screened for their applicability and potential use by municipal wastewater treatment plants needing to reduce sulfate from their discharge in the future. The screening criteria included effectiveness, operability and maintainability, relative costs, degree and complexity of additional pre- and post-treatment, residuals management, and ability to remove other parameters of concern. The technologies reviewed were grouped into six general categories: chemical precipitation, ion exchange, membrane separation, electrochemical, biological, and evaporative treatment. Because removal of sulfate from municipal wastewater has not previously been widely implemented, technologies still in early stages of testing and development were also included for completeness and future reference and to gauge the "state of the industry" at this time.

The technology screening process results indicate that reverse osmosis and nanofiltration are the most well-developed and effective alternatives for sulfate removal. This class of technologies is able to remove sulfate from wastewater to low concentrations (e.g., <50 mg/L). However, membrane technologies generate a salty, liquid waste (concentrate) that is technically challenging and costly to manage. While membrane treatment is widely used and commercialized, concentrate management is an active area of research and development in the wastewater treatment industry due to the complexity and cost of final waste management and disposal. As a result, concentrate management must be carefully considered when planning for implementation of membrane technologies. Chemical precipitation and ion exchange scored slightly below reverse osmosis and nanofiltration (membrane technologies), primarily due to limited ability to remove sulfate to low concentrations (e.g., less than 50 mg/L), fewer commercial applications, and higher risks to operator and public health. However, depending upon the influent sulfate concentration, if a wastewater treatment plant effluent limit for sulfate is above 50 mg/L, a chemical precipitation or ion exchange treatment technology may be effective for the required sulfate removal. The screening results also reflect the state of the industry today in terms of municipal wastewater treatment for sulfate removal and provide an indication of additional technologies that may be viable in the future pending further commercialization, demonstration of reliable operation, and residuals management developments.

Because municipal wastewater treatment plants use biological treatment for removal of common pollutants from wastewater (e.g., biochemical oxygen demand, suspended solids, and nutrients), it is logical to consider biological treatment options for sulfate removal. The literature review identified numerous biological treatment processes that are under development for sulfate removal, but few that are commercialized and have demonstrated reliability in full-scale applications as would be required for sulfate removal from municipal WWTPs. Biological treatment of sulfate has primarily been applied to mine water treatment, where metals removal by converting sulfate to sulfide is the primary goal, not sulfate removal; so in those settings, low-efficiency biological treatment systems like constructed wetlands and mine pit reactors are practical. Fundamentally, due to the slow growth of sulfate-reducing bacteria, a much longer retention time is required in the biological reactor than is typically practical in municipal wastewater treatment. This class of treatment technologies, overall, requires significant development of design and operational strategies to ensure the success of sulfate-reducing bacteria growth before they can be employed to full-scale implementation for municipal wastewater treatment. These limitations resulted in biological treatment receiving technology screening scores on the lowest end of the range compared to the other treatment technologies.

The utility of controlling sources of sulfate to municipal wastewater through source reduction was also examined to determine if enough sulfate could be removed upstream of treatment plants to impact the discharge concentration. The primary sources of sulfate and sulfide into a typical municipal wastewater plant include the drinking water supply (reporting to the domestic wastewater), industrial discharges, and the contents of domestic wastewater itself. The sulfate concentration in Minnesota's drinking water supply varies widely by geographic region, and the presence of industrial dischargers will also vary greatly. Thus, the ability to use source reduction to comply with potential future sulfate limits will be highly site-specific. Not all industrial discharges contain sulfate, but those that do may not be able to provide additional pre-treatment or process modifications to reduce the sulfate or sulfide in their discharges to the collection system. Municipalities faced with the need for compliance options for meeting a new sulfate limit, however, should consider source reduction as part of their evaluations, starting with a basic mass balance of sources into their plant compared with the mass of sulfate that needs to be removed.

This report (Part 1 of the two-part study) provides an overview of the treatment technologies available and those currently under development for sulfate removal, and synthesizes the findings into guidance for municipalities and other interested parties to follow in their initial assessments of how to comply with potential future sulfate limits. Part 1 of the study also reviewed if and to what degree the sulfate removal technologies may provide added benefit for removal of other parameters of concern, such as chloride, mercury, nitrogen, phosphorus, and total dissolved solids. In Part 2 of the project, conceptual designs of select treatment approaches were developed to illustrate key technical considerations that are associated with technology implementation. Cost estimates for the conceptual designs were also developed.

1.0 Introduction

1.1 Background

The Minnesota Pollution Control Agency (MPCA) is in the process of revising the existing sulfate surface water quality standard. Minnesota is unique in that it is the only state in the United States with a sulfate standard for the protection of wild rice, currently 10 mg/L. The new rule is expected to include consideration of site-specific chemistry when calculating the in-stream water quality standards. As a consequence, wastewater effluent sulfate limits will typically need to be calculated and imposed to meet the in-stream water quality standard. Some municipal wastewater treatment plants may be required to remove sulfate in the future to comply with potential future NPDES permit effluent limits for sulfate.

Historically, sulfate treatment has primarily been applied to industrial water and wastewater treatment in industries such as mining, metal finishing, and wood products for the purposes of metals removal, total dissolved solids reduction, and sulfate removal. It is removed (as a component of dissolved solids removal) in many high-pressure industrial boiler applications as part of boiler feed water production. Municipal wastewater systems have not typically considered sulfate treatment (beyond considerations related to corrosion or odor control). Therefore, little information is available concerning the applicability of sulfate treatment technologies to municipal wastewater processes for the purpose of effluent limit compliance.

Municipal wastewater sulfate concentrations in Minnesota range from about 10 to over 1,500 mg/L and originate from a drinking water source (i.e., river or aquifer), human waste, or industrial sources [Ref. (2)]. As shown on Figure 1-1, there are currently 152 municipal WWTPs in Minnesota that monitor effluent sulfate concentrations. Minnesota has over 600 municipal WWTPs permitted to discharge to surface water. The MPCA assigns municipal WWTPs sulfate monitoring requirements for the following reasons:

- The facility has been identified as being upstream of a wild rice water.
- The facility is a continuous discharger that discharges to a low-dilution receiving water.
- The facility receives flow from industrial users known to have high salt concentrations.

Figure 1-1 shows the average sulfate concentrations across the state for the WWTPs currently monitoring effluent sulfate.

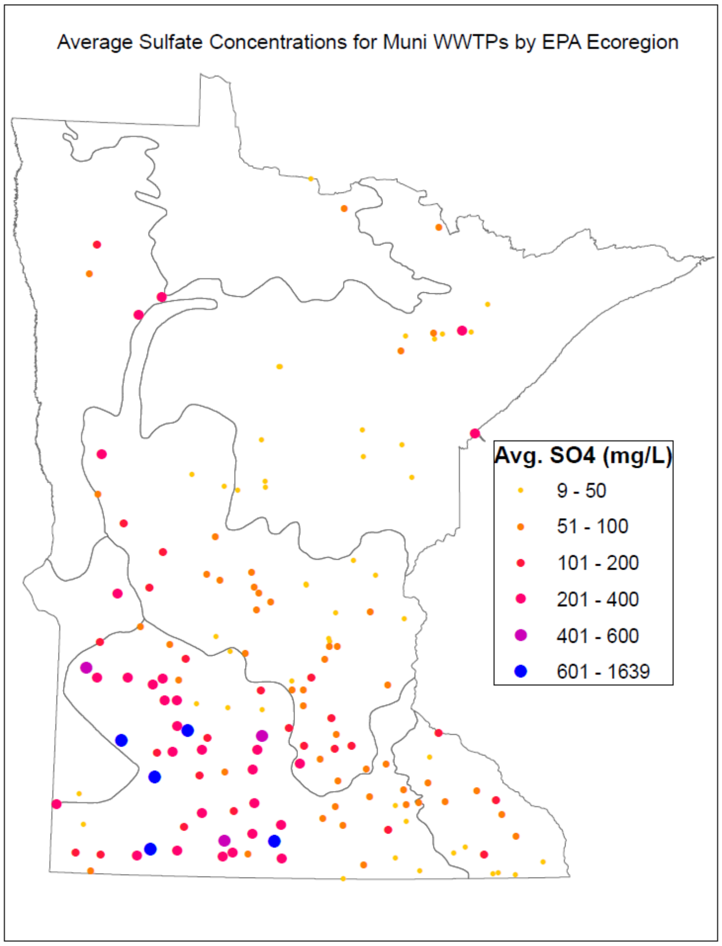

Figure 1-1 **Average sulfate concentrations for municipal wastewater treatment plants**

The objectives of this project are to:

- Identify and describe existing alternatives to remove sulfate from water
- Evaluate these alternatives for feasibility to treat municipal wastewater in Minnesota
- Evaluate whether the sulfate-removal technologies may also provide additional benefits by removing other parameters of concern, such as nitrogen, phosphorus, salts, and mercury
- Provide a framework for decision-making when considering sulfate removal technologies
- Provide a report to serve as a resource for communities, consultants, and regulators

1.2 Project Approach

The approach to the project was as follows. First, existing and emerging sulfate treatment technologies were identified, evaluated, and described in the context of applicability to municipal wastewater treatment (Section 2.0). Next, screening criteria were developed to evaluate these technologies for municipal wastewater treatment. Those technologies that have full-scale installations (either municipal or industrial) and are able to reduce sulfate to less than 250 mg/L were carried forward for detailed screening and evaluation. This value, 250 mg/L sulfate, was agreed upon with the MPCA as a reasonable threshold at this time for use in focusing on technologies that hold the greatest potential for reliable treatment. Additional screening criteria were applied and promising technologies were ranked (Section 3.0). In addition, secondary technologies for managing treatment residuals and byproducts, such as brine, sludge, and sulfide, were also researched and described (Section 4.0). Based on technology screening, some examples regarding how municipalities and regulators can use this information to assist in selecting appropriate sulfate treatment technologies were developed (Section 5.0). Conclusions from the study are summarized (Section 6.0).

When considering and identifying treatment technologies, to the extent possible, the focus was placed on technology categories rather than specific proprietary technologies. Within any one treatment technology category, there may be many proprietary and non-proprietary versions available by which to implement the process. This report does not attempt to identify all versions of a particular process or technology category. Where appropriate, some specific proprietary technologies are given. In these cases, these technologies provide a useful illustration of variations in configurations available or highlight a unique process element for consideration. Where a specific proprietary technology has been included in this report, no endorsement of the product is explicit or implied.

2.0 Primary Technologies for Reducing Sulfate in Municipal Wastewater Effluents

2.1 Sulfur in the Environment

Sulfur is an essential element for life on earth. It is present throughout most of the earth's crust at a reported average concentration of approximately 500 mg/Kg [Ref. (3)]. The fate of sulfur in the environment has been studied extensively [Ref. (4)], due to its potential interactions with many other elements in soil, sediments, aqueous solutions, and the atmosphere. In the environment, sulfur can exist in up to five different states. These oxidation states are shown in Table 2-1, ranging from sulfide (the most reduced form with a formal charge of -2 on S) to sulfate (the most oxidized form with a formal charge of +6 on S). The oxidation state and the chemical form of sulfur depend on the degree of oxygenation, pH, microbial activity, and temperature of the environment. Both oxidized and reduced sulfur are reactive following biological and chemical pathways.

Table 2-1 Common oxidation states of sulfur

Species	Oxidation state (formal charge on S)
HS^- (sulfide)	-2
H_2S (hydrogen sulfide)	-2
S (elemental sulfur)	0
SO_3^{2-} (sulfite)	+4
SO_4^{2-} (sulfate)	+6

2.1.1 Oxidation States and Solubility of Sulfur Affect Water Treatment Options

Of the oxidation states presented in Table 2-1, two are of particular importance in the treatment of sulfate-laden water: sulfide (mainly HS^-) and sulfate (SO_4^{2-}). These types of sulfur are the most commonly encountered in treatment processes. The forms of sulfide and sulfate in the environment are both dependent on the acidity or basicity (as measured by pH) of the water they are in. Sulfide, under acidic conditions (low pH), is present as the weak acid, hydrogen sulfide (H_2S). This species has low water solubility [Ref. (5)] and has potential to off-gas. It is also corrosive to many metals, highly toxic, and is a common cause of odor complaints in settings such as municipal sewer systems, municipal and industrial treatment plants, and livestock manure pits. Hydrogen sulfide is the predominant species from pH 1 to 7. At more basic pH, from pH 7 to 13, HS^- dominates, and at pH greater than 13, S^{2-} (sulfide) is the dominant form. In the reduced form, sulfide will readily combine with metal cations, such as iron, to form insoluble compounds. Both of these routes—off-gassing and precipitation—offer potential pathways for removal of sulfur from water.

In the oxidized form of sulfate, solubility varies in relation to other chemicals in the water. Sodium, magnesium, and potassium sulfate all dissolve readily in water. In contrast, calcium sulfate (gypsum) has a moderate solubility and barium sulfate is generally insoluble, which makes these salts amenable to sulfate removal via chemical precipitation.

Elemental sulfur, $S_{(s)}$, can form in some conditions, but its formation can be difficult to control, as evidenced by the small area shown for elemental sulfur on Figure 2-1 as $S_{(s)}$.

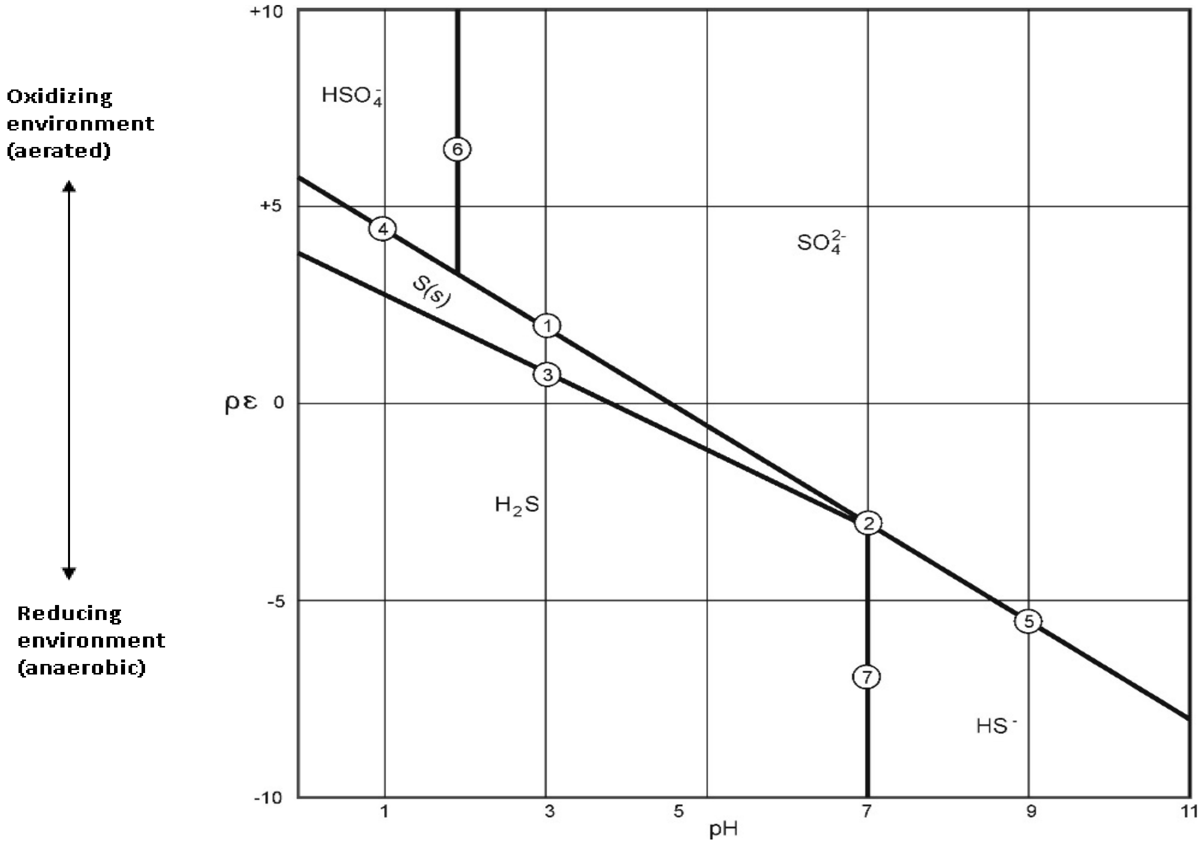

Figure 2-1 Eh – pH diagram of sulfate – sulfide system, only [Ref. (5)]

One of the most challenging aspects of sulfate removal is that sulfur can be readily transformed from sulfate to sulfide (and back to sulfate) biologically and chemically (by exposure to oxygen in air, for example). Each of these routes offers potential options for removing sulfur mass (and therefore sulfate mass) from wastewater, but it also means that all aspects of the treatment process must be managed so that sulfur is actually removed from the system rather than *temporarily* transformed to a different form, but not permanently removed from the environment where it can convert back to sulfate.

2.2 Treatment Technology Categories

Table 2-2 provides the sulfate treatment categories identified and treatment technologies specifically evaluated as part of the study. Sulfate influent source reduction was evaluated separately in Section 2.3 and not as a specific treatment technology category.

Table 2-2 Sulfate treatment categories

Technology Category	Treatment Technology
Chemical Precipitation	Gypsum Precipitation
	Ettringite Precipitation (Cost-Effective Sulfate Removal (CESR) or SAVMIN)
	Ettringite Precipitation with Aluminum Recovery (LoSO4)
	Barite Precipitation
	Co-Precipitation with Aluminum
Ion Exchange	Conventional Ion Exchange
	Sulf-IX
Membranes	Closed-circuit Desalination Reverse Osmosis (CCD RO)
	Electrodialysis Reversal (EDR)
	Zero Discharge Desalination (ZDD)
	Membrane Distillation
	Nanofiltration (NF)
	Conventional Reverse Osmosis (RO)
	Vibratory Shear Enhanced Processing (VSEP)
	Forward Osmosis
Electrochemical	Electrocoagulation
	Electrochemical Reduction
Biological	Constructed Wetlands
	Floating Wetlands
	Pit Lake or In-Pit Treatment
	Constructed Trench Bioreactors/ Permeable Reactive Barriers
	Suspended-Growth Reactor (Activated Sludge Modification)
	Membrane Bioreactor
	Upflow Anaerobic Sludge Blanket (UASB) Reactor with Sulfide Treatment
	Packed Bed Bioreactor
	Packed Bed (BioSulphide)
	Bioelectrochemical
	Sulfate Reduction Deammonification
	Liquid-phase biofilters
	Sulfate Reduction, Autotrophic Denitrification, and Nitrification Integrated Process (SANI)
Evaporative	Direct Heat-contact Evaporation (LM-HT Concentrator)
	Mechanical Vapor Recompression Evaporation with Crystallization or Spray Drying

The following sections broadly describe the sulfate treatment technology categories included in Table 2-2, and also addresses source control in Section 2.3. More detailed information about specific technologies, including descriptions, existing vendor examples, lowest achievable sulfate concentrations, chemical additives, and additional treatment requirements, are shown in Large Table 1.

2.3 Influent Source Reduction

The amount of sulfur (as sulfate or sulfide) entering a municipal wastewater treatment plant is highly site-specific and depends primarily on the concentration of sulfate in the area drinking water source(s) and contributions by industrial dischargers. The typical sulfate concentration of untreated domestic wastewater ranges from 20 to 50 mg/L above the sulfate concentration in the drinking water supply [Ref. (1)]. In Minnesota, drinking water supplies consist of both groundwater and surface water. Figure 2-2 shows the variations in sulfate concentrations in groundwater throughout the state, and Figure 2-3 shows sulfate concentrations in surface water across the state (figures from Scott Kyser at MPCA, personal communications). As illustrated on Figure 2-2, groundwater sulfate concentrations range from less than 10 mg/L in northeastern Minnesota to greater than 500 mg/L in the southwestern part of the state. As a result, and since most municipalities in Minnesota use groundwater to source drinking water, the sulfate concentration in municipal wastewater treatment plant effluents would be expected to have geographic variation.

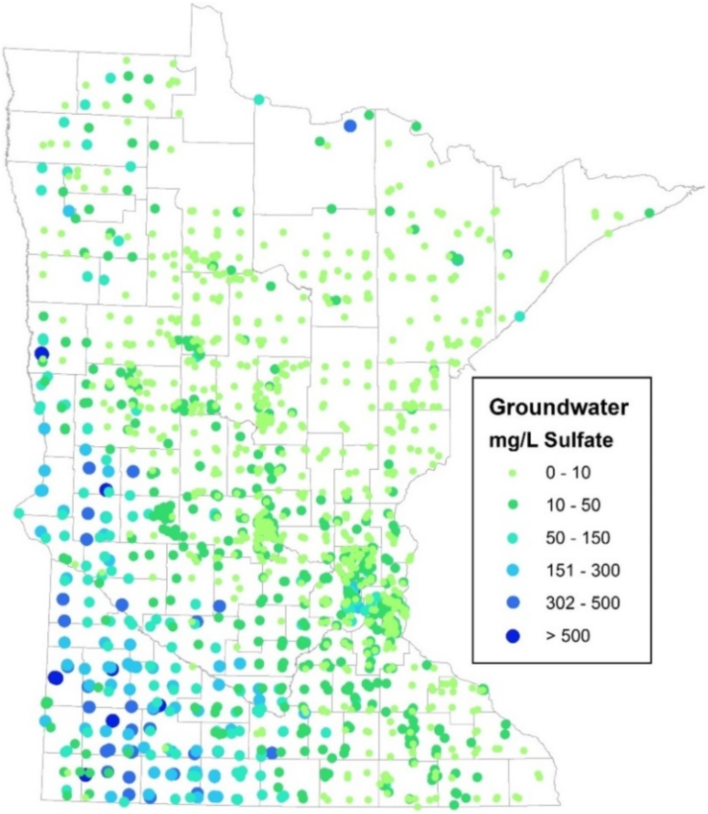

Figure 2-2 **Groundwater sulfate concentrations in Minnesota**

Figure 2-3 illustrates a similar geographic variation in sulfate concentrations in surface water sources across the state.

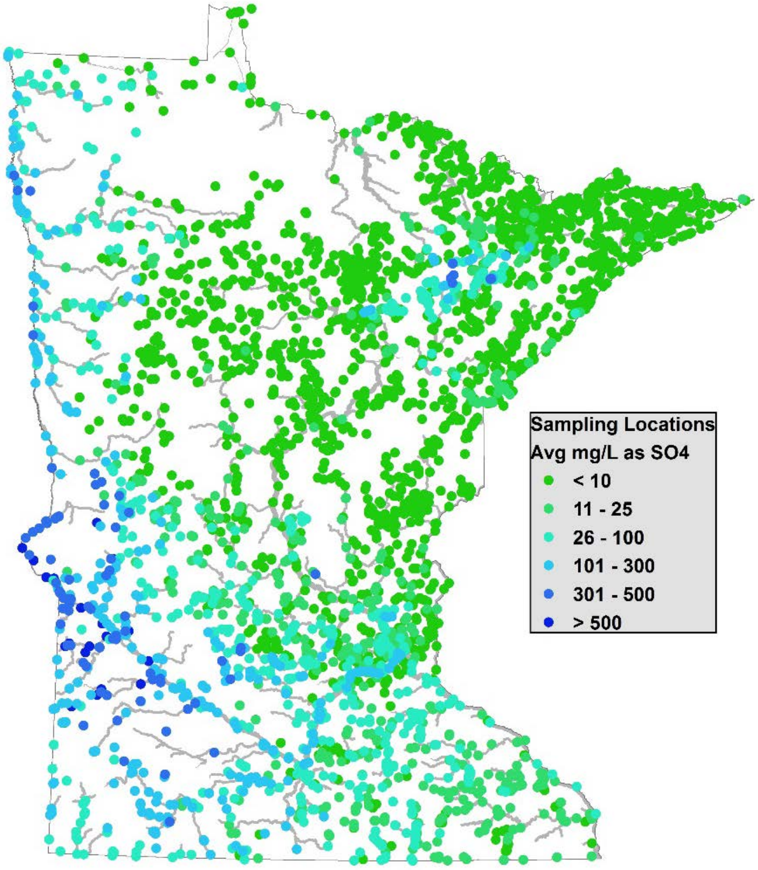

Figure 2-3 **Surface water sulfate concentrations in Minnesota**

Three primary strategies may be employed for lowering the concentration of sulfate or sulfide entering the wastewater treatment plant: (1) modifications to the potable water supply quality, either through changes in treatment or source, (2) modifications to industrial pre-treatment agreements to lower sulfate or sulfide discharges from industrial dischargers, or (3) control of sulfide in the municipal wastewater collection system or treatment plant through chemical addition and precipitation. The potential efficacy of these options depends on the concentration and mass of sulfate contributed by the primary contributors to the wastewater system, and the ability to effectively capture and bind the sulfide. If one or several of these options would result in meeting a sulfate discharge limit, a wastewater treatment plant may be able to avoid more significant wastewater treatment plant modifications. Not all wastewater treatment plants will receive a sulfate effluent limit, and those that do may not be able to meet the limit through influent source reduction alone. As shown on Figure 2-2, the practical limit of achieving sulfate discharge limitations through source reduction is very site-specific. Additional information on the three influent source reduction options, their benefits, and limitations is presented in Section 3.4.

2.4 Chemical Precipitation

One common way to remove sulfate from water is to remove it as a solid, insoluble sulfate salt. Chemical precipitation for sulfate removal is used widely in both mining and industrial applications. The minimum achievable sulfate concentration depends on the specific salt formed. For example, lime (calcium hydroxide) can be added to water to remove sulfate as gypsum (calcium sulfate); however, this method can only reduce the sulfate concentration to about 1,500 mg/L. This is significantly higher than the sulfate concentrations typically found in wastewater. Other sulfate salts, such as ettringite and barium sulfate, are less soluble in water, so can be used to remove sulfate to lower concentrations, around 100 mg/L and 50 mg/L, respectively [Ref. (6) and (7)]. While some salts, like gypsum and barium sulfate, are relatively easy to precipitate, others, such as ettringite, require more complex chemical conditions to form reliably; thus, ettringite precipitation technology is more complex to operate. Metal salts are not effective at precipitating sulfate, but can be used to remove sulfide from solution and provide another means to remove sulfur from an aqueous system. The use of sulfide precipitation is discussed in Section 4.3.1.

Chemical precipitation processes produce sludges that must be managed and disposed. Typically, the sludge is dewatered to reduce the volume as much as possible, then disposed of in a landfill or sometimes land-applied. Sludge disposal options are further discussed in Section 4.2.

2.5 Ion Exchange

Ion exchange is a common water treatment process used in a wide range of applications, from municipal drinking water treatment to mining and power generation. It is also commonly used in home water softeners. Ion exchange treatment media (resins) are available to remove different constituents, such as calcium and magnesium hardness (e.g., as in home water softeners), and are also available to remove sulfate. Ion exchange involves passing water through specialized ion "exchange" resins in a closed vessel. The resin surface has active sites, which remove the constituent of interest in exchange for other, less problematic or more desirable ions when the water passes through. Figure 2-4 provides a visual of the ion exchange process.

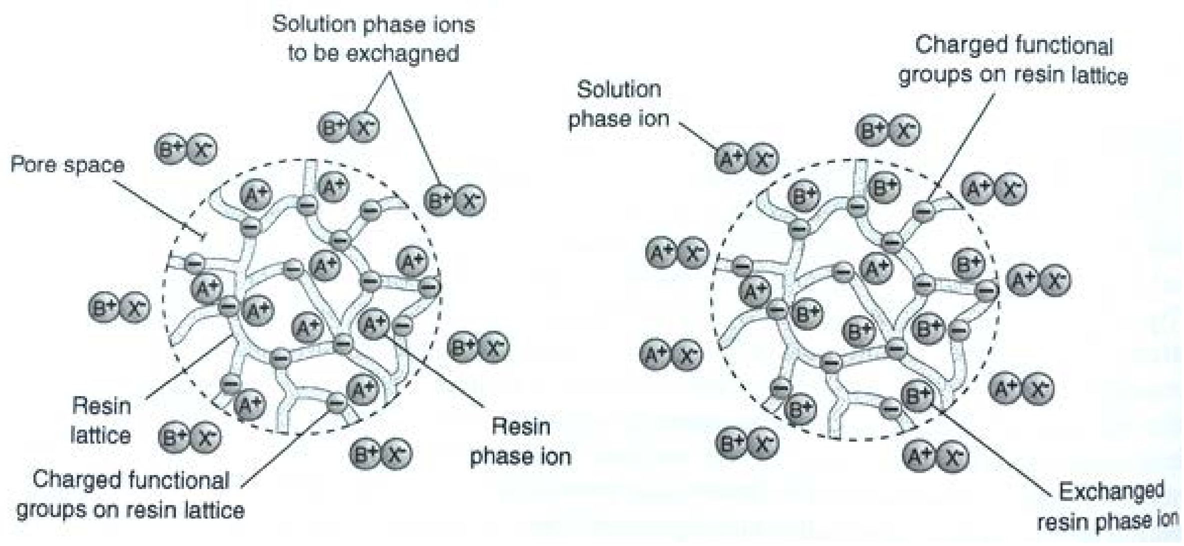

Figure 2-4 **Ion exchange process [Ref. (8)]**

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Once all the active sites have been used, the resin capacity for treatment must be restored (regenerated). The regeneration process involves exposing the resin to a concentrated salt, acid, or base solution to restore the active sites by switching the ions back to the initial condition. For ion exchange treatment of a water with 500 mg/L sulfate, treated water would contain less than 200 mg/L sulfate if operated correctly, and concentrated regeneration waste would contain about 10,000 mg/L sulfate in about 2%-5% of the initial flow [Ref. (9)].

For sulfate removal, the regeneration process most commonly produces a concentrated liquid salt waste (brine), containing an elevated concentration of sulfate that needs to be disposed. Brine disposal options are further discussed in Section 4.1. In the specialized Sulf-IX system, sulfate is removed from the concentrated brine solution using chemical precipitation.

2.6 Membrane Separation

Membrane separation is another common, well-established water treatment technology that can be used for sulfate removal. Membrane treatment is used for treating sea water for use as drinking water, and for a wide variety of industrial applications such as high-purity water treatment for boilers and semiconductor manufacturing. Use of this technology is uncommon in municipal wastewater treatment, though some facilities with water reuse programs do employ this advanced polishing treatment, depending on the end use of the water.

In membrane separation, water is forced (using applied pressure or electrical potential) through membranes with very small openings (“pores”) that prevent particles and some chemicals such as sulfate from passing through. These technologies require energy to provide enough pressure to overcome the osmotic pressure and push water through the membranes, which ranges from approximately 100 to 1,000 pounds per square inch (psi), for brackish waters and seawater desalination, respectively [Ref. (8)]. As a result, the flow to be treated is separated into a cleaned water stream ("permeate") and a concentrated liquid waste stream ("concentrate"). The membrane separation process uses water pressure to force water through the membrane, as shown on Figure 2-5. The electrodialysis reversal (EDR) process uses electrical potential to force water through the membrane, as shown on Figure 2-6.

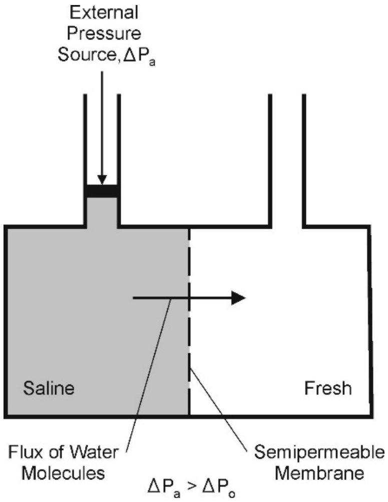

Figure 2-5 **Membrane separation process [Ref. (8)]**

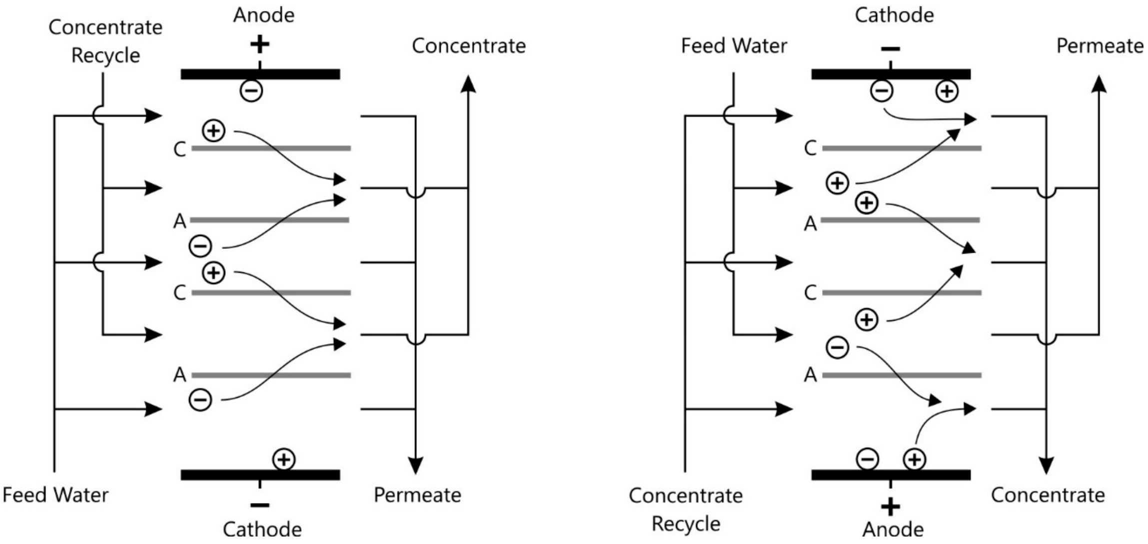

Figure 2-6 **Electrodialysis reversal process [Ref. (8)]**

The various membrane technologies have different pore sizes (e.g., reverse osmosis [RO] versus nanofiltration [NF]) that determine their chemical removal efficiencies, as shown on Figure 2-7. Note that Figure 2-7 focuses on classes of contaminants that membranes are capable of removing, not just sulfate (which would be considered a "dissolved solid") [Ref. (10)]. For conventional NF membrane treatment of a water with 500 mg/L sulfate, treated water would contain less than 50 mg/L sulfate if correctly operated, and concentrate waste would contain about 2,500 mg/L sulfate in about 20% of the initial flow. Using conventional RO membrane treatment can achieve less than 10 mg/L sulfate with an influent concentration of 500 mg/L, and achieve approximately 70-90% recovery of the initial flow. To achieve these high recoveries, it will be necessary to implement multi-stage treatment, where the concentrate from the first stage is sent to a second stage of membrane treatment, which will be covered under Activity 2.

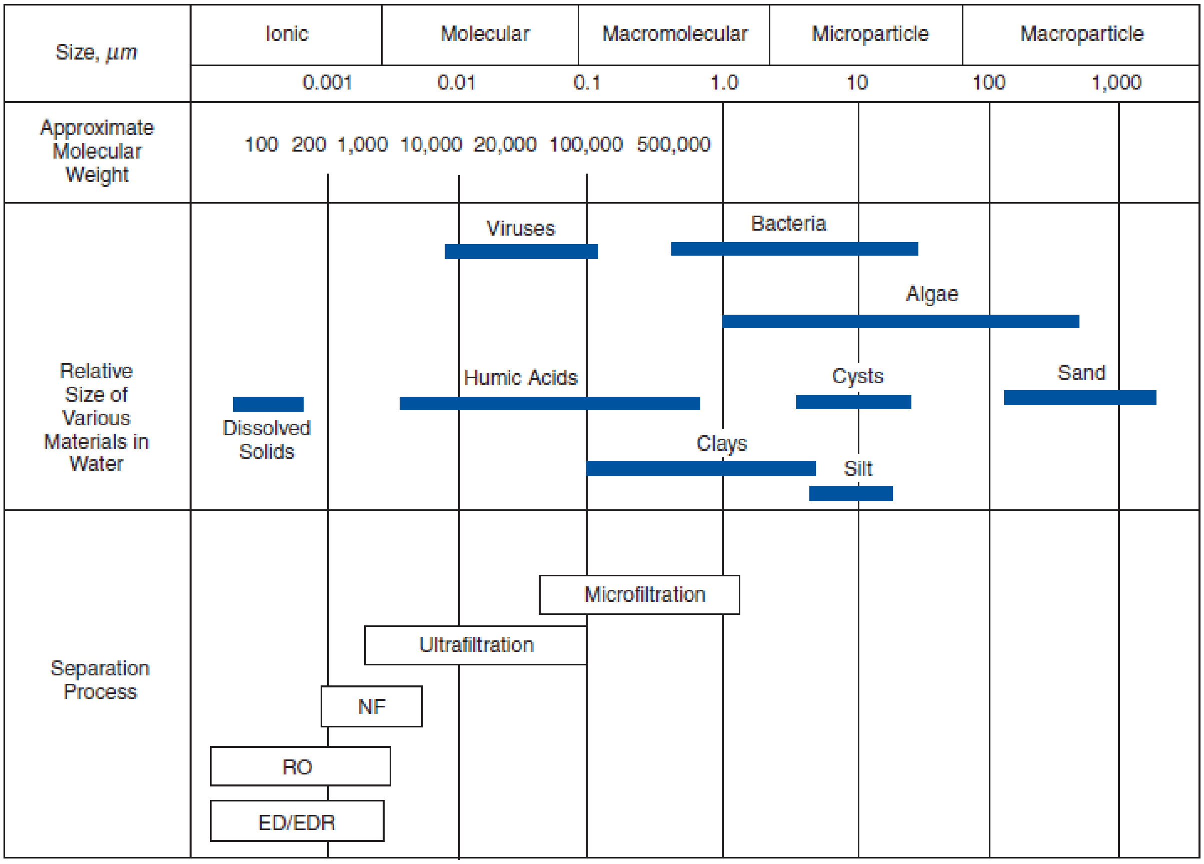

Figure 2-7 **Removal abilities of various membrane technologies [Ref. (10)]**

(*Reprinted with permission from Manual of Water Supply Practices, M46 (2nd ed.). Reverse Osmosis and Nanofiltration. © AWWA, Denver, 2007. All rights reserved.*)

Membrane separation using EDR, RO, and NF also produces a concentrated salt waste requiring disposal, and concentrate disposal costs can far exceed the membrane system costs. Multi-stage membrane treatment is one way to reduce the volume of concentrate requiring management and disposal, as shown on Figure 2-8. Concentrate disposal options are further discussed in Section 4.1. In addition, membrane systems typically require pre-treatment to protect the membranes from fouling and may require post-treatment to restore pH, reduce corrosivity, and to return some salts and minerals to the water (depending on the end use of the water). Pre- and post-treatment for RO are further discussed in Section 5.2.2.

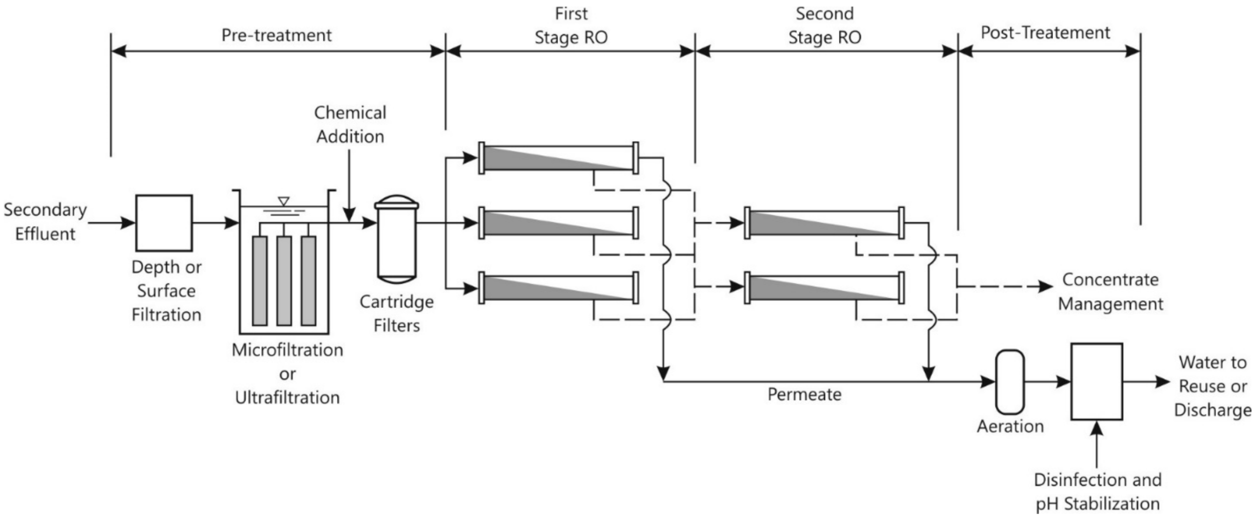

Figure 2-8 Multi-stage membrane treatment example [Ref (11)]

2.7 Electrochemical Treatment

Electrochemical treatment of sulfate can be achieved in two primary ways. Metal ions formed in an electrochemical cell are used to precipitate metal hydroxides, which can remove anions such as sulfate from water. Alternately, sulfate can be converted to sulfide using electrical means, but must be done at high temperatures. Abiotic sulfate reduction to sulfide is not energetically favorable, as the sulfate ion is very stable and unreactive. This process requires the input of large amounts of energy in the form of heat. As discussed in Section 2.1, chemical reactions to change sulfate into other forms of sulfur for removal require large amounts of external energy and are unlikely to be feasible in a municipal wastewater treatment setting.

Full-scale use of electrochemical treatment for sulfate removal is not reported in any industry.

2.8 Biological Treatment

Municipal wastewater treatment plants employ a combination of biological, physical, and chemical processes to remove carbon (as biochemical oxygen demand [BOD]), nitrogen, and phosphorus from wastewater. Sulfate can be removed from water biologically by bacteria. It cannot be used as a bacterial food source, but can be used as an electron sink, similar to the way that humans use oxygen. Using sulfate instead of oxygen or other compounds is relatively inefficient, so bacteria can only use it in conditions without oxygen present. If oxygen is present, the bacteria will not use sulfate. When bacteria use sulfate, it is converted to sulfide, which can escape as toxic hydrogen sulfide gas. Thus, any biological system to remove sulfate must also be equipped with a way to remove hydrogen sulfide that is produced.

The bacteria that use sulfate are called sulfate-reducing bacteria (SRBs), and are strict anaerobes and slow growers. This means that biomass needs to stay in the system for a minimum of about 20 days (depending on the reactor conditions), or the SRBs will not grow fast enough to keep a population within the system sufficient to remove appreciable amounts of sulfate. Solids retention time for BOD removal in a typical activated sludge wastewater treatment plant, by comparison, is approximately three to five days

[Ref. (11)]. Other factors that affect solids retention time include temperature and desired level of nitrification. The required solids retention time for sulfate removal is approximately four to seven times longer in duration than activated sludge wastewater treatment plants typically employ. Activated sludge treatment plants are designed around a target solids retention time, which impacts treatment process performance, aeration tank volume, sludge production, and oxygen requirements. As a result, making modifications to accommodate biological treatment of sulfate using an activated-sludge-type process can be difficult.

This can be accomplished in a variety of different reactors under anaerobic conditions. An example packed bed reactor is shown on Figure 2-9. A food source must be supplied to any biological sulfate reduction technology, and can be a chemical addition, such as methanol, or direct addition of electrons from an electrochemical source.

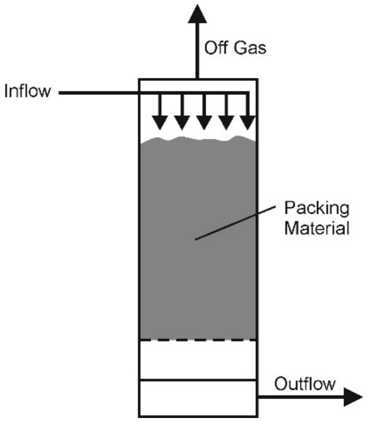

Figure 2-9 Packed bed reactor biological treatment [Ref. (11)]

Biological treatment of sulfate has primarily been applied in mine water treatment, where sulfate removal is a secondary consequence of primary treatment goals such as metals removal. In mine water treatment, sulfate is converted to sulfide, which reacts with and immobilizes metals in the water. Because sulfate removal is not the primary goal, the removal efficiency can be relatively low, so low-efficiency biological treatment systems like constructed wetlands and mine in-pit lake treatment configurations can be practical. Oxidation reduction potential (ORP) in these passive-type systems fluctuates seasonally; therefore, consistent, overall sulfate removal is variable.

2.9 Evaporative Treatment

Another option for removing sulfate from water is to evaporate the water. Because salts cannot be evaporated, they remain behind as a concentrated brine or a solid residual. The evaporated water can be recovered and reused, similar to a distillation process. Evaporative technologies are also called zero-liquid discharge (ZLD) technologies and are occasionally used in power and refining industry sectors, but are rarely used in municipal wastewater treatment due to their high capital, operation, and maintenance costs. Municipalities rarely require treatment of parameters of concern to meet effluent limits that would necessitate such technology. This type of technology is very energy-intensive, as it requires enough energy to evaporate water. Given the large flow rates of municipal wastewater requiring treatment, the energy cost would be very high ($10 to $20 per 1,000 gallons) [Ref. (12)]. In addition, concentrated brine or salt solids would need to be disposed. Residuals management alternatives are presented in Sections 4.1 and 4.2. Evaporative technologies typically have high capital costs because they are often mechanically complex and require corrosion-resistant materials.

3.0 Technology Screening

3.1 Overview of Approach to Screening

The application of the treatment technologies included in Table 2-2 to municipal wastewater treatment for the purposes of sulfate removal was reviewed in a detailed screening process that included three steps:

1. Threshold screening based on the technology's degree of development and commercialization and ability to achieve a threshold sulfate removal performance;
2. Technology screening based on performance, cost, and other factors; and
3. Screening based on removal performance for other parameters of concern.

The goal of the screening process was to understand the advantages and limitations of each sulfate treatment approach, and to identify the most feasible treatment technologies for reducing sulfate in municipal wastewater effluent using a uniform scoring and ranking methodology. The outcome of the screening process is a ranked list of feasible technologies, which can be used as a guide or starting point for further investigation and detailed review of sulfate removal options by municipal wastewater treatment plants.

3.1.1 Threshold Screening

The purpose of the threshold screening step was to limit the treatment technologies for the full screening effort to those that would be viable for municipal wastewater treatment application in Minnesota (i.e., those technologies with proven effectiveness in full-scale applications). Each of the treatment technologies included in Table 2-2 was evaluated against the two threshold screening criteria:

- The ability to remove sulfate to a concentration of 250 mg/L (assuming an influent sulfate concentration of 500 mg/L); and
- The existence of full-scale installations for treatment of any contaminant in any industry.

An influent sulfate concentration of 500 mg/L represents the upper end of the range of expected sulfate concentrations in municipal wastewater from groundwater contributions alone, as shown on Figure 2-2. The selected threshold concentration of 250 mg/L represents the ability of a technology to remove at least half of the sulfate. The MPCA concurred with the threshold screening criteria selection approach prior to screening completion.

It was assumed in this study that municipal wastewater treatment plants would be unlikely to implement technologies that either have not been applied at full-scale or cannot remove significant amounts of sulfate. If either criterion was not met, the technology was not evaluated further in this study.

Of the 31 treatment technologies included in the literature review and threshold screening, 18 technologies were screened out. Several technologies evaluated during the initial research collection phase of the project remain in the exploratory phase of development with only bench- or pilot-scale demonstrations, but indicate promise, especially those in the biological sulfate treatment category.

The biological treatment technologies identified and reviewed had few full-scale applications for sulfate removal and a limited ability to remove sulfate below 250 mg/L. While biological processes do exist to transform and remove sulfate, additional investigations and development are needed to establish reliable means by which to leverage the full potential of this category of treatment options. Sulfate treatment technologies actively being researched at the University of Minnesota (U of M) include bioelectrochemical sulfate removal and liquid-phase biofilters. Suspended-growth reactors (activated sludge modification) and SANI demonstrations have indicated the ability to remove sulfate to below 250 mg/L; however, no full-scale systems exist. Further development of these technologies and application beyond the pilot scale is required and could improve the viability of the biological treatment options.

Treatment technologies that were found to remove sulfate to below 250 mg/L and have at least one, full-scale demonstration are summarized in Table 3-1 and received additional screening as described in Section 3.1.2. Descriptions of treatment technologies, basic technical information and references for additional information for all of the treatment options identified and reviewed, including those that were screened out, is available in Large Table 1.

Table 3-1 Sulfate treatment technology threshold screening

Technology Category	Treatment Technology	Threshold Criteria		Receives full screening criteria
		Ability to remove sulfate to 250 mg/L[1]	Demonstrated at full-scale[2]	
Chemical Precipitation	Gypsum Precipitation	No	Yes	No
	Ettringite Precipitation (CESR or SAVMIN)	Yes	Yes	Yes
	Ettringite Precipitation with Aluminum Recovery (LoSO4)	Yes	No	No
	Barite Precipitation	Yes	Yes	Yes
	Co-Precipitation with Aluminum	No	No	No
Ion Exchange	Conventional Ion Exchange	Yes	Yes	Yes
	Sulf-IX	Yes	Yes	Yes
Membranes	Closed-circuit Desalination Reverse Osmosis (CCD RO)	Yes	Yes	Yes
	Electrodialysis Reversal (EDR)	Yes	Yes	Yes
	Zero Discharge Desalination (ZDD)	Yes	No	No
	Membrane Distillation	No	Yes	No
	Nanofiltration (NF)	Yes	Yes	Yes
	Conventional Reverse Osmosis (RO)	Yes	Yes	Yes
	Vibratory Shear Enhanced Processing (VSEP)	Yes	Yes	Yes
	Forward Osmosis	No	Yes	No
Electrochemical	Electrocoagulation	No	No	No
	Electrochemical Reduction	No	No	No
Biological	Constructed Wetlands	No	Yes	No
	Floating Wetlands	No	No	No
	Pit Lake or In-Pit Treatment	No	No	No
	Constructed Trench Bioreactors/ Permeable Reactive Barriers	No	Yes	No
	Suspended-Growth Reactor (Activated Sludge Modification)	Yes	No	No
	UASB Reactor with Sulfide Treatment	Yes	Yes	Yes
	Packed Bed Bioreactor	Yes	Yes	Yes
	Packed Bed (BioSulphide)	No	Yes	No
	Bioelectrochemical	No	No	No
	Sulfate Reduction Deammonification	No	No	No
	Liquid-phase Biofilters	No	No	No
	Sulfate Reduction, Autotrophic Enitrification, and Nitrification Integrated Process (SANI)	Yes	No	No
Evaporative	Direct Heat-contact Evaporation (LM-HT Concentrator)	Yes	Yes	Yes
	Mechanical Vapor Recompression Evaporation with Crystallization or Spray Drying	Yes	Yes	Yes

Notes

[1] Assumes an influent sulfate concentration of 500 mg/L.

[2] Demonstrated at full scale but not necessarily for sulfate removal, specifically.

3.1.2 Technology Screening

The 13 technologies that passed the threshold screening were evaluated using the following screening criteria:

- Effectiveness
- Operability/Maintainability
- Relative Cost
- Degree/Complexity of Pre- and Post-Treatment Requirements
- Residuals Management

Each of the five criteria above were broken down into two or more sub-criteria. For example, the effectiveness criteria were broken down to these sub-criteria:

- Ability to meet treated water quality goals
- Degree of commercialization

3.1.2.1 Rationale for Sub-Criteria Weighting

Each of the sub-criteria were given a numeric weight to reflect their relative importance for a general municipal wastewater treatment plant. Weighting was based on generic criteria to apply to a broad cross-section of wastewater applications. It is possible that weighting could vary for an individual wastewater treatment plant, depending on site-specific circumstances and priorities; this should be taken into consideration when evaluating treatment technologies on a case-by-case basis. Each technology was assigned rankings for each criteria using information readily available in reports, studies, research papers, vendor literature, etc. Where information was not readily available, assumptions based on process knowledge and engineering judgment were used to assign ranks for each technology. The screening criteria are described in more detail in Section 3.1.2.2. Large Table 2 provides the scoring key associated with each sub-criteria and criteria. All weights were multiplied by ranks to produce a score as described in this section. The scores for each technology were then summed to obtain a numerical total score for each technology. The technologies were then ordered from high to low by their total scores. This scoring is not intended to be absolute, but rather should be considered a starting point for considering technologies. The higher-scored technologies reflect the more reliable, proven technologies for sulfate and/or those with the greatest demonstrated removal capability. The overall total scores are intended to enable relative comparisons among the technologies.

For example, under the effectiveness criteria, the sub-criteria ability to meet treated water quality goals for sulfate and degree of commercialization both had weights of three (3). Each sub-criteria was given a ranking choice from one to five, with five indicating the highest level of achievement for that technology and one being the lowest achievement.

RO received a ranking of five (5) under both of these sub-criteria because it has the ability to meet the lowest achievable sulfate treatment goal evaluated, 5 mg/L, and has been commercialized in three or more industries, including municipal wastewater treatment. The overall score under the effectiveness category for RO was 30, which was calculated as follows:

Overall effectiveness score = sum of (sub-criteria weight x sub-criteria rank)

Overall effectiveness score = (3 x 5) + (3 x 5) = 30

3.1.2.2 Sub-Criteria Weights and Rankings

Effectiveness

The effectiveness criteria describe the ability of a technology to remove sulfate, including the degree of commercialization (i.e., technical maturity in the marketplace, degree of development, and how broadly each technology is used throughout industry). Effectiveness criteria included the following.

Weight:

- Both sub-criteria under effectiveness received a weight of three (3). The ability of each technology to achieve treated water goals for sulfate was the primary concern of this study. Degree of commercialization received the same weight, because municipal wastewater treatment plants are most likely to implement reliable, well-commercialized technologies and specifically those that have been employed in municipal wastewater treatment.

Ranking:

- Ability to meet treated water quality goals for sulfate (5-250 mg/L)
  - Implementation of the wild rice in-stream water quality standard is expected to result in a range of possible effluent limits for municipal wastewater treatment plants, depending on conditions in receiving waters they discharge into. This screening criterion is intended to reflect a range of potential limits. The ability of a technology to remove sulfate was based on treated water quality goals for sulfate provided by the MPCA, with 250 mg/L used as the threshold screening value. Technologies receiving the highest scores have demonstrated sulfate removal to concentrations below 10 mg/L, including removal to below 5 mg/L for reverse osmosis.
  - Scores correspond with the following treatment abilities:
    - 1 - <=250 mg/L
    - 2 - <=100 mg/L
    - 3 - <=50 mg/L
    - 4 - <=10 mg/L
    - 5 - <=5 mg/L

- Degree of commercialization
  - Technologies with a range of commercialization were evaluated in order to include a large number of feasible options.
  - Scores correspond with the following levels of commercialization:
    - 1 - not commercialized
    - 2 - commercialized in one industry primarily
    - 3 - commercialized in one to three industries

    - 4 - commercialized in more than three industries
    - 5 - commercialized in more than three industries, including municipal wastewater treatment

Operability/maintainability

Operability and maintainability refer to the complexity of a technology's operation and maintenance requirements, and resulting reliability of performance. Operability and maintainability sub-criteria included the following.

Weight:

- The reliability of performance, including cold climate suitability, received the highest weight under this category, a weight of three (3). With ability to meet sulfate treatment targets being the primary concern, reliable performance year-round is necessary.
- General complexity of operation/maintenance of primary technology received a weight of two (2). While an operationally simple technology would be preferred in a wastewater treatment plant retrofit, some of the more complex technologies are capable of meeting the most stringent sulfate water treatment goals. A weight of two (2) was assigned to balance the ability to remove sulfate to low concentrations with operational simplicity.
- Operator and public health received a weight of one (1). The primary hazard identified for some of the sulfate removal approaches was the generation of hydrogen sulfide, which can be both a health and odor concern, depending on concentration. Hydrogen sulfide is a common hazard that must already be managed now in many current wastewater treatment plants and collections systems, through monitoring, ventilation, and other means. Given the industry-wide familiarity and experience with this hazard, a lower weight was assigned.

Ranking:

- Reliability of performance, including cold climate suitability
    - Reliability of performance, including cold climate suitability, applies to the technology's ability to operate and produce the required treated water quality consistently given variable influent water quality and weather conditions, including extreme winter temperatures observed across Minnesota.
- General complexity of operation/maintenance of primary technology
    - Relative complexity of primary technology operation was evaluated based on number of treatment process steps, pre- and post-treatment requirements, level of operator attention required, and anticipated amount of operational changes required under normal operation conditions.
- Operator and public health
    - The operator and public health criterion refers to known risks associated with operation of each technology to the individuals operating the treatment system and the general public.

Another operability consideration is WWTP operator certification level. While this was not considered in the screening process, operation of the technologies evaluated in this report will require a high level of operator certification and training. The implications of this for municipalities are considered in Part 2 of this project.

Relative Costs

Relative cost criteria were used to compare anticipated costs associated with each technology based on available information from existing full-scale applications and technology vendors. Relative cost criteria included the following.

Weight:

- Capital costs for primary technology received a weight of three (3), and O&M costs for primary technology received a weight of two (2). In addition to sulfate treatment effectiveness, cost impacts are a primary concern for most municipalities and their customers. Depending on the degree of sulfate removal required, municipalities requiring sulfate treatment may be required to increase fees to pay for the additional treatment through a combination of connection fees and volume of use fees. The degree of impact on rates will depend on the size of the wastewater treatment plant and technology selected for implementation. Both capital costs and O&M costs have the potential to increase typical sewer rates by a significant amount [Ref. (2) and (13)].

Ranking:

- Capital costs for primary technology
    - Under this criterion, lower rankings were given to the most expensive technologies and higher rankings to relatively low-cost technologies. Technologies that incorporated less mechanical equipment and fewer tanks and reactors had the lowest capital costs.
- O&M costs for primary technology
    - Operating and maintenance (O&M) costs consist of power, labor, parts and maintenance, chemicals for operations and cleaning processes, consumables, and residuals management.

Degree/Complexity of Pre- and Post-Treatment

Degree and complexity of pre- and post-treatment applies to the extent and difficulty of treatment required in addition to the primary sulfate treatment technology. For example, in order for the primary sulfate removal technology to be used to treat municipal wastewater effluent, additional steps or processes may be necessary to ensure reliable operation of the sulfate removal technology. These additional steps are considered “pre-treatment.” Similarly, for post-treatment, the water produced after using the sulfate removal technology may require additional polishing or stabilization in order to meet all water quality requirements for discharge. Screening considered pre- and post-treatment assumed for retrofit of an existing wastewater treatment plant with secondary treatment. Thus, processes already included in typical secondary wastewater treatment were not factored into the screening. Degree and complexity of pre- and post-treatment sub-criteria included the following.

Weight:

- Pre-treatment and post-treatment complexity and cost each received a weight of two (2). With the primary focus being sulfate removal, the degree and complexity of pre- and post-treatment was secondary.
- Beneficial reuse of residuals and treated water received a weight of one (1). While beneficial reuse is an important factor, especially if it can provide some offsetting of costs, it is considered a secondary effect of sulfate removal and hence received a lower weight.

Ranking:

- Influent pre-treatment complexity/cost
    - Influent pre-treatment complexity and cost refers to the degree of additional treatment required prior to use of the primary treatment technology. Pre-treatment varies and is generally required to protect some function of the primary treatment technology or improve its effectiveness and/or reliability.
- Effluent post-treatment complexity/cost
    - Effluent post-treatment complexity and cost refers to additional treatment required downstream of the primary treatment technology. Post-treatment is generally required to stabilize the effluent prior to discharge to protect the beneficial reuse of the receiving water and prevent downstream toxicity. Post-treatment evaluation for this study did not include typical tertiary treatment already in place at municipal wastewater treatment plants or chlorine or ultraviolet disinfection.
- Beneficial reuse of residuals and treated water
    - This criterion applies to the potential use of residuals resulting from primary treatment and the treated water itself, such as water reuse instead of discharge. Beneficial reuse of either the residuals or the treated water may enable some offsetting of costs of sulfate treatment, though this is very site-specific.

Residuals Management

Residuals are materials that result as a byproduct of the primary treatment process that may or may not have a beneficial reuse. Residuals management criteria refer to the complexity of managing residuals associated with the primary treatment technology and the volume of residuals requiring management. Large Table 1 includes residuals resulting from sulfate treatment technology operation. Screening sub-criteria included the following.

Weight:

- Residuals management complexity and cost received a weight of three (3). Residuals management can contribute significantly to overall treatment costs, which were a primary concern of the study. This criterion also emphasized the high costs and energy requirements for membrane treatment concentrate management and evaporative treatment residual slurries and salts management. This criteria weight was equal to those of the effectiveness category to balance the complex residuals management requirements for some of the most effective sulfate treatment technologies.

- Residuals stability received a weight of one (1). This criteria was included to capture the uncertainty of stability in residuals resulting from some treatment technologies including ettringite precipitation and the evaporative technologies. Residuals stability was considered a tertiary concern of the overall study as it does not relate to sulfate removal effectiveness and has relatively minimal impacts on treatment technology selection.

Ranking:

- Residuals management complexity/cost
    - Residuals management complexity and cost applies to the anticipated costs of managing residual materials, including the mechanical and/or operational complexity of processes needed, special disposal requirements, hazardous waste disposal costs, residuals volume and storage requirements, etc.
- Residuals stability
    - Residuals stability refers to the composition and disposition of the residual material and how likely it is to transform into another material (e.g., through chemical or biological reactors or transformations) or phase (such as through dissolution) at some point during its management and disposal.

3.1.3 Screening for Removal of Other Parameters

Each treatment alternative was also evaluated for its ability to remove other parameters of concern. The purpose of this screening was to evaluate whether removal of these other parameters of concern could co-occur with the evaluated sulfate removal technologies. Removal of other parameters is considered a secondary goal to sulfate removal.

The other parameters screening included:

- Chloride
- Total mercury
- Total nitrogen
- Total phosphorus
- Total dissolved solids

The ability to remove these parameters from the water phase was evaluated relative to specific treatment targets, shown in Table 3-4. Treatment targets for total nitrogen, total phosphorus, and total mercury were provided by the MPCA. Treatment targets for chloride, total mercury, and total dissolved solids were selected based on the most stringent water quality standards included in Minnesota Rules Chapter 7050, Water Quality Standards for Protection of Waters of the State [Ref. (14)].

3.2 Screening Results

3.2.1 Summary of Screening Results

Each rank resulting from the technology screening process was multiplied by a weight assigned to each sub-criteria, and these sub-criteria scores were added together for a final score for each technology. As described earlier, this score is intended to enable relative comparisons among the technologies. However, the scoring is not absolute and is not intended to recommend a specific technology for a given application. The approach taken for selection of sulfate removal technologies for a given wastewater treatment plant will be site-specific. For examples regarding the use of the screening information provided, please refer to Section 5.0. The spread of total scores for the treatment technologies ranged from 69 to 89 with higher scores representing the technologies that would best meet the primary focuses of the study.

Large Table 2 provides the detailed results of the technology screening process. The technology scores fell into three broad groups as shown in Table 3-2. Group 1 includes technologies that are well-commercialized, proven successful in sulfate removal, and have broad applications across multiple industries. Group 2 includes technologies that are moderately commercialized, but not in municipal wastewater treatment, and are more often secondary treatment technologies rather than primary. Group 3 consists of technologies that have important technical or economical limitations and are limited in terms of sulfate removal abilities.

Table 3-2 Technology screening summary

Separation of scores	Technology category
Group 1: > 85	
Reverse osmosis	Membranes
Nanofiltration	Membranes
Group 2: 75 – 85	
Barite precipitation	Chemical precipitation
Ettringite precipitation	Chemical precipitation
Sulf-IX	Ion exchange
VSEP	Membranes
EDR	Membranes
CCD RO	Membranes
Group 3: < 74	
Conventional ion exchange	Ion exchange
UASB reactor	Biological
Direct heat-contact evaporation (LM-HT Concentrator)	Evaporative
Packed bed bioreactor	Biological
Mechanical vapor recompression evaporation with crystallization or spray drying	Evaporative

3.2.2 Effectiveness

NF and RO received the highest scores for commercialization in multiple industries including municipal wastewater treatment. Membrane technologies, in general, are more commercialized and have the ability to remove sulfate down to concentrations of 5 mg/L under some conditions, resulting in the highest scores for effectiveness.

The biological sulfate treatment technologies that received full technology screening had few full-scale applications and a limited ability to remove sulfate below 100 mg/L, resulting in the lowest scores for effectiveness.

3.2.3 Operability/Maintainability

Higher scores were given to operationally simple technologies such as NF and RO. Biological treatment technologies require a higher level of attention to maintain favorable conditions for SRBs, resulting in lower scores for this criteria. This criteria only evaluates the primary technology and does not consider pre- or post-treatment or residuals management.

Membrane technologies, including NF, RO, and VSEP, received the highest scores under reliability of performance, including cold climate suitability. These technologies are commonly installed within buildings to avoid exposure to inclement weather. Water temperature can impact water throughput and sulfate removal, but to a lesser degree than some biological processes such as treatment wetlands. These membrane technologies are well-established and commercialized, so have more available data and installed experience to inform an assessment of reliable performance.

Most technologies screened were found to have no significant health risk to operators or the public. Lower scores were assigned to biological treatment technologies due to risks associated with hydrogen sulfide gas production and management. Hydrogen sulfide gas management is discussed further in Section 4.3. Additionally, production of barium sulfate in the barium precipitation process poses risks to operators handling the waste.

3.2.4 Relative Costs

Technologies with the highest capital costs, VSEP, and the evaporative technologies, also had the highest operating and maintenance (O&M) costs, largely associated with energy consumption. The primary O&M costs by technology category are identified in Table 3-3. Costs are generally listed from highest cost to lowest cost. Exact order will depend on site-specific conditions and plant size.

Table 3-3 Primary O&M costs by treatment category

Chemical Precipitation	Ion Exchange	Membranes	Biological	Evaporative
Chemical addition	Regeneration chemicals	Concentrate handling	Substrate addition	Power
Sludge handling (dewatering and disposal)	Power	Power	Power	Salt or slurry management
Labor	Labor	Clean-in-place (CIP) waste handling and disposal	Labor	Cleaning chemicals and associated waste disposal
Power	Ion exchange media	Labor	Sludge handling (dewatering and disposal)	Operating chemicals
–	–	Anti-scalant chemicals	–	–
–	–	CIP chemicals	–	–

3.2.5 Degree/Complexity of Pre- and Post-Treatment

Membrane technologies, while having a long history of reliable treatment, also require relatively complex pre-treatment in order to sustain reliable operation. Ion exchange is rarely applied to municipal wastewater treatment, though it is common in municipal drinking water treatment. As a result, the degree of pre-treatment required for these systems is not well characterized in the context of municipal wastewater.

There are an increasing number of installations of membranes in the U.S. following secondary or tertiary municipal wastewater treatment, primarily for water reuse applications instead of environmental discharge requirements [Ref. (8)]. Wastewater effluent fed to membrane treatment requires more pre-treatment than groundwater or surface water, because organic material and bacteria in the water can cause biofouling and organic fouling. Biofouling (growth of bacteria films on a membrane surface) and organic fouling (buildup of organic matter on a membrane surface) interfere with membrane operation by clogging and narrowing membrane pores; this makes it more difficult to push clean water through the membranes [Ref. (8)]. Pre-treatment for membrane separation may include settling, sand or cartridge filtration, membrane filtration, chemical addition, advanced oxidation, etc., depending on wastewater chemistry, scaling potential, and operational limitations of the primary treatment technology. All membrane technologies require a similar extent of pre-treatment, with the exception of VSEP, which may require less extensive pre-treatment, depending on the specific application. In contrast to traditional spiral-wound membranes, VSEP uses flat-sheet membranes in a cross-flow configuration, which reduces the boundary layer at the membrane surface. This, in combination with applied vibratory shear, reduces fouling and scaling.

Post-treatment across the membrane technology category can be relatively complex. Membrane treatment is highly effective for removing sulfate, but it does not selectively remove sulfate. Other constituents in the water such as dissolved minerals (e.g., hardness and alkalinity) are also removed. Constituents such as dissolved gasses (carbon dioxide or hydrogen sulfide) will pass through the membrane into the treated water. As a result, the membrane-treated water is likely to require additional treatment prior to discharge or reuse. Common post-treatment processes include:

- Mixing with membrane feed water to achieve the final desired composition based on a mass balance
- Degasification
- pH adjustment
- Stabilization/remineralization using lime or calcite

Specific requirements will depend on the wastewater chemistry after membrane treatment and the final effluent limits and/or the final use of the water (if reused, for example).

3.2.5.1 Beneficial Reuse

Most of the treatment technologies evaluated in the full screening do not produce residuals with beneficial reuse. Solid gypsum precipitated from the Sulf-IX process can be repurposed as a construction material or fertilizer [Ref. (9)]. Biological sludge can be managed with other biological sludge streams from the wastewater treatment plant.

Depending on the municipal wastewater treatment plant site, treated effluent from membrane treatment technologies can potentially be reused onsite or by some other industry, business, or irrigation need in the vicinity. Because of the high-quality water that membrane treatment produces, reuse of the treated water in some capacity to decrease either potable or non-potable water demand is worth evaluating and may help offset capital and O&M costs associated with the primary treatment technology. Reuse of treated effluent may also reduce or eliminate post-treatment requirements.

3.2.6 Residuals Management

Residuals from each technology category requiring management vary in their degrees of stability depending on application and water quality. Sludge management associated with ettringite precipitation may result in the loss of sulfate through reactions with atmospheric CO_2 [Ref. (15)]. The ultimate fate of sulfur is also uncertain in the management of biological sludges and metal sulfide sludges. If sulfur is bound with iron, it may be subject to oxidation and loss of sulfate to the environment. Salt residuals resulting from evaporative treatment technologies used as primary treatment and residuals management for membrane treatment readily dissolve. As a result, and as introduced in Section 2.1, residuals management for most of the treatment categories will require additional investigation and planning to mitigate the unintentional or unwanted reintroduction of sulfate into the receiving water. The residuals management planning process is of equal importance to the selection of the primary treatment technology itself, and is critical to the success of the selected treatment process.

The membrane treatment technologies received the lowest overall scores under residuals management. Concentrate management for membrane treatment technologies represents a significant technical and economic challenge for inland municipalities, including those outside of Minnesota that employ these technologies for drinking water production. Options for concentrate management and a brief review of the “state of the industry” is provided in Section 4.1.

3.2.7 Screening for Removal of Other Parameters

A table summarizing the ability of the technologies to remove parameters of concern other than sulfate from municipal wastewater is included in Table 3-4. A “Yes” indicates the technology can meet the treatment target, and a “No” indicates the technology cannot meet the target. Some technologies had limited data or no data available, as noted in the table.

This information provides a useful summary for municipalities challenged with removal of other regulated constituents in addition to sulfate. RO, for example, can also effectively remove chloride, total nitrogen, total phosphorus, and total dissolved solids, and therefore if implemented for sulfate removal, would provide additional benefits for the removal of other constituents as well. Membrane treatment, in general, can effectively remove chloride, total phosphorus, and total dissolved solids, with exceptions noted in Table 3-4. Biological treatment is capable of removing total nitrogen but requires both nitrification and denitrification processes. Evaporation with crystallization produces a distillate that removes chloride, total phosphorus, and total dissolved solids.

Table 3-4 Screening for removal of other parameters

					Chemical Precipitation		**Ion Exchange**		**Membranes**					**Biological**		**Evaporative**	
Ability to remove other parameters	**Units**	**Target**	**Source[1]**	**Ranking Key**	Ettringite Precipitation (CESR or SAVMIN)	Barite Precipitation	Conventional Ion Exchange	Sulf-IX	Closed-circuit Desalination Reverse Osmosis (CCD RO)	Electrodialysis Reversal (EDR)	Nanofiltration (NF)	Conventional Reverse Osmosis (RO)	Vibratory Shear Enhanced Processing (VSEP)	UASB Reactor with Sulfide Treatment	Packed Bed Bioreactor	Direct heat-contact evaporation (LM-HT Concentrator)	Mechanical vapor recompression evaporation with crystallization or spray drying
Chloride, Cl	mg/L	230	MN SW 2A/2B State Waters 7050	Yes - technology can meet limit No - technology cannot meet limit	Possible/ limited data	No	Possible/ limited data	Not available	Yes	Yes	No	Yes	Yes	No	No	Not applicable	Yes
Total Mercury, Hg	ng/L	6.9	MPCA		Possible/ limited data	No	Not available	No	Possible/ limited data	No	No	Possible/ limited data	Possible/ limited data	No	No	Not applicable	Possible/ limited data
Total Mercury, Hg	ng/L	1.3	MN SW 2A/2Bd State Waters 7050		Possible/ limited data	No	Not available	No	Possible/ limited data	No	No	Possible/ limited data	Possible/ limited data	No	No	Not applicable	Possible/ limited data
Total Nitrogen, N	mg/L	7	MPCA		Possible/ limited data	No	Possible/ limited data	Not available	Possible/ limited data	Possible/ limited data	No	Yes	Yes	Yes, if after nitrification	Yes, if after nitrification	Not applicable	Possible/ limited data
Total Phosphorus, P	mg/L	0.5	MPCA		Possible/ limited data	Possible/ limited data	Possible/ limited data	Not available	Yes	Possible/ limited data	Possible/ limited data	Yes	Yes	No	No	Not applicable	Yes
Total Dissolved Solids, TDS	mg/L	700[2]	MN SW 4A State Waters 7050		Possible/ limited data	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	Not applicable	Yes

Notes

[1] Limits for total nitrogen, total phosphorus, and total mercury were provided by the MPCA for this study. Limits for chloride, total dissolved solids, and salinity were selected based on the most stringent water quality standards included in Minnesota Administrative Rules Chapter 7050, Water Quality Standards for Protection of Waters of the State.

[2] Typical TDS levels in municipal wastewater are 270-860 mg/L [Ref. (16)], so some WWTPs may already be meeting the 700 mg/L target. In this table, "No" represents limited TDS removal ability and "Yes" represents some or significant TDS removal ability.

Typical TDS levels in municipal wastewater are 270-860 mg/L [Ref. (16)], so some wastewater treatment plants may already be meeting the 700 mg/L target. In Table 3-4, "No" represents limited TDS removal ability and "Yes" represents some or significant TDS removal ability.

Direct heat-contact evaporation (e.g., the LM-HT Concentrator) was “not applicable” for all parameters because there is typically no treated water/liquid stream for discharge. A liquid stream remaining after concentration would be either “brine” or “slurry” (more concentrated than brine). These are not distillate streams like with other evaporative technologies or ZLD. The brine or slurry would be disposed of by some other method and not discharged.

3.3 Summary of Achievable Effluent Concentrations

As previously discussed, the current sulfate water quality standard is 10 mg/L but is undergoing revision. Due to this, and site-specific considerations for the determination of effluent limits, there is uncertainty regarding the range of actual effluent limits that will result for individual wastewater treatment plants. Because the future water quality standard and derived effluent limits are unknown, this study was designed to provide useful information over a range of possible influent conditions and effluent limits. Potential sulfate treatment technologies meeting the threshold criteria were evaluated for their ability to achieve a range of effluent sulfate concentrations given a range of influent concentrations. Table 3-5 summarizes the ability of each technology to achieve given influent/effluent combinations. In some cases, definitive data regarding full-scale sulfate removal capabilities were not available; in these cases, removal capabilities were estimated based on laboratory studies and relevant chemical and microbiological information.

These data are also presented visually on Figure 3-1, where the line for each technology reflects the boundary between “not likely” and “possible.” In some cases, similar technologies with equivalent removal abilities were grouped together. A wastewater treatment plant with a specific anticipated effluent limit and expected influent concentration can plot that point on the chart; any technology plotted below the selected point should be evaluated as a potential treatment option. Technologies plotted above the selected point are unlikely to meet the treatment requirements.

Table 3-5 Achievable effluent sulfate concentrations

		Chemical Precipitation		Ion Exchange		Membranes					Biological		Evaporative	
	Effluent Sulfate Target (mg/L)	Ettringite Precipitation (CESR or SAVMIN)	Barite Precipitation	Conventional Ion Exchange	Sulf-IX	Closed-circuit Desalination Reverse Osmosis (CCD RO)	Electrodialysis Reversal (EDR)	Nanofiltration (NF)	Conventional Reverse Osmosis (RO)	Vibratory Shear Enhanced Processing (VSEP)	UASB Reactor with Sulfide Treatment	Packed Bed Bioreactor	Direct heat-contact evaporation (LM-HT Concentrator)	Mechanical vapor recompression evaporation with crystallization or spray drying
Influent Sulfate >500 mg/L	500	Likely	Likely	Likely	Likely	Likely	Likely	Likely	Likely	Likely	Likely	Likely	Likely	Likely
	100	Possible	Likely	Possible	Likely	Likely	Likely	Likely	Likely	Likely	Possible	Possible	Likely	Likely
	25	Not Likely	Possible	Not Likely	Possible	Possible	Possible	Possible	Likely	Possible	Not Likely	Not Likely	Likely	Likely
	10	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Possible	Not Likely	Not Likely	Not Likely	Likely	Likely
	1	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Likely	Likely
Influent Sulfate 300 mg/L	100	Possible	Likely	Possible	Likely	Likely	Likely	Likely	Likely	Likely	Possible	Possible	Likely	Likely
	25	Not Likely	Possible	Not Likely	Possible	Likely	Likely	Likely	Likely	Likely	Not Likely	Not Likely	Likely	Likely
	10	Not Likely	Not Likely	Not Likely	Not Likely	Possible	Possible	Possible	Possible	Possible	Not Likely	Not Likely	Likely	Likely
	1	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Likely	Likely
Influent Sulfate 100 mg/L	25	Not Likely	Possible	Not Likely	Possible	Likely	Likely	Likely	Likely	Likely	Not Likely	Not Likely	Likely	Likely
	10	Not Likely	Not Likely	Not Likely	Not Likely	Likely	Likely	Likely	Likely	Likely	Not Likely	Not Likely	Likely	Likely
	1	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Not Likely	Possible	Not Likely	Not Likely	Not Likely	Likely	Likely
Influent Sulfate 25 mg/L	10	Not Likely	Not Likely	Not Likely	Not Likely	Likely	Likely	Likely	Likely	Likely	Not Likely	Not Likely	Likely	Likely
	1	Not Likely	Not Likely	Not Likely	Not Likely	Likely	Likely	Likely	Likely	Likely	Not Likely	Not Likely	Likely	Likely

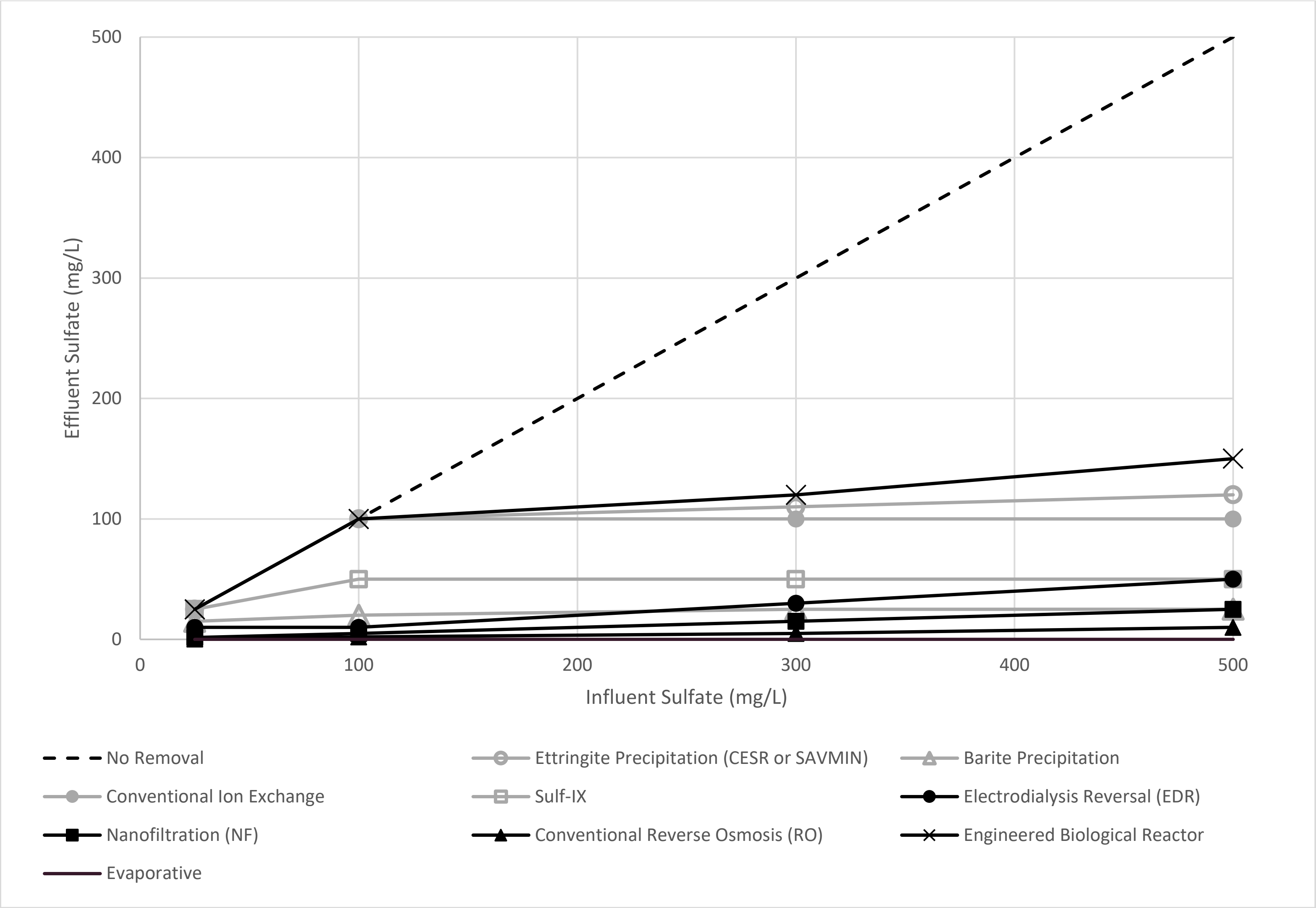

Figure 3-1 **Sulfate removal capabilities based on influent concentrations**

3.4 Considerations for Source Reduction

Source reduction may be a practical alternative if the degree of sulfate removal required is low. The maximum achievable sulfate reduction depends on the amount of sulfate originating from the targeted source, and additional treatment may still be needed to meet effluent limits. Source reduction options are outlined on Figure 3-2.

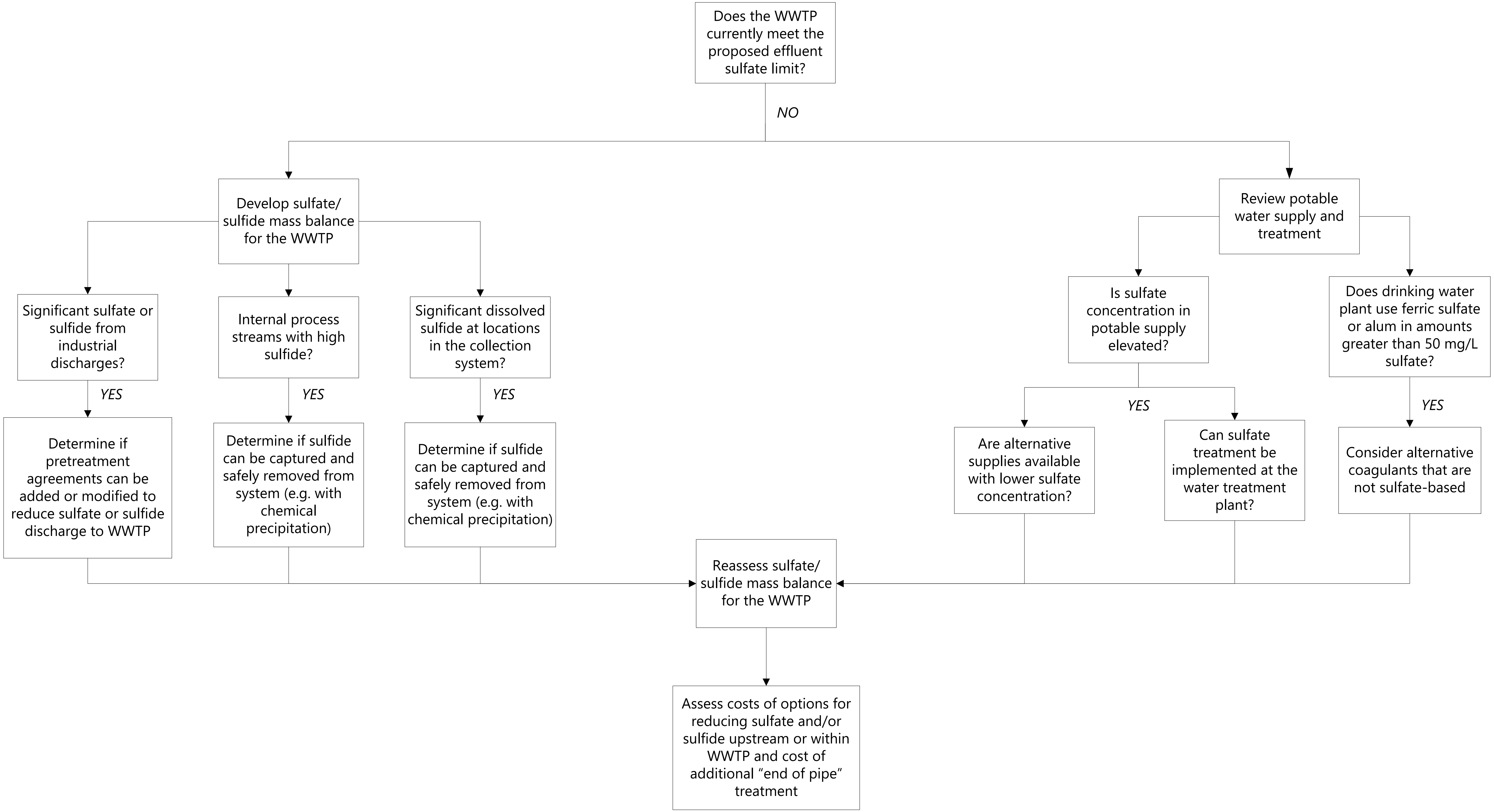

Figure 3-2 **Source reduction options chart**

3.4.1 Understanding the Sulfur Mass Balance

Developing a sulfur mass balance around a wastewater treatment plant will help identify potential means to reduce the mass of sulfate or sulfide coming to the plant. This mass balance approach would include identifying sources of sulfur in its various forms and species entering the plant or recycled within the plant and confirming that they match the measured amount of sulfur in influent and internal streams. External sources are industrial waste streams and domestic sewage, while potential internal sources include anaerobic digester sludge dewatering filtrate and digester decant. If the mass balance indicates that sulfate concentration in the potable water supply is elevated, a mass balance around the entire system, including water treatment, should be completed.

3.4.1.1 Removal of Sulfide from Collection System

Generally, sulfide is easier to remove from water streams than sulfate, because it is volatile as hydrogen sulfide gas in certain pH ranges and readily precipitates with metals as insoluble metal sulfides. In systems that see hydrogen sulfide corrosion of wastewater collection systems, it may be possible to capture sulfide in collection systems before it reaches the wastewater treatment plant through air stripping and/or addition of iron salts. These methods can also be used to remove sulfide from internal recycle streams containing sulfide. Sulfide will only occur in water downstream of an anaerobic process. Any pipe or tank with enough sulfide to precipitate a meaningful amount is likely to see hydrogen sulfide corrosion or health issues, unless the pH is above 8. At low pH, remaining hydrogen sulfide can be stripped from solution, but must be managed to limit equipment damage and public health risk as described in Section 4.3.2.

Iron sulfide salts produced will end up in primary or secondary treatment sludges. Ultimately, the success of this approach relies on the stability of the iron sulfide precipitate. The fate of iron sulfide in the aeration basin and other places where it is exposed to oxidizing should be considered and understood prior to implementation.

3.4.1.2 Industrial Pre-treatment Agreement Modifications

Sulfate in wastewater effluent originates from industrial, commercial, and municipal waste streams. If a substantial mass of sulfate in a specific wastewater influent comes from industrial sources, the municipality could potentially implement more restrictive pre-treatment requirements for those industries contributing significant amounts of sulfate or sulfide. The achievable sulfate reduction is limited to the sulfur mass originating from industrial facilities. Industrial facilities, such as ethanol plants, may be able to implement changes to minimize sulfate discharges to the wastewater treatment plant by switching to processes that use less sulfuric acid, for example.

In addition to reducing the influent sulfate to the wastewater treatment plant, external source reduction has the added benefit of reducing the potential for sulfide-induced corrosion of wastewater collection systems. Corrosion is caused by bacterial activity that converts sulfate in wastewater to sulfide and then to sulfuric acid, so reducing sulfate concentrations decreases the potential for corrosion.

3.4.2 Water Supply Modifications

If a municipality sources its drinking water from groundwater aquifers, sulfate naturally present in groundwater travels through drinking water distribution, water use, and disposal to wastewater treatment where it contributes to influent and effluent sulfate concentrations. If the amount of sulfate present in the groundwater source is above the sulfate effluent limit at the wastewater treatment plant and there is a surface water source readily available, wastewater sulfate concentrations may be reduced by switching the drinking water source from groundwater to surface water. The achievable sulfate reduction is limited to the difference between the sulfate concentration in the groundwater and the sulfate concentration in the surface water.

If the source water contains elevated sulfate, many of the treatment technologies previously described could be used to reduce the sulfate concentration in the drinking water supply, and in fact, the use of some of these technologies (e.g., membrane treatment) is more common in the drinking water industry. Removing sulfate in the drinking water supply rather than at the outlet of the wastewater treatment plant may reduce the complexity of the pretreatment that is required. However, for the membrane and ion exchange technologies, the technical challenges of residuals management remain.

Another option for source reduction is to reduce sulfate added to the water during drinking water treatment. Some drinking water treatment plants use ferric sulfate or alum, both of which contain sulfate, to treat their water. If a specific wastewater treatment plant collects wastewater from an area serviced by a drinking water plant using these chemicals, they may be able to reduce influent sulfate by having the drinking water plant use different chemicals that do not add sulfate. The achievable sulfate reduction is limited to the sulfate mass originating from these chemicals. The sulfate salts used have the advantage of being readily soluble in water. The primary alternatives are ferric chloride and polyaluminum chloride.

4.0 Secondary Technologies for Managing Residuals and Byproducts

It is often the case when evaluating treatment options for various constituents, including sulfate, that the primary treatment objective can be met simply. However, the more difficult challenge is how to manage the waste products (residuals) from the treatment process. Whether the parameter of concern is sulfate, mercury, nitrogen, or chloride, the management and final disposition of the residuals can be more technically complex and often more costly than the primary treatment technology itself. In this section, technical considerations for residuals management are reviewed, beginning with the membrane technologies. Membrane treatment using either RO or NF can provide reliable removal of sulfate; however, it generates a salty, liquid waste stream. Management of this concentrate is a challenge that extends beyond Minnesota’s borders. It is encountered in other states that use these same technologies for drinking water production and in industries that use RO and NF for high-purity water production or wastewater treatment. The purpose of this section is to provide an overview of the “state-of-the-industry” with respect to residuals management, what approaches are being used elsewhere, and what technical, regulatory, and economic challenges remain.

4.1 Membrane Residuals: Concentrate Management

Sulfate and other contaminants separated in membrane treatment processes end up in a concentrated brine solution that requires disposal. Membrane separation often consists of multiple stages of treatment, where the concentrate from the first stage is sent to the second stage to reduce the volume requiring further management. Management of concentrate is commonly managed in the following ways [Ref. (17)]:

- Surface water disposal
- Discharge to the sanitary sewer (for potable water and industrial applications)
- Deep-well injection
- Land application
- Evaporation ponds

Some industries also employ thermal evaporative technologies, as has been previously discussed. Within Minnesota and across the country, the technical, economic, or regulatory viability of these approaches is often significantly constrained. As a result, there are efforts currently underway to develop alternatives for managing the concentrate from these otherwise very promising treatment technologies. These efforts include resource recovery to extract or create materials that have market value from the concentrate and creative volume reduction and water reuse techniques. The importance of these efforts cannot be overstated. In fact, the U.S. Bureau of Reclamation recently launched a series of Advanced Water Treatment Prize Competitions to spur cross-disciplinary innovation in key areas [Ref. (18)]. Two of the competition areas revolve around concentrate management. The sections that follow provide an overview of technologies under development and examples of creative approaches being pursued by the drinking water industry to manage membrane concentrates.

4.1.1 Deep-well Injection

Deep-well injection is regulated under the federal Underground Injection Control program (UIC) and the Safe Drinking Water Act (SDWA). In Minnesota, there is a moratorium on injection wells [Ref. (14)], preventing this as an option for concentrate disposal. However, an Underground Injection Control Permit Application can be filed with the United States Environmental Protection Agency (USEPA) Region 5, and a rule variance request submitted to the Minnesota Department of Health (MDH), which is responsible for granting variances to the administrative rule prohibiting use of wells for disposal or injection. Variances would likely require significant technical and legal review. Outside of Minnesota, deep-well injection is more commonly employed. One example of this is the El Paso Water Utilities (EPWU) Kay Bailey Hutchison Desalination Plant, which is the world's largest inland desalination plant and produces 15.5 million gallons per day (MGD) of permeate and 3 MGD of concentrate [Ref. (19)]. The planning for this facility included extensive investigations into concentrate management options, which reviewed six alternatives for disposal. According to EPWU [Ref. (19)]:

> *Two methods were determined to be the most feasible: evaporation and deep-well injection. EPWU then tested evaporation methods, including conventional evaporation ponds, evaporation misting equipment and evaporation ponds with concentrators. Deep-well injection was selected as the preferred method of disposal, and the concentrate is placed in porous, underground rock through wells. The sites would confine the concentrate to prevent migration to fresh water, provide storage volume sufficient for 50 years of operation and meet all the requirements of the Texas Commission on Environmental Quality.*
>
> *Deep-well injection entailed extensive study of local geological and hydrological conditions as well as the examination of existing data, including seismic analysis and water samples. The University of Texas at El Paso conducted a geophysics study that EPWU used to create a geologic model and the Army drilled four wells to test for geological formation.*

This facility is illustrative of the challenges posed by inland applications of membrane technologies, the importance of residuals management planning and the level of effort required for it, but also the potential for successful, large-scale inland applications.

4.1.2 Volume Reduction Technologies

Volume reduction technologies are designed to reduce the volume and thus the cost of disposal of a residual liquid stream [Ref. (20)] and can be used in combination with other concentrate management approaches. Mature volume reduction technologies include specialized membrane systems, such as electrodialysis (ED), Vibratory Shear Enhanced Processing (VSEP), High Efficiency Reverse Osmosis (HERO), and mechanical thermal technologies, such as evaporation, crystallization, and spray dryers. Further information on these technologies is included in Large Table 3.

Other volume reduction technologies under development include forward osmosis (FO), membrane distillation, slurry precipitation and reverse osmosis (SPARRO), and advanced reject recovery of water (ARROW). Further details regarding these technologies are included in Section 4.1.4 and Large Table 3.

4.1.3 Zero Liquid Discharge (ZLD)

The original definition of the general term ZLD referred to no discharge of liquid streams across the plant boundary. Treated water or liquid wastes were managed by internal reuse or further treatment of liquid streams (by mechanical evaporation, for example). In the context of this report, ZLD refers to no liquid *waste* discharge. Treated water, on the other hand, *is* discharged. Wastes are subject to further treatment or solidification and not discharged. The term ZLD, in its current context, also does not necessarily mean taking concentrate or the wastewater feed in general all the way to solids or completely processing using thermal evaporation. ZLD is considered a subset of high recovery where the final residual wastes contain zero liquid [Ref. (17)]. Mechanical or thermal evaporation of membrane concentrate is one type of ZLD process. In this case, the product resulting from the ZLD system is typically a solid salt residue requiring disposal at an appropriate facility [Ref. (20)].

Given the high capital and O&M costs associated with evaporation and crystallization or spray drying and the requirement to further manage resulting brine streams or salt solids, the water and wastewater treatment industry is shifting toward combinations of treatment technologies for primary membrane concentrate minimization rather than direct use of evaporation with crystallization, thereby reducing the flow to these systems if they are implemented. There are three steps in a typical ZLD process, as shown on Figure 4-1 [Ref. (21)].

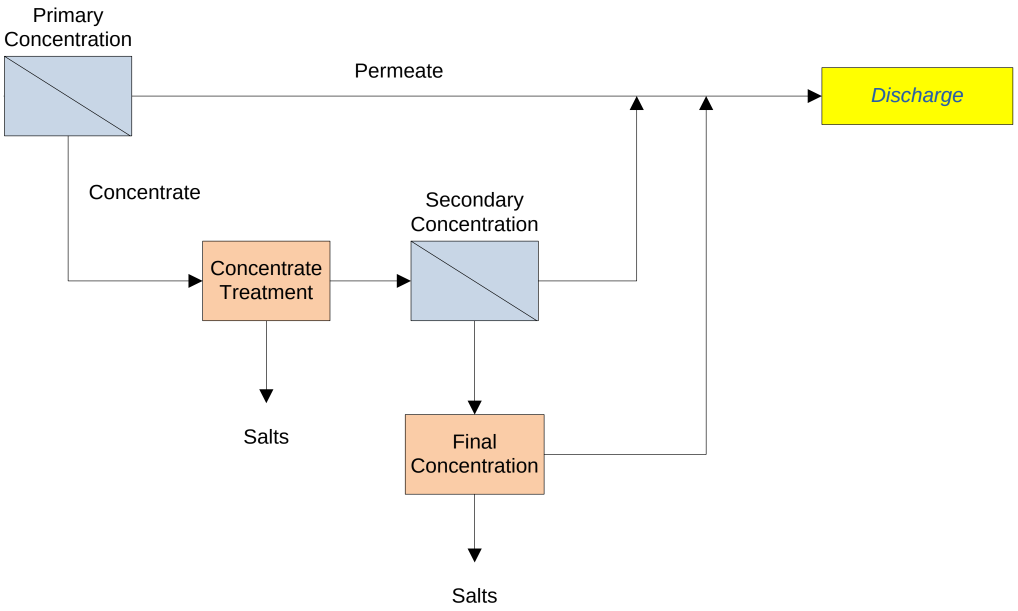

Figure 4-1 Typical ZLD process

In a sulfate treatment application, “primary concentration” represents the membrane treatment technology for sulfate removal, such as conventional NF or RO. “Concentrate treatment” represents solids contact clarification, chemical precipitation clarification, water softening, or some other step to condition concentrate for further membrane treatment. “Secondary concentration” consists of some additional membrane treatment to further minimize the concentrate stream, and the “final concentration” step can consist of further clarification, a third stage of membrane treatment, or a thermal process to evaporate any remaining liquid leaving only salts for final disposal.

Combining multiple technologies provides operational flexibility and the ability to modify the concentrate management process based on water quality, using less chemical additives. Water and wastewater treatment plants in cities including Palm Coast, Florida; El Paso, Texas; and Chino, California have implemented combinations of treatment technologies to achieve ZLD to manage primary membrane concentrate. The primary membranes at these facilities are not necessarily for sulfate treatment. However, the concentrate management practices in place reflect options that could be applied to concentrate streams from primary membranes installed for sulfate removal.

Concentrate management at the City of Palm Coast, Florida drinking water treatment plant is used to reduce the concentrate volume requiring treatment and increase treated water supply for drinking water distribution. The ZLD system consists of a solids contact clarifier, followed by ultrafiltration (UF). Lime-soda ash softening is used as pre-treatment to ultrafiltration to precipitate carbonate and non-carbonate hardness, and a polymer is added to improve solids settling. Sulfuric acid and polyphosphate are added to softened water to inhibit scale formation on UF membranes. UF removes most of the remaining suspended solids. UF filtrate is disinfected prior to mixing with the existing water treatment plant permeate for distribution as drinking water [Ref. (22)].

Sludge removed from the softening clarifier is sent to a solids handling system that includes thickening and dewatering. Liquid removed from the sludge is recycled back to the head of the ZLD process. Dewatered lime solids are reused in the production of concrete aggregate and paver base [Ref. (22)].

Using this concentrate management combination of technologies, the City of Palm Coast is able to achieve zero liquid discharge and manage the concentrate through less energy-intensive means compared to evaporation with crystallization. A process flow diagram of concentrate management at the City of Palm Coast Water Treatment Plant #2 is provided on Figure 4-2.

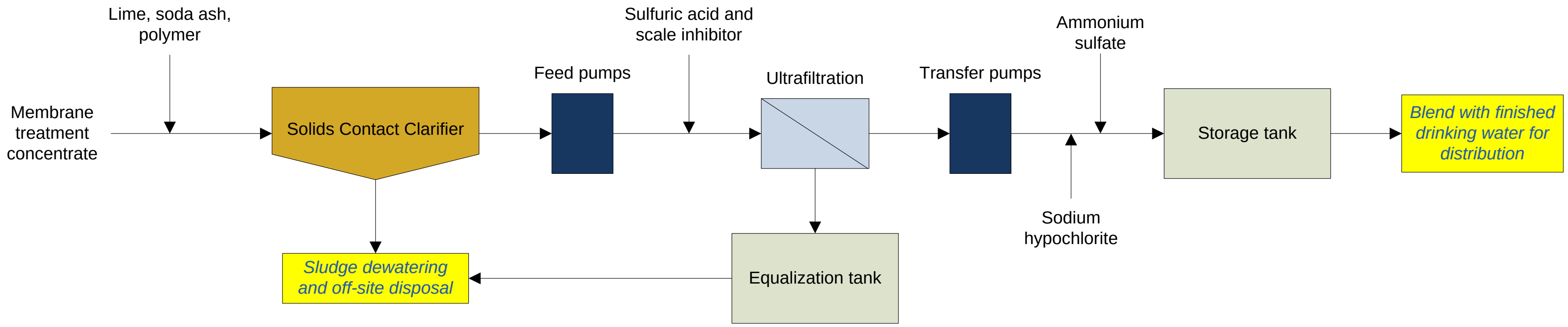

Figure 4-2 **Zero liquid discharge concentrate management, City of Palm Coast Water Treatment Plant #2**

EPWU's Kay Bailey Hutchison Drinking Water Desalination Plant (KBH) uses deep-well injection as a primary concentrate disposal technique. However, EPWU continues pioneering work around concentration management and is partnering with Enviro Water Minerals Company (EWM) to test and operate a ZLD product recovery plant to manage concentrate at the facility. The product recovery plant began operation on April 25, 2017. The EWM Plant (EWM P1) converts the 1.25 MGD concentrate stream from KBH plus 1.0 MGD raw brackish water into 2.1 MGD potable-quality water that is distributed as drinking water [Ref. (23)]. Using a proprietary combination of membrane treatment technologies followed by multiple chemical precipitation steps, the following products are recovered for beneficial reuses [Ref. (23)]:

- Potable-quality water (TDS<700 mg/L)
- Caustic soda
- Hydrochloric acid
- Gypsum
- Magnesium hydroxide

EWM P1 is the first of its type in the world and a demonstration of concentrate management that results in production of marketable chemical and mineral products in addition to eliminating waste disposal associated with concentrate management. As operation of EWM P1 continues and similar full-scale ZLD product recovery systems are installed, full economic impacts can be evaluated to determine the processes viability for concentrate management in other applications and states.

The concentrate minimization process in place at the Chino II Concentrate Reduction Facility (CRF), in Jurupa Valley, Southern California, combines chemical softening and membrane filtration to achieve ZLD. The Chino II CRF receives concentrate from the Chino II Desalter, a facility in Jupiter Valley, California that utilizes ion exchange (IX) and RO treatment trains to treat brackish groundwater for drinking water. Concentrate is first sent through a pellet softener system to remove calcium and silica from RO concentrate. Softened water is then passed though granular media filters for particle removal ahead of a second-stage RO process. With this concentrate management approach, the primary RO recovery, which is the ratio of the product water flow to the feed water flow, increased from 83.5 percent to 95 percent, which results in a smaller volume of concentrate for disposal [Ref. (24)]. A process flow diagram of concentrate management at the Chino II CRF is provided on Figure 4-3.

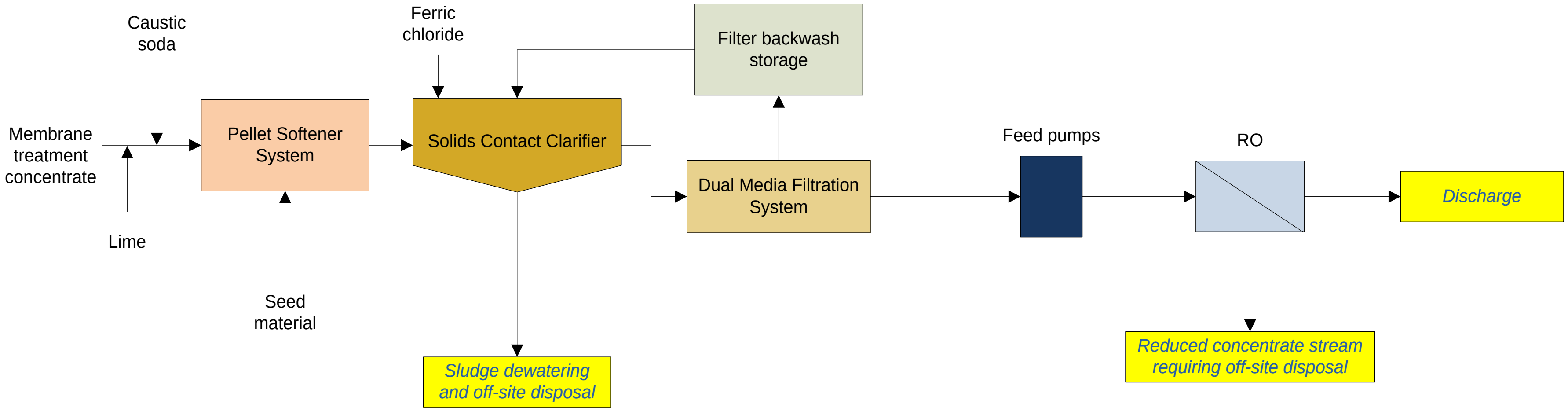

Figure 4-3 **Concentrate minimization process, Chino II Concentrate Reduction Facility**

4.1.4 Concentrate Management Technologies under Development

While thermal technologies have the broadest range of existing applications with the highest liquid recovery, high capital and energy costs are spurring the development of pressure driven, electric potential, or intermediate precipitation processes for concentrate management as alternatives to thermal technologies [Ref. (21)]. Use of waste heat or biogas could potentially be viable options to reduce costs associated with evaporation with crystallization, as well as co-locating thermal concentrate management with other industries that generate waste heat, such as the power industry.

A number of concentrate management technologies are currently under development and have the potential to become viable options once pilot and full-scale applications are installed and successful operation is demonstrated. Large Table 3 includes a selection of emerging technologies and notable advantages and disadvantages associated with each. As mentioned in Section 4.1.3, new concentrate management commonly incorporate combinations of additional membrane treatment, softening, etc., rather than an energy-intensive thermal process to reduce the volume of primary membrane concentrate.

4.1.5 Concentrate Management in Minnesota

The viability of concentrate management processes will depend upon the sulfate mass balance, unless zero liquid discharge is implemented. In Minnesota, concentrate management options with the greatest viability include deep-well injection and ZLD coupled with high-recovery membrane processes. Deep-well injection remains prohibited in Minnesota, as described in Section 4.1. Further research and development that evaluates combinations of membrane treatment and chemical precipitation to achieve ZLD would be valuable to support concentrate management alternatives to thermal treatment.

Selective salt recovery and development of a saleable product from a ZLD process is dependent on specific salts in the concentrate, concentrate quality, concentrate quantity, market size, and stability. Research and evaluation of the likely composition of saleable products resulting from municipal wastewater treatment concentrate management would be valuable because this could help to offset capital and O&M costs associated with the ZLD system. While ZLD processes may not require costly thermal treatment technologies, the full economic impacts associated with multiple treatment processes, when fully accounted for, may be equally cost-prohibitive.

As mentioned in Section 4.1, in 2017, the U.S. Bureau of Reclamation (USBR) launched a series of Advanced Water Treatment Prize Competitions to solve critical water and water-related issues. The Advanced Water Treatment Grand Challenge Framework includes the following stages:

- Stage 1 – conceptual proposal
- Stage 2 – lab-scale prototype tests
- Stage 3 – field-scale demonstrations

Of the specific challenge topics identified to date, two relate to concentrate management:

- *More Water Less Concentrate Stage 1* (Stage 1 launched December 2016 and closed March 2017)
- *Beneficial Uses for Concentrate Stage 1* (has not yet launched)

Award notices have not been released after the close of Stage 1 of the *More Water Less Concentrate* challenge topic [Ref. (25)]. Moving forward, the USBR will determine scope and level of effort for future challenge competitions based on funding available. A topic selection advisory committee will be assembled and they will continue to recruit partners from the public, industry, venture capital, and non-profit organizations for specific prize competitions [Ref. (25)]. Following concentrate management, innovative ideas, as they unfold through this competition, could provide valuable insight for applications in Minnesota.

4.2 Biological and Chemical Treatment Residuals: Sludge and Solids Management

Both chemical precipitation and biological treatment processes produce solids that require management. Either type of sludge should be thickened and/or dewatered prior to disposal to reduce the volume. Dewatered sludge can be disposed of in landfills.

Chemical precipitation sludges from sulfate removal processes consist of gypsum, ettringite, or barite salts, depending on the process used, along with any organic matter or other salts removed in the process. Depending on the concentration and leachability of barium in the barite sludge, it may require disposal in a hazardous waste landfill, if toxicity characteristic leaching procedure (TCLP) concentrations are greater than 100 mg/L. Because ettringite is a more complex salt that requires specific conditions to form, ettringite sludge is less stable than either gypsum or barite sludge, and can dissolve to release sulfate at low pH. It also has a looser crystal structure, and therefore is more difficult to settle; in some cases, centrifugation may be needed to separate ettringite from solution [Ref. (26)].

Biological sludge from sulfate removal processes can be managed like other biological wastewater sludge. Ultimate disposal can be achieved in landfills or via land application, depending on the biosolid grade achieved. The sulfate-reducing bacteria are slow growers and would be expected to have minimal impact on overall mass of biosolids that need to be managed.

4.3 Sulfide Management

Sulfide, which is produced in all biological sulfate treatment processes, poses a safety risk to operators and nearby public. Hydrogen sulfide is detectable by the human nose at concentrations as low as 0.01 ppm, and toxic to humans at concentrations over 2 ppm. Health effects of hydrogen sulfide gas are well known [Ref. (27)].

Due to this high toxicity, any biological sulfate treatment technology should be paired with a sulfide management technology. Sulfide can be managed in several different ways, as described in the following sections.

4.3.1 Chemical Sulfide Removal

When sulfide is combined with metals, the resulting compounds are very insoluble in water, so they form solids that settle out of solution. The most common chemical method to remove sulfide is addition of iron or other metal salts [Ref. (28)]. Iron filings or minerals such as magnetite can be used to precipitate sulfide in ponds or reactors [Ref. (29)]. Sulfide can also be chemically oxidized using hydrogen peroxide, chlorine, or potassium permanganate, but this process converts the sulfide back into sulfate [Ref. (28)]. Produced metal sulfide sludge can be disposed of in landfills. Depending on landfill degradation processes, sulfide could be released as sulfates into landfill leachate.

4.3.2 Air Stripping of Sulfide and Associated Treatment

The least complex sulfide treatment option involves moving the hydrogen sulfide from the water into the gas phase using a process called stripping, with either air or an inert gas, such as nitrogen, and then treating the hydrogen sulfide-containing gas using physical, chemical, or biological methods. The pH of the water is a critical operational component for the efficacy of air stripping. The water must have a pH lower than about 6 for this option, because hydrogen sulfide stays dissolved in the liquid at higher pH values. After stripping the hydrogen sulfide into the air stream, one option is to route the contaminated air through a bed of woodchips or other organic matter, which serves as a biofilter where bacteria eat the sulfide and produce elemental sulfur or sulfate. Biofilters require a large surface area and the biofilter material must be replaced intermittently and landfilled.

Another option is to remove the sulfide using a chemical reaction with solids such as reduced iron or granulated activated carbon (GAC). The resulting materials would end up as a solid waste, which could be landfilled. In either case, sequestered sulfur would end up in the landfilled material, and may leach out again in the future as sulfate. In some cases, spent GAC can be reactivated using heat and reused.

5.0 Use of Information

5.1 Treatment Technology Selection Process

The screening process presented in Section 3.0 reviewed and scored treatment technologies that are reasonably well-commercialized and have a demonstrated ability to remove sulfate to a given concentration. Membrane technologies scored high in the screening exercise, but it is important to understand that this is not the only class of technologies that may be an option for a given wastewater treatment plant. Each wastewater treatment plant that may be required to reduce the sulfate concentration in its wastewater effluent will have unique conditions and circumstances that must be considered. For example, not all municipalities will be required to achieve very low concentrations of sulfate (i.e., tens of mg/L). In those circumstances, a polishing-level of treatment may be all that is required and technologies other than membrane treatment may be more viable.

In that light, this section is intended to provide guidance to municipalities on how to use the data presented in this report to begin the process of assessing their unique situation. What follows is a framework for informing decision-making to select sulfate reduction technologies. This framework was developed assuming that the primary considerations for a wastewater treatment plant are the ability to reliably meet sulfate targets and cost.

1. Evaluate whether source reduction can meet the sulfate target using the flow chart presented on Figure 3-2. If source reduction is not practical or unable to meet sulfate target, evaluate sulfate treatment technologies in the following steps.

2. If sulfate removal to greater than 250 mg/L is all that is required, review the technology information outlined in Large Table 1. This table contains a summary of all technologies reviewed, including those not fully commercialized yet and those that remove sulfate down to only 250 mg/L. If treatment to less than 250 mg/L is required, compare the influent and effluent sulfate concentrations to the sulfate removal estimates depicted on Figure 3-1. List the technologies that are below the point, which are the technologies that are likely able to meet the sulfate treatment requirements.

3. Review the technology information outlined in Large Table 1 for the technologies selected in Step 1. If any of the technology characteristics are incompatible with the existing wastewater treatment plant or with the needs of the community, remove those from the list.

4. Compare the screening criteria and their weights to the priorities of the wastewater treatment plant and the community. Review the screening table outlined in Large Table 2 for technologies remaining after Step 2 and favorably consider technologies that score high overall and for the criteria that are most important to the community. Weighting of factors may vary by municipality and should be adjusted accordingly.

5. Contact MPCA to identify other parameters that might require additional removal. Review the ability of the technologies to remove other parameters that may be of concern presented in Table 3-4 and favorably consider technologies that also remove other required parameters.

6. Develop management possibilities for residuals and byproducts using Section 4.0.

7. Develop a preliminary cost estimate, including primary technology and ancillary technologies for pre- or post-treatment or residuals and byproduct management, to inform relative costs of different options.

5.2 Treatment Technology Selection – Facility Examples

This section provides examples of how two types of municipalities may employ the treatment processes described in Section 3.0.

5.2.1 Treatment Technology Selection – Pond System Example

An example pond wastewater treatment system process flow diagram is provided on Figure 5-1. This example illustrates a stabilization pond wastewater treatment plant with an influent sulfate concentration of approximately 300 mg/L and an effluent sulfate limit of 100 mg/L. In this example, 66% sulfate removal is required, and biological sulfate treatment with a packed bed bioreactor may be able to provide the required removal. Sulfate treatment technology process equipment and pre- and post-treatment are shown in red. Note that site-specific bench- and pilot-testing would be needed to evaluate the ability of any technology to meet effluent limits.

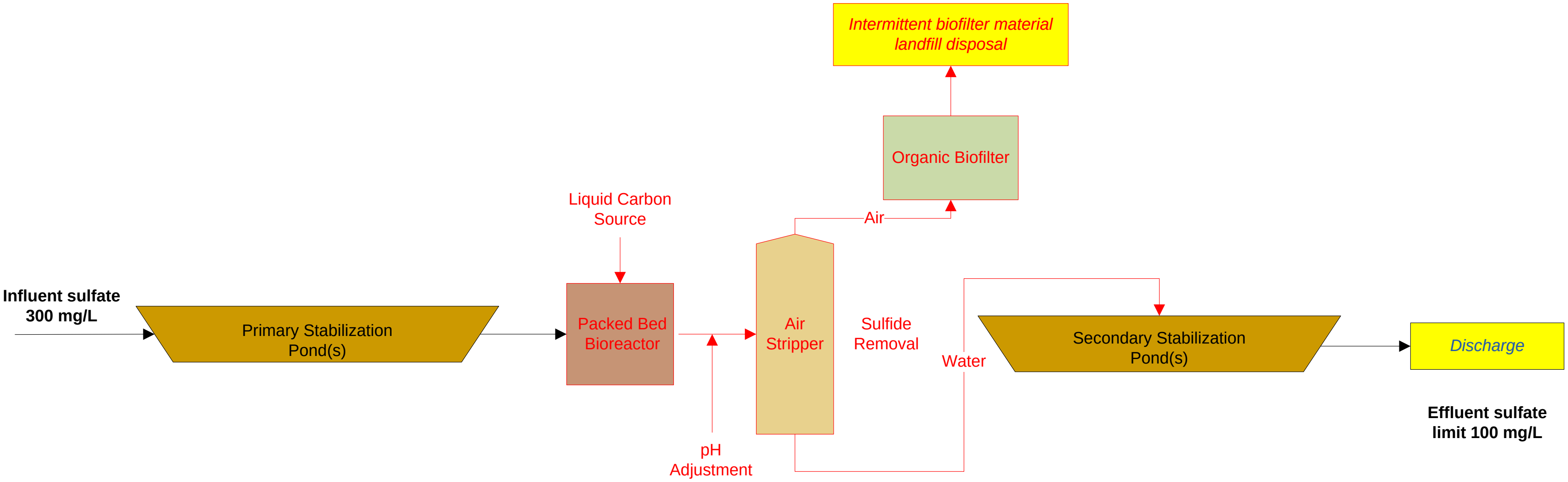

Figure 5-1 **Pond system example sulfate treatment retrofit**

In this stabilization pond treatment system example, the first stabilization pond serves as solids removal pre-treatment to the packed bed bioreactor, where an optional liquid carbon source, such as methanol, can be added to the reactor as food for the sulfate-reducing bacteria. The feed for the packed bed could potentially be drawn from the bottom of the facultative lagoon so that it is already at a low ORP. Seasonal mixing effects should be considered. Bioreactor effluent is routed through an air stripper to separate the hydrogen sulfide-containing gas from the treated wastewater. pH adjustment to less than 6 would be required ahead of the air stripper for optimal hydrogen sulfide removal, and additional pH adjustment may be necessary downstream to keep the effluent into the range of 6-9. Water leaving the air stripper would be routed to the second stabilization pond for removal of remaining influent BOD and any extra supplemental carbon not used in the bioreactor.

Hydrogen sulfide-laden air removed in the air stripper would be routed through an organic biofilter consisting of woodchips or other organic matter, where bacteria consume the sulfide and convert it to elemental sulfur. Biofilter material would be replaced periodically and landfilled.

Further considerations for a pond system retrofit for sulfate removal using a packed bed bioreactor include:

- Liquid carbon and pH adjustment chemical metering and storage requirements
- Biofilter selection based on available footprint – generally requires a large surface area
- Truck access for biofilter material removal
- Temperature impacts biofilter and packed bed reactor performance
- WWTP operator certification level required for operation

5.2.2 Treatment Technology Selection – Activated Sludge System Example

An example activated sludge system sulfate treatment technology process flow diagram is provided on Figure 5-2. This example represents an activated sludge wastewater treatment plant with an influent sulfate concentration of greater than 500 mg/L and an effluent sulfate limit of 25 mg/L. With 95% sulfate removal required, RO or NF membrane separation is the only sulfate treatment technology likely to meet the effluent limit. Sulfate treatment technology process equipment and pre- and post-treatment are shown in red. Note that site-specific bench- and pilot-testing would be needed to evaluate the ability of any technology to meet effluent limits. Additionally, multiple stages of membrane separation and subsequent concentrate management may be required beyond what is shown on the figure. Complete treatment system design needs to be evaluated on a site-specific basis.

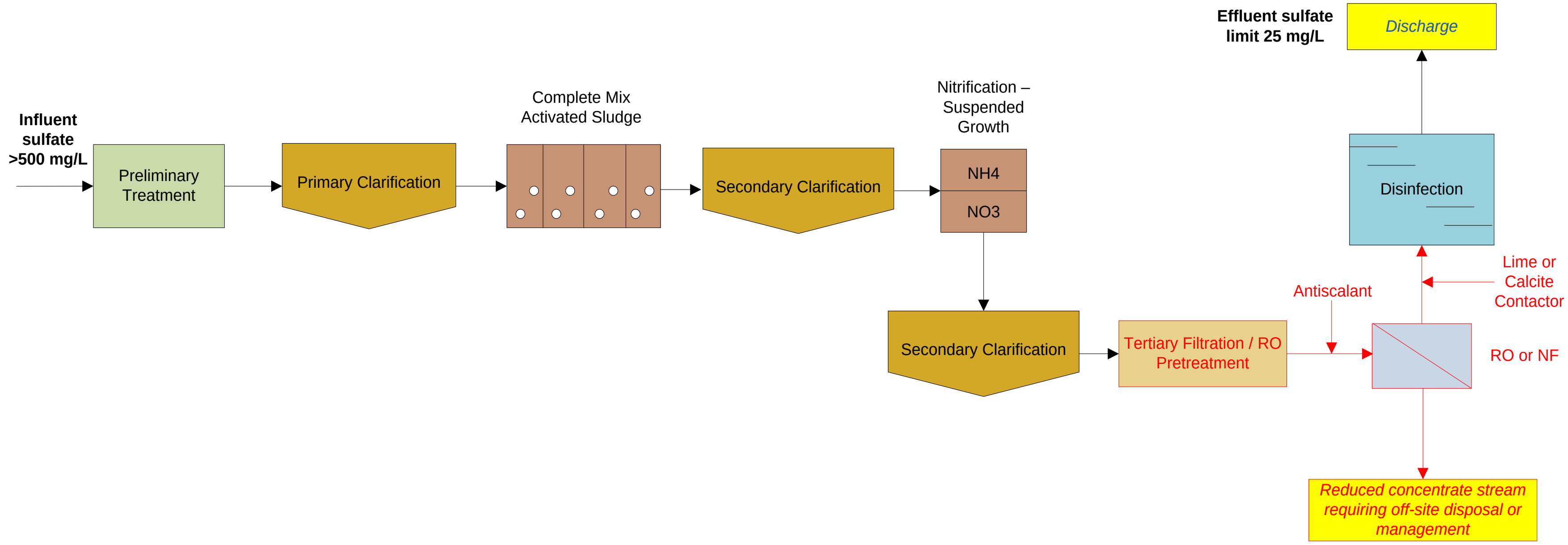

Figure 5-2 **Activate sludge system example sulfate treatment retrofit**

If tertiary filtration is already in place at an activated sludge facility, this can potentially be retrofitted to meet membrane pre-treatment requirements. However, there are several parameters of general fouling concern for RO treatment, and other membrane technologies, including total organic carbon (TOC), total suspended solids (TSS), calcium carbonate, organics, iron, manganese, barium sulfate, calcium sulfate, strontium sulfate, calcium phosphate, silica, and aluminum. In waters with high concentrations of organic matter and nutrients, membranes are susceptible to fouling due to biological activity at the membrane surface, where conditions support the growth of microorganisms and permeability can decrease as microorganisms grow in the membrane pores [Ref. (8)].

TOC presents significant concerns for membrane treatment systems by providing a substrate for biofouling and by fouling the membranes directly. The TOC concentration required to minimize biofouling potential depends on the character of the organic matter present [Ref. (30)]. Potentially viable TOC removal technologies include carbon adsorption, coagulation/flocculation/filtration, and biofiltration [Ref. (10)]. Ferric chloride use, for example, ahead of microfiltration or ultrafiltration provides a surface for TOC adsorption.

Strategies commonly used to control membrane fouling include [Ref. (8)]:

- Pre-treatment of feed water
    - Microfiltration or ultrafiltration
- Hydraulic flushing
    - Cross-flow velocity across the membrane
- Chemical treatment and conditioning
    - Adding antiscalants and dispersants ahead of the membrane
    - Maintaining the optimal pH using acid
    - Maintaining residual chloramines throughout the system to control the presence of microorganisms
- Chemical cleaning of the membranes
- Careful membrane selection
    - Taking pore size into consideration
    - Smooth, hydrophilic membrane for high and constant flux [Ref. (31)]

Membrane treatment systems produce high-quality, low-TDS treated water. This permeate water quality is often better than is required for its final use. In order to minimize the cost of the treatment system and associated concentrate management, in typical applications such as drinking water treatment, membrane treatment systems are sized to treat the portion of the flow adequate to bring final product water to the target water quality. In the case of treating municipal wastewater for sulfate removal, the sulfate mass balance in the final polishing step should be carefully examined and optimized to assist with concentrate minimization.

Extreme conditions including the low-flow, high-sulfate concentration condition and the high-flow, low-sulfate concentration condition should be evaluated based on historic water quality and flow data. If a high-flow condition controls required membrane treatment system sizing, additional equalization capacity should also be considered.

Further considerations for activated sludge system retrofit for sulfate removal by membrane treatment include:

- Pre- and post-treatment chemical storage and metering and space requirements
- Concentrate management selection based on available footprint
- Salt storage and truck access for salt removal if evaporation with crystallization is the selected concentrate management method
- WWTP operator certification level required for operation

6.0 Conclusions

Alternatives to remove sulfate from wastewater include source reduction, chemical precipitation, ion exchange, membrane treatment, biological treatment, and evaporative treatment. This study evaluated the feasibility of these alternatives and specific technologies associated with each category. Several technologies were eliminated as feasible options for sulfate removal based on a threshold screening process. Technologies that have been found able to remove sulfate to below 250 mg/L and have been demonstrated at full-scale were further evaluated in a detailed technology screening process.

The technology screening process results indicate that reverse osmosis and nanofiltration are the most well-developed and effective alternatives for sulfate removal. However, the management of the residuals from these technologies poses a significant impediment to their implementation, and approaches for concentration management must be carefully considered when planning for implementation of membrane technologies. Chemical precipitation and ion exchange scored slightly below reverse osmosis and nanofiltration (membrane technologies), primarily due to limited ability to remove sulfate to low concentrations (e.g., less than 50 mg/L), fewer commercial applications, and higher risks to operator and public health. However, depending upon the influent sulfate concentration, if a wastewater treatment plant effluent limit for sulfate is above 50 mg/L, a chemical precipitation or ion exchange treatment technology may be effective for the required sulfate removal. The screening results also reflect the state of the industry today in terms of municipal wastewater treatment for sulfate removal and provide an indication of additional technologies that may be viable in the future pending further commercialization, demonstration of reliable operation, and residuals management developments.

As demonstrated by the threshold screening, numerous biological treatment processes are under development for sulfate removal. Due to the slow growth of sulfate-reducing bacteria, a much longer retention time is required in the biological reactor than is typically practical in municipal wastewater treatment. In addition, biological treatment systems for sulfate removal require significant development of design and operational strategies to ensure the success of sulfate-reducing bacteria growth before they can be employed to full-scale implementation for municipal wastewater treatment. Biological treatment of sulfate has primarily been applied to mine water treatment, where metals removal by converting sulfate to sulfide is the primary goal, not sulfate removal; so in those settings, low-efficiency biological treatment systems like constructed wetlands and mine pit reactors are practical. However, for municipal wastewater treatment, the retention time requirement and other operational limitations resulted in technology screening scores on the lowest end of the range compared to the other treatment technologies.

The technologies were also screened for their ability to remove other parameters of concern, including other major ions, mercury, and total dissolved solids in addition to sulfate. This was not a primary focus in selecting treatment technologies for research and screening; however, the ability to remove parameters of concern in addition to sulfate can help inform technology selection for wastewater treatment plants. This phase of screening found that while there is limited information on the use of some technologies for the removal of these other parameters, certain membrane technologies based on reverse osmosis membranes provide the most removal of these constituents.

The sulfate treatment technology screening results presented as part of this study helped inform Part 2 of this study, which considered the implementation of sulfate removal at municipal wastewater treatment plants. In Part 2, preliminary designs for sulfate removal for several municipal case studies were developed. The goal of the designs was to identify and illustrate key technical considerations that are associated with technology implementation. Cost estimates for the conceptual designs were also developed.

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Large Tables

Large Table 1 Sulfate reduction technology details

Primary Sulfate Removal Categories	Technology	Technology description	Lowest achievable sulfate concentration (mg/L)	Primary Technology	Concentrate Management Technology	Additives Required	Pre-treatment requirements [1]	Post-treatment requirements [2]	Residuals management and secondary impacts	Degree of commercialization	Relative cost / complexity of operation
Influent source sulfate reduction	Change Drinking Water Source (if groundwater source)	Change drinking water to a surface water source with lower chloride concentrations.	Reduction of 100-1,000 mg/L, depending on concentration in source [Ref. (32)]	X	-	N/A	N/A	N/A	N/A	Common practice	Drinking water supply and plant would require major modifications
	Change Drinking Water Coagulant (if alum and surface water source)	Change drinking water treatment process to use ferric chloride instead of aluminum sulfate as the primary coagulant.	Reduction of 10-50 mg/L, depending on alum dose	X	-	N/A	N/A	N/A	N/A	Common practice	Similar chemical cost, drinking water plant would require some adaptations
	Restrict Industrial Discharges	Implement tighter pre-treatment requirements to reduce sulfate concentration in discharges.	Reduction varies depending on industrial sources	X	-	N/A	N/A	N/A	N/A	Common practice	May have economic implications
	Influent and Recycle Sulfide Control	Remove sulfide from influent and WWTP recycle streams through precipitation with metal salts	Reduction varies depending on sulfide mass	X	-	Iron or other metal salts	N/A	N/A	N/A	Common practice in collection systems	May have economic implications
Chemical precipitation	Gypsum Precipitation	Calcium is added in the form of lime, and combines with sulfate to form gypsum solids, which can be removed from the water by settling. Final concentration is limited by solubility of gypsum to about 1,500 mg/L [Ref. (33)].	1,200 mg/L [Ref. (34); (33)]	-	X	Lime	None	Recarbonation and pH adjustment	Sludge management required	Common in mine water treatment	Similar in operation to lime softening
	Ettringite Precipitation (CESR or SAVMIN)	Lime and Gibbsite are added to form ettringite, which can be removed in a clarifier. Gibbsite can be recovered from ettringite and reused.	100-200 mg/L [Ref. (34); (33)]	X	X	Lime, aluminum reagent	Most cost-effective if gypsum removed first (if influent sulfate is greater than 1,000 mg/L)	Recarbonation and pH adjustment	Sludge management required	Common in mine water treatment	Aluminum reagent expensive, ettringite formation requires specific conditions, sludge unstable

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	Ettringite Precipitation with Aluminum Recovery (LoSO4) *Example Vendor: Veolia*	Lime and aluminum reagent are added to form ettringite, which can be removed in a clarifier. Sludge is then processes to recover aluminum reagent for reuse. Designed for mine water treatment of nanofiltration (NF) reject [Ref. (6)].	100 mg/L [Ref. (6)]	X	X	Lime, aluminum reagent	Most cost-effective if gypsum removed first (if influent sulfate is greater than 1,000 mg/L)	Recarbonation and pH adjustment	Sludge management required	Pilot scale only	Aluminum reagent expensive, ettringite formation requires specific conditions
	Barite Precipitation	Barium chloride or barium hydroxide is added, then barium combines with sulfate to form barium sulfate, which is removed by settling [Ref. (33); (7)].	50 mg/L [Ref. (7)]	X	X	Lime, barium salt	Most cost-effective if gypsum and carbonate removed first	pH adjustment	Sludge management required, barium toxic to aquatic life	Some cases in mine water treatment	Barium reagent is expensive
	Co-Precipitation with Aluminum	Sulfate ions can form complexes with aluminum precipitates and be removed from solution at pH 4-5 [Ref. (35)].	400 mg/L [Ref. (35)]	X	-	Aluminum coagulant, acid	Secondary wastewater treatment.	pH adjustment	Sludge management required	Bench-scale only	Requires precise pH control and reagent dosing
Ion exchange	Conventional Ion Exchange *Example Vendor: Dow*	A strong base anion exchange resin can be used to remove all anions along with sulfate and sulfite [Ref. (36)].	<100 mg/L	X	-	Lime	Most cost-effective if gypsum removed first. Filtration to remove solids and organic matter to prevent resin fouling.	pH adjustment	Regeneration waste	Common in mine water treatment and commercial/public water supply applications	Moderate complexity and cost
	Sulf-IX *Proprietary technology. Vendor: BQE Water*	Sulfate removal is completed in a two-stage process. Feed water passed through a series of vessels containing cation exchange resin to remove calcium and magnesium, then passed through a second set of contactors containing anion exchange resins to remove sulfate [Ref. (9)]. Resin regeneration process uses lime and sulfuric acid and generates gypsum, rather than a liquid waste.	<50 mg/L [Ref. (37)]	X	-	Lime, sulfuric acid	Pilot studies have shown best sulfate removal when water is treated to pH ~10.6 prior to IX [Ref. (9)] or if hardness is present primarily as calcium hardness. Filtration to remove solids and organic matter to prevent resin fouling.	pH adjustment	Regeneration waste - regeneration streams from both stages are recycled, except for precipitated gypsum. Regeneration process produces a clean gypsum product that can be used as a construction material.	Moderately commercialized for mine water treatment and commercial/ public water supply applications	Moderate complexity and cost

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Membranes	Closed-circuit Desalination Reverse Osmosis (CCD RO) *Proprietary technology. Vendor: Desalitech*	Uses conventional RO membranes. Permeate is produced at a rate equal to the incoming flow rate, and when a desired (high) recovery percentage is reached, brine is throttled out of the system, displaced by feed water in a single "plug flow" sweep [Ref. (38)].	Assumed similar to conventional RO, ~99% removal	X	X	Unknown	Filtration to remove solids and organic matter to prevent membrane fouling, anti-scalant addition to control scale formation	Similar to conventional RO	Brine management and disposal	Moderately commercialized, industrial, agricultural and wastewater reuse and concentration management applications [Ref. (39)]	Moderate complexity and cost - generally lower operation costs than conventional RO.
	Electrodialysis Reversal (EDR) *Example Vendor: GE*	An electric current is used to move dissolved salt ions through layers of charged membranes [Ref. (40)].	<50 mg/L [Ref. (41)]	X	X	Unknown	Filtration to remove solids, potential need for removal of organic matter to prevent membrane fouling.	Unknown	Brine management and disposal	Highly commercialized, commercial applications in groundwater treatment, desalination, drinking water	High complexity and cost - cost typically higher than NF/RO.
	Zero Discharge Desalination (ZDD) *Proprietary technology. Vendor: Veolia*	Combines conventional reverse osmosis with electrodialysis metathesis (EDM) to remove salts from water a high recovery levels. EDM prevents divalent salts from precipitating while producing clean water [Ref. (42)].	~99% removal [Ref. (42)]	X	X	Electrode rinse (Na_2SO_4), sodium chloride [Ref. (42)]	pH adjustment with hydrochloric acid followed by filtration to remove solids and organic matter to prevent membrane fouling and antiscalant addition [Ref. (42)].	Similar to conventional RO	Mixed salts disposal, low waste volume	Pilot scale only	Moderate complexity and cost - anticipated lower capital and operation costs than conventional softening followed by high recovery RO or ZLD evaporation.
	Membrane distillation *Example Vendor: Memsys*	A separation process that is thermally-driven, in which only vapor molecules transfer through a microporous hydrophobic membrane. Membrane distillation is driven by the vapor pressure difference that results from the temperature difference across the hydrophobic membrane [Ref. (43)].	Unknown	X	X	Unknown	Filtration to remove solids and organic matter, as well as alcohols and surfactants [Ref. (44)].	Post treatment to remove permeated volatile compounds and gases may be required. [Ref. (44)].	Brine management and disposal	Pilot scale only	Moderate complexity and cost - anticipated lower operation costs than conventional RO. Distillation can take place at temperatures as low as 70 C, and required energy

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											can come from waste heat sources or alternative heat sources [Ref. (45)].
	Nanofiltration (NF) *Example Vendors: GE, Dow, Hydranautics, Toray, Koch*	Pressure is applied to force a solution through the membrane. The membrane allows the water to pass through but restricts some salts and other compounds. NF membranes have a larger pore size than conventional RO; monovalent ions can pass through the membrane.	~95% removal	X	-	Unknown	Filtration to remove solids and organic matter to prevent membrane fouling, antiscalant/ chemical pre-treatment; treatments to remove organics and mitigate biofouling also required.	Degasification, stabilization, pH adjustment	Brine management and disposal	Highly commercialized	Lower complexity and cost of operation - generally slightly lower operation costs than conventional RO.
	Conventional Reverse Osmosis (RO) *Example Vendors: GE, Dow, Hydranautics, Toray, Koch*	Pressure is applied to force a solution through a spiral-wound membrane. The membrane allows the water to pass through but restricts some salts and other compounds. Membranes have a smaller pore size than NF; monovalent ions are rejected by the membrane/cannot pass through.	~99% removal	X	-	Unknown	Filtration to remove solids and organic matter to prevent membrane fouling, antiscalant/ chemical pre-treatment; treatments to remove organics and mitigate biofouling also required.	Degasification, stabilization, pH adjustment	Brine management and disposal	Highly commercialized	Lower complexity and cost of operation, when compared to other membrane technologies.

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Primary Sulfate Removal Categories	Technology	Technology description	Lowest achievable sulfate concentration (mg/L)	Primary Technology	Concentrate Management Technology	Additives Required	Pre-treatment requirements [1]	Post-treatment requirements [2]	Residuals management and secondary impacts	Degree of commercialization	Relative cost / complexity of operation
	Vibratory Shear Enhanced Processing (VSEP) *Proprietary technology. Vendor: New Logic*	High-pressure membrane treatment. In contrast to traditional spiral-wound membranes, VSEP uses flat-sheet membranes in a cross-flow configuration, which in combination with applied vibratory shear, reduces the boundary layer at the membrane surface [Ref. (46)].	~90% removal	X	X	Antiscalant, pH adjustment	Antiscalant addition and pH adjustment potentially.	Similar to conventional RO	Brine management and disposal	Several commercial applications for industrial wastewater treatment, chemical processing, food and beverage manufacturing, and petroleum and biofuels - some commercial applications for treatment of RO concentrate [Ref. (46)].	Moderate complexity and high cost - generally higher operation costs than conventional RO.
	Forward osmosis *Example Vendor: Oasys*	Uses natural osmotic process to separate water from dissolved solids. Driving force for this separation is a "draw" solution of higher concentration than the feed water. The osmotic gradient between the two streams creates a flow of water through the membrane, allowing clean water to mix with the draw solution separating it from salt and other contaminants [Ref. (47)].	Unknown	-	X	Unknown	Metals and hardness removal. Minimum feed TDS of 50,000 mg/L required (Gordon Carter at Oasys Water, personal communication)	Unknown	Brine management and disposal	Common in power and oil and gas industries oil and gas - some commercial applications for treatment of RO concentrate. Zero liquid discharge (ZLD) option [Ref. (48)].	High complexity and cost - especially if ZLD is desired.
Electrochemical treatment	Electrocoagulation	Metal ions formed in an electrochemical cell are used to precipitate metal hydroxides, which can remove anions such as sulfate from solution through adsorption [Ref. (49)].	Unknown	X		Unknown	Unknown	Unknown	Sludge management	Bench scale only	Adsorption process difficult to control
	Electrochemical Reduction	Sulfate is reduced to sulfide on a graphite electrode at a temperature of 120 degrees Celsius [Ref. (50)].	Unknown	X		Unknown	Unknown	Sulfide management/removal	Unknown	Bench scale only	Requires high temperature and pressure

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Biological treatment	Constructed Wetlands	Bacteria present in wetland sediments reduce some sulfate to sulfide, which then removes metals from industrial wastewaters [Ref. (34)].	Minimal removal (10%) [Ref. (34)]	X		Carbon source	None	Sulfide management/removal	Sulfide	Common in mine water treatment	Low complexity and cost, but unreliable in cold weather. need to maintain conditions favorable to SRBs
	Floating Wetlands	Islands consisting of floating media and wetland plants can remove some sulfate from a larger body of water. Floating wetlands are most practical in existing water bodies [Ref. (34)].	Minimal removal (10%) [Ref. (34)]	X		Carbon source	None	Sulfide management/removal	Unknown	Used in mine water treatment	Low complexity and cost, but unreliable in cold weather, and needs large surface area
	Pit Lake or In-Pit Treatment	Naturally-occurring microbiological communities in pit lakes or constructed pits remove some sulfate to sulfide [Ref. (51)].	500 mg/L [Ref. (51)]	X	X	Carbon source	None	Sulfide management/removal	Unknown	Used in mine water treatment	Low complexity and cost, but unreliable in cold weather
	Constructed Trench Bioreactors/ Permeable Reactive Barriers	Water is routed through a soil bed trench packed with carbon substrate, which grows a biofilm to reduce some sulfate to sulfide.	500 mg/L [Ref. (51); (34)]	X	X	Carbon source	None	Sulfide management/removal	Unknown	Used in mine water treatment	Low complexity and cost, but unreliable in cold weather
	Suspended-Growth Reactor (Activated Sludge Modification)	Anaerobic suspended-growth treatment, similar to an activated sludge process, could be used upstream of traditional activated sludge treatment systems, but would require a long solids retention time [Ref. (52); (53)].	200 mg/L [Ref. (53); (34)]	X		Liquid carbon source	Nitrate removal if nitrate present in feed	Sulfide management/removal	Sludge management	Not used for sulfate removal	High complexity - need high SRT to maintain SRB biomass in the reactor
	Membrane bioreactor *Example vendor: GE*	Suspended-growth treatment that uses membrane to retain biomass in the reactor.	200 mg/L [Ref. (53); (34)]	X		Liquid carbon source	Nitrate removal if nitrate present in feed, solids removal	Sulfide management/removal	Sludge management	Not used for sulfate removal	Membrane fouling potential
	Suspended-Growth Reactor (Sequencing Batch Reactor)	A sequencing batch reactor (SBR) allows for more efficient biological removal by suspended bacteria in the liquid phase and lower tank volume, but requires more sophisticated operations and control that activated sludge-like operation.	10 mg/L [Ref. (54)]	X		Liquid carbon source	Nitrate removal if nitrate present in feed	Sulfide management/removal	Sludge management	Not used for sulfate removal	Need high SRT to maintain SRB biomass in the reactor

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	UASB Reactor with Sulfide Treatment *Example Vendor: Paques*	A UASB reactor provides sufficient SRT to grow sulfate-reducers and reduce sulfate to sulfide if influent concentrations are greater than 1,000 mg/L (Shashi Gorur and Nina Kang at Paques, personal communication).	300 mg/L (Shashi Gorur and Nina Kang at Paques, personal communication).	X	X	Liquid carbon source	Nitrate removal if nitrate present in feed	Sulfide management/removal	Minimal sludge produced	Limited use in mine water treatment and other industries	Need to maintain conditions favorable to SRBs, difficult to only partially oxidize sulfide to sulfur
	Packed Bed Bioreactor	Sulfate reducing bacteria retained on synthetic or natural media in a tank, where sulfate is reduced to sulfide [Ref. (55)].	<150 mg/L [Ref. (55)]	X	X	Liquid carbon source	Nitrate removal if nitrate present in feed	Sulfide management/ removal	Minimal sludge produced	Limited use in mine water treatment	Moderate complexity - need to maintain conditions favorable to SRBs
	Packed Bed Sulfide Reactor *Example Vendor: BQE Water (BioSulphide)*	Commercial process to produce sulfide from sulfate reduction primarily designed to precipitate and recover metals from industrial wastewaters [Ref. (56)].	Unknown	X	X	Liquid carbon source	Nitrate removal if nitrate present in feed	Sulfide management/removal	Minimal sludge produced	Limited use in mine water treatment	Moderate complexity - need to maintain conditions favorable to SRBs
	Bioelectrochemical	Bioreactors with electrodes can reduce sulfate to recover sulfur as elemental sulfur or iron sulfide using electrons (Chanlun Chun at U of MN Duluth, personal communication).	Unknown	X	X	Liquid carbon source	Nitrate removal if nitrate present in feed	Sulfide management/removal	Minimal sludge produced , Possible sulfur recovery	Bench scale only	High complexity
	Sulfate reduction deammonification	Using a biological metabolism similar to ANAMMOX, sulfate can be used to remove ammonia [Ref. (57)].	Unknown	X	X	Ammonia, if not present	Nitrate removal if nitrate present in feed	Unknown	Minimal sludge produced	Theoretical only - no known bench application	High complexity - three reactors with different specific operation requirements
	Liquid-phase biofilters	Biofilms growing on GAC or biochar can reduce sulfate to sulfide, which can be precipitated with metals as metal sulfides (Sebastian Behren at U of MN, personal communication).	Unknown	X	X	Carbon source	Nitrate removal if nitrate present in feed, solids removal	Sulfide management/removal	Minimal sludge produced	Bench scale only	High complexity

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	Sulfate reduction, autotrophic denitrification, and nitrification integrated process (SANI)	SANI includes removal of ammonia, nitrate, and sulfate in three separate reactors. Sulfate is reduced to sulfide, which feeds dinitrifiers in a second reactor. Ammonia is then removed in a third, aerated reactor. This system would replace activated sludge treatment and decrease sludge production [Ref. (58); (59)].	<100 mg/L (Lu, 2012)	X	X	Unknown	None	Unknown	Sludge management	Pilot scale only	High complexity - three reactors with different specific operation requirements
Evaporative treatment	Direct heat-contact evaporation (LM-HT Concentrator) *Example Vendor: Heartland Technologies*	The system involves the direct contact of hot gases and water/brine to evaporate water and produce a more concentrated brine or salt slurry, which is then stabilized and disposed. No heat exchangers are used, less fouling, but requires a source of hot gas for the process [Ref. (60)].	N/A	-	X	Unknown	Unknown	No high-quality distillate stream, liquids separated from solids can be returned to the evaporative section [Ref. (60)].	If evaporating all liquid, salt cake disposal, needs to pass TCLP for non-hazardous waste disposal. Otherwise, slurry stabilization/ solidification required for disposal.	Highly commercialized - several applications in oil and gas, power, industrial wastewater, landfill leachate - no specific municipal applications information [Ref. (61)].	High complexity and cost, potentially lower cost than conventional ZLD if waste heat is available.
	Mechanical vapor recompression evaporation with crystallization or spray drying *Example Vendor: Veolia*	Evaporation with crystallization includes brine concentration, where brine is heated and recirculated until about 95% is converted to high purity distillate, followed by crystallization which uses heat to reduce brine concentrate to a dry solid. Overall water recovery up to 99%. High-purity distillate suitable for reuse, discharge, or aquifer reinjection. Produces solid salt cake suitable for landfill disposal [Ref. (62)] .	Unknown, but likely given less than 10 mg/L TDS of distillate [Ref. (20)]	-	X	Unknown	Scale and foam control	Unknown	Salt cake disposal, needs to pass TCLP for non-hazardous waste disposal.	Highly commercialized - several applications in oil and gas, power, drinking water - no specific municipal applications information [Ref. (63)].	High complexity and cost

[1] Pre-treatment requirements only include those that would be needed in addition to secondary wastewater treatment, assuming that the technology would be implemented downstream of existing plant processes.

[2] Post-treatment processes include only those for the treated water, and do not include brine, sludge, or sulfide management.

Large Table 2 **Sulfate treatment technology screening**

				Chemical Precipitation		**Ion Exchange**		**Membranes**					**Biological**		**Evaporative**	
Criteria	**Sub-criteria**	**Sub-criteria Weight**	**Sub-criteria Ranking Key**	Ettringite Precipitation (CESR or SAVMIN)	Barite Precipitation	Conventional Ion Exchange	Sulf-IX	Closed-circuit Desalination Reverse Osmosis (CCD RO)	Electrodialysis Reversal (EDR)	Nanofiltration (NF)	Conventional Reverse Osmosis (RO)	Vibratory Shear Enhanced Processing (VSEP)	UASB Reactor with Sulfide Treatment	Packed Bed Bioreactor	Direct heat-contact evaporation (LM-HT Concentrator)	Mechanical vapor recompression evaporation with crystallization or spray drying (ZLD)
Effectiveness				***12***	***15***	***12***	***15***	***18***	***21***	***27***	***30***	***21***	***12***	***9***	***15***	***15***
Effectiveness	Ability to meet treated water quality goals for sulfate (5-250 mg/L)	3	1 - <=250 mg/L 2 - <=100 mg/L 3 - <=50 mg/L 4 - <=10 mg/L 5 - <=5 mg/L	1	2	2	3	3	3	4	5	3	2	1	1	1
	Degree of commercialization	3	1 - not commercialized 2 - commercialized in 1 industry primarily 3 - commercialized in 1-3 industries 4 - commercialized in more than 3 industries 5 - commercialized in more than 3 industries, including municipal wastewater treatment	3	3	2	2	3	4	5	5	4	2	2	4	4
Operability / maintainability				***19***	***23***	***21***	***20***	***23***	***23***	***25***	***25***	***26***	***15***	***14***	***23***	***25***
Operability / maintainability	Reliability of performance, including cold climate suitability	3	1 - not reliable 2 - uncertain/unknown 3 - inconsistent reliability, cold climate sensitivity 4 - reliable, potential cold climate sensitivity 5 - consistently reliable, no sensitivity to cold climate	3	4	4	3	4	4	4	4	5	3	3	4	4
	General complexity of operation / maintenance of primary technology	2	1 - most complex 2 - relatively complex 3 - average complexity 4 - relatively simple 5 - most simple	3	4	3	4	3	3	4	4	3	2	2	3	4
	Operator and public health	1	1 - significant additional health risk 3 - moderate additional health risk 5 - no additional health risk	4	2	3	3	5	5	5	5	5	2	1	5	5

Large Table 2 Sulfate treatment technology screening

				Chemical Precipitation		**Ion Exchange**		**Membranes**					**Biological**		**Evaporative**	
Criteria	**Sub-criteria**	**Sub-criteria Weight**	**Sub-criteria Ranking Key**	Ettringite Precipitation (CESR or SAVMIN)	Barite Precipitation	Conventional Ion Exchange	Sulf-IX	Closed-circuit Desalination Reverse Osmosis (CCD RO)	Electrodialysis Reversal (EDR)	Nanofiltration (NF)	Conventional Reverse Osmosis (RO)	Vibratory Shear Enhanced Processing (VSEP)	UASB Reactor with Sulfide Treatment	Packed Bed Bioreactor	Direct heat-contact evaporation (LM-HT Concentrator)	Mechanical vapor recompression evaporation with crystallization or spray drying (ZLD)
Relative costs				***18***	***16***	***15***	***13***	***14***	***12***	***14***	***14***	***7***	***15***	***15***	***5***	***5***
Relative costs	Capital costs for primary technology	3	1 - high relative capital cost 3 - average relative capital cost 5 - low relative capital cost	4	4	3	3	2	2	2	2	1	3	3	1	1
	O&M costs for primary technology	2	1 - high relative O&M cost 3 - average relative O&M cost 5 - low relative O&M cost	3	2	3	2	4	3	4	4	2	3	3	1	1
Degree / complexity of pre-treatment and post-treatment				***17***	***17***	***19***	***15***	***13***	***13***	***13***	***13***	***17***	***16***	***19***	***22***	***16***
Degree / complexity of pre-treatment and post-treatment	Influent pre-treatment complexity/cost	2	1 - complex, energy-intensive 2 - complex, average relative energy requirements 3 - average complexity and relative energy requirements 4 - simple, average relative energy requirements 5 - simple, low relative energy requirements	3	3	3	2	2	2	2	2	4	4	4	5	4
	Effluent post-treatment complexity/cost	2	1 - complex, energy-intensive 2 - complex, average relative energy requirements 3 - average complexity and relative energy requirements 4 - simple, average relative energy requirements 5 - simple, low relative energy requirements	4	4	5	3	3	3	3	3	3	3	4	5	3

Large Table 2 **Sulfate treatment technology screening**

				Chemical Precipitation		**Ion Exchange**		**Membranes**					**Biological**		**Evaporative**	
Criteria	**Sub-criteria**	**Sub-criteria Weight**	**Sub-criteria Ranking Key**	Ettringite Precipitation (CESR or SAVMIN)	Barite Precipitation	Conventional Ion Exchange	Sulf-IX	Closed-circuit Desalination Reverse Osmosis (CCD RO)	Electrodialysis Reversal (EDR)	Nanofiltration (NF)	Conventional Reverse Osmosis (RO)	Vibratory Shear Enhanced Processing (VSEP)	UASB Reactor with Sulfide Treatment	Packed Bed Bioreactor	Direct heat-contact evaporation (LM-HT Concentrator)	Mechanical vapor recompression evaporation with crystallization or spray drying (ZLD)
	Beneficial reuse of residuals and treated water	1	1 - no beneficial reuse 2 - uncertain/unknown 3 - likely no beneficial reuse 4 - likely beneficial reuse 5 - established beneficial reuse	3	3	3	5	3	3	3	3	3	2	3	2	2
Residuals management				***15***	***10***	***7***	***17***	***7***	***7***	***7***	***7***	***7***	***16***	***13***	***8***	***8***
Residuals management	Residuals management complexity/cost	3	1 - complex, energy-intensive 2 - complex, average relative energy requirements 3 - average complexity and relative energy requirements 4 - simple, average relative energy requirements 5 - simple, low relative energy requirements	4	2	1	4	1	1	1	1	1	4	3	2	2
	Residuals stability	1	1 - unstable 2 - uncertain/unknown 3 - potentially unstable 4 - likely stable 5 - stable	3	4	4	5	4	4	4	4	4	4	4	2	2
			Total Score	**81**	**81**	**74**	**80**	**75**	**76**	**86**	**89**	**78**	**74**	**70**	**73**	**69**

Large Table 3 Concentrate management technologies

Management Type	Status	Management Category	Technology	Description	Advantages	Disadvantages	Sources
Volume Reduction Technologies	Conventional/ currently in use	Electric Potential Driven Technology	Electrodialysis (ED), electrodialysis reversal (EDR)	Uses an electric current to move dissolved salt ions through layers of charged membranes.	Less energy intensive than thermal evaporation, effective for high influent silica content.	Limited effectiveness with high calcium sulfate saturation resulting in precipitation on membrane surface.	[Ref. (64)] [Ref. (21)]
		Pressure Driven Technologies	High-Efficiency Reverse Osmosis (HERO)	Process combines a two-phase RO process with chemical pre-treatment of primary RO feed, intermediate IX treatment of primary RO concentrate, and high pH operation of a secondary RO. The secondary RO step operates at high efficiency due to IX pre-treatment and operations at a high pH.	Results in higher recovery/less concentrate volume than traditional RO systems, relatively small footprint.	High capital and O&M costs, complex process control system, produces two concentrated waste streams.	[Ref. (20)]
			Vibratory Shear-Enhanced Processing (VSEP)	High-pressure membrane treatment that uses flat-sheet membranes in a cross-flow configuration, which reduces the boundary layer at the membrane surface, which in combination with applied vibratory shear, reduces the boundary layer at the membrane surface.	High recovery rates, production of high-quality permeate, potentially no pre-treatment required.	No municipal wastewater treatment applications, frequent clean-in-place (CIP) required, higher capital and O&M costs than traditional RO, proprietary technology from a single vendor.	[Ref. (20)]
	Under development	Advanced Technologies	Forward osmosis (FO)	Osmotic process that uses a semi-permeable membrane to separate salts from water using an osmotic pressure gradient instead of hydraulic pressure to create a driving force to push water through the membrane.	Lower energy requirement than RO, high energy efficiency.	Draw solute requirement to create an effective drawing force needs to be added continuously, economic feasibility has not been demonstrated, emerging technology.	[Ref. (64)] [Ref. (21)]
			Membrane distillation with crystallization (MDC)	Concentrates salts up to supersaturated state which allows crystallization.	High contact area provided by hollow fiber membranes allows reliable evaporation flux at moderate temperatures, comparatively lower energy consumptions compared to evaporation/ crystallization, no applied pressure.	Not yet commercially available at industrial scale.	[Ref. (64)] [Ref. (21)]
			Eutectic freeze crystallization	Based on achieving the eutectic temperature as a means to separate aqueous solutions into pure water and solid salts.	Energy required to separate the water as ice is significantly lower than that required to separate it by evaporation, simultaneous production of pure ice and pure salts, significant cost savings over evaporation/crystallization, no applied pressure.	High initial investment, complex operation, emerging technology.	[Ref. (64)] [Ref. (21)]

Large Table 3 Concentrate management technologies

Management Type	Status	Management Category	Technology	Description	Advantages	Disadvantages	Sources
		Pressure Driven Technologies	Advanced Reject Recovery of Water (ARROW)	High-recovery, advanced membrane system that couples softening process with RO to increase water recovery.	High-quality product water, high water recovery, compact/small footprint system.	Process still under development, high pre-treatment costs associated with softening, complex operation.	[Ref. (20)]
			Slurry Precipitation and Reverse Osmosis (SPARRO)	Involves circulating a slurry of seed crystals within the RO system, which serve as preferential growth sites for calcium sulfate and other calcium salts and silicates.	Lower energy requirement than thermal processes, less pre-treatment needs compared to other hybrid technologies.	Limited to use of membrane configurations such as tubular membrane systems that do not plug to allow the continued circulation of slurry, large footprint, complex operation, process still under development with no full-scale applications.	[Ref. (20)]
Zero Liquid Discharge	Conventional/ currently in use	Thermal Technology	Evaporation/ Crystallization/Spray Drying	Evaporators are mechanical systems that minimize membrane concentrate through a combination of thermal evaporation and increased surface area, and crystallizers use thermal energy to separate dissolved salts from the water.	Proven technology for concentrate volume reduction, small site footprint, most organic and inorganic constituents removed resulting in a high-quality produced water.	High capital and O&M costs, potential noise issues/sound enclosures needed, aesthetic issues, not feasible for projects with specific height limitations.	[Ref. (20)]
	Under development	Evaporation Ponds	Solar evaporation	Shallow, lined pond where water evaporates naturally by using solar energy.	Easy to construct, little operation attention required, no mechanical equipment.	Requires large land areas, especially in areas with low evaporation rates, such as Minnesota, evaporated water not recovered.	[Ref. (64)]
		Technology Combinations	ZLD	RO tandem (two stages of RO) with intermediate treatment, followed by post-treatment of superconcentrates. Additional combinations: 1) RO - IX - RO 2) RO - precipitation - RO 3) RO - wind-aided intensified evaporation (WAIV) RO - membrane crystallizer - precipitation 4) RO - ED/EDR 5) RO - lime-soda ash treatment - RO - evaporation 6) RO - intermediate treatment - RO - brine concentrator + pond	High recovery, successful demonstrations with a number of combinations.	Zero discharge goal not necessarily or consistently accomplished, antifouling and antiscalant compounds used in RO pre-treatment have negative effects in the post-treatment of concentrates, technology combinations may end up being as costly as evaporation/ crystallization.	[Ref. (64)]

Analyzing Alternatives for Sulfate Treatment in Municipal Wastewater

Part 2: Cost Analysis for Implementation of Sulfate Removal Technology at Full Scale Wastewater Treatment Facilities

Prepared for
Minnesota Pollution Control Agency

May 1, 2018

Certifications

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the State of Minnesota.

Responsible for Part 2 of this Report.

Herman A. Dharmarajah
PE #: 18256
Date: May 1, 2018

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the State of Minnesota.

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PE #: 16540
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Analyzing Alternatives for Sulfate Municipal Wastewater Treatment

Part 2: Cost Analysis for Implementation of Sulfate Removal Technology at Full Scale Wastewater Treatment Facilities

May 1, 2018

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Acronyms

Acronym	Description
ARROW^{TM}	Advanced reject recovery of water
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
CCD RO	Closed-circuit desalination reverse osmosis
CCPP	Calcium carbonate precipitation potential
CESR	Cost-effective sulfate removal
CIP	Clean-in-place
CRF	Concentrate reduction facility
ED	Electrodialysis
EDR	Electrodialysis reversal
EPWU	El Paso Water Utilities
EWM	Enviro Water Minerals Company
FO	Forward osmosis
GAC	Granulated activated carbon
HEEPM^{TM}	High efficiency electro-pressure membrane
HERO^{TM}	High efficiency reverse osmosis
IX	Ion exchange
KBH	Kay Bailey Hutchison Drinking Water Desalination Plant
MDC	Membrane distillation with crystallization
MDH	Minnesota Department of Health
MF	Microfiltration
MGD	Million gallons per day
MPCA	Minnesota Pollution Control Agency
NF	Nanofiltration
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and maintenance
RO	Reverse osmosis
SANI	Sulfate reduction, autotrophic denitrification, and nitrification integrated
SBR	Sequencing batch reactor
SDWA	Safe Drinking Water Act
SPARRO	Slurry precipitation and reverse osmosis
SRB	Sulfate-reducing bacteria
SWRO	Seawater reverse osmosis
TCLP	Toxicity characteristic leaching procedure
TDS	Total dissolved solids
TN	Total nitrogen
TOC	Total organic carbon
TSS	Total suspended solids

U of MN	University of Minnesota
UF	Ultrafiltration
UIC	Underground Injection Control
USBR	United States Bureau of Reclamation
UASB	Upflow anaerobic sludge blanket
USEPA	United States Environmental Protection Agency
VSEP^{TM}	Vibratory shear enhanced processing
WET	Whole effluent toxicity
WWTP	Wastewater treatment plant
ZDD	Zero discharge desalination
ZLD	Zero-liquid discharge

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Abstract

The current revision of the State of Minnesota's surface water quality standard for sulfate may result in some municipal wastewater treatment plants having to treat for sulfate in their discharge. This report addressed sulfate treatment in municipal wastewater treatment facilities in two integrated reports; the first activity identified and evaluated 31 technologies for removal of sulfate from municipal wastewater and the second activity takes the top two technologies reviewed, Reverse Osmosis (RO) and Nano Filtration (NF) and addresses implementation requirements and costs of those treatments. The sulfate treatment evaluation criteria used to select membrane treatment (RO & NF) as the best technology available were: effectiveness, operability/maintainability, cost, complexity of pre and post treatment, and residual management. Using membrane treatment to treat sulfate, six hypothetical new wastewater treatment scenarios were developed across a range of treatment plant sizes and sulfate treatment goals in order to address costs and implementation concerns for the range of wastewater plants found in Minnesota. There is also a discussion regarding the retrofit existing treatment plants to treat sulfate. The case studies include: biological wastewater treatment plant costs, membrane treatment costs, concentrate management costs, and if required, intermediate water treatment with a second stage of membrane treatment for concentrate minimization. The membrane treatment costs include the cost of pretreatment, which includes flow equalization and particle removal, such as rapid sand filtration or ultrafiltration (UF). The main driver of sulfate treatment costs and complexity was treating membrane concentrate using evaporation and crystallization. Sulfate treatment using RO membranes and evaporation with crystallization was found to be both extremely expensive and very complex and difficult to operate. Evaporation and crystallizer capital costs were found to be least $30 million per 1 Million Gallon per Day (MGD) of treatment with annual operation and maintenance costs of at least $9.4 million per 1 MGD. Operating an evaporator and crystallizer system is not only expensive but is also labor intensive, would require a totally new operator skillset, would increase waste disposal costs, and would be very energy intensive. Design engineers should make every effort to minimize the volume of RO concentrate produced during sulfate treatment in order to minimize overall treatment costs. Further research and development into cost-effective means for managing the waste concentrate generated using membranes is needed.

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Activity I using a screening process and a ranking system ranked the available sulfate removal technologies for use in a publicly operated treatment works (POTW). Activity II used the two top ranked technologies and developed capital and operating and maintenance (O&M) costs for POTW's ranging in flows from 0.5 to 10 MGD. The two ranked treatment processes are Reverse Osmosis (RO) and Nano Filtration (NF) membrane processes.

Table ES-1 shows the various flow rates and biological treatment processes considered for evaluation.

Table ES-1 Analysis cases for cost evaluations in Activity 2

Case Number	Flow (MGD)	Type Biological Treatment	Common Name for Treatment	
1	10	Suspended Growth	Activated Sludge	BNR
2	2.5	Fixed Film	Biotower / Trickling Filter	
3	2.5	Suspended Growth	Activated Sludge	BNR
4 & 5	0.5	Suspended Growth	Activated Sludge	BNR
6	0.5	Suspended Growth	Controlled Discharge Facultative Pond	

Although the Activity I ranked RO and NF as the two top ranked treatment process, Activity II used only RO treatment for developing the detailed costs for the six different case studies. The reasons for not considering NF membrane process for detailed evaluation were based on discussions with membrane manufacturers Dow Chemical and Toray membranes. Both these membrane manufacturers stated that the sulfate rejection by NF membrane is dependent on the monovalent ions present in the feed water, and computer projection is only an estimate and has to be verified by pilot studies. Original equipment manufacturer (OEM) of membrane skid Wigen Water Technologies, Chaska, Minnesota, stated that there is no significant capital cost difference between skids using NF and RO membranes. The NF membranes costs are about 15 percent higher than RO membrane costs and this cost difference offsets the savings with a slightly lower-cost feed pump for NF skid.

The hypothetical water quality characteristics for influent with various sulfate levels are presented in Table ES-2.

Table ES-2 Standardized water chemistry profiles for various initial sulfate concentrations

		Initial Sulfate in WWTP Effluent			
Parameter	**Unit**	**25 mg/L**	**100 mg/L**	**250 mg/L**	**500 mg/L**
Calcium	mg/L	50	100	150	250
Magnesium	mg/L	15	50	75	125
Sodium	mg/L	45	200	300	400
Potassium	mg/L	6.5	15	27	27
Chloride	mg/L	136	393	502	687
Alkalinity	mg/L as $CaCO_3$	120	300	400	520
Sulfate	mg/L as SO_4	25	100	250	500
Phosphorus	mg/L	14	14	14	14
Ammonia	mg/L as N	30	30	30	30
Organic Nitrogen	mg/L as N	10	10	10	10
$CBOD_5$	mg/L	200	200	200	200
TSS	mg/L	200	200	200	200
pH		7.3	7.5	7.9	7.55
TDS	mg/L	398	1158	1754	2637

Table ES-3 presents the details of the six case studies with percentage of water that has to be treated to meet the required sulfate effluent level.

Table ES-3 Details of six case studies and the percentage to be treated by RO system

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Biological Treatment Technology	Activated Sludge	Trickling Filter	Activated Sludge	Activated Sludge	Activated Sludge	Facultative Pond
Design Flow (MGD)	10	2.5	2.5	0.5	0.5	0.5
Sulfate Influent (mg/L)	100	25	600	300	300	600
Required Sulfate Effluent (mg/L)	10	10	100	10	100	250
Percent of Flow Treated by RO System	93%	63%	89%	99%	74%	68%

Depending on the influent and the required effluent level for sulfate, the percentage that had to be treated by the RO membrane system ranged from 60 to 99 percent.

The design, in addition to meeting the required sulfate level, had to meet other NPDES requirements. The additional NPDES requirements are shown in Table ES-4.

Table ES-4 NPDES biological treatment parameters

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Facility Type	**Activated Sludge**	**Trickling Filter**	**Activated Sludge**	**Activated Sludge**	**Activated Sludge**	**Facultative Pond**
Parameter:	**(Influent/Effluent Limit)**					
Fecal Coliform (/100 mL)	na/200	na/200	na/200	na/200	na/200	na/na
$CBOD_5$ (mg/L)	200/5	200/25	200/5	200/5	200/5	200/25
TSS (mg/L)	200/30	200/30	200/30	200/30	200/30	200/45
Total Nitrogen (mg/L as N)	40/7	40/na	40/7	40/7	40/7	40/na
Total Phosphorus (mg/L)	14/0.5	14/0.5	14/0.5	14/0.5	14/0.5	14/0.5
pH	na/6-9	na/6-9	na/6-9	na/6-9	na/6-9	na/6-9

Further, the effluent has to pass the whole effluent toxicity tests (WET). Since the RO permeate is very low in alkalinity and hardness, in order to pass the WET tests, the permeate required post treatment with lime or caustic soda to adjust the water to a near zero calcium carbonate precipitation potential (CCPP) value. This generally ensures a slightly positive Langelier Saturation Index (LSI).

The RO membrane treatment had its benefits and disadvantages. One of the major benefits of RO treatment is that it reduced the total nitrogen (TN) and total phosphorus removal required in the conventional biological treatment in the POTW. Table ES-5 shows the TN removal required with the BNR process with and without RO treatment.

Table ES-5 Required BNR nitrate and phosphorus removal with vs. without RO treatment

Case	Flow (MGD)	Biological Treatment Technology	% of Flow Treated by RO System	Required BNR Nitrate Removal w/o RO Treatment	Required BNR Nitrate Removal with RO Treatment
1	10	Activated Sludge	93%	85.0%	31.5%
2	2.5	Trickling Filter	63%	n/a	n/a
3	2.5	Activated Sludge	89%	85.0%	47.9%
4	0.5	Activated Sludge	99%	85.0%	1.4%
5	0.5	Activated Sludge	74%	85.0%	64.4%
6	0.5	Facultative Pond	68%	n/a	n/a

Similarly, phosphorus is also removed, reducing the amount of chemical polishing needed after biological treatment processes to drop a plant effluent's total phosphorus below 0.5 mg/L. Some polishing is still needed, as not all water leaving the biological processes is passes through the RO system, but the added treatment by the RO still results in capital and O&M cost savings for communities.

As with nitrogen and phosphorus removal, RO can also assist with mercury removal. Table ES-6 describes mercury removal by various membrane processes, including RO. This removal ranges from 79-83%, and it should be noted that when the RO filters are preceded by UF, mercury removal will be higher [Ref. 81].

Table ES-6 Mercury removal by reverse osmosis filtration [1]

Initial Mercury (µg/L)	Final Mercury (µg/)	Percent Removal
5,000	880	82.4%
9,000	1,503	83.3%
8	1.5-1.7	79-81%
[1] Data from EPA Capsule Report on Aqueous Mercury Treatment, Ref. 81		

The major disadvantage with the RO treatment process is the concentrate disposal. A rule of thumb is that RO treatment for a water treatment facility is not cost effective if the concentrate cannot be disposed to the sewer system. The only viable concentrate disposal for when RO treatment is used at POTW is a mechanical thermal evaporation (MTE) process. MTE is sometimes referred to as a zero liquid discharge (ZLD) process since all the liquid is evaporated and a solid residue remains to be disposed of in a landfill. The MTE process is very expensive both in terms of capital and operating costs, mainly because it is so energy intensive.

Table ES-7 presents the RO concentrate volume that needs to be disposed of by the MTE process for the six case studies. Some values in the last column are highlighted red, because when an RO concentrate flow rate is 100 GPM or more, volume minimization should be considered before the MTE process.

Table ES-7 Estimated RO concentrate flow

Case Study	Flow (MGD)	Percentage of Flow to be Treated by RO System for Sulfate Removal	RO Reject Flow (GPM)
1	10	93%	1100
2	2.5	63%	110
3	2.5	89%	500
4	0.5	99%	85
5	0.5	74%	65
6	0.5	68%	75

Table ES-8 presents the biological treatment costs for the six cases considered. The biological treatment costs include all capital and O&M costs for processes prior to the sulfate removal. This includes pretreatment components, such as solids removal and primary clarification, in addition to biological nutrient removal, such as activated sludge or trickling filters.

Table ES-8 **Estimated costs for biological treatment costs for liquid treatment and biosolids**

Case Study	Biological Liquids Treatment		Biosolids Processing	
	Capital Costs ($)	O&M Costs ($)	Capital Costs ($)	O&M Costs ($)
1	24,578,000	2,651,000	10,054,000	7,006,000
2	18,721,000	631,000	5,714,000	1,810,000
3	22,791,000	903,000	6,052,000	1,940,000
4	10,514,000	569,000	1,946,000	534,000
5	10,497,000	570,000	1,946,000	535,000
6	14,000,000	96,000	N/A	N/A

Table ES-9 presents the sulfate removal costs and the concentrate disposal costs for the six cases. For Cases 1, 3 and 4 concentrate minimization or volume reduction was analyzed by treating RO reject by lime softening or pellet softening and then processing through a secondary RO system and a proprietary VSEP membrane treatment process.

Table ES-9 **Estimated costs for sulfate removal by RO membrane treatment process and concentrate management**

Case Study	Sulfate Removal		Concentrate Treatment		Sulfate & Concentrate Treatment
	Capital Costs ($)	O&M Costs ($)	Capital Costs ($)	O&M Costs ($)	20-Year Present Costs ($)
1	33,821,000	1,623,000	(1) 34,000,000 (2) 28,500,000 (3) 65,308,000	(1) 14,033,000 (2) 14,598,000 (3) 6,878,000	(1) 294,172,871 (2) 297,781,611 (3) 210,073,221
2	11,748,000	449,000	16,250,000	3,478,000	84,098,151
3	11,318,000	466,000	(1) 25,250,000 (2) 17,750,000 (3) 38,400,000	(1) 5,979,000 (2) 5,203,000 (3) 2,964,000	(1) 133,003,633 (2) 112,988,672 (3) 97,526,957
4	7,318,000	94,000	(1) 14,600,000 (2) 10,000,000 (3) 17,000,000	(1) 1,841,000 (2) 1,429,000 (3) 948,000	(1) 51,617,122 (2) 40,370,046 (3) 39,616,565
5	7,293,000	133,000	12,000,000	2,094,000	53,062,716
6	5,452,000	88,00	13,000,000	2,479,000	58,434,717

(1) Lime softening is used prior to secondary (concentrate reduction) RO treatment.
(2) Pellet softening is used prior to secondary (concentrate reduction) RO treatment.
(3) A VSEP concentrator process is used treat RO concentrate.

Table ES-10 presents the summary of the total capital costs, total O&M costs and the 20-year present value costs for the six case studies evaluated. These costs incorporate all of those previously mentioned, including biological liquids and solids treatment, and sulfate removal.

Table ES-10 Summary of the total capital costs, O&M costs and a 20-year present cost for all six case studies

Case Study	Total Capital Costs ($)	Total O&M Costs ($)	20-Year Present Costs ($)
1	(1) 102,453,000 (2) 96,953,000 (3) 133,761,000	(1) 25,313,000 (2) 25,878,000 (3) 18,158,000	(1) 510,751,642 (2) 514,360,382 (3) 426,651,992
2	52,432,688	6,367,243	155,136,318
3	(1) 65,411,000 (2) 57,911,000 (3) 78,561,000	(1) 9,287,000 (2) 8,511,000 (3) 6,272,000	(1) 215,207,205 (2) 195,192,224 (3) 179,730,529
4	(1) 34,378,000 (2) 29,778,000 (3) 36,778,000	(1) 3,039,000 (2) 2,626,000 (3) 2,146,000	(1) 83,388,571 (2) 72,141,495 (3) 71,388,014
5	31,736,000	3,331,000	85,467,866
6	32,452,00	2,662,000	75,397,024
(1) Lime softening is used prior to secondary (concentrate reduction) RO treatment. (2) Pellet softening is used prior to secondary (concentrate reduction) RO treatment. (3) A VSEP concentrator process is used treat RO concentrate.			

1.0 Background

1.1 Introduction

The State of Minnesota is currently revising the surface water quality standard of 10 mg/L. A revised water quality standard may result in some municipal wastewater treatment plants (WWTPs) needing to reduce the concentration of sulfate in their discharges. Historically, WWTPs have not been required to treat sulfate to achieve compliance with a NPDES permit. This report presents the results of the second of a two-part study commissioned by the Minnesota Pollution Control Agency through funding from the Minnesota Environment and Natural Resources Trust Fund to assess the current technologies and tools available to WWTPs to reduce sulfate concentrations in their discharges and identifies the challenges of meeting potential sulfate limits in the future.

In Part 1 of the study (2017), a wide range of established and emerging sulfate treatment technologies from the municipal and industrial sectors and source control options were reviewed, screened, and ranked to understand their advantages and disadvantages and to identify potentially feasible technologies currently available for sulfate removal. While several potential treatment technologies may be available for municipal WWTPs, several key technical challenges still need to be overcome.

Of the technologies reviewed, reverse osmosis and nanofiltration, both membrane technologies, were identified as the most promising, well-established technologies for sulfate removal. Part 1 also stated that further research and development on cost-effective means for managing the salt-laden, liquid waste generated by these processes is needed. This liquid waste stream is called either concentrate or reject. The process and cost of managing this waste stream became a major part of Activity 2.

Activity 2 (2018) examines the practical design, implementation considerations, and costs of select treatment technologies for use in removing sulfate in typical WWTP applications. Six hypothetical case studies are presented, based on four water chemistry scenarios, three wastewater treatment plant technologies, and four effluent requirements. The case studies include: biological wastewater treatment plant costs, membrane treatment costs, concentrate management costs, and if required, intermediate water treatment with a second stage of membrane treatment for concentrate minimization.

1.2 Technology Summary from Volume 1

The report on Activity 1 identified and evaluated 31 sulfate treatment technologies in the context of municipal wastewater treatment. This report will not re-evaluate or comment on the conclusions of Activity 1, but will take the two technologies that rated highest and perform detailed evaluation, design and cost estimations for implementation of the highest-rated technologies.

1.2.1 Overall Ranking Method Summary

The screening process used in Activity 1 was a three-step process that included:

1. Threshold screening based on the technology's degree of development and commercialization, and ability to achieve a threshold sulfate removal performance;
2. Technology screening based on performance, cost, and other factors; and
3. Screening based on removal performance for other parameters of concern.

The goal of the screening process used in Activity 1 was to understand the advantages and limitations of each sulfate treatment approach, and to identify the most feasible treatment technologies for reducing sulfate in municipal wastewater effluent using a uniform scoring and ranking methodology.

The criteria for success in the evaluation covered in the first report were successful full-scale implementation of the technology and the ability to treat sulfate down to a level of 250 mg/L or less.

Figure 1-1 lists the 31 technologies evaluated during Activity 1 relative to their potential for implementation at a municipal scale to successfully remove sulfate from treated wastewater effluent.

In addition to sulfate removal, there are secondary contaminants of interest (parameters of concern), the removal of which were also evaluated, with regard to each technology class. These secondary parameters are: chloride, total mercury, total nitrogen (TN), total phosphorous, and total dissolved solids (TDS). The ability of the technology to remove each of these contaminants to a specified target level was evaluated. The treatment targets were provided by MPCA. The treatment targets for chloride, total mercury, and total dissolved solids were selected based on the most stringent water quality standards included in Minnesota Rules Chapter 7050, Water Quality Standards for Protection of Waters of the State.

1.2.2 Technology Evaluation Table

Technology Category	Treatment Technology
Chemical Precipitation	Gypsum Precipitation
	Ettringite Precipitation (Cost-Effective Sulfate Removal (CESR) or SAVMIN)
	Ettringite Precipitation with Aluminum Recovery (LoSO4)
	Barite Precipitation
	Co-Precipitation with Aluminum
Ion Exchange	Conventional Ion Exchange
	Sulf-IX
Membranes	Closed-circuit Desalination Reverse Osmosis (CCD RO)
	Electrodialysis Reversal (EDR)
	Zero Discharge Desalination (ZDD)
	Membrane distillation
	Nanofiltration (NF)
	Conventional Reverse Osmosis (RO)
	Vibratory Shear Enhanced Processing (VSEP)
	Forward osmosis
Electrochemical	Electrocoagulation
	Electrochemical Reduction
Biological	Constructed Wetlands
	Floating Wetlands
	Pit Lake or In-Pit Treatment
	Constructed Trench Bioreactors/ Permeable Reactive Barriers
	Suspended-Growth Reactor (Activated Sludge Modification)
	Membrane Bioreactor
	Upflow anaerobic sludge blanket (UASB) Reactor with Sulfide Treatment
	Packed Bed Bioreactor
	Packed Bed (BioSulphide)
	Bioelectrochemical
	Sulfate reduction deammonification
	Liquid-phase biofilters
	Sulfate reduction, autotrophic denitrification, and nitrification integrated process (SANI)
Evaporative	Direct heat-contact evaporation (LM-HT Concentrator)
	Mechanical vapor recompression evaporation with crystallization or spray drying

Figure 1-1 31 Treatment Technologies Evaluated During Activity 1

1.2.3 Top Ranked Technologies for Further Analysis

Thirteen technology classes met the first round screening criteria and were further evaluated and ranked based on effectiveness, operability/maintainability, relative cost, degree/complexity of pre and post treatment requirements, and management of treatment residuals.

Effectiveness is defined as the ability of the technology to remove sulfate. The original screening criteria for effectiveness was the ability to reduce sulfate to 250 mg/L. In the second screening round, the criteria becomes the ability of the technology to reduce sulfate down to 10 mg/L. The rating is a function of how low the technology will reduce the sulfate. The effectiveness criteria also included consideration of the degree of commercialization or technical maturity in the marketplace and how broadly the technology is used throughout the industry.

Operability/maintainability refers to the complexity of the technologies operating and maintenance and the subsequent reliability of the process in removing sulfate. The reliability specifically considered cold temperature performance. Relative complexity was evaluated based on number of treatment process steps, pre and post treatment requirements, level of operator attention required, and number of operational changes required under normal operating conditions. Operator health and public health risk associated with operations were considered.

Relative cost was based on literature information as well as vendor supplied information. Relative costs considered capital costs, and operation and maintenance (O&M) costs, which included power, labor, parts, chemicals for operations and cleaning, consumables, and residual management.

Degree/complexity of pre and post treatment reflects the additional treatment required to allow successful sulfate removal by the primary sulfate removal process. Addition of these additional unit operations was considered in the screening process. Processes included in a standard/conventional wastewater treatment plant for producing secondary effluent were not considered in the screening process. If post treatment creates a product with beneficial reuse opportunities, post treatment can be a benefit rather than a cost.

Residual management is the cost and complexity required to manage the secondary side streams (waste) generated by the sulfate removal process. As mentioned in the previous paragraph, this category can be a benefit or a cost. This category refers to the complexity of managing residuals associated with the primary treatment technology as well as the volume of residuals generated.

Of the 31 technologies evaluated (Figure 1-1), 18 technologies were screened out, and 13 technologies were successful in the first level of screening and were then screened using these second level criteria. The detailed weighting factors have not been presented here. These 13 technologies were ranked, as summarized in Table 1-1.

Table 1-1 Ranking of successful technologies for sulfate removal

Separation of Scores	Technology Category
Group 1: > 85	
Reverse osmosis	Membranes
Nanofiltration	Membranes
Group 2 : 75 – 85	
Barite precipitation	Chemical precipitation
Ettringite precipitation	Chemical precipitation
Sulf-IX	Ion exchange
VSEP	Membranes
EDR	Membranes
CCD RO	Membranes
Group 3: < 74	
Conventional ion exchange	Ion exchange
UASB reactor	Biological
Direct heat-contact evaporation (LM-HT Concentrator)	Evaporative
Packed bed bioreactor	Biological
Mechanical vapor recompression evaporation with crystallization or spray drying	Evaporative

The treatment technologies that received the top ratings were two membrane technologies: reverse osmosis (RO), and nanofiltration (NF). These technologies got the highest scores in effectiveness and operability/maintainability, including cold weather performance. The membrane technologies also received very high scores in the area of removing secondary contaminants of concern. Membranes have a high potential for beneficial reuse of the treated wastewater. Both of the membrane technologies will produce a very high quality effluent for a wide variety of water reuse applications. The pre and post treatment requirements for membranes is well understood from wastewater reuse applications in the arid southwest, and it is relatively high in order to prevent biofouling, silting in, and precipitation fouling of the membranes. The membrane technologies received the lowest overall scores under the residuals management category. This will play an important role in this cost evaluation.

1.3 Chemistry

1.3.1 Minnesota Ground Water (GW) and Surface Water (SW) Sulfate Levels

A potential water quality standard for sulfate in surface waters could be site-specific, and has the potential to generate a wide range of protective sulfate concentrations from less than 1 mg/L to greater than 1,000 mg/L. Historically, municipal wastewater systems have not been required to consider sulfate treatment for discharge compliance purposes, so little information is available concerning the applicability of technologies for this application.

Sulfur in wastewater is most commonly present as sulfate or sulfide, which originates primarily from drinking water sources, human waste, and industrial discharges. More than 95 percent of municipalities in Minnesota use ground water as the source for their drinking water. The concentration of sulfate in the ground water varies geographically across the State from less than 10 mg/L to over 500 mg/L. Untreated domestic wastewater constituents typically add another 20 to 50 mg/L of sulfate [Ref. 1], and some municipalities have industrial users who produce significant contributions of sulfate. The form of sulfur is dependent on the condition of the wastewater, with sulfate present in oxygen-rich waters and sulfide present in oxygen-depleted water. The environmental conditions that help determine the species of sulfur present in the wastewater may be readily transformed, either biologically or chemically, by natural and engineered processes.

The sulfate in most Minnesota waters is from natural processes. There are a large number of mineral forms that are sulfide based. These are only slightly soluble, but they oxidize readily to sulfates in the presence of atmospheric oxygen. These sulfate minerals are more soluble than the sulfide counterpart. This oxidation by atmospheric oxygen accounts for most of the sulfates in ground water and surface water. There are two notable exceptions. One is community wastewater collection systems that have discharges from industrial users that use or produce sulfate in their process. The other exception is anthropogenic activities that increase the surface area of sulfide minerals exposed to atmospheric oxygen. A good indication of the natural sulfate levels in the community water systems is the sulfate levels in ground waters of the State. Figure 1-2 shows typical Minnesota ground water and surface water sulfate concentrations. It is important to understand that the source water for a community will strongly influence the overall water chemistry of the effluent for the community’s wastewater treatment plant.

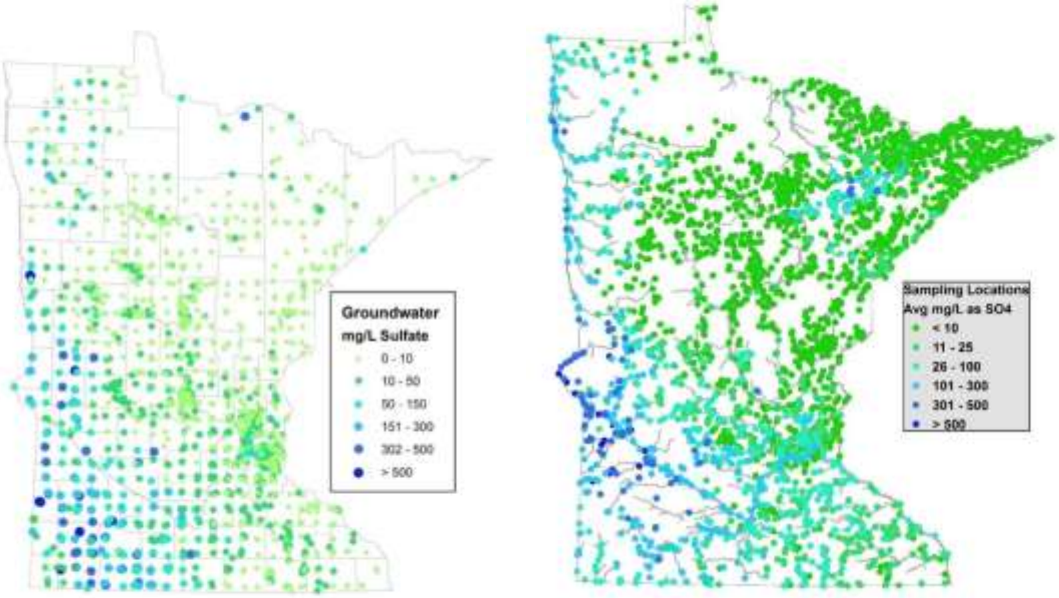

Figure 1-2 **Minnesota Ground Water (left image) and Surface Water Sulfate Levels (right image)**

1.3.2 Minnesota Municipal Wastewater Effluent Sulfate Levels

Figure 1-3 shows the average sulfate levels measured in municipal wastewater treatment plant effluents. In the majority of municipalities, the effluent sulfate concentration is in the range of 20–50 mg/L increase over the drinking water source concentration. This is primarily due to sulfate present in the food. The average daily intake of sulfate in foods is estimated to be 453 mg (78). A substantial portion of this intake is excreted into the wastewater. The communities with a significant industrial discharge may contribute more sulfate to the wastewater.

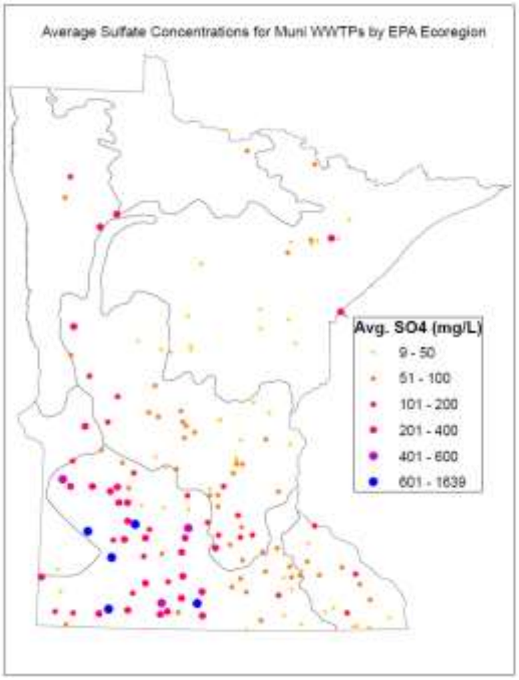

Figure 1-3 **Average Sulfate Concentrations for Selected Minnesota Municipal Wastewater Treatment Plant Discharges**

The majority of the elevated sulfate levels seen in municipal wastewater discharges are in the southwestern and western parts of the State where there are naturally high levels of sulfate in the ground water and the surface waters.

Because levels of sulfate in WWTP effluent depend greatly on the sulfate levels in a community's source water, one possible approach would be to attempt removal at the source of water entering the drinking water system, rather than at the end of the wastewater treatment system. However, this would present little advantage over treating the wastewater, because the same technologies would still need to be considered as are already discussed in this study for the treatment of wastewater. Additionally, because significant sulfate is added into the water stream by the users, in order to meet potential future limits in wastewater effluent, processes removing sulfate at the water source or at a drinking water treatment facility would need to achieve even lower sulfate levels than the processes discussed in this study, which would likely present further challenges.

1.3.3 Synthetic Water Used in this Study

Based on a combination of data, the MPCA provided water chemistry for five different scenarios. Table 1-2 shows water chemistry profiles used for performing full-scale treatment plant cost evaluations.

Table 1-2 Standardized water chemistry profiles for various initial sulfate concentrations

		Initial Sulfate in WWTP Effluent			
Parameter	**Unit**	**25 mg/L**	**100 mg/L**	**250 mg/L**	**500 mg/L**
Calcium	mg/L	50	100	150	250
Magnesium	mg/L	15	50	75	125
Sodium	mg/L	45	200	300	400
Potassium	mg/L	6.5	15	27	27
Chloride	mg/L	136	393	502	687
Alkalinity	mg/L as $CaCO_3$	120	300	400	520
Sulfate	mg/L as SO_4	25	100	250	500
Phosphorus	mg/L	14	14	14	14
Ammonia	mg/L as N	30	30	30	30
Organic Nitrogen	mg/L as N	10	10	10	10
$CBOD_5$	mg/L	200	200	200	200
TSS	mg/L	200	200	200	200
pH		7.3	7.5	7.9	7.55
TDS	mg/L	398	1158	1754	2637

Within the proposed regulatory framework, the effluent (discharge) sulfate concentrations required for municipal wastewater treatment plants may vary depending on the site and discharge stream conditions, so a number of final sulfate concentrations were considered for evaluation purposes. In addition to removal of sulfate, the removal of secondary contaminants of interest were also considered. These include mercury, nitrogen, phosphorous, and chloride.

It is important to realize that these are synthetic water profiles, and may not be representative of a specific community. As seen in Figure 1-2 above, water chemistry profiles for both ground water and surface water change dramatically across the State of Minnesota from the southwest to the northeast. For a specific community with an interest in sulfate removal, an evaluation should be performed for the technology of interest and for the water chemistry profile for that community.

1.4 Range of Flow

The flow from a wastewater treatment plant comes from a combination of sources: those correlated with population, and those not correlated with population. The population-correlated flows include: residential use, commercial use, and institutional use. The non-population-correlated wastewater flow is typically industrial contribution. The average annual daily flow and the peak diurnal flow is predicted based on community population.

1.4.1 Minnesota Wastewater Treatment Plant Flows

Minnesota wastewater treatment plant flows range from very small (< 9,000 gpd) to large (314 MGD). The following Figure 1-4 shows the ranking of treatment plants with continuous discharge and controlled discharge at a given flow rate. From the figure, it is seen that that the median value for a stabilization pond system with controlled discharge is about 0.1 million gallons per day (MGD) and the median value for continuous discharge facility is about 0.9 MGD. The purpose of Figure 1-4 is to make it clear that the theoretical flow rates considered in this study are reasonable, and tend to reflect the large end of the flow spectrum for Minnesota communities. The MPCA's goal is to control the mass of sulfate being discharged into the surface waters of the State, and smaller communities discharge significantly less sulfate than larger ones, simply because their effluent flows are smaller.

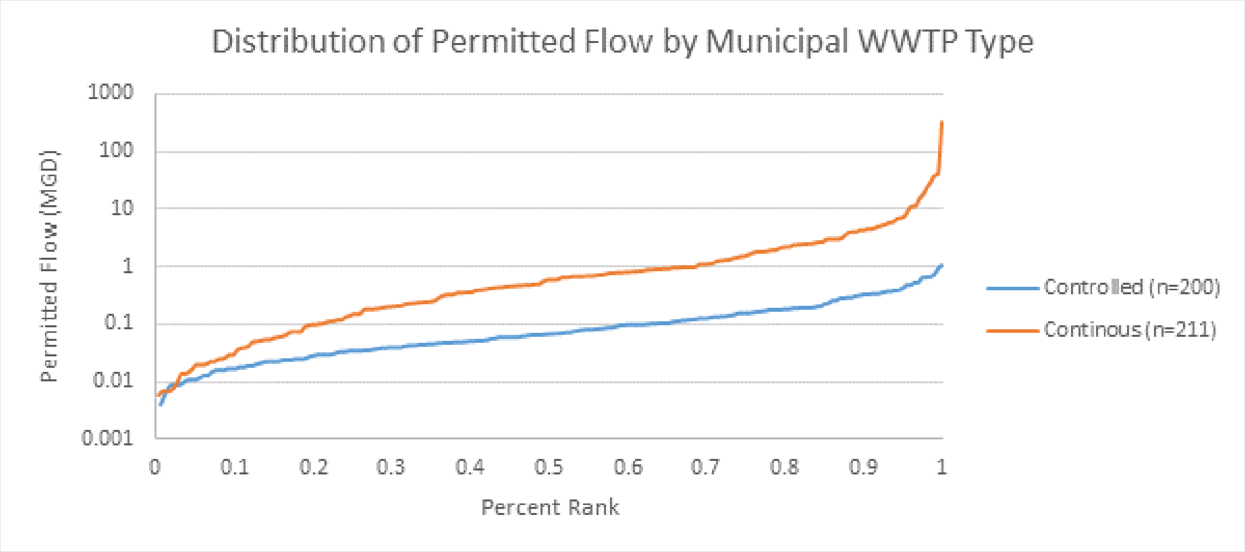

Figure 1-4 **Ranking of Treatment Plants with Continuous Discharge and Controlled Discharge at a Given Flow Rate**

1.4.2 Wastewater Flows Used in this Study

For purposes of this evaluation, a subset was selected for cost estimating: 10 MGD, 2.5 MGD, and 0.5 MGD. The majority (~ 50 percent) of the treatment plants in Minnesota are small systems, and many of these are controlled discharge facultative pond systems. These have been represented by the 0.5 MGD (500,000 gpd) facultative pond system. This is a large flow for a facultative pond, but not an unrealistic flow. The majority of the treatment plants 0.5 MGD and larger will be mechanical plants, dominated by conventional activated sludge systems. Although there are some larger treatment plants in the State, 10 MGD is a reasonable flow to represent the large treatment plants. The flow of 2.5 MGD is representative of a large number of the mechanical plants in between these two extremes. The wastewater flows given above are average flows. Average flows are adjusted to Peak flows using a peaking factor for wastewater from the "10 States Standards". For cost evaluation purposes, these three wastewater flows are combined with selected water chemistry profiles previously presented.

1.4.3 Wastewater Flows Associated with Specific Water Chemistry

Table 1-3 represents the intent of the treatment matrix for the evaluation.

Table 1-3 Intent of the treatment matrix for the evaluation

Facility Size	Average Wet Weather Flow (MGD)	Sulfate Treatment Target	Total N Limit	Total P Limit	Total Mercury Limit
Small	0.5	Low, Medium, High	7 mg/L	0.5 mg/L	6.9 ng/L
Medium	2.5	Low, Medium, High	7 mg/L	0.5 mg/L	6.9 ng/L
Large	10	Low, Medium, High	7 mg/L	0.5 mg/L	6.9 ng/L

From this table, six cases were selected for full design and cost evaluation. These six represent a range of the treatment flows, technologies, and treatment requirements. These six cases are detailed in Table 2-1.

1.5 Secondary Contaminants of Interest

The sulfate removal treatment considered in Part 2 of this report has the ability to remove other constituents in addition to sulfate, including other undesirables. Some of these other affected parameters are discussed in Section 2.1.2. In addition to these, which would normally be treated biologically, the membrane technology considered in this study to remove sulfate will remove a significant portion of the chloride which is correlated to electro-conductivity, TDS and salinity in the effluent.

2.0 Overview of Technologies and Flows

2.1 Treatment Matrix

Part 2 of this study focuses on the implementation of sulfate removal technology, specifically RO filtration, at municipal WWTPs and the costs involved. In order to be as authentic and specific as possible, six unique cases were developed to represent scenarios that plausibly could be faced by Minnesota communities. Some of the details for these cases were decided by the MPCA, and others by Barr and Bolton & Menk. Details of the six cases are described in Table 2-1.

Table 2-1 Details of six case studies

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Biological Treatment Technology	Activated Sludge	Trickling Filter	Activated Sludge	Activated Sludge	Activated Sludge	Facultative Pond
Design Flow (MGD)	10	2.5	2.5	0.5	0.5	0.5
Sulfate Influent (mg/L)	100	25	600	300	300	600
Required Sulfate Effluent (mg/L)	10	10	100	10	100	250
Percent of Flow Treated by RO System	93%	63%	89%	99%	74%	68%

When estimating costs for each case, it was assumed that an entirely new treatment plant was being constructed, with wastewater characteristics and effluent limits known, and sulfate removal considered from the beginning. It should be noted that the costs associated with retrofitting an existing wastewater treatment plant to remove sulfate would likely vary significantly from the costs for constructing sulfate removal equipment/processes at an entirely new facility. Although in the event of a new sulfate limit retrofitting an existing treatment facility would be far more common than the construction of a new one, when comparing costs for the scenarios considered in this study it made sense to compare the costs of constructing new facilities. This is due to the widely varying costs for retrofitting existing facilities, given each one's uniqueness.

Four of the six cases involve new facilities using activated sludge treatment processes for their biological nutrient removal (BNR). Activated sludge is the most common type of BNR used in mechanical wastewater treatment plants in the State, and therefore it was paired with all three influent flow rates and the three highest influent sulfate values considered. Case 2 is the only one in which a trickling filter biological treatment process is used, and it is paired with the second highest flow rate considered (2.5 MGD). A facultative pond system is examined in Case 6 to determine the cost effects of adding sulfate treatment for a smaller community, for which it would not make sense to construct a new mechanical treatment facility solely for the purpose of removing sulfate.

2.1.1 Flows and Sulfate Levels

The influent sulfate concentrations and effluent sulfate concentration limits for each case were stipulated by the MPCA, while the design flows for each facility were assigned to realistically model the type of wastewater treatment facilities seen in Minnesota. The design flows range from 0.5 MGD to 10 MGD. In addition to influent sulfate concentrations and effluent limits, the MPCA also specified additional NPDES limits to be met by each facility. These limits are discussed further in Section 2.1.2.

As discussed in Part 1 of this study, the technologies considered for implementation in sulfate removal need to be effective over a wide range of influent sulfate concentrations. This is to account for the wide variances in source water sulfate levels (see Figure 1-2) and the range of sulfate loads discharged by municipal and industrial users. The highest influent sulfate concentration considered is 600 mg/L, seen in Cases 3 and 6, while the lowest is 25 mg/L, from Case 2. Similarly, there is a wide range in the required effluent concentrations, from 250 mg/L (Case 6) down to 10 mg/L (Cases 1, 2, and 4). The varying effluent concentrations are used because future sulfate requirements are as yet unknown, and could possibly vary from one facility to another. Depending on the varying sulfate influent and effluent concentrations, a certain fraction of the facility influent was sent through the sulfate removal processes. The RO/advanced membrane filtration processes were sized to treat a portion of the daily flow to nearly zero sulfate, with the recombining of the two flow streams resulting in a plant effluent that meets the required sulfate limit. This strategy saved costs compared to constructing an advanced treatment system large enough to handle the entire daily flow. The percent of the flow stream for each case that was required to be sent through the sulfate removal system is shown in Table 2-1, and ranges from 99 percent (Case 4), where sulfate had to be reduced from 300 mg/L to 10 mg/L, to 63 percent (Case 2), where sulfate was reduced from 25 mg/L to 10 mg/L. Although some water was always diverted around the sulfate treatment processes for the Cases in this study, it was determined that for a facility where less than either 5% of the total influent or 35 gpm was being diverted around the processed, it would no longer be economically feasible to have a bypass stream, and all flow should be sent through the sulfate treatment processes.

2.1.2 NPDES Limits for Biological Treatment

In addition to the sulfate influent and effluent concentrations, the MPCA also provided the wastewater starting parameters and effluent limits for biological treatment. These parameters and limits are similar to what might normally be encountered in municipal wastewater and required on a facility's NPDES permit, respectively. Influent values are the same for each case, while effluent limits varied depending on what was reasonable for the type of BNR technology. Table 2-2 outlines the limits.

Table 2-2 NPDES biological treatment parameters

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Facility Type	**Activated Sludge**	**Trickling Filter**	**Activated Sludge**	**Activated Sludge**	**Activated Sludge**	**Facultative Pond**
Parameter:	**(Influent/Effluent Limit)**					
Fecal Coliform (/100 mL)	na/200	na/200	na/200	na/200	na/200	na/na
$CBOD_5$ (mg/L)	200/5	200/25	200/5	200/5	200/5	200/25
TSS (mg/L)	200/30	200/30	200/30	200/30	200/30	200/45
Total Nitrogen (mg/L as N)	40/7	40/na	40/7	40/7	40/7	40/na
Total Phosphorus (mg/L)	14/0.5	14/0.5	14/0.5	14/0.5	14/0.5	14/0.5
pH	na/6-9	na/6-9	na/6-9	na/6-9	na/6-9	na/6-9

As discussed previously, not all of the wastewater passing through the plant must be treated by the sulfate removal processes in order to meet the designated sulfate limit, so there is a portion of the wastewater flow leaving the biological treatment which passes through the sulfate treatment and another portion which proceeds directly to the disinfection processes. Many of the NPDES limits, and in particular the TN and the TP limits shown in Table 2-2, were not achieved prior to the wastewater leaving the biological treatment processes, but instead after the BNR effluent had been blended with the permeate from the sulfate removal train, just prior to the disinfection processes. It was recognized that the advanced membrane filtration technology that would be used for sulfate removal also removes other wastewater constituents, such as solids, organics, bacteria, and heavy metals [Ref. 67]. This doesn't mean that the biological treatment processes are unnecessary and that advanced filtration alone could be used to treat the raw wastewater. If this were attempted, the outcome would likely be rapid and frequent fouling of the filters as they tried to remove an excessive load of numerous constituents [Ref. 67]. However, by accounting for the additional parameters that are further treated by the sulfate removal processes, cost savings can be realized by marginally downsizing the BNR treatment facilities. Table 2-3 below, demonstrates this effect by exhibiting for each case the percentage of the influent nitrate that would need to be removed from the wastewater stream via the biological treatment processes, compared with this same percentage when the RO system is in place for sulfate treatment. The last two columns demonstrate the same effect for phosphorus, displaying the required concentration to be achieved by the BNR and chemical polishing processes so that once the main wastewater stream and RO permeate are blended back together, the plant effluent limit is met. A similar effect is seen for TSS and other NPDES-mandated parameters.

Table 2-3 Required BNR nitrate removal with vs. without RO treatment

Case	Flow (MGD)	Biological Treatment Technology	% of Flow Treated by RO System	Required BNR Nitrate Removal w/o RO Treatment	Required BNR Nitrate Removal with RO Treatment	Required TP after BNR and Chemical Addition (mg/L)	Effluent TP Limit (mg/L)
1	10	Activated Sludge	93%	85.0%	31.5%	5.0	0.5
2	2.5	Trickling Filter	63%	n/a	n/a	1.1	0.5
3	2.5	Activated Sludge	89%	85.0%	47.9%	2.5	0.5
4	0.5	Activated Sludge	99%	85.0%	1.4%	Not Required	0.5
5	0.5	Activated Sludge	74%	85.0%	64.4%	1.4	0.5
6	0.5	Facultative Pond	68%	n/a	n/a	n/a	n/a

2.2 Design Tools

2.2.1 Hydromantis CapdetWorks

A computer program created by the company Hydromantis called CapdetWorks was used to size and estimate costs for the biological treatment processes in the treatment facilities considered by Cases 1-5. CapdetWorks allows the user to easily assemble a treatment plant based on the processes used, and uses consistent unit cost estimation techniques to help size and estimate costs for the various treatment processes. It breaks the costs down into Construction (capital), Labor, Material, Chemical, and Energy categories and can amortize capital costs for the life of the facility. Sizing of the processes is performed by entering influent data and desired effluent quality, in addition to selecting the processes and order to be used. The engineer enters or modifies design parameters to represent their best judgement, resulting in a design that meets the intended needs. In order to visualize and compare the costs for each case, the overall costs generated by CapdetWorks are summarized in Tables 3.2, 4.2, 5.2, 6.2, 7.2, 9.1, and 10.3, and an example of the full cost breakouts generated by the program (for Case 1) are included in Appendix B.

2.2.2 EnviroSim BioWin

BioWin, by EnviroSim, is a wastewater treatment process simulator program, used primarily for modelling biological wastewater treatment processes. It was used during design of the various treatment plant cases for design of the BNR processes, specifically to achieve total nitrogen (TN) limits leaving the BNR processes. As was mentioned previously, these limits were not typically the same as the NPDES limits for plant effluent, because of the additional treatment received in the RO filters for at least a portion of the wastewater stream.

2.2.3 MPCA Reliability for Mechanical Wastewater Treatment Facilities

For design of the BNR facilities, expressly for the cases using activated sludge or trickling filters for biological treatment (Cases 1-5), the MPCA's "Reliability for activated sludge and fixed film reactor wastewater treatment facilities" guidelines were followed. The guidelines specify the type of flow splitting and bypass that must be used, depending on whether there are duplicate components or not. They also dictate the capacity of each process that must be available if the largest unit is out of service, be it an aeration basin/reactor, a clarifier, a blower, a diffuser, etc. The number, capacities, and costs of the main biological treatment plant processes are heavily influenced by these guidelines. See Appendix A for the complete MPCA guidelines document.

2.3 Membrane Treatment

Part 1 of this report completed a screening process to determine which technologies might be best suited for sulfate removal at Minnesota wastewater treatment facilities. The technologies investigated in detail were those that were able to reduce sulfate to below 250 mg/L and have been implemented in full scale installations in either an industrial or water treatment setting. These technologies were also evaluated for their ability to remove major wastewater constituents of concern other than sulfate, including other major ions, heavy metals, and total dissolved solids. This ability was not recognized as essential for a technology to be considered for sulfate removal, but was taken into account when determining which technologies could realistically be applied at wastewater treatment facilities.

The screening process from Part 1 revealed that advanced membrane filtration processes, mainly RO and NF, are the most mature and usable sulfate removal technologies currently available. While they come with their own problems and challenges, these processes can effectively remove sulfate and other constituents from the wastewater stream and are already used in many full-scale installations both in industrial applications and in municipal water treatment. For the example cases studied in the second part of this report, RO membrane filtration technology was the focus for theoretical design and cost estimation. Literature has shown that if NF overcomes the limitations identified, the costs to implement NF would be very similar to the cost to implement RO.

2.3.1 Overview of Reverse Osmosis/Nanofiltration Technology

As discussed in Part 1 of this report, membrane filtration is technology in which water is forced by pressure through a membrane/membranes with small openings, or pores, allowing certain molecules such as water to pass through, but trapping molecules and/or particles larger than a certain size on the upstream side of the membrane. The main membrane filtration technologies, in order of descending pore size, are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and electrodialysis/electrodialysis reversal (ED/EDR). ED/EDR differs from the other membrane technologies in that it uses a direct electric current to migrate dissolved ions toward cationic and anionic membrane layers, and it was not considered for full-scale cost analysis due to its higher capital and O&M costs, and its lack of large-scale industry installations. Membrane technologies require pumps to either generate upstream pressure or downstream vacuum (in tank MF and UF) in order to force the water molecules through the membrane pores. The smaller the pores in a membrane, the greater the pressure needed to force water through them, and the more energy the membrane will consume during operation. Table 2-4 details the typical pore sizes and feed pressures for each membrane type.

Table 2-4 Typical pore sizes and feed pressures for membrane technologies

Membrane Category	Typical Pore size (µm)[1]	Typical Feed Pressure (psig)[1]
Microfiltration	0.05-20	2-40 (-3 to -12 vacuum)
Ultrafiltration	0.0015-0.2	7-150
Nanofiltration	<0.0015	70-300
Reverse Osmosis	<0.0015	125-600[2]
[1] Ref. 66 [2] For low and standard pressure systems (not high pressure/saltwater), US EPA		

RO and NF are the only two membrane technologies with pore sizes small enough to reliably reject the sulfate ion, and of the two, RO is the more effective, having a marginally smaller pore size than NF [Ref. 66]. Based on projections by Dow Water & Process Solutions, NF membranes can perform at similar levels to RO filters, but only under certain conditions. The examples given for full size installations in Florida were for removing color (manganese sulfate) from drinking water, and had a relatively pure starting solution. When natural waters with complex ionic makeups are involved, sulfate rejection by NF is significantly reduced [Ref. 77]. Additionally, sulfate rejection is also reduced by higher temperatures, though at the same time feed pressure and energy consumption are both also reduced (see Table 2-5). It was determined that for NF to be used for sulfate removal, each community would probably need to be individually considered and a pilot test performed to determine whether it would be effective. While generally higher in feed pressure/energy consumption, RO is a more widely used and proven technology in water treatment, and was consequently used in this study as the primary sulfate removal process.

Table 2-5 Projected sulfate removal by NF membrane treatment

Design Details				8°C (46°F)[1]		12°C (46°F)[1]		20°C (68°F)[1]	
Case	Influent Flow (MGD)	Influent SO_4 (mg/L)	Max. SO_4 in Permeate (mg/L)	Feed Pressure (psi)	Permeate SO_4 (mg/L)	Feed Pressure (psi)	Permeate SO_4 (mg/L)	Feed Pressure (psi)	Permeate SO_4 (mg/l)
1	10	100	10	101	3.4	92	4.1	77	5.8
2	2.5	25	10	92	0.9	84	1.1	70.9	1.5
3	2.5	600	100	90	17.5	80	21.2	71.5	30
4	0.5	300	10	107	6.1	95	7.4	77.1	**11.1**
5	0.5	300	100	94	10.5	85	12.7	70.5	18.1
6	0.5	600	250	88	17.8	79	21.7	63.7	31.5
[1] All information from Dow Water and Process Solutions									

During operation, an RO membrane concentrates particles and molecules on its upstream side, and two separate flow streams leave the unit. The clean water, or "permeate" is the finished product that leaves the membrane system, with unwanted constituents removed. The concentrate (reject) is the water stream that does not pass through the filter, and which contains elevated levels of the rejected substances. Figure 2-1 shows a simplified representation of an RO membrane at the molecular level.

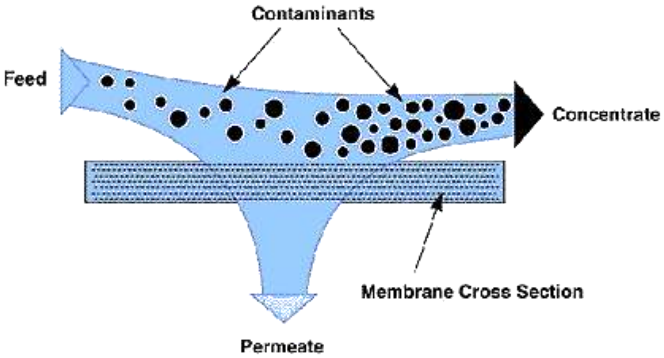

Figure 2-1 Functioning RO Membrane

One variation on the conventional RO process is the VSEP® (Vibratory Shear Enhanced Processing) system. In this proprietary system, the RO filter cartridges are vigorously vibrated in a direction tangential to the face of the membranes. Theoretically, the shear waves produced by this vibration are supposed to prevent solids and scale from fouling the pores of the membranes, as shown below. The capital costs associated with a VSEP® installation are significantly greater than those for a standard RO system, but the operating costs are lower [Ref. 53]. Consequently, VSEP® in the cases associated with this study, was not considered for primary sulfate removal process, but was used in Cases 1, 3, and 4 for secondary filtration/concentrate reduction (discussed in Section 2.3.4). See Figure 2.2 for the VSEP® membrane comparison.

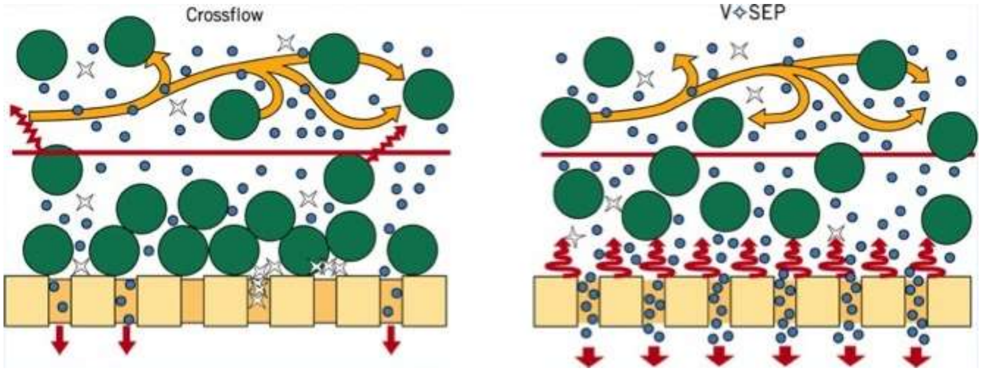

Figure 2-2 VSEP® Membrane Comparison

The reason a process like VSEP® might be used is to prevent excessive scaling on the membrane surface, which will cause the membrane to need cleaning more frequently. This is not as critical an issue in RO wastewater treatment for sulfate removal as it is in concentrate minimization (see Section 2.3.4), but it must still be considered during process design. RO treatment recovery depends on certain constituents, such as calcium, barium, strontium and silica, which leave deposits on the membrane surface and can foul the pores if the problem is not addressed. During RO treatment for sulfate removal, silica in particular needs to be taken into account; a 10 ppm increase in silica concentration, from 15 to 25 ppm can reduce water recovery from 90 percent to 86 percent [Ref. 73, Table 2-6]. Loss of recovery could in theory be mitigated by adjusting both water temperature and pH, but this would in all likelihood be neither practical nor cost-effective.

Table 2-6 Summary of sulfate removal by RO treatment process for the six case studies

Case	Flow (MGD)	Sulfate Influent Conc. (mg/L)	Required Sulfate Effluent Conc. (mg/L)	Biological Treatment Technology	RO Sulfate Rejection	Sulfate Conc. in Permeate (mg/L)	RO System Recovery (%)[a]	% of Flow to be Treated by RO System	Rounded up %	Feed Flow to RO (MGD)	Non RO Treated Flow (MGD)	Reject Flow (MGD)	Reject Flow (GPM)
1	10	100	10	Activated Sludge	99.0%	1	83%	92.3%	93%	9.3	0.7	1.581	1098
2	2.5	25	10	Trickling Filter	99.0%	0.2	90%[b]	63.0%	63%	1.575	0.925	0.1575	109
3	2.5	600	100	Activated Sludge	99.2%	5	68%	88.6%	89%	2.225	0.275	0.712	494
4	0.5	300	10	Activated Sludge	99.0%	3	76%	98.2%	99%	0.495	0.005	0.1188	83
5	0.5	300	100	Activated Sludge	99.0%	3	76%	73.1%	74%	0.37	0.13	0.0888	62
6	0.5	600	250	Facultative Pond	99.2%	5	68%	67.8%	68%	0.34	0.16	0.1088	76

[a] RO System Recovery was limited by $CaCO_3$ precipitation potential.

[b] RO System Recovery will be reduced if silicate in water equals or exceeds 25 mg/L.

When employing RO membrane filters at a wastewater treatment facility, some additional treatment may be needed for the permeate stream to bring it into compliance for discharge to the environment. These specific adjustments are addressed further in Section 2.3.3. The most significant challenge presented by RO treatment in water or wastewater treatment is how to process concentrate waste stream, for which there is no simple or inexpensive disposal. Concentrate management is addressed in Sections 2.3.2, 2.3.4, and 2.4.

2.3.2 Equalization/UF Pretreatment /RO Treatment and Concentrate Management

Compared to other filtration processes normally associated with wastewater treatment, RO presents a unique set of operational challenges that must be considered. Among these are equalization of the flow stream prior to it reaching the filtration process, pretreatment such as tertiary filtration prior to RO to reduce the biological fouling of membranes, and management of the concentrate stream leaving the RO treatment system.

The implementation of RO/NF filters as a primary treatment process at a WWTP generates the need for flow equalization. Municipal wastewater plants are designed to treat wastewater flow that is not equalized as it comes from the sanitary sewer collection system. This results in substantial variation in influent flow, typically in a diurnal (two significant flow peaks per day) pattern. RO filter units require a constant hydraulic loading, and there isn't a way to vary flow to the units to match the flow entering the plant, other than taking entire RO skid assemblies in and out of service [Ref. 67]. The solution is to add an equalization basin or basins prior to the sulfate removal processes to absorb flow peaks and to feed effluent from the biological treatment processes to the sulfate treatment ones at a constant rate. Typically, these equalization basin(s) should be designed to hold approximately 20 percent of the average daily flow into the plant [Ref. 67].

Nearly all RO membrane setups require some type of pretreatment ahead of them to remove significant amounts of solids, microbes, and organic material from the influent stream. This is especially the case when treating wastewater. The aforementioned constituents can foul or plug the RO membrane pores, increasing the operating pressure and energy required to move water through the membrane, and decreasing its life. RO and NF filters encounter this issue more frequently than other types of membrane filters (MF and UF) because of their small pore size [Ref. 66]. In the wastewaters considered in the six cases, preliminary and biological treatment processes have already significantly improved the water quality compared to what was seen in the influent; however, additional pretreatment is still needed before the water is sent to the RO process. A few possible solutions include: deep bed granular media filtration and microfiltration (MF) or ultrafiltration (UF). For facilities that already use tertiary filtration to meet effluent requirements, it likely makes sense to use this process for RO/NF pretreatment. If no tertiary filtration exists or an entirely new facility is constructed, MF or UF would be the better option. Table 2-7 presents flux rates through RO and NF filters, measured in gallons per square foot per day, after pretreatment by both granular media filtration and MF/UF filtration. The latter provides higher daily flux rates because granular media filtration doesn't provide the high-quality polishing that MF/UF provide, and when it's used for pretreatment, the RO/NF filters need to be taken out of service and cleaned more frequently to avoid fouling. Consequently, to meet a similar flow capacity, a larger RO/NF setup would be needed, leading to additional costs. Because all of the treatment plants in the six cases were assumed to be new facilities, UF filters were used as advanced filtration pretreatment for all of the cases.

Table 2-7 RO/NF flux rates based on pretreatment

Process	RO Flux Rate (gal./day/ft.^{2})[1]	NF Flux Rate (gal./day/ft.^{2})[1]
Granular Media Filtration	8-10	10-12
MF/UF Filtration	10-12	12-14

[1] Information from Toray Membrane

As previously mentioned, the most difficult and expensive part of treating wastewater with RO membranes is the processing and disposal of the generated waste stream, or concentrate. The concentrate is salty, and contains large accumulations of undesirable constituents. Some of the most common conventional options for dealing with RO concentrate are listed below:

- Surface water disposal
- Sanitary sewer
- Land application
- Landfilling
- Deep well injection
- Evaporation ponds/spray evaporation
- Conventional zero liquid discharge (ZLD) processes

Surface water disposal was immediately ruled out with the obvious reason being that the purpose of this report was to study the removal of sulfate from the wastewater stream prior to discharge to natural waters. Sanitary sewer disposal is often considered when dealing with RO concentrate from a drinking water treatment facility, but because this study deals with the WWTPs treating sanitary wastewater, it is not an option for this application. Land application via irrigation with concentrate presents its own challenges, including the need to over-irrigate so as not to harm the plants being watered with excess salt buildup and the possibility of the salts and other constituents leaching into underlying ground water [Ref. 47]. Most of Minnesota's streams are gaining streams, which means the ground water may well end up in the surface water, which is what is being avoided by the treatment that created the concentrate in the first place. Similarly, landfilling the concentrate has a number of hurdles, which include widely varying landfill permit requirements and high container, transport, and disposal costs [Ref. 47]. Most landfills require that material placed in the landfill have no free water, and concentrate is, in essence, salty water. Deep well injection is a technology in which liquid concentrate is stored underground in a geologic formation that is not connected to anything used for beneficial purposes, such as areas where oil and/or gas have been extracted. The key to deep well injection is to identify a subsurface water chemistry that is compatible with the water chemistry of the concentrate. In Minnesota, there is a moratorium on injection wells because its geology is deemed unsuitable for it, so this is another option that is unavailable [Ref. 68]. Evaporation ponds take advantage of ambient conditions to naturally evaporate concentrate, leaving dissolved solids and particulates behind. The ponds require great areas of land and perpetual warm weather, solar radiation, and low natural precipitation. They are common in the arid southwest of the U.S., but would not be practical or functional in Minnesota [Ref. 66]. There are guidelines from the MPCA for designing evapotranspiration systems for small scale wastewater, but a system for municipal RO concentrate management would be very large. Spray evaporation also utilizes evaporative ponds, but uses mechanical means to spray the concentrate into the air in small droplets, creating more surface area for faster evaporation. Nevertheless, in Minnesota's continental climate, the evaporative ponds still would not function effectively, and spray evaporation can be problematic if high winds cause the sprayed concentrate to drift away from the pond site.

Evaporation ponds and spray evaporation are two types of zero liquid discharge (ZLD) treatment. The last major technological category used for concentrate treatment are conventional ZLD processes. It should be noted that in the context of this report, the use of the term "zero liquid discharge" should not be understood to mean that there is no liquid effluent leaving a treatment facility. During this cost study, ZLD processes were considered solely to handle the RO reject (concentrate) as a means of eliminating it while incurring the least possible costs, and without violating any permits, statutes, or laws.

As the name suggests, after ZLD treatment, the only products from the concentrate stream that must be disposed of are solids or near-solids, with all or almost all water from the concentrate stream having either been recycled or evaporated. Because of the discussed obstacles and complications associated with other types of concentrate disposal, ZLD is the most commonly-employed process in industrial and desalination applications, and during this study, ZLD, combined with concentrate reduction, was used for all of the considered cases. Although precipitate salts and crystal solids must still be disposed of, the landfilling restrictions and costs for this are considerably less than for a liquid waste stream [Ref. 69]. In some cases, the solids produced can themselves be recycled and used, but they often contain significant levels of regulated metals and other contaminants [Ref. 69]. A hazardous waste characterization should be conducted to make these determinations.

Conventional ZLD processes generally involve some combination of a concentrator/evaporator unit and a crystallizer. For each of the theoretical cases considered in this study, this combination was used, while the method of concentrate reduction was varied. The details of these processes are further discussed in Section 2.4, while the need for concentrate reduction is covered in Section 2.3.4.

As discussed in Part 1 of this report, there are a number of potential developing or combined technologies that could be used to deal with concentrate management, possibly without the high energy use and costs of conventional ZLD processes; however, because these technologies are, on the whole, unproven, and are not in wide use yet in any industry, they were not investigated further as part of this study.

2.3.3 Post-Membrane Permeate Treatment

Wastewater that has been treated both by biological treatment processes and RO membrane filtration is not yet ready for discharge to the environment. As discussed previously, the RO membranes are effective at filtering out sulfate, as well as numerous other particles, dissolved solids, and molecules, with no way to selectively control what is removed. Consequently, some final adjustment to the RO permeate is necessary.

The WWTP effluent must meet all of the NPDES permit requirements, including a pH range of 6-9. Permeate water leaving the RO membranes has a low pH and is very low in hardness and alkalinity; as a result, it can be corrosive to downstream pipes and processes. For these reasons, pH adjustment is necessary prior to the permeate rejoining the main plant effluent stream.

Treated wastewater effluent must also meet whole effluent toxicity (WET) standards for the State of Minnesota. WET testing is a proactive method of determining whether a wastewater discharge will have adverse effects on organisms in the receiving water, without necessarily specifically focusing on one particular contaminant or another. The specific organisms used for WET tests are certain species of the water flea family (*daphnia magna/daphnia pulex/ceriodaphnia dubia*) and the fathead minnow (*pimephales promelas*). In verbal discussions with the MPCA, it was agreed that as long as the calcium carbonate precipitation potential (CCPP) was adjusted to be slightly negative, an effluent would likely pass the WET test. The CCPP is a practical parameter which can be used to measure the amount of calcium carbonate which theoretically can precipitate out of a water, and takes into account calcium content, pH, and alkalinity.

The post-RO treatment for Case 1 involved a lime slurry feed at 115 mg/L using a concrete tank and rapid mixer, while all other cases used a caustic soda feed system with concentrations ranging from 8.5 mg/L to 39 mg/L, depending on the amount of adjustment required (see Appendix C for more details). Lime was used instead of caustic in Case 1 because while a lime feed system requires a higher capital cost, the chemical itself costs less than caustic soda, and for the highest-flow (10 MGD) scenario cost savings were realized over time. Similar to the design of the biological treatment, the amount of post-membrane treatment performed was the minimum required to bring the final WWTP effluent stream into compliance with the NPDES permit and WET test once the RO permeate rejoined the main facility stream.

2.3.4 Concentrate Minimization

For several reasons, it's necessary to minimize the flow to the concentrate disposal processes, which in this study were comprised of a combination of evaporators and crystallizers. As shown in Table 2-8, the energy use for operating a brine concentrator is 75-95 kWh/1000 gal and energy use accounts for about 75 percent of the total operating costs; therefore, it is important to reduce the concentrate volume by other treatment methods before sending to a brine concentrator.

Table 2-8 Energy use for various membrane and thermal evaporation processes

Treatment Process	Volume Reduction	Energy Use
Low Pressure RO/Nano-Filtration (Feed TDS <3000 mg/L)	65 to 85%	1.8-2.0 kWh/1000 gal
Brackish Water RO (Feed 3000<TDS <10,000 mg/L)	65 to 85%	2.8-3.0 kWh/1000 gal
Seawater RO (Feed TDS =35,000 mg/L)	50 to 75%	10-13 kWh/1000 gal
Brine Concentrator (Concentrate TDS 160,000 to 360,000 mg/L)	Up to 95%	75-95 kWh/1000 gal
Crystallizer	Removes 99.99% water	200-250 kWh/1000 gal

The above table indicates that the seawater RO (SWRO) process is capable of concentrate volume minimization much more cost effectively at a low energy use compared to mechanical thermal evaporative (MTE) process such as brine concentrator and crystallizer; however, the SWRO process has a limitation in that it cannot concentrate the RO reject above a TDS level of 75,000-100,000 mg/L. This limitation arises from the osmotic pressure limitation. The maximum feed pressure currently available for a SWRO system is 1000 psi. This feed pressure will be reached when the osmotic pressure of the concentrate reaches 54 atm or 800 psi due to a 200 psi driving force differential necessary for operation.

Table 2-9 shows the TDS level to reach an osmotic pressure of 800 psi.

Table 2-9 Salinity at which osmotic force reaches 54 atmospheres

Salt	Salinity, (mg/L)
$NaCl$	65,000
$NaHCO_3$	71,869
$CaCl_2$	83,300
Na_2SO_4	105,800
$Ca(HCO_3)_2$	106,307

Table 2-10 below compares the calculated concentrate flows from the sulfate removal RO processes for the six cases.

Table 2-10 **Calculated concentrate flows from the sulfate removal RO processes for the six cases comparison**

Case	Flow (MGD)	Sulfate Influent Concentration (mg/L)	Required Sulfate Effluent Concentration (mg/L)	Sulfate Removal RO Reject Flow (MGD / gpm)	Sulfate Removal RO Percent Reject
1	10	100	10	1.58 / 1100	15.8%
2	2.5	25	10	0.16 / 110	6.4%
3	2.5	600	100	0.72 / 500	28.8%
4	0.5	300	10	0.12 / 85	24.0%
5	0.5	300	100	0.09 / 65	18.0%
6	0.5	600	250	0.11 / 75	22.0%

Both capital and O&M costs for evaporative processes are extremely high. Table 2-11 displays varying costs for a brine evaporator (concentrator)/crystallizer setup using varying influent flows and TDS concentrations.

Table 2-11 **Projected concentrator and crystallizer costs**

	[1]			
Flow (gpm)	139	153	318	488
TDS (ppm)	15,675	21,536	15,675	13,197
MVR Brine Concentrator Cost	$3,500,000	$4,000,000	$5,000,000	$6,500,000
MVR Brine Crystallizer Cost	$3,250,000	$3,500,000	$4,000,000	$4,500,000
Estimated Total Installation Cost[2]	$7,000,000	$7,000,000	$9,000,000	$11,000,000
Solids (tons/day @ 10% moisture)	16.34	24.71	37.38	48.3
Power Use (kWh/day)	4,400	6,200	10,000	13,500
Spares/Maintenance Allowance (3%)	$203,000	$225,000	$270,000	$330,000

[1] All information from Veolia

[2] For Gulf Coast installation

The cost of a mechanical/thermal evaporation unit (MTE) to treat 1 MGD (695 gpm) of concentrate, paired with a crystallizer to treat an estimated 0.05 MGD (35 gpm) of concentrate remaining after the MTE is roughly $30,000,000 [Ref. 47]. Additionally, evaporator and crystallizer units, because they use heat to evaporate and eliminate the liquid from the waste stream, use substantial amounts of energy, in the vicinity of 200-250 kWh/1000 gallons [Ref. 47]. Annual O&M costs for the 1 MGD setup are approximately $9,500,000 [Ref. 47]. In comparison, a low-pressure secondary RO system that could reduce the volume sent to the final concentrate disposal processes by 65-85 percent might use roughly 1.8-2.0 kWh/1000 gallons [Ref. 70]. Based on this cost data, it became apparent that every opportunity to reduce the ultimate flow being directed to the evaporative processes should be pursued.

Aside from the costs associated with evaporator and crystallizer units, their size and complexity is another factor governing installation and use. A falling film concentrator (evaporator) sized to handle 250 gpm is approximately 100 ft. in height, and units of this type are frequently not assembled on-site [Ref. 70]. Instead, they must be transported to the location of use and installed, which is a complicated and labor-intensive process. Evaporators can be sized up to approximately 750 gpm and crystallizers up to roughly 100 gpm [Ref. 71], but based on their exceptionally high O&M costs and the complications associated with their transport and installation, it was determined for the purpose of this study to attempt to minimize the concentrate flow being directed to these processes to 100 gpm or less.

Figure 2-3 shows a 250-gpm falling film evaporator at a facility in Chandler, Arizona.

Figure 2-3 Concentrate Evaporator Rated for 250 gpm at a Facility in Chandler, Arizona

For Cases 2, 5, and 6, which had some of the lowest RO reject flows and for which concentrate minimization may not be cost-effective, sulfate removal RO concentrate was sent directly to the evaporative processes. For all other cases, some type of concentrate minimization was implemented. Below is a list of some of the most common technologies and systems associated with reduction of concentrate volume:

- Electrodialysis Reversal (EDR) Technologies
- ARROW^{TM} Technology (O'Brien & Gere)
- VSEP^{TM} Technology (New Logic Research)
- HEEPM^{TM} Technology (EET)
- HERO^{TM} Technology (SAMCO)
- Conventional softening combined with secondary RO

The majority of technologies used for reducing concentrate involve some type of membrane filter, usually RO again. Impeding the use of merely another relatively straightforward RO setup like that used in the primary sulfate treatment are the high concentrations of salt and hardness-causing molecules, which tend to precipitate on RO membrane surfaces and quickly clog the pores. Most concentrate reduction processes either use pre-softening or some more elegant solution to stop scale from forming on the membranes.

As can be inferred by the acronyms in the names, many of the technologies listed above are proprietary, and many are still emerging or in developmental phases. Electrodialysis/electrodialysis reversal, as previously discussed, is a membrane filtration technique that uses direct electrical current to attract ions to anionic and cationic plates. ARROW^{TM} stands for Advanced Reject Recovery of Water, and uses unique flow configurations of standard membrane technologies and high-pH caustic softening to remove silica and carbonates to achieve high recovery [Ref. 72]. The VSEP^{TM} technology was discussed already and uses RO filters mounted on a vibrator process which prevents scale precipitation. HEEPM^{TM} (High Efficiency Electro-Pressure Membrane) uses a combination of ED and RO technology, as well as a feed tank, in a unique loop that has been able to achieve higher recoveries than either type of system by itself [Ref. 72]. Finally, the HERO^{TM} (High-Efficiency Reverse Osmosis) system by SAMCO uses pretreatment or interstage lime softening or ion exchange (IX) processes to reduce scaling potential, and high pH through the second-stage RO if silica is present.

For those cases that were determined to require concentrate reduction after RO for sulfate removal, three different options were explored in order to compare projected costs, both for installation and operation over time. These three options were: lime softening followed by UF and RO filters; pellet softening followed by gravity filtration and RO filters; and a VSEP^{TM} concentrator setup. The detailed costs associated with each option for each case can be found in Sections 3.0, 5.0, 6.0, and Appendix C. To determine lime softening capital costs, a recent water treatment plant project designed by Bolton & Menk was used. The plant was designed to treat 1200 gpm (~1.7 MGD) and the capital cost was roughly $10,000,000. Only costs for processes that would be needed for treating the concentrate were taken into account (process pumping, etc., were not considered). The following equation was used to scale the capital costs for lime softening concentrate minimization treatment for plants with different influent flows:

$$Cost\ X = Cost\ \ Y\left(\frac{Flow\ X}{Flow\ Y}\right)^{0.66}$$

2.4 Concentrate (Reject) Management

As discussed in Section 2.3.2, the technologies that were evaluated for ultimate concentrate disposal in this study were conventional ZLD processes, specifically an evaporator/brine concentrator unit followed by a crystallizer unit. The concentrator's purpose is to greatly reduce the water content in the concentrate, while the crystallizer eliminates the remaining liquid and generates solids for final disposal. One advantage of this type of conventional ZLD process is the ability to handle concentrate streams of widely varying quality, without the need for extensive operational adjustment.

2.4.1 Evaporation/Concentration

2.4.1.1 Theory and Process Variability

There are various types of evaporation processes used in conventional ZLD treatment. In a mechanical evaporation process, mechanical heating is used to add heat to the concentrate, ultimately vaporizing the majority of the water and reducing the concentrate volume. This type of evaporator is classified based on arrangement of heat transfer surfaces and the method used to impart heat. Common types include multiple effect, vapor compression, vertical-tube falling-film, horizontal-tube spray-film, and forced circulation. Figure 2-4 shows a detailed diagram of a vertical-tube, falling-film, and vapor compression evaporator (also called a brine concentrator).

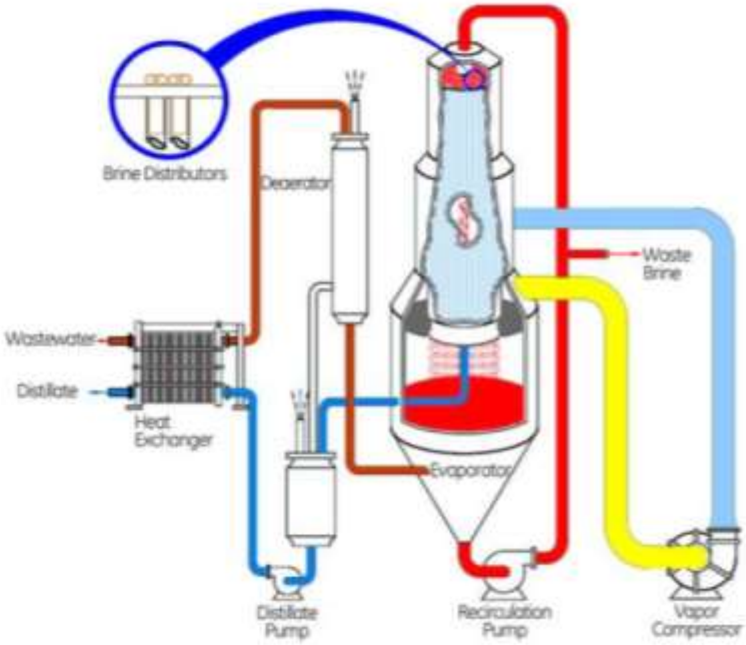

Figure 2-4 Mechanical Vapor Recompression Brine Concentrator (image courtesy of GE)

In this type of process, concentrate is first pumped through a heat exchanger, which uses heat energy from the distillate leaving the process to raise the temperature of the incoming concentrate. The heated concentrate then moves through a deaerator, which strips carbon dioxide to reduce corrosion and scaling potential, and into the main body of the evaporator where it combines with the concentrate slurry. Slurry is continuously recirculated with a pump to a flood box at the top of the evaporator, which sits at the top of a number of heat transfer tubes. As the mixed slurry falls through these tubes, a portion of it is evaporated. This vapor passes through mist eliminators and the vapor compressor, which imparts more heat to the vapor. It reenters the main evaporator, this time on the outside of the heat transfer tubes, and imparts heat to the tubes, at the same time cooling and condensing on them. The vapor, now in the form of distillate, is collected at the base of the heat transfer tubes and pumped out of the process, passing through the heat exchanger as it leaves and transferring some of its remaining heat energy to the incoming condensate. Somewhere between 1-10 percent of concentrate slurry flow is wasted, with the purpose being to maintain 20-30 percent (200,000-300,000 mg/L) total solids in the slurry.

Another major category of evaporative processes is the submerged combustion evaporator. In this type of process, a fuel (usually natural gas, propane, butane, or fuel oil) is burned just above the surface of the concentrate and the hot exhaust gases are forced down through the liquid before rising to the liquid surface and leaving the unit. As the hot gases come into contact with the condensate, a portion of the water in it is evaporated. In most cases, the evaporated water is exhausted out of the unit with the burned fuel and is not recoverable. Solids are removed from the evaporator either by a conveyor connected to the bottom of the unit, or in a sediment separate from the unit through which the slurry from the base of the unit is cycled, via a pump. Whereas a mechanical evaporator doesn’t remove all liquids in the concentrate and must be paired with a crystallizer, the combustion evaporator is itself the final process in a ZLD train and produces for disposal only crystalline solids. Figure 2-5 shows a simplified schematic of a submerged combustion evaporator.

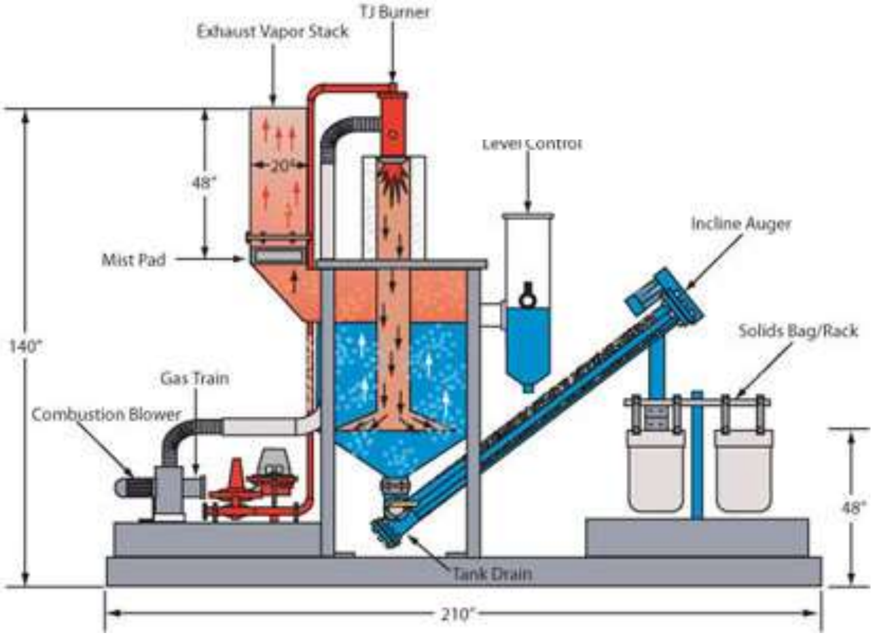

Figure 2-5 Submerged Combustion Evaporator (image courtesy of EvapoDry)

2.4.1.2 Limitations

Mechanical evaporators, such as the one described in Figure 2-4, require special labor skills for operation and maintenance. They are proven in industrial applications and remove most constituents to produce a high-quality distillate; however, they create notable noise pollution, may be considered aesthetically unattractive, and have high capital and operating costs, as previously discussed. In order to function properly, acid may need to be added before the deaerator to lower the concentrate pH and force more bicarbonate to be converted to carbon dioxide for removal [Ref. 69]. The removal of carbon dioxide also removes alkalinity and reduces the possibility of calcium carbonate scaling onto heat transfer surfaces and reducing process efficiency. It also may be necessary to seed calcium sulfate crystals into the recirculated slurry to constitute precipitation nuclei for crystal growth for prevention of scaling, or to add other chemicals for the same purpose. Even so, it may be necessary to periodically (every 2-6 weeks) boil out the unit with distillate to remove scaling [Ref. 79].

Submerged combustion evaporators offer a higher thermal efficiency than mechanical types, and the absence of heat transfer surfaces means that scaling does not present the challenges that mechanical units face. They do face a number of challenges, including safety and noise concerns. Ultimately though, submerged combustion processes are not widely sized to handle the scale of flows covered in this study. Discussion with Industrial Process Heat Engineering Ltd., a manufacturer of this type of unit, determined that the largest unit they had constructed would handle about 20,000 gpd (13.9 gpm), an order of magnitude smaller than what was needed for the six cases [Ref. 74]. Thus, a mechanical falling-film brine concentrator, paired with a crystallizer, was used for all six cases.

2.4.2 Crystallization

2.4.2.1 Theory and Process Variability

Like evaporators, crystallizers use mechanical vapor compression to remove water from concentrate, producing a slurry of solids. The reason that brine concentrators are used in sequence with crystallizers for concentrate disposal, rather than using crystallizers alone, relates to energy consumption. Whereas brine concentrators use in the range of 60-90 kWh/1000 gallons processed, a crystallizer uses closer to 180-250 kWh/1000 gallons, meaning a significant difference in per-unit treated operating cost [Ref. 69, Ref. 75].

The input to a crystallizer comes directly from the waste brine stream produced by the mechanical brine concentrator (see Section 2.4.1.1). While the brine concentrator further reduces the amount of liquid in the RO reject stream, the crystallizer eliminates nearly all remaining water. Like evaporators, there are a few different types of large-scale crystallizers. Most commonly seen in industry applications are steam-driven or vapor compression crystallizers, similar to the one shown in Figure 2-6.

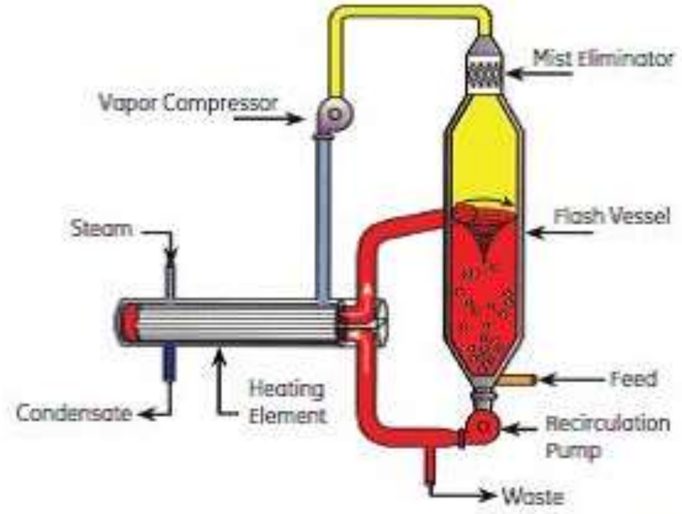

Figure 2-6 **Steam-Driven Crystallizer (image courtesy of Prodromos Technologies)**

Brine concentrate is fed into the stream entering the recirculation pump, which comes from the main body of the crystallizer, called the vapor body. The brine is superheated in a series of tubes contained in a heater unit, with the outside of the tubes being heated by compressed vapor to above its atmospheric pressure boiling point. It then enters the vapor body, where a portion of the water flash-evaporates and insoluble salt crystals form in the remaining liquid. As it enters the vapor body, the concentrate is circulated at high speed to avoid formation of scale on surfaces, and to force developing crystals into the center bottom of the tank. After passing through a mist eliminator, the evaporated water is pulled from the top of the vapor body and compressed and heated by a vapor compressor, before being forced through the heater to transfer heat to the incoming concentrate. In some cases, especially those involving a low inflow rate of 2-6 gpm, an outside source of steam may be used in the heater, either without or in conjunction with (see Figure 2-6) the vaporized concentrate water [Ref. 72]. After condensing on the outside of the heat transfer tubes, the finished distillate leaves the process, and in the case of the WWTP installations covered in this study, rejoins the RO permeate stream. From 1-5 percent of the crystal liquor recirculation stream is wasted from the system to separate insoluble salt from liquid. Typically this is done in a centrifuge or filter press, and removed liquid is sent back into the crystallizer recirculation stream [Ref. 47]. The crystallized solids are landfilled or disposed of in a similar method.

2.4.2.2 Limitations

Crystallizers have been widely proven in industrial applications and are effective at eliminating essentially all water from a waste stream; however, compared to other ZLD and evaporative treatment processes, they have the highest per-unit energy and operations costs. As with brine concentrators, they are mechanically complex and require close supervision and specialized training to operate. Depending on the type of solids and salts being removed, a unit may require frequent boil-out or cleaning to prevent scale buildup. A single crystallizer unit can handle up to roughly 50 gpm [Ref. 72], meaning that if the flow leaving the brine concentrator processes is higher than this, multiple units would be needed.

2.4.3 Costs (Capital and O&M)

As previously mentioned multiple times, capital and operational costs are the largest challenge facing traditional ZLD processes. This is mainly due to the extreme amounts of energy required to evaporate the water out of the concentrate stream. Specific costs for both evaporators and crystallizers for the six cases considered in this study are detailed in Section 3.0. Table 2-12 below details estimated capital and O&M costs for a 1-MGD ZLD system, containing both a mechanical thermal evaporator and a forced circulation crystallizer.

Table 2-12 Conventional ZLD capital and O&M costs (1-MGD facility) [1]

	Evaporator (1 MGD) Capital & Annual Costs	Crystallizer (0.05 MGD) Capital & Annual Costs	Conventional ZLD Capital & Annual Costs
Capital Costs	**$17,698,000**	**$2,864,000**	**$20,562,000**
Annual Power [a]	$4,000,000	$243,000	$4,243,000
Annual Parts	$885,000	$144,000	$1,029,000
Annual Chemicals	$250,000	$15,000	$265,000
Annual Maintenance	$531,000	$86,000	$617,000
Annual Labor	$180,000	-	$180,000
Total Annual O&M Costs	**$5,846,000**	**$488,000**	**$6,334,000**
[1] Information from Ref. 47 a- Power cost are calculated at $0.08/kWh			

2.5 Cost Estimation Planning Level and Sources

The American Association of Cost Engineers International (AACEI) Recommended Practice 18R-97 provides guidelines classifying cost estimates based on their relative accuracy. Table 2-13 describes the different classes of total, installed cost estimates, the relative accuracy, and the project definition based on percent of design complete for each class of estimate.

Table 2-13 Cost estimating classes [1]

Estimate Class	Level of Accuracy	Project Definition
5	+100%/-50%	0-2%
4	+50%/-30%	1-15%
3	+30%/-20%	10-40%
2	+20%/-15%	30-70%
1	+20%/-10%	50-100%
[1] Ref. 76		

The costs developed for this study and presented in Section 3.0 fall under Estimate Class 4, meaning that the level of error on the overestimation of costs could theoretically be as high as 50 percent, or the costs could be underestimated by as much as 30 percent. Class 4 assumes a Project Definition in the 1-15 percent range, meaning that was the percentage of design that was assumed to have been completed, were the facilities in this study to actually be constructed.

The estimations made in this study for capital costs were not just for the equipment itself, but also took into account the other major cost categories that might be associated with the installation of major treatment processes. These other cost categories, along with their proportional relation to the equipment costs, are detailed in Table 2-14.

Table 2-14 Standard capital cost breakdown

Factor	Component	Estimation Method
Direct Construction Cost	Equipment	Technology-Specific Cost
	Installation	25-55% of Equipment Cost
	Piping	31-66% of Equipment Cost
	Instrumentation and Controls	6-30% of Equipment Cost
Indirect Cost	Engineering	15% of Total Construction Cost
	Contingency	15% of Total Construction Cost

As stated in Section 2.2, the program CapdetWorks was used to generate most of the costs for preliminary and biological treatment in the theoretical WWTPs. For Case 6, which involved facultative ponds, the costs developed from recent facultative pond project designed by Bolton & Menk Inc.

The following OEM vendors were contacted to provide equipment costs for sulfate treatment and concentrate reduction and disposal:

- Wigen Water Technologies, Chaska, MN- UF pretreatment and sulfate removal RO equipment costs
- WesTech, Salt Lake City, Utah- Lime softening, Pellet softening, RO equipment costs for concentrate volume minimization.
- New Logic Research, Inc., Emeryville, California- VSEP equipment costs for concentrate volume minimization.
- Veolia Water/HPD- Brine Concentrator and Evaporator costs
- GE Water Process Technology (Suez Water)- Brine Concentrator and Evaporator costs

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3.0 Case Study 1

3.1 10 MGD Activated Sludge Treatment Facility

See a process flow diagram for 2.5 and 10 MGD activated sludge process on the following page.

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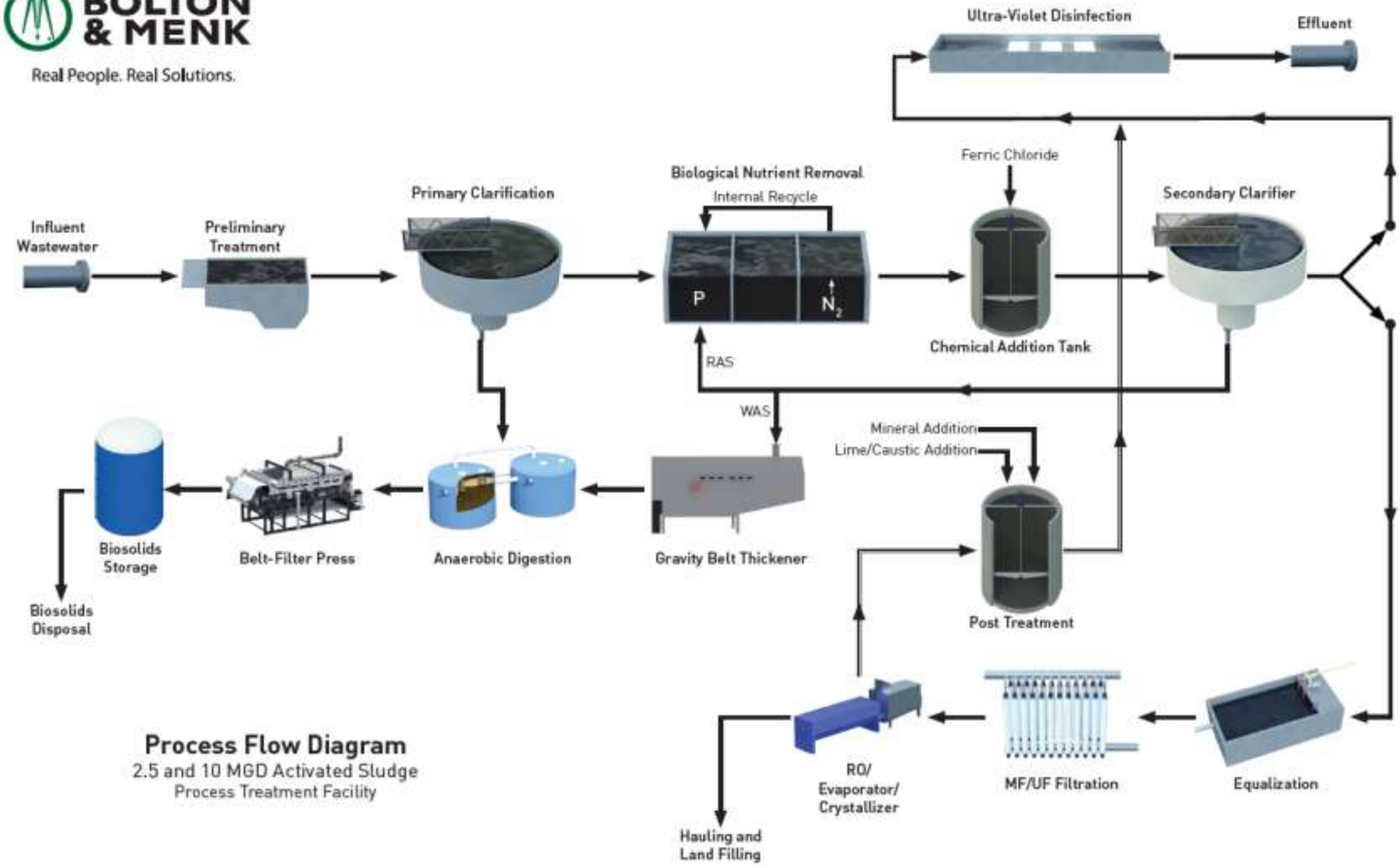


Process Flow Diagram

2.5 and 10 MGD Activated Sludge

Process Treatment Facility

3.2 Biological Pretreatment Costs

Table 3-1 Case 1 Preliminary and biological treatment costs

Biological Liquids Treatment			Biosolids Processing		
Process	**Capital Costs**	**Annual O&M Costs**	**Process**	**Capital Costs**	**Annual O&M Costs**
Preliminary Treatment	$1,030,000	$171,000	Gravity Belt Thickener	$1,540,000	$41,000
Primary Clarifiers	$673,000	$109,000	Anaerobic Digestion	$3,850,000	$211,000
Biological Nutrient Removal	$5,470,000	$856,000	Belt-Filter Press	$914,000	$101,000
Chemical Phosphorus Removal	$235,000	$47,000	Sludge Storage	$2,700,000	$333,000
Final Clarifiers	$1,040,000	$158,000	Hauling/Landfilling Sludge	$1,050,000	$6,320,000
UV Disinfection	$1,030,000	$60,000			
Other Costs[1]	$15,100,000	$1,250,000			
Total Costs	**$24,578,000**	**$2,651,000**	**Total Costs**	**$10,054,000**	**$7,006,000**

[1] Other Costs include various miscellaneous costs not directly associated with a major process, such as engineering and administration, mobilization, site preparation, electrical, and piping, and instrumentation & control

3.3 Membrane Treatment Costs

Table 3-2 Case 1 Reverse osmosis treatment costs

Sulfate Removal		
Process	**Capital Costs**	**Annual O&M Costs**
Control Splitter	$326,000	$134,000
Equalization	$1,705,000	N/A
MF/UF Pretreatment	$14,647,500	$248,000
RO Filtration	$15,112,500	$1,132,000
Neutralization	$2,030,000	$110,000
Total Costs	**$33,821,000**	**$1,624,000**

3.4 Concentrate Minimization & Elimination Costs

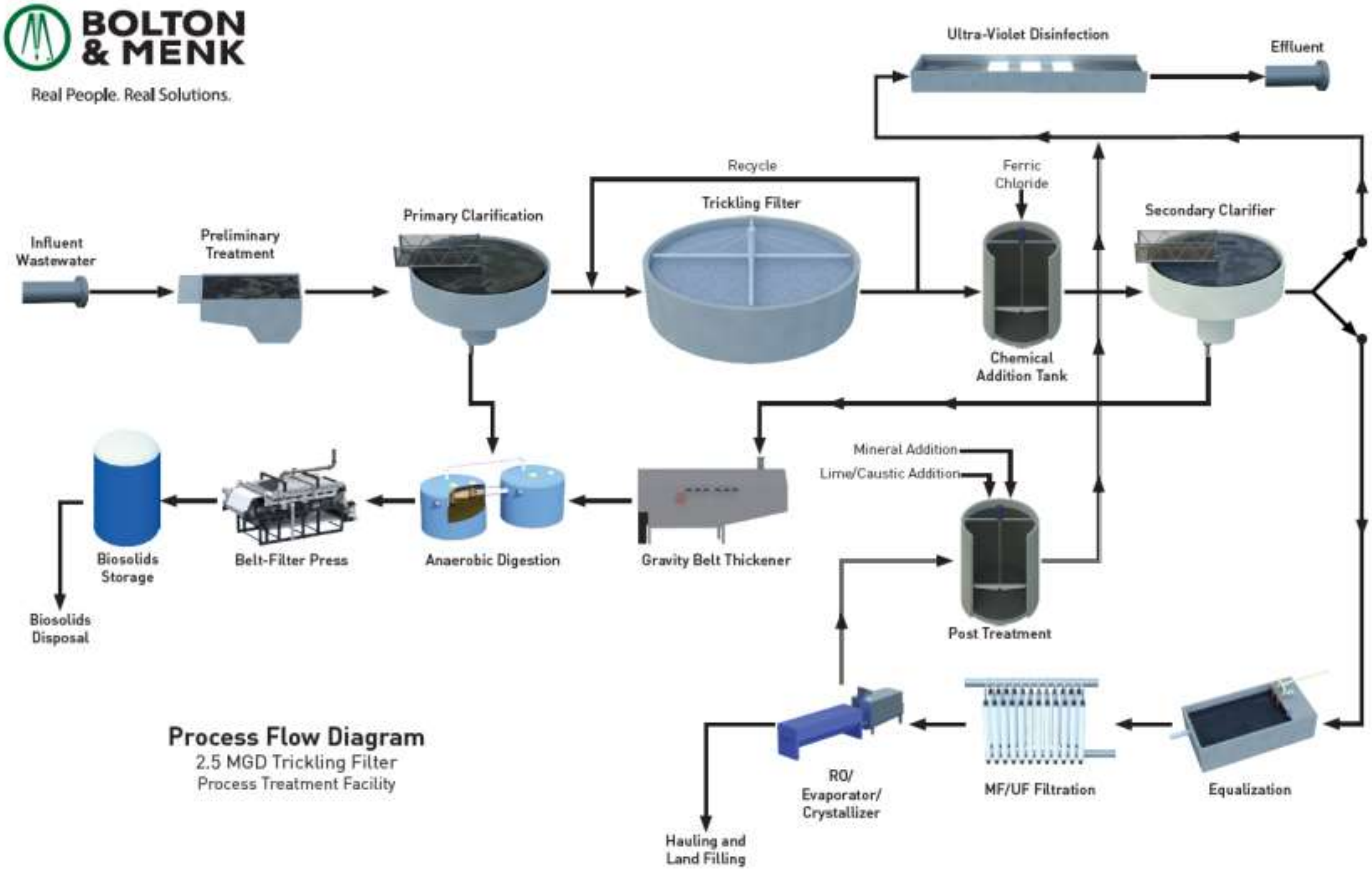
Table 3-3 Case 1 Concentrate minimization and evaporator/crystallizer costs

Concentrate Treatment		
Process	**Capital Costs**	**Annual O&M Costs**
Lime Softening, UF/RO (Option 1)	$16,000,000	$4,920,000
Evaporator/Crystallizer (Op. 1)	$18,000,000	$8,604,000
Hauling/Landfilling Crystal Solids (Op. 1)	N/A	$509,000
Pellet Softening, RO (Option 2)	$6,500,000	$1,550,000
Evaporator/Crystallizer (Op. 2)	$22,000,000	$12,378,000
Hauling/Landfilling Crystal Solids (Op. 2)	N/A	$670,000
VSEP Concentrator (Option 3)	$52,708,000	$3,920,000
Crystallizer (Op. 3)	$12,600,000	$2,311,000
Hauling/Landfilling Crystal Solids (Op. 3)	N/A	$647,000
Total Costs Op. 1	**$34,000,000**	**$14,033,000**
Total Costs Op. 2	**$28,500,000**	**$14,598,000**
Total Costs Op. 3	**$65,308,000**	**$6,878,000**

4.0 Case Study 2

4.1 2.5 MGD Fixed Film Treatment Facility

See a process flow diagram for a 2.5 MGD trickling filter on the following page.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Recycle
Ferric Chloride
Trickling Filter
Secondary Clarifier
Primary Clarification
Preliminary Treatment
Influent Wastewater
Chemical Addition Tank
Mineral Addition
Lime/Caustic Addition
Biosolids Storage
Belt-Filter Press
Anaerobic Digestion
Gravity Belt Thickener
Biosolids Disposal
Post Treatment
Process Flow Diagram
2.5 MGD Trickling Filter
Process Treatment Facility
RO/ Evaporator/ Crystallizer
MF/UF Filtration
Equalization
Hauling and Land Filling

4.2 Biological Pretreatment Costs

Table 4-1 Case 2 Preliminary and biological treatment costs

Biological Liquids Treatment			Biosolids Processing		
Process	**Capital Costs**	**Annual O&M Costs**	**Process**	**Capital Costs**	**Annual O&M Costs**
Preliminary Treatment	$511,000	$76,000	Gravity Belt Thickener	$808,000	$10,000
Primary Clarifiers	$322,000	$58,000	Anaerobic Digestion	$1,750,000	$104,000
Intermediate Pumping	$175,000	$52,000	Belt-Filter Press	$808,000	$24,000
Trickling Filters	$1,040,000	$96,000	Sludge Storage	$1,950,000	$196,000
Final Clarifiers	$463,000	$78,000	Hauling/Landfilling Sludge	$398,000	$1,476,000
Chemical Phosphorus Removal	$235,000	$45,000			
UV Disinfection	$875,000	$43,000			
Other Costs	$15,100,000	$182,000			
Total Costs	**$18,721,000**	**$630,000**	**Total Costs**	**$5,714,000**	**$1,810,000**

4.3 Membrane Treatment Costs

Table 4-2 Case 2 Reverse osmosis treatment costs

Sulfate Removal		
Process	**Capital Costs**	**Annual O&M Costs**
Control Splitter	$144,000	$60,000
Equalization	$1,008,000	N/A
MF/UF Pretreatment	$4,418,000	$62,000
RO Filtration	$4,365,000	$283,000
Neutralization	$1,814,000	$44,000
Total Costs	**$11,749,000**	**$449,000**

4.4 Concentrate Minimization & Elimination Costs

Table 4-3 Case 2 Concentrate minimization and evaporator/crystallizer costs

Concentrate Treatment		
Process	**Capital Costs**	**Annual O&M Costs**
Evaporator/Crystallizer	$16,250,000	$3,378,000
Hauling/Landfilling Crystal Solids	N/A	$100,000
Total Costs	**$16,250,000**	**$3,478,000**

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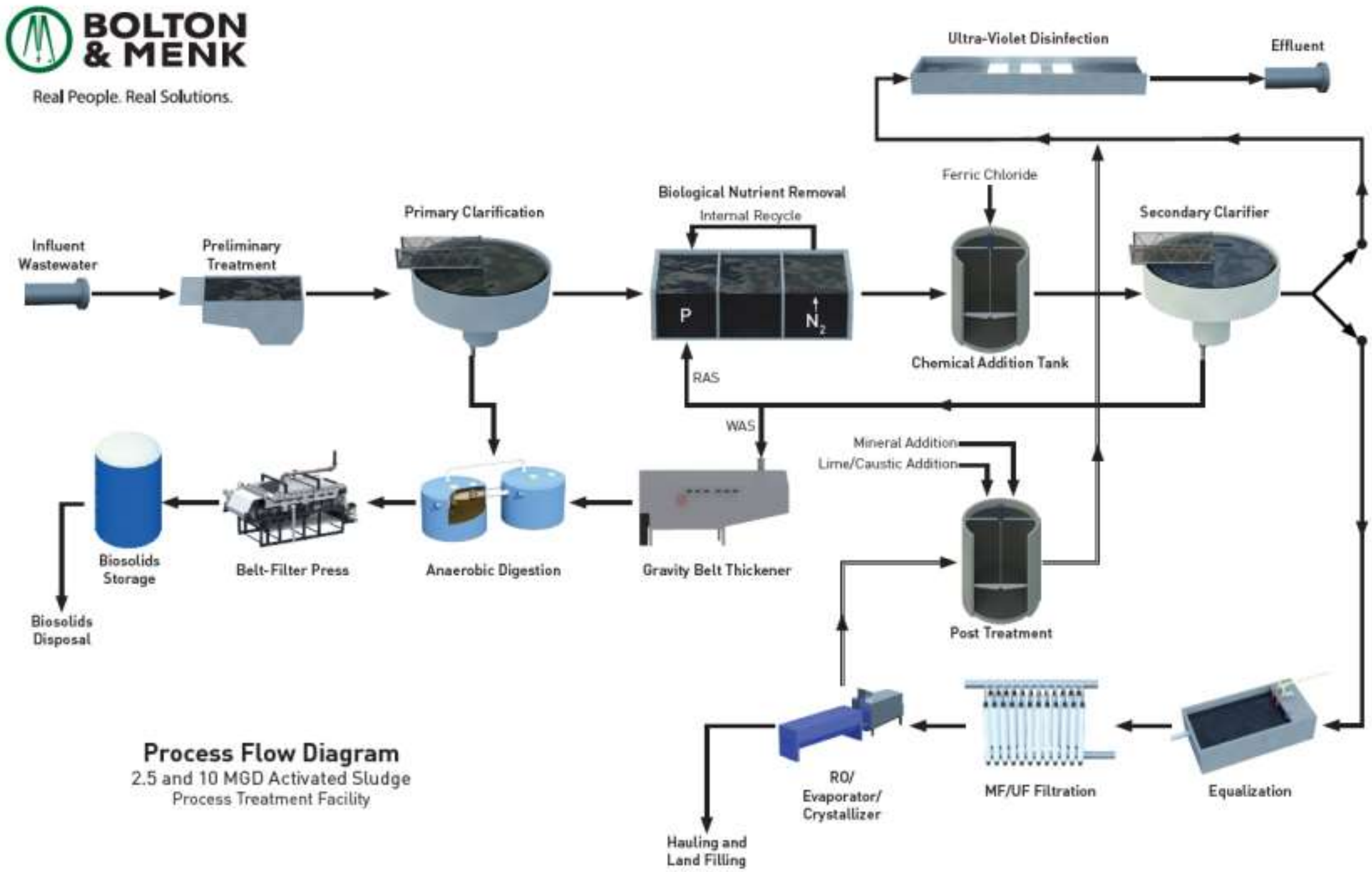
5.0 Case Study 3

5.1 2.5 MGD Activated Sludge Treatment Facility

See a process flow diagram for 2.5 and 10 MGD activated sludge on the following page.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Preliminary Treatment
Primary Clarification
Biological Nutrient Removal
Internal Recycle
P
N_2
RAS
WAS
Ferric Chloride
Chemical Addition Tank
Secondary Clarifier
Ultra-Violet Disinfection
Effluent
Mineral Addition
Lime/Caustic Addition
Post Treatment
Biosolids Storage
Belt-Filter Press
Anaerobic Digestion
Gravity Belt Thickener
Biosolids Disposal
Process Flow Diagram
2.5 and 10 MGD Activated Sludge
Process Treatment Facility
RO/ Evaporator/ Crystallizer
MF/UF Filtration
Equalization
Hauling and Land Filling

5.2 Biological Pretreatment Costs

Table 5-1 Case 3 Preliminary and biological treatment costs

Biological Liquids Treatment			Biosolids Processing		
Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs
Preliminary Treatment	$511,000	$76,000	Gravity Belt Thickener	$808,000	$10,000
Primary Clarifiers	$322,000	$58,000	Anaerobic Digestion	$1,750,000	$106,000
Biological Nutrient Removal	$3,124,000	$391,000	Belt-Filter Press	$808,000	$26,000
Chemical Phosphorus Removal	$235,000	$38,000	Sludge Storage	$2,280,000	$220,000
Final Clarifiers	$924,000	$139,000	Hauling/Landfilling Sludge	$406,000	$1,578,000
UV Disinfection	$375,000	$18,000			
Other Costs	$17,300,000	$182,000			
Total Costs	**$22,791,000**	**$902,000**	**Total Costs**	**$6,052,000**	**$1,940,000**

5.3 Membrane Treatment Costs

Table 5-2 Case 3 Reverse osmosis treatment costs

Sulfate Removal		
Process	Capital Costs	Annual O&M Costs
Control Splitter	$166,000	$68,000
Equalization	$1,008,000	N/A
MF/UF Pretreatment	$4,418,000	$62,000
RO Filtration	$3,836,000	$283,000
Neutralization	$1,891,000	$52,000
Total Costs	**$11,319,000**	**$465,000**

5.4 Concentrate Minimization & Elimination Costs

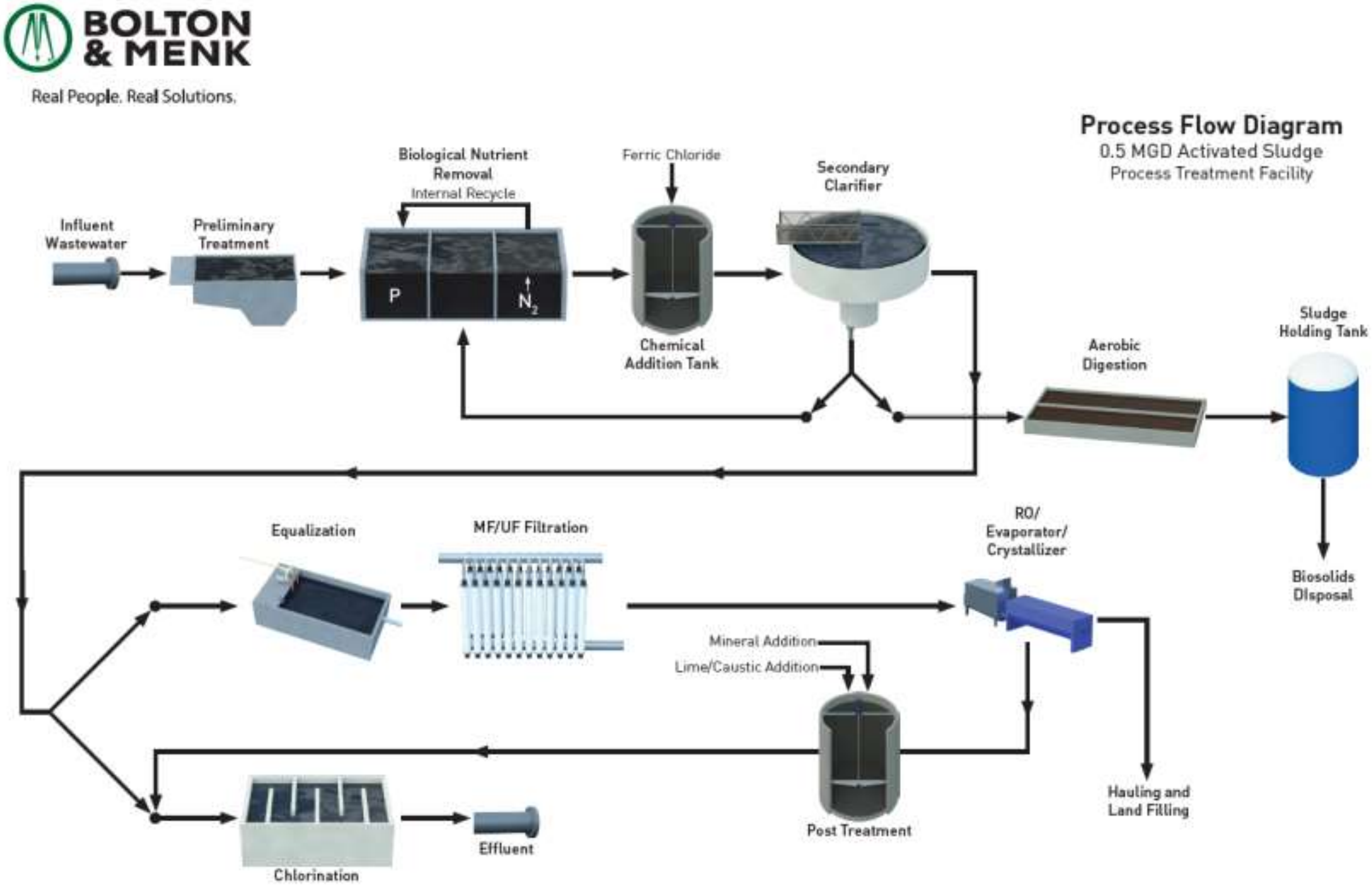
Table 5-3 Case 3 Concentrate minimization and evaporator/crystallizer costs

Concentrate Treatment		
Process	**Capital Costs**	**Annual O&M Costs**
Lime Softening, UF/RO (Option 1)	$11,500,000	$1,942,000
Evaporator/Crystallizer (Op. 1)	$13,750,000	$3,825,000
Hauling/Landfilling Crystal Solids (Op. 1)	N/A	$212,000
Pellet Softening, RO (Option 2)	$4,000,000	$729,000
Evaporator/Crystallizer (Op. 2)	$13,750,000	$4,154,000
Hauling/Landfilling Crystal Solids (Op. 2)	N/A	$321,000
VSEP Concentrator (Option 3)	$30,000,000	$1,624,000
Crystallizer (Op. 3)	$8,400,000	$1,075,000
Hauling/Landfilling Crystal Solids (Op. 3)	N/A	$265,000
Total Costs Op. 1	**$25,250,000**	**$5,979,000**
Total Costs Op. 2	**$17,750,000**	**$5,204,000**
Total Costs Op. 3	**$38,400,000**	**$2,964,000**

6.0 Case Study 4

6.1 0.5 MGD Activated Sludge Treatment Facility

See a process flow diagram for a 0.5 and 10 MGD activated sludge on following page.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Process Flow Diagram
0.5 MGD Activated Sludge
Process Treatment Facility
Influent Wastewater
Preliminary Treatment
Biological Nutrient Removal
Internal Recycle
P
N_2
Ferric Chloride
Chemical Addition Tank
Secondary Clarifier
Aerobic Digestion
Sludge Holding Tank
Biosolids DIsposal
Equalization
MF/UF Filtration
RO/ Evaporator/ Crystallizer
Mineral Addition
Lime/Caustic Addition
Post Treatment
Hauling and Land Filling
Chlorination
Effluent

6.2 Biological Pretreatment Costs

Table 6-1 Case 4 Preliminary and biological treatment costs

Biological Liquids Treatment			Biosolids Processing		
Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs
Preliminary Treatment	$213,000	$42,000	Aerobic Digestion	$330,000	$114,000
Biological Nutrient Removal	$2,425,000	$271,000	Sludge Storage	$1,310,000	$115,000
Final Clarifiers	$235,000	$50,000	Hauling/Landfilling Sludge	$306,000	$305,000
Chemical Phosphorus Removal	$235,000	$36,000			
Chlorination	$316,000	$46,000			
Other Costs	$7,090,000	$124,000			
Total Costs	**$10,514,000**	**$569,000**	**Total Costs**	**$1,946,000**	**$534,000**

6.3 Membrane Treatment Costs

Table 6-2 Case 4 Reverse osmosis treatment costs

Sulfate Removal		
Process	Capital Costs	Annual O&M Costs
Equalization	$558,000	N/A
MF/UF Pretreatment	$2,732,000	$12,000
RO Filtration	$2,369,000	$57,000
Neutralization	$1,659,000	$25,000
Total Costs	**$7,318,000**	**$93,000**

6.4 Concentrate Minimization & Elimination Costs

Table 6-3 Case 4 Concentrate minimization and evaporator/crystallizer costs

Concentrate Treatment		
Process	**Capital Costs**	**Annual O&M Costs**
Lime Softening, UF/RO (Option 1)	$7,600,000	$1,247,000
Evaporator/Crystallizer (Op. 1)	$7,000,000	$576,000
Hauling/Landfilling Crystal Solids (Op. 1)	N/A	$18,000
Pellet Softening, RO (Option 2)	$2,000,000	$477,000
Evaporator/Crystallizer (Op. 2)	$8,000,000	$911,000
Hauling/Landfilling Crystal Solids (Op. 2)	N/A	$41,000
VSEP Concentrator (Option 3)	$10,000,000	$490,000
Crystallizer (Op. 3)	$7,000,000	$411,000
Hauling/Landfilling Crystal Solids (Op. 3)	N/A	$47,000
Total Costs Op. 1	**$14,600,000**	**$1,841,000**
Total Costs Op. 2	**$10,000,000**	**$1,429,000**
Total Costs Op. 3	**$17,000,000**	**$948,000**

7.0 Case Study 5

7.1 0.5 MGD Activated Sludge Treatment Facility

See a process flow diagram for a 0.5 MGD activated sludge process on the following page.

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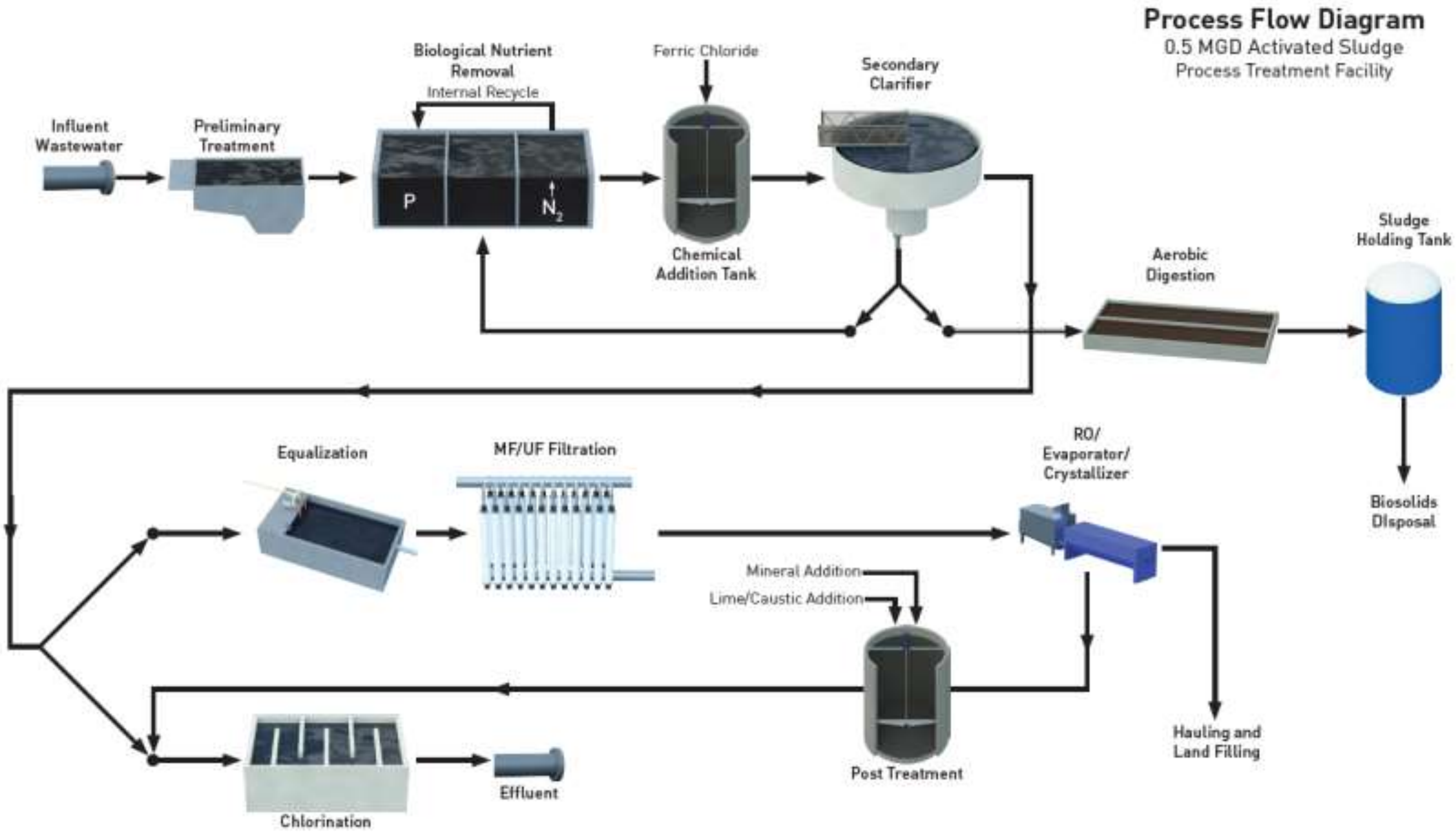

7.2 Biological Pretreatment Costs

Table 7-1 Case 5 Preliminary and biological treatment costs

Biological Liquids Treatment			Biosolids Processing		
Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs
Preliminary Treatment	$213,000	$42,000	Aerobic Digestion	$330,000	$114,000
Biological Nutrient Removal	$2,425,000	$272,000	Sludge Storage	$1,310,000	$115,000
Final Clarifiers	$235,000	$50,000	Hauling/Landfilling Sludge	$306,000	$305,000
Chemical Phosphorus Removal	$235,000	$36,000			
Chlorination	$319,000	$46,000			
Other Costs	$7,070,000	$124,000			
Total Costs	**$10,497,000**	**$570,000**	**Total Costs**	**$1,946,000**	**$534,000**

7.3 Membrane Treatment Costs

Table 7-2 Case 5 Reverse osmosis treatment costs

Sulfate Removal		
Process	Capital Costs	Annual O&M Costs
Control Splitter	$92,000	$43,000
Equalization	$558,000	N/A
MF/UF Pretreatment	$2,732,000	$12,000
RO Filtration	$2,369,000	$57,000
Neutralization	$1,542,000	$21,000
Total Costs	**$7,293,000**	**$132,750**

7.4 Concentrate Minimization & Elimination Costs

Table 7-3 Case 5 Concentrate minimization and evaporator/crystallizer costs

Concentrate Treatment		
Process	Capital Costs	Annual O&M Costs
Evaporator/Crystallizer	$12,000,000	$2,048,000
Hauling/Landfilling Crystal Costs	N/A	$45,000
Total Costs Op. 3	**$12,000,000**	**$2,093,000**

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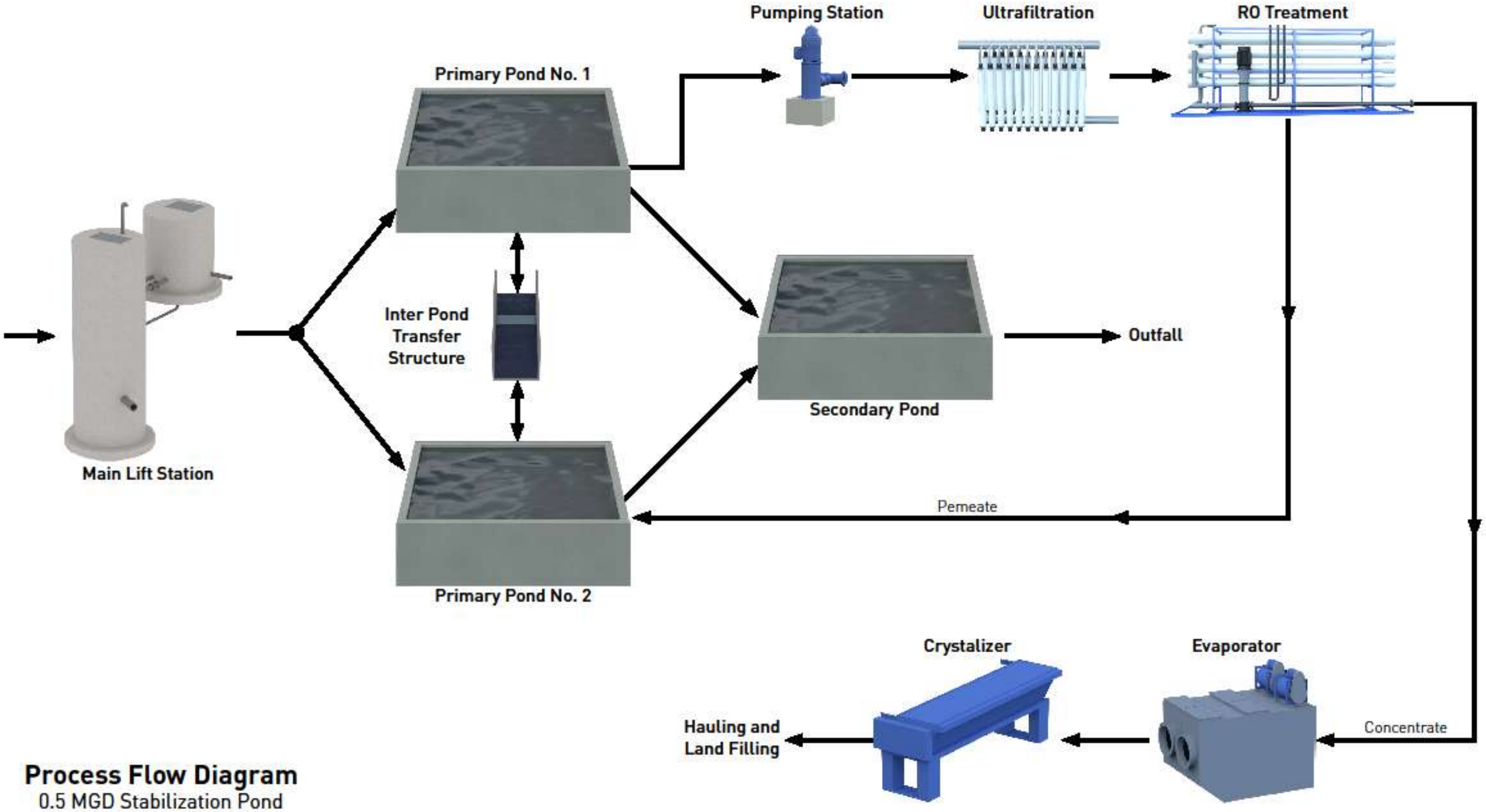
8.0 Case Study 6

8.1 0.5 MGD Stabilization Pond Treatment Facility

See a process flow diagram for a 0.5 MGD stabilization pond on the following page.

Many of the smaller systems are served by controlled discharge facultative stabilization ponds. It is not practical to attempt to treat the effluent from these systems during discharge. The system will discharge 180 days of stored/treated water in a short period of time. Treatment of this discharge would result in an extremely oversized sulfate removal system. It is suggested that these systems should be thought of in the context of mass removed rather than treating the effluent from the system to a specific treatment target (effluent concentration). This mass removal can be accomplished using RO/NF. In a typical three cell treatment system with two primary ponds and a secondary pond, the RO/NF system can be set so that it extracts water from the second primary pond or the secondary pond. Either a rapid sand filter or a MF/UF module followed by the RO/NF system would remove the sulfate, and then discharge the water back into the head of the facultative pond system.



Process Flow Diagram
0.5 MGD Stabilization Pond
Treatment Facility

8.2 Biological Pretreatment Costs

Table 8-1 Case 6 Preliminary and biological treatment costs

Biological Liquids Treatment		
Process	**Capital Costs**	**Annual O&M Costs**
Ponds	$13,000,000	$72,000
Control Structures/Lift Station	$1,000,000	$24,000
Total Costs	**$14,000,000**	**$96,000**

8.3 Membrane Treatment Costs

Table 8-2 Case 6 Reverse osmosis treatment costs

Sulfate Removal		
Process	**Capital Costs**	**Annual O&M Costs**
UF Pretreatment	$2,732,000	$12,000
RO Filtration	$1,360,000	$57,000
RO Permeate Treatment	$1,360,000	$19,000
Total Costs	**$5,452,000**	**$88,000**

8.4 Concentrate Minimization & Elimination Costs

Table 8-3 Case 6 Concentrate minimization and evaporator/crystallizer costs

Concentrate Treatment		
Process	**Capital Costs**	**Annual O&M Costs**
Crystallizer	$13,000,000	$2,417,000
Hauling/Landfilling Crystal Solids	N/A	$62,000
Total Costs	**$13,000,000**	**$2,479,000**

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9.0 Summary

9.1 Costs Associated with Treating Municipal Wastewater Effluent to Remove Sulfate

See the following pages for Table 9-1, cost summary table.

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Table 9-1 Cost summary table

Case Overview		Biological Liquids Treatment			Biosolids Processing			Sulfate Removal			Concentrate Treatment			Total Capital Costs	Total 20-Year O&M Costs	20-Year Present Worth	20-Year Costs Annualized
		Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs				
Case 1	Activated Sludge Influent Flow: 10 MGD Sulfate Influent-Effluent Required: 100 mg/L-10 mg/L	Preliminary Treatment	$1,030,000	$171,050	Gravity Belt Thickener	$1,540,000	$40,860	Control Splitter	$326,000	$133,680	Lime Softening, UF/RO (Option 1)	$16,000,000	$4,920,000				
		Primary Clarifiers	$673,000	$109,430	Anaerobic Digestion	$3,850,000	$211,200	Equalization	$1,705,000	N/A	Evaporator/Crystallizer (Op. 1)	$18,000,000	$8,604,000				
		Biological Nutrient Removal	$5,470,000	$855,800	Belt-Filter Press	$914,000	$100,950	MF/UF Pretreatment	$14,647,500	$247,543	Hauling/Landfilling Crystal Solids (Op. 1)	N/A	$508,974				
		Phosphorus Removal	$235,000	$46,900	Sludge Storage	$2,700,000	$332,900	RO Filtration	$15,112,500	$1,131,500	Pellet Softening, RO (Option 2)	$6,500,000	$1,550,000				
		Final Clarifiers	$1,040,000	$158,170	Hauling/Landfilling Sludge	$1,050,000	$6,320,000	Neutralization	$2,030,000	$110,190	Evaporator/Crystallizer (Op. 2)	$22,000,000	$12,377,500				
		UV Disinfection	$1,030,000	$59,850							Hauling/Landfilling Crystal Solids (Op. 2)	N/A	$670,182				
		Other Costs	$15,100,000	$1,250,000							VSEP Concentrator (Option 3)	$52,708,000	$3,920,000				
											Crystallizer (Op. 3)	$12,600,000	$2,310,750				
											Hauling/Landfilling Crystal Solids (Op. 3)	N/A	$647,379				
		Total Costs	**$24,578,000**	**$2,651,200**	**Total Costs**	**$10,054,000**	**$7,005,910**	**Total Costs**	**$33,821,000**	**$1,622,913**	**Total Costs Op. 1**	**$34,000,000**	**$14,032,974**	**$102,453,000**	**$408,298,642**	**$510,751,642**	**$25,537,582**
											Total Costs Op. 2	**$28,500,000**	**$14,597,682**	**$96,953,000**	**$417,407,382**	**$514,360,382**	**$25,718,019**
											Total Costs Op. 3	**$65,308,000**	**$6,878,129**	**$133,761,000**	**$292,890,992**	**$426,651,992**	**$21,332,600**
Case 2	Trickling Filter Influent Flow: 2.5 MGD Influent-Effluent Required Sulfate: 25 mg/L-10 mg/L	Preliminary Treatment	$511,000	$75,750	Gravity Belt Thickener	$808,000	$9,645	Control Splitter	$144,000	$60,210	Evaporator/Crystallizer	$16,250,000	$3,378,000				
		Primary Clarifiers	$322,000	$58,047	Anaerobic Digestion	$1,750,000	$104,390	Equalization	$1,007,500	N/A	Hauling/Landfilling Crystal Solids	N/A	$100,020				
		Intermediate Pumping	$175,000	$52,140	Belt-Filter Press	$808,000	$23,858	MF/UF Pretreatment	$4,417,500	$61,886							
		Trickling Filters	$1,040,000	$96,250	Sludge Storage	$1,950,000	$196,300	RO Filtration	$4,365,188	$282,875							
		Final Clarifiers	$463,000	$78,302	Hauling/Landfilling Sludge	$398,000	$1,475,800	Neutralization	$1,813,500	$43,750							
		Phosphorus Removal	$235,000	$45,230													
		UV Disinfection	$875,000	$42,790													
		Other Costs	$15,100,000	$182,000													
		Total Costs	**$18,721,000**	**$630,509**	**Total Costs**	**$5,714,000**	**$1,809,993**	**Total Costs**	**$11,747,688**	**$448,721**	**Total Costs**	**$16,250,000**	**$3,478,020**	**$52,432,688**	**$102,703,630**	**$155,136,318**	**$7,756,816**

Case Overview		Biological Liquids Treatment			Biosolids Processing			Sulfate Removal			Concentrate Treatment			Total Capital Costs	Total 20-Year O&M Costs	20-Year Present Worth	20-Year Costs Annualized
		Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs				
Case 3	Activated Sludge Influent Flow: 2.5 MGD Influent-Effluent Required Sulfate: 600 mg/L-100 mg/L	Preliminary Treatment	$511,000	$76,150	Gravity Belt Thickener	$808,000	$10,359	Control Splitter	$166,000	$68,460	Lime Softening, UF/RO (Option 1)	$11,500,000	$1,941,563				
		Primary Clarifiers	$322,000	$58,347	Anaerobic Digestion	$1,750,000	$106,340	Equalization	$1,007,500	N/A	Evaporator/Crystallizer (Op. 1)	$13,750,000	$3,825,000				
		Biological Nutrient Removal	$3,124,000	$391,200	Belt-Filter Press	$808,000	$25,560	MF/UF Pretreatment	$4,417,500	$61,886	Hauling/Landfilling Crystal Solids (Op. 1)	N/A	$212,072				
		Phosphorus Removal	$235,000	$38,420	Sludge Storage	$2,280,000	$219,700	RO Filtration	$3,836,250	$282,875	Pellet Softening, RO (Option 2)	$4,000,000	$728,750				
		Final Clarifiers	$924,000	$138,520	Hauling/Landfilling Sludge	$406,000	$1,577,600	Neutralization	$1,891,000	$52,330	Evaporator/Crystallizer (Op. 2)	$13,750,000	$4,153,500				
		UV Disinfection	$375,000	$18,410							Hauling/Landfilling Crystal Solids (Op. 2)	N/A	$320,504				
		Other Costs	$17,300,000	$182,000							VSEP Concentrator (Option 3)	$30,000,000	$1,624,000				
											Crystallizer (Op. 3)	$8,400,000	$1,075,125				
											Hauling/Landfilling Crystal Solids (Op. 3)	N/A	$264,837				
		Total Costs	**$22,791,000**	**$903,047**	**Total Costs**	**$6,052,000**	**$1,939,559**	**Total Costs**	**$11,318,250**	**$465,551**	**Total Costs Op. 1**	**$25,250,000**	**$5,978,635**	**$65,411,250**	**$149,795,955**	**$215,207,205**	**$10,760,360**
											Total Costs Op. 2	**$17,750,000**	**$5,202,754**	**$57,911,250**	**$137,280,994**	**$195,192,244**	**$9,759,612**
											Total Costs Op. 3	**$38,400,000**	**$2,963,962**	**$78,561,250**	**$101,169,279**	**$179,730,529**	**$8,986,526**
Case 4	Activated Sludge Influent Flow: 0.5 MGD Influent-Effluent Required Sulfate: 300 mg/L-10 mg/L	Preliminary Treatment	$213,000	$41,890	Aerobic Digestion	$330,000	$114,200	Equalization	$558,000	N/A	Lime Softening, UF/RO (Option 1)	$7,600,000	$1,247,227				
		Biological Nutrient Removal	$2,425,000	$271,000	Sludge Storage	$1,310,000	$114,900	MF/UF Pretreatment	$2,731,875	$12,377	Evaporator/Crystallizer (Op. 1)	$7,000,000	$575,650				
		Final Clarifiers	$235,000	$50,338	Hauling/Landfilling Sludge	$306,000	$305,130	RO Filtration	$2,369,175	$56,575	Hauling/Landfilling Crystal Solids (Op. 1)	N/A	$18,386				
		Phosphorus Removal	$235,000	$36,071				Neutralization	$1,658,500	$24,567	Pellet Softening, RO (Option 2)	$2,000,000	$476,500				
		Chlorination	$316,000	$46,190							Evaporator/Crystallizer (Op. 2)	$8,000,000	$911,300				
		Other Costs	$7,090,000	$124,000							Hauling/Landfilling Crystal Solids (Op. 2)	N/A	$41,369				
											VSEP Concentrator (Option 3)	$10,000,000	$490,000				
											Crystallizer (Op. 3)	$7,000,000	$411,400				
											Hauling/Landfilling Crystal Solids (Op. 3)	N/A	$47,082				
		Total Costs	**$10,514,000**	**$569,489**	**Total Costs**	**$1,946,000**	**$534,230**	**Total Costs**	**$7,317,550**	**$93,519**	**Total Costs Op. 1**	**$14,600,000**	**$1,841,263**	**$34,377,550**	**$49,011,021**	**$83,388,571**	**$4,169,429**
											Total Costs Op. 2	$10,000,000	$1,429,169	$29,777,550	$42,363,945	$72,141,495	$3,607,075
											Total Costs Op. 3	$17,000,000	$948,482	$36,777,550	$34,610,464	$71,388,014	$3,569,401

Case Overview		Biological Liquids Treatment			Biosolids Processing			Sulfate Removal			Concentrate Treatment			Total Capital Costs	Total 20-Year O&M Costs	20-Year Present Worth	20-Year Costs Annualized
		Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs	Process	Capital Costs	Annual O&M Costs				
Case 5	Activated Sludge Influent Flow: 0.5 MGD Influent-Effluent Required Sulfate: 300 mg/L-100 mg/L	Preliminary Treatment	$213,000	$41,990	Aerobic Digestion	$330,000	$114,400	Control Splitter	$91,600	$42,601	Evaporator/Crystallizer	$12,000,000	$2,048,250				
		Biological Nutrient Removal	$2,425,000	$271,500	Sludge Storage	$1,310,000	$115,000	Equalization	$558,000	N/A	Hauling/Landfilling Crystal Solids	N/A	$45,353				
		Final Clarifiers	$235,000	$50,438	Hauling/Landfilling Sludge	$306,000	$305,130	MF/UF Pretreatment	$2,731,875	$12,377							
		Phosphorus Removal	$235,000	$36,071				RO Filtration	$2,369,175	$56,575							
		Chlorination	$319,000	$46,300				Neutralization	$1,542,250	$21,197							
		Other Costs	$7,070,000	$124,000													
		Total Costs	**$10,497,000**	**$570,299**	**Total Costs**	**$1,946,000**	**$534,530**	**Total Costs**	**$7,292,900**	**$132,750**	**Total Costs**	**$12,000,000**	**$2,093,603**	**$31,735,900**	**$53,731,966**	**$85,467,866**	**$4,273,393**
Case 6	Facultative Pond Influent Flow: 0.5 MGD Influent-Effluent Required Sulfate: 600 mg/L-250 mg/L	Ponds	$13,000,000	$72,000				UF Pretreatment	$2,731,875	$12,377	Crystallizer	$13,000,000	$2,416,750				
		Control Structures/Lift Station	$1,000,000	$24,000				RO Filtration	$1,360,125	$56,575	Hauling/Landfilling Crystal Solids	N/A	$62,022				
								Post-RO Treatment	$1,360,125	$18,700							
		Total Costs	**$14,000,000**	**$96,000**	**Total Costs**	**$0**	**$0**	**Total Costs**	**$5,452,125**	**$87,652**	**Total Costs**	**$13,000,000**	**$2,478,772**	**$32,452,125**	**$42,944,899**	**$75,397,024**	**$3,769,851**

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9.2 Retrofit Costs

Activity 2 is based on the assumption that the activated sludge treatment plant proceeding the RO is a new BNR treatment plant. In a retrofit situation, the systems that would be considered are conventional activated sludge, fixed film biotowers or trickling filters and stabilization ponds. If the activated sludge is an existing BNR facility it may not have advanced tertiary filters. In that situation, a particle filter will have to be added in addition to the equalization and RO/NF membrane systems. If sulfate management is the only concern, an existing secondary or advanced secondary treatment plant will be acceptable with post clarification solids removal (rapid sand filtration or UF) followed by the RO/NF. Either suspended growth or fixed film will be acceptable. The main consideration in comparing the costs presented in Part 2 to the costs of upgrading a BNR plant will be an increase in the O&M cost on the membranes due to a greater potential for organic fouling if adequate pretreatment is not provided.

In all Cases, the membrane treatment will be similar to the membrane treatment for new construction. Pretreatment will be required to allow the membranes to have a reasonable cleaning cycle and life expectancy. The additional treatment that would be required between the existing technology and the RO/NF system will include a shorter cycle time between clean-in-place and a full cleaning of the membranes. The other additional cost will relate to the reduction in membrane flux rate due to a lower water quality and a shorter life cycle for the membranes due to increased biofouling and siltation.

9.3 New Construction Costs

As mentioned in the previous section, all of the costs generated for this study assume construction of a new treatment facility. Section 2.5 details the level of cost estimations developed and their various sources. The costs include those for the equipment/processes themselves, as well as construction/installation, supporting processes, piping, electrical/controls, and engineering/administrative costs. Not presented in this report were the costs associated with purchasing the land to construct the brand new facilities.

9.4 Operational Complexity

There are two issues that should be considered in contemplating impacts on staffing. The biotowers/trickling filter plants (typically Class B and C operator license) and pond systems (typically Class C and D operator license) will require an operator license below the highest rating. When the RO/NF system is added to the treatment plant the licensing requirements will go to the highest level (A). In addition, it is suggested that the 2.5 MGD activated sludge plant total operational staff may double, and the license requirement for staff involved in working with the RO/Evaporative Condenser/ Crystallizer will be at the highest level and will require significant advanced training. The Valero Welcome Ethanol Plant in Welcome, MN ran a ZLD system for a period of time and has abandoned its use for internal recycle of concentrate into their product. Operating the system is not trivial, but a larger question may be the impact of this advanced technology on the pool of available operational professionals and the need for improving operator training facilities to incorporate this information in existing curriculums. The existing operator training programs train all of the pupils who come to them interested in treatment plant operations. Questions to consider are how to expand this pool, and what will be the required time frame to see a significant increase in operators on the high end of the licensure ladder. Also, what a utility will have to pay these individuals to keep them in the smaller communities when there is a shortage and the smaller utilities are in essence bidding against the large utilities for qualified individuals. Perhaps some thought needs to be given as to how licensure is done in these systems.

10.0 Conclusions

Six case studies were considered for detailed cost analyses. The costs included biological treatment and biosolids treatment and disposal costs, sulfate removal by RO membrane treatment, and RO concentrate disposal with and without concentrate minimization. Costs presented in this section and previous sections were rounded to the nearest $1,000, with the starting values being outputs of the various programs and calculations used to generate them. The only values not rounded were the 20-year present cost summaries, generated by the equation presented later in this section. Table 10-1 summarizes the details of the evaluated Cases.

Table 10-1 Details of six case studies

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Biological Treatment Technology	Activated Sludge	Trickling Filter	Activated Sludge	Activated Sludge	Activated Sludge	Facultative Pond
Design Flow (MGD)	10	2.5	2.5	0.5	0.5	0.5
Sulfate Influent (mg/L)	100	25	600	300	300	600
Required Sulfate Effluent (mg/L)	10	10	100	10	100	250
Percent of Flow Treated by RO System	93%	63%	89%	99%	74%	68%

Table 10-2 presents the estimated RO concentrate flows leaving the sulfate removal treatment that must be managed, treated, and disposed of for each case study. Concentration minimization was considered for Cases 1, 3, and 4.

Table 10-2 Estimated RO concentrate flow

Case Study	Flow (MGD)	Percentage of Flow to be Treated by RO System for Sulfate Removal	RO Reject Flow (GPM)
1	10	93%	1100
2	2.5	63%	110
3	2.5	89%	500
4	0.5	99%	85
5	0.5	74%	65
6	0.5	68%	75

Table 10-3 presents the biological treatment costs for liquid treatment and for the resulting biosolids.

Table 10-3 Estimated costs for biological treatment costs for liquid treatment and biosolids

Case Study	Biological Liquids Treatment		Biosolids Processing	
	Capital Costs ($)	O&M Costs ($)	Capital Costs ($)	O&M Costs ($)
1	24,578,000	2,651,000	10,054,000	7,006,000
2	18,721,000	631,000	5,714,000	1,810,000
3	22,791,000	903,000	6,052,000	1,940,000
4	10,514,000	569,000	1,946,000	534,000
5	10,497,000	570,000	1,946,000	535,000
6	14,000,000	96,000	N/A	N/A

Table 10-4 presents the costs for sulfate removal by RO membrane treatment process and concentrate management and disposal costs by mechanical and thermal evaporative process. The ultimate disposal of RO concentrate is to a municipal solid waste landfill as crystallized solid product.

Table 10-4 Estimated costs for sulfate removal by ro membrane treatment process and concentrate management

Case Study	Sulfate Removal		Concentrate Treatment	
	Capital Costs ($)	O&M Costs ($)	Capital Costs ($)	O&M Costs ($)
1	33,821,000	1,623,000	(1) 34,000,000 (2) 28,500,000 (3) 65,308,000	(1) 14,033,000 (2) 14,598,000 (3) 6,878,000
2	11,748,000	449,000	16,250,000	3,478,000
3	11,318,000	466,000	(1) 25,250,000 (2) 17,750,000 (3) 38,400,000	(1) 5,979,000 (2) 5,203,000 (3) 2,964,000
4	7,318,000	94,000	(1) 14,600,000 (2) 10,000,000 (3) 17,000,000	(1) 1,841,000 (2) 1,429,000 (3) 948,000
5	7,293,000	133,000	12,000,000	2,094,000
6	5,452,000	88,000	13,000,000	2,479,000

(1) Lime softening is used prior to secondary (concentrate reduction) RO treatment.
(2) Pellet softening is used prior to secondary (concentrate reduction) RO treatment.
(3) A VSEP concentrator process is used treat RO concentrate.

One additional subject of consideration during the development of this report was the theoretical minimum cost of a sulfate removal system at a wastewater treatment facility with extremely low flows. Table 10-5, below, shows the estimated capital costs for implementation of these processes at a 200,000 gpd plant, with the assumption that 90% of the daily flow would be treated by the processes. The base level costs are dictated by the smallest crystallizer unit, which itself costs $8,000,000.

Table 10-5 Costs for Sulfate Removal at 200,000 GPD Facility

Process	Capital Cost ($)
UF Pretreatment	$1,700,000
RO Treatment	$1,500,000
RO Permeate Treatment	$800,000
Concentrate Disposal	$8,000,000
Total	**$12,000,000**

Figure 10-1 shows, solely for the Case 1 scenario, the total compiled costs over 20 years for construction and operation of the concentration minimization and evaporative disposal processes, with the comparative variable being the type of concentrate minimization process that is used.

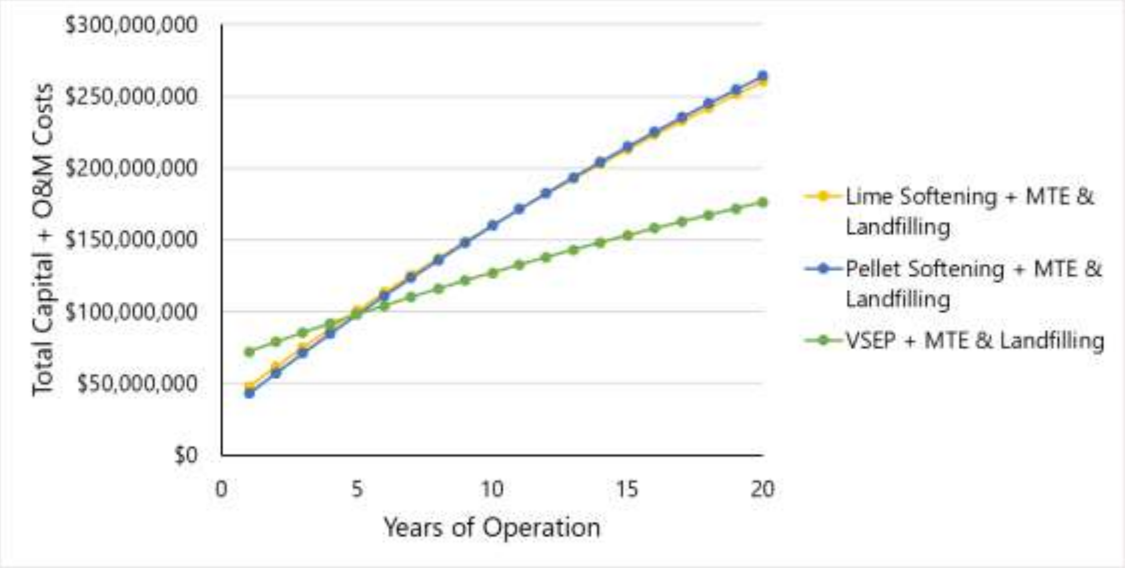

Figure 10-1 Case 1 Concentrate Minimization Lifetime Cost Comparison

Present worth analysis was carried with discount rate of 5.375% and inflation rate of 3% using the following equation:

$$P = A\left\{\left(\frac{1+E}{i-E}\right) * \left[1-\left[\frac{1+E}{1+i}\right]^{n}\right]\right\} + \text{Capital Cost}$$

Where:

P: Present worth
A: Annual O&M costs
i: Discount rate (5.375%)
E: Inflation rate (3%)
N: Period (20 years)

Table 10-6 presents the summary of the total capital costs, O&M costs and a 20-year present cost for all six case studies.

Table 10-6 Summary of the total capital costs, O&M costs and a 20-year present cost for all six case studies

Case Study	Total Capital Costs ($)	Total O&M Costs ($)	20-Year Present Costs ($)
1	(1) 102,453,000 (2) 96,953,000 (3) 133,761,000	(1) 25,313,000 (2) 25,878,000 (3) 18,158,000	(1) 510,751,642 (2) 514,360,382 (3) 426,651,992
2	52,433,000	6,367,000	155,136,318
3	(1) 65,411,000 (2) 57,911,000 (3) 78,561,000	(1) 9,287,000 (2) 8,511,000 (3) 6,272,000	(1) 215,207,205 (2) 195,192,224 (3) 179,730,529
4	(1) 34,378,000 (2) 29,778,000 (3) 36,778,000	(1) 3,039,000 (2) 2,626,000 (3) 2,146,000	(1) 83,388,571 (2) 72,141,495 (3) 71,388,014
5	31,736,000	3,331,000	85,467,866
6	32,452,000	2,662,000	75,397,024

(1) Lime softening is used prior to secondary (concentrate reduction) RO treatment.
(2) Pellet softening is used prior to secondary (concentrate reduction) RO treatment.
(3) A VSEP concentrator process is used treat RO concentrate.

For Cases 1, 3, and 4, three types of concentrate minimization treatment were considered: lime softening, pellet softening, and VSEP treatment. Lime softening and pellet softening reduce the calcium in the RO reject so that lime-softened water can be further treated by RO treatment to reduce the concentrate volume that needs to be treated in the thermal evaporator and crystallizer for ultimate disposal. In Figure 10-1 and Table 10-6 it can be seen that the 20-year present value cost is significantly lower for the VSEP process for concentrate volume reduction compared to lime and pellet softening, although the VSEP process has very high initial capital costs. No concentrate volume minimization was considered for Case 2, Case 5 and Case 6. By comparing the present value costs for the life cycles of Cases 4 and 5, it becomes apparent that concentrate volume reduction by lime softening does not provide adequate savings to consider it in comparison to pellet softening or VSEP process.

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