



WATER PINCH ANALYSIS OF ROC PLANT

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Abstract

This thesis focused on the implementation of water pinch to optimize the water using network of ROC plant. This plant normally consumes over 1,100 tons of water per hour. In this work, three key contaminants including silica, total dissolved solids (TDS) and chemical oxygen demand (COD) have been analyzed. These key contaminants were firstly analyzed separately as a single contaminant and the amount of required fresh water was calculated for all of them. In this stage, the pinch point was located at silica concentration of 90 ppm, TDS of 1200 ppm and COD of 45 ppm which are equal to the outlet concentration of the cooling tower. Therefore, the optimal water-using network could be designed by investigating and de-bottlenecking of the cooling tower. In the next stage, these three contaminants were analyzed simultaneously. The optimal water-using networks were investigated by using GAMS (General Algebraic Modeling System). There were six cases of water-using network in this stage. Each case had different constraints. The results show that the amount of required fresh water could be reduced by 17.655, 11.491, 45.14, 29.174, 31.491 and 35.491 tons/hr for cases 1 to 6, respectively. The suitable water-using network need to be investigated after the investment cost for each case is calculated.

Keywords: Water Pinch Analysis/ Multiple Contaminants/ Water-using Network/
Minimize Fresh Water

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บทคัดย่อ

เนื่องจากการปริมาณการใช้น้ำในกระบวนการผลิตของบริษัท ROC นั้นเป็นปริมาณที่สูง หรือประมาณ 1,100 ตันต่อชั่วโมง จึงเป็นที่มาของวัตถุประสงค์หลักของโครงการวิจัยนี้ นั่นคือ เพื่อหาปริมาณน้ำที่ใช้น้อยที่สุด และโครงสร้างการใช้น้ำที่เหมาะสม ซึ่งการศึกษานี้ได้สนใจสิ่งเจือปนทั้งหมด 3 ชนิด ได้แก่ Silica, TDS และ COD ซึ่งจะแบ่งการศึกษาออกเป็น 2 ประเภท นั่นคือ แบบสนใจสิ่งเจือปนเดียว (Single contaminant) และสนใจสิ่งเจือปนหลายชนิดพร้อมๆ กัน (Multiple contaminants) จากการศึกษาแบบสิ่งเจือปนเดียวนั้น จุดพินช์ที่ได้นั้น ได้แก่ จุดที่มีความเข้มข้นของ Silica, TDS และ COD เท่ากับ 90, 1200 และ 45 ppm ตามลำดับ ซึ่งเป็นจุดที่มีความเข้มข้นเท่ากับ ความเข้มข้นขาออกของหอหล่อเย็น (Cooling tower) ผลจากการศึกษาแบบสิ่งเจือปนเดียวนอกได้ว่าการใช้น้ำในส่วนของหอหล่อเย็นเป็นจุดที่จะต้องทำการวิเคราะห์เพื่อลดปริมาณการใช้น้ำเนื่องจากเป็นบริเวณคอขวด และในการศึกษาแบบสิ่งเจือปนหลายชนิดพร้อมกันนั้นจะใช้วิธีโปรแกรมทางคณิตศาสตร์ในการแก้ปัญหา ซึ่งโปรแกรมที่ใช้คือ General Algebraic Modeling System (GAMS) ซึ่งผลจากการศึกษาแบบหลายสิ่งเจือปนนั้นจะแบ่งออกเป็น 6 โครงสร้าง ซึ่งแต่ละโครงสร้างนั้นแตกต่างกันที่ข้อกำหนด จากผลที่ได้นั้นพบว่าปริมาณน้ำที่ใช้สามารถลดลงได้ 17.655, 11.491, 45.14, 29.174, 31.491 และ 35.491 ตันต่อชั่วโมง สำหรับโครงสร้างที่ 1 ถึง 6 ตามลำดับ ซึ่งหลังจากที่ทำการศึกษาคำนวณเงินที่ต้องลงทุนในการสร้างท่อน้ำเพิ่มในแต่ละโครงสร้าง จะทำให้ทราบว่าโครงสร้างการใช้น้ำที่เหมาะสมที่สุดที่จะนำไปใช้ในกระบวนการนั้นเป็นโครงสร้างใด

คำสำคัญ: การวิเคราะห์พินช์น้ำ/ โครงสร้างการใช้น้ำ/ การหาปริมาณการใช้น้ำที่น้อยที่สุด

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CONTENTS

	PAGE
ENGLISH ABSTRACT	ii
THAI ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
CONTENTS	v
LIST OF TABLES	vii
LIST OF FIGURES	viii
NOMENCLATURES	ix
CHAPTER	
1. INTRODUCTION	1
1.1 Background	1
1.2 Objectives	2
1.3 Scope of work	2
1.4 Expected result	2
2. THEORIES AND LITERATURE REVIEWS	3
2.1 Theories	3
2.1.1 Water Pinch Technology	3
2.2 Literature reviews	8
3. METHODOLOGY	10
3.1 Methodology	10
3.2 Work plan	12
4. RESULTS AND DISCUSSION	13
4.1 Process description	13
4.2 Single contaminant approach	17
4.3 Multiple contaminants approach	27
4.3.1 Model setup	27
4.3.2 Results and discussion	30
5. CONCLUSIONS AND RECOMMENDATIONS	40
5.1 Conclusions	40
5.2 Recommendations	41
REFERENCES	42
APPENDIX	43
A GAMS input and output for case 1	43
B GAMS input and output for case 2	63

C	GAMS input and output for case 3	84
D	GAMS input and output for case 4	105
CURRICULUM VITAE		126

LIST OF TABLES

TABLE	PAGE
2.1 The example of limiting process data	5
2.2 The example of limiting process data with the limiting water flowrates	5
3.1 Detail of work plan	12
4.1a Limiting inlet and outlet concentration of each contaminant for each operation	15
4.1b Capacity and flowrate loss of each operation	16
4.1c Mass load of each operation	16
4.2a Capacity and removal ration of each regeneration	16
4.2b Limiting inlet concentration of each regeneration constructions of the EHIDiC with uniform heat distribution scheme	16
4.3 List of selected operations	17
4.4 Concentration interval diagram in term of Silica	19
4.5 Concentration interval diagram in term of TDS	22
4.6 Concentration interval diagram in term of COD	25
4.7 Concentration of each contaminant of each source of water	27
4.8 Inlet and outlet concentration of each contaminant for each operation case1	32
4.9 Inlet and outlet concentration of each contaminant for each operation case2	34
4.10 Inlet and outlet concentration of each contaminant for each operation case3	35
4.11 Inlet and outlet concentration of each contaminant for each operation case4	37

LIST OF FIGURES

FIGURE	PAGE
2.1 Countercurrent contact between a contaminant-rich process and a contaminant-lean water stream	4
2.2 Contaminant concentration versus mass load of contaminant transferred	4
2.3 The lines of any operations.	6
2.4 Concentration-composite curve	7
2.5 Concentration-composite curve and water supply line	7
2.6 Grid diagram of the preliminary water-using network	8
3.1 Steps of performing this project	10
4.1 The block flow diagram with the flowrate of the water balances	14
4.2 The block flow diagram of selected water-using network	15
4.3 Concentration composite curve in term of Silica	18
4.4 Preliminary block diagram in term of Silica	20
4.5 Concentration composite curve in term of TDS	21
4.6 Preliminary block diagram in term of TDS	23
4.7 Concentration composite curve in term of COD	24
4.8 Preliminary block diagram in term of COD	26
4.9 Block diagram of water-using network for case1	31
4.10 Block diagram of water-using network for case2	33
4.11 Block diagram of water-using network for case3	35
4.12 Block diagram of water-using network for case4	36
4.13 Block diagram of water-using network for case5	37
4.14 Block diagram of water-using network for case6	48

NOMENCLATURES

$C_f(J)$	Concentration of contaminant J of fresh water in ppm
$C_d(J)$	Concentration of contaminant J of water from diversion box in ppm
$C_b(J)$	Concentration of contaminant J of boiler blowdown in ppm
$M_1(J)$	Mass load of contaminant J for operation 1 in kg/hr
$M_2(J)$	Mass load of contaminant J for operation 2 in kg/hr
$M_3(J)$	Mass load of contaminant J for operation 3 in kg/hr
$M_4(J)$	Mass load of contaminant J for operation 4 in kg/hr
$M_{5C}(J)$	Mass load of contaminant J for operation 5C in kg/hr
$M_{5D}(J)$	Mass load of contaminant J for operation 5D in kg/hr
$C_{in,1}^{lim}(J)$	Limiting inlet concentration of contaminant J for operation 1 in ppm
$C_{in,2}^{lim}(J)$	Limiting inlet concentration of contaminant J for operation 2 in ppm
$C_{in,3}^{lim}(J)$	Limiting inlet concentration of contaminant J for operation 3 in ppm
$C_{in,4}^{lim}(J)$	Limiting inlet concentration of contaminant J for operation 4 in ppm
$C_{in,5C}^{lim}(J)$	Limiting inlet concentration of contaminant J for operation 5C in ppm
$C_{in,5D}^{lim}(J)$	Limiting inlet concentration of contaminant J for operation 5D in ppm
$C_{in,6}^{lim}(J)$	Limiting inlet concentration of contaminant J for operation 6 in ppm
$C_{out,1}^{lim}(J)$	Limiting outlet concentration of contaminant J for operation 1 in ppm
$C_{out,2}^{lim}(J)$	Limiting outlet concentration of contaminant J for operation 2 in ppm
$C_{out,3}^{lim}(J)$	Limiting outlet concentration of contaminant J for operation 3 in ppm
$C_{out,4}^{lim}(J)$	Limiting outlet concentration of contaminant J for operation 4 in ppm
$C_{out,5C}^{lim}(J)$	Limiting outlet concentration of contaminant J for operation 5C in ppm
$C_{out,5D}^{lim}(J)$	Limiting outlet concentration of contaminant J for operation 5D in ppm
$C_{out,6}^{lim}(J)$	Limiting outlet concentration of contaminant J for operation 6 in ppm
$C_{in,R1}^{lim}(J)$	Limiting inlet concentration of contaminant J for regeneration 1 in ppm
$C_{in,R2}^{lim}(J)$	Limiting inlet concentration of contaminant J for regeneration 2 in ppm
$C_{in,R3}^{lim}(J)$	Limiting inlet concentration of contaminant J for regeneration 3 in ppm
$F_{i,loss}$	Water loss for operation i in ton/ hr
$F_{i,gain}$	Water gain for operation i in ton/ hr
$R_{R1}(J)$	Removal ration of contaminant J for regeneration 1
$R_{R2}(J)$	Removal ration of contaminant J for regeneration 2
$R_{R3}(J)$	Removal ration of contaminant J for regeneration 3
Capacity _i	Capacity of operation i in ton/ hr
D^{lim}	Limiting total flowrate of water from diversion box in ton/ hr
B^{lim}	Limiting total flowrate of boiler blowdown in ton/ hr
F_i	Flowrate of freshwater to operation i in ton/hr
D_i	Flowrate of water from diversion box to operation i in ton/hr
B_i	Flowrate of boiler blowdown to operation i in ton/hr
$X_{i,j}$	Flowrate of water from operation j to operation i in ton/hr

$X_{i,R1}$	Flowrate of water to operation i from regeneration 1 in ton/hr
$X_{i,R2}$	Flowrate of water to operation i from regeneration 2 in ton/hr
$X_{i,R3}$	Flowrate of water to operation i from regeneration 3 in ton/hr
$X_{R1,i}$	Flowrate of water from operation i to regeneration 1 in ton/hr
$X_{R2,i}$	Flowrate of water from operation i to regeneration 2 in ton/hr
$X_{R3,i}$	Flowrate of water from operation i to regeneration 3 in ton/hr
X_{reject}	Flowrate of water from regeneration 1 to rejected stream in ton/hr
$C_{in,1}(J)$	Inlet concentration of contaminant J for operation 1 in ppm
$C_{in,2}(J)$	Inlet concentration of contaminant J for operation 2 in ppm
$C_{in,3}(J)$	Inlet concentration of contaminant J for operation 3 in ppm
$C_{in,4}(J)$	Inlet concentration of contaminant J for operation 4 in ppm
$C_{in,5C}(J)$	Inlet concentration of contaminant J for operation 5C in ppm
$C_{in,5D}(J)$	Inlet concentration of contaminant J for operation 5D in ppm
$C_{in,6}(J)$	Inlet concentration of contaminant J for operation 6 in ppm
$C_{out,1}(J)$	Outlet concentration of contaminant J from operation 1 in ppm
$C_{out,2}(J)$	Outlet concentration of contaminant J from operation 2 in ppm
$C_{out,3}(J)$	Outlet concentration of contaminant J from operation 3 in ppm
$C_{out,4}(J)$	Outlet concentration of contaminant J from operation 4 in ppm
$C_{out,5C}(J)$	Outlet concentration of contaminant J from operation 5C in ppm
$C_{out,5D}(J)$	Outlet concentration of contaminant J from operation 5D in ppm
$C_{out,6}(J)$	Outlet concentration of contaminant J from operation 6 in ppm
$C_{in,R1}(J)$	Inlet concentration of contaminant J for regeneration 1 in ppm
$C_{in,R2}(J)$	Inlet concentration of contaminant J for regeneration 2 in ppm
$C_{in,R3}(J)$	Inlet concentration of contaminant J for regeneration 3 in ppm
$C_{out,R1}(J)$	Outlet concentration of contaminant J from regeneration 1 in ppm
$C_{out,R2}(J)$	Outlet concentration of contaminant J from regeneration 2 in ppm
$C_{out,R3}(J)$	Outlet concentration of contaminant J from regeneration 3 in ppm
W_i	Flowrate of wastewater from operation i in ton/hr
F_{R1}	Flowrate of freshwater to regeneration 1 in ton/hr
F_{R2}	Flowrate of freshwater to regeneration 2 in ton/hr
F_{R3}	Flowrate of freshwater to regeneration 3 in ton/hr
D_{R1}	Flowrate of water from diversion box to regeneration 1 in ton/hr
D_{R2}	Flowrate of water from diversion box to regeneration 2 in ton/hr
D_{R3}	Flowrate of water from diversion box to regeneration 3 in ton/hr
B_{R1}	Flowrate of boiler blowdown to regeneration 1 in ton/hr
B_{R2}	Flowrate of boiler blowdown to regeneration 2 in ton/hr
B_{R3}	Flowrate of boiler blowdown to regeneration 3 in ton/hr
F_{lim}	Freshwater consumption for overall process system in ton/hr

CHAPTER 1 INTRODUCTION

1.1 Background

In the chemical process industry, water is a major resource for both utility system and process system. Water is normally used in the process as either direct or indirect ways. Wastewater contained with various hazardous or toxic pollutants that need to be strictly controlled is also generated from many sources in the process. Nowadays, management of wastewater has become one of the greatest challenges facing the chemical process industries. Because wastewater is one of industry's major waste products, the ability to reclaim wastewater for reuse is an important step toward overall waste reduction. Rayong Olefins Co., Ltd. (ROC), a chemical company of Siam Cement Group (SCG), uses about 1,100 m³/h of fresh water, and releases 875,609 m³/year of wastewater to the environment. The large cost of fresh water and the wastewater treatment are a strong incentive to minimize water usage and wastewater generation. Therefore, minimizing fresh water flowrate throughout the system or maximizing the reuse of water within the plant can be of great help.

There are two basic strategies for reducing water usage in the process. The first strategy is modifying individual process and utility units to reduce their inherent need for water. The second strategy is seeking opportunities to use the outlet water from one operation to satisfy the water requirement of the same or another operation. In some cases, the water may require some regeneration prior to reuse. Examples of regeneration include pH adjustment, filtration, membrane separation, sour-water stripping and ion exchange.

Water pinch analysis, a tool for designing an optimal water network, is one of the most significant advances in the area of water minimization [1]. Water-using operation can be minimized through four methods which are process changes, water reuse, regeneration reuse and regeneration recycling. Reuse, wastewater can be reused directly in the operation, provide the level of previous contamination that does not interfere with the process. It may require wastewater to be blended with wastewater from other operations and/or fresh water. For regeneration reuse, wastewater can be regenerated to remove the contaminants, which would prevent its reuse in other operations. After regeneration, the generated water is not allowed to re-enter operation in which it has previously been used. For regeneration recycling, wastewater can be regenerated to remove contaminants, which have built up, and then the water is recycled to the other previous operations. There have been two approaches to obtain fundamental designs of the water-using systems, which are conceptual graphical design (water pinch) and mathematical programming.

Water pinch analysis is a simple method but it has beneficial results when applied to the water-using industries. However, it will be more difficult when the number of concerned contaminants increases. Therefore, mathematical optimization outperforms water pinch analysis for multiple contaminants or constraints. Since mathematical optimization approaches of Nonlinear Programming (NLP) and Mixed-Integer

Nonlinear Programming (MINLP) are sensitive to the choice of initial values, it may identify a local optimum and less than global optimal configuration of a water using network.

1.2 Objective

1. To apply pinch analysis and optimization technique for solving the water-using minimization problem.
2. To develop and optimum water-using system of the ROC plant to reduce fresh water consumption in the process system.
3. To propose the recommendations about water-using system to ROC plant

1.3 Scope of work

1. Formulate an optimization program to target minimum water usage throughout the process system.
2. Focus on process with multiple contaminants which are Silica, TDS and COD.
3. Consider water-using system including water reuse, regeneration reuse and regeneration recycling.

1.4 Expected Results

1. Fresh water consumption and wastewater generation in the ROC plant are reduced.

CHAPTER 2 THEORIES AND LITERATURE REVIEWS

The theories and literature reviews which concern the pinch water technology will be presented in this chapter.

2.1 Theories

2.1.1 Water Pinch technology [1]

2.1.1.1 Mass integration and mass-exchange networks

Water pinch technology is a type of mass-exchange integration involving water-using operations. Mass-exchange integration is a recent development in pinch technology that deals with pollution prevention, resource recovery, waste reduction, and etc. This technique is used to analyze water networks in order to increase the efficiency of water using in the process. There are four methods to water minimization which are process changes, water reuse, regeneration reuse and regeneration recycling. In water reuse method, wastewater from some operations can be directly used in other operations. Blending and/or mixing with some fresh water may be required. In regeneration reuse method, wastewater from some operations is regenerated to remove contaminants before it is used in other operations. In regeneration recycling method, the regenerated water could eventually be redirected to an operation where it was previously used. Mass-exchange operations include absorption, adsorption, ion exchange, leaching, solvent extraction, stripping, and similar process. A mass-exchange integration problem involves transferring mass from rich process streams (decreasing their concentrations) to lean process stream (increasing their concentrations). Thus, each stream reaches its desired outlet concentration while minimizes waste production and utility consumption.

2.1.1.2 Water-pinch technology concept

Water-pinch technology can be divided into three tasks which are analysis, synthesis and retrofit. The first task is water-pinch analysis. The objective of this task is to identify the minimum fresh water consumption and wastewater generation in water-using operation. The second task is water-pinch synthesis. This task aims to design a water-using network that achieves the identified flowrate targets for fresh water and wastewater. The last task is water-pinch retrofit that aims to modify an existing water-using network to maximize water reuse and minimize wastewater generation through effective process changes.

In water pinch technology, a water-using operation is defined as a contaminant source that requires water as shown in Figure 2.1.

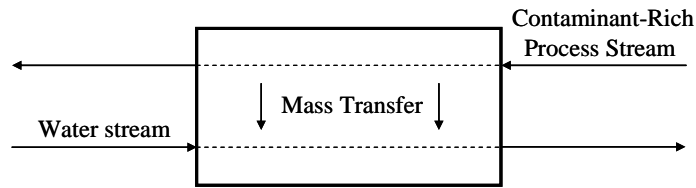


Figure 2.1 Countercurrent contact between a contaminant-rich process stream and a contaminant-lean water stream

The constraints on the contaminant concentration at the inlet and outlet of a water-using operation appear as equilibrium constraints at the outlet and inlet, respectively. In the process-stream representation, the mass load of the contaminant transfer from the water-using operation to the water stream is equal to the mass transfer from the rich stream to the lean stream.

After understanding the water pinch technology, mathematical optimization techniques are used to minimize the objective functions (e.g., the total cost of fresh water consumption and wastewater treatment) subject to constraint relationships among the independent variables

2.1.1.3 Wastewater minimization through water reuse

1) Water-using Operation as a contaminant mass-transfer problem

The water stream that enters the water-using unit must have a contaminant concentration less than the limiting concentration at the process stream outlet and water that leave the water-using must have a contaminant concentration less than the limiting concentration at the process stream inlet. The relative of contaminant concentration and mass load transfer is shown in Figure 2.2.

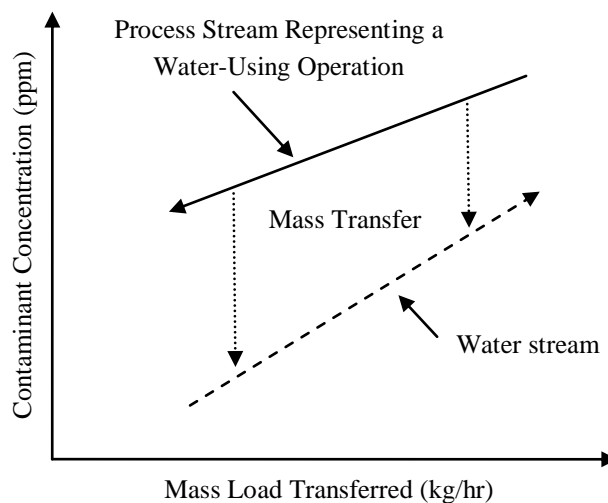


Figure 2.2 Contaminant concentration versus mass load of contaminant transferred

2) Data Extraction

Firstly, the inlet streams must be defined. These streams are prepared to use as alternative sources of water (to allow water reuse) and the outlet streams are the streams that will be sent to wastewater treatment. The contaminants are the substances or properties such as suspended solids (SS) or chemical oxygen demand (COD) that limit water reuse within the operation.

There are three constrains for each operation which are contaminant level in the inlet streams ($C_{i,in}^{lim}$), contaminant level in the outlet streams ($C_{i,out}^{lim}$) and the total mass load of contaminant that will be transferred ($\Delta m_{i,tot}$). Afterwards, the limiting water flowrate (f_i^{lim}) will be calculated from equation (2.1)

$$f_i^{lim} [ton/hr] = \frac{\Delta m_{i,tot} [kg/hr]}{(C_{i,out}^{lim} - C_{i,in}^{lim}) [ppm]} \times 10^3 \quad (2.1)$$

The limiting water flowrate is the flowrate that is needed to achieve the required mass transfer of contaminant ($\Delta m_{i,tot}$) and gives the limiting inlet and outlet concentrations.

Table 2.1 shows an industrial system which has three separate water-using operations which are called operations 1, 2 and 3.

Table 2.1 The example of limiting process data

Operation	$\Delta m_{i,tot}$	$C_{i,in}^{lim}$	$C_{i,out}^{lim}$
i	(kg/h)	(ppm)	(ppm)
1	3.75	0	75
2	1	50	100
3	1	75	125

After that, equation 2.1 will be applied to calculate the limiting water flowrates shown in table 2.2.

Table 2.2 The example of limiting process data with the limiting water flowrates

Operation	$\Delta m_{i,tot}$	$C_{i,in}^{lim}$	$C_{i,out}^{lim}$	f_i^{lim}
I	(kg/h)	(ppm)	(ppm)	(ton/h)
1	3.75	0	75	50
2	1	50	100	20
3	1	75	125	20

3) Water-pinch analysis

After the data extraction was done, the next step is the water-pinch analysis. Graphical method or concentration-composite curve is four-step procedure. Firstly, plot all of the water-using operations involved on a single graph of contaminant concentration versus mass load are plotted as shown in Figure 2.3. Then, the y-axis into concentration intervals by drawing horizontal lines (shown as dashed lines on Figure 2.3) at the limiting inlet and outlet concentrations for each water-using operations are formulated. Those horizontal lines mark the interval boundaries, denoted as C_k^* (where $k = 1, 2, 3$). Finally, the concentration-composite curve is constructed by eliminating the original water-using operation lines from the diagram and leaving only the sum of the mass loads within each concentration interval as shown in Figure 2.4. Then the water supply line will be drawn and rotated until this line first become tangent to a corner of the concentration-composite curve. The point of tangency is called the fresh water pinch shown in Figure 2.5. The system does not require fresh water above the fresh water pinch concentration. The minimum fresh water required is the reverse of the slope of the water-supply line as equation 2.2.

$$f_{\min} [\text{ton/hr}] = \frac{\Delta m_{\text{pinch}} [\text{kg/hr}]}{C_{\text{pinch}}^* [\text{ppm}]} \times 10^3 \quad (2.2)$$

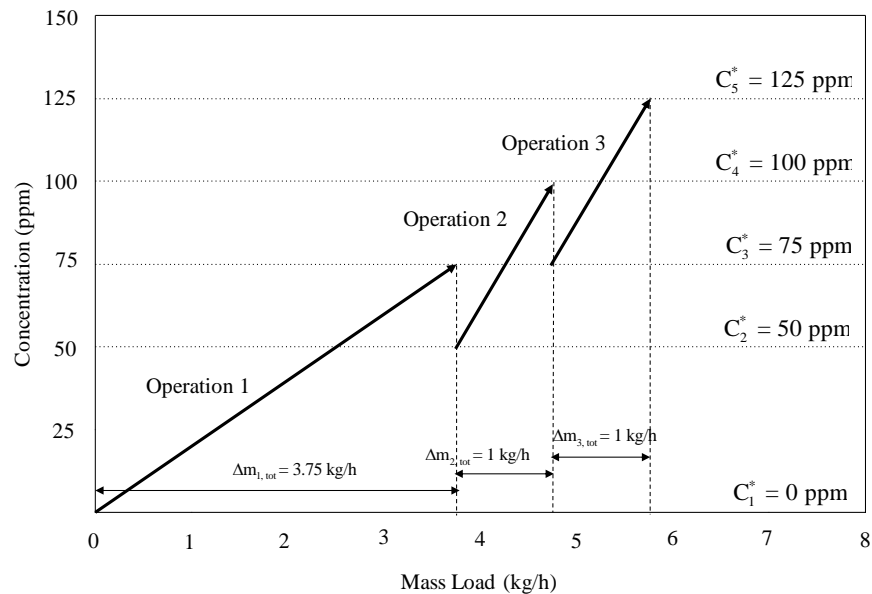


Figure 2.3 The lines of any operations.

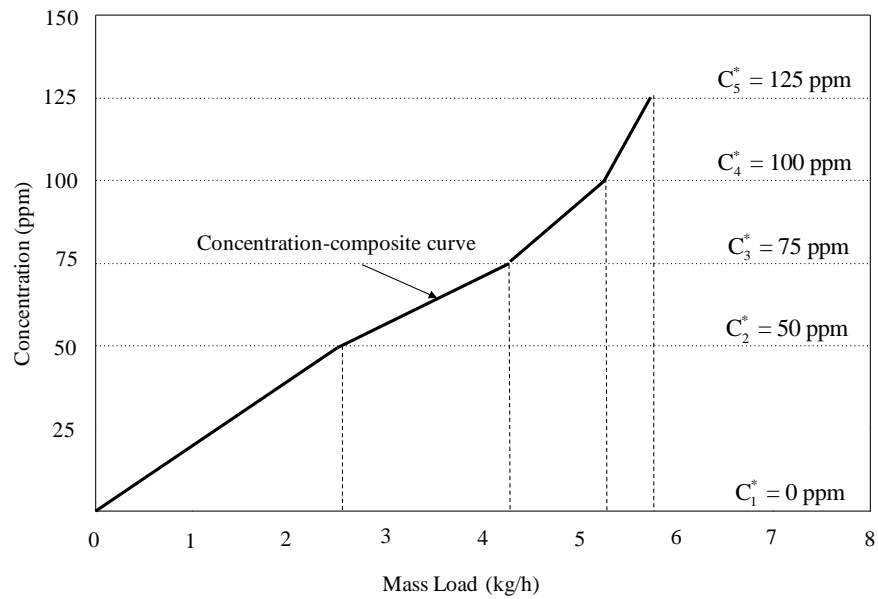


Figure 2.4 Concentration-composite curve.

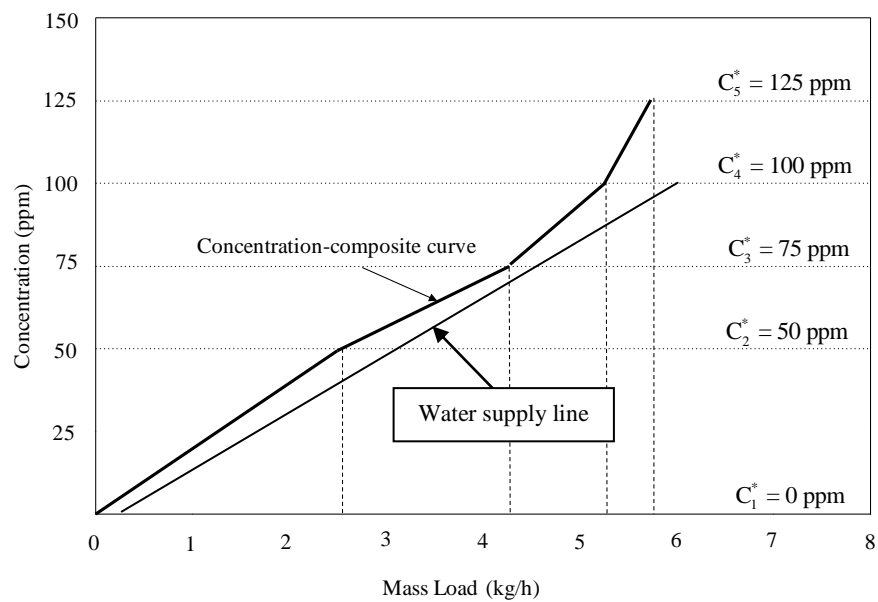


Figure 2.5 Concentration-composite curve and water supply line.

4) Water-pinch synthesis

This part concerns about the design of water-using network. Once water reuse method is applied to the system, the process of designing the water-using network becomes more complex.

In the design of preliminary water-using network, there are three ways to synthesize the water-using network which are block diagram, grid diagram and mass-content diagram. The grid diagram is the better suited to designing systems with water reuse. The example of the grid diagram is shown in Figure 2.6.

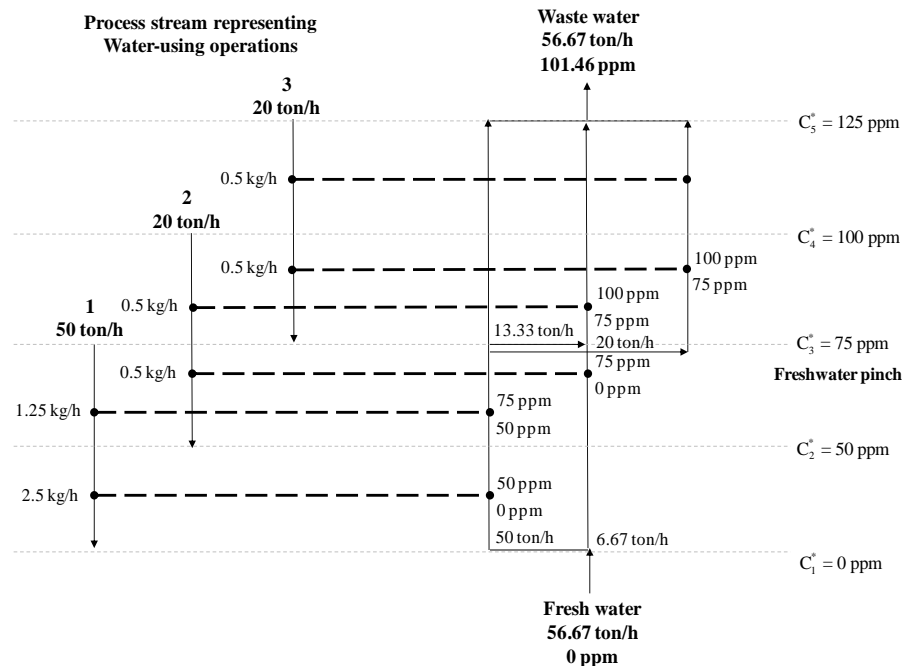


Figure 2.6 Grid diagram of the preliminary water-using network.

The solid horizontal and vertical lines in the right of the diagram represent the water streams. These streams flow from the bottom (fresh water) to the top (water treatment) of the diagram. The solid vertical lines in the left of diagram represent each process stream of water-using operations in the system. The dashed horizontal lines that connect each process stream to water streams represent a water-using unit and those lines are labeled with the appropriate mass load of contaminant. The inlet and outlet concentrations of the contaminant in each water stream are noted at the point where the dashed horizontal connecting line intersects the solid water line.

2.2 Literature reviews

The first mathematical optimization-based approach for water regeneration was introduced by Takama et al. [2]. They included all possible reuse and regeneration opportunities for minimizing of the total cost in a petroleum refinery. The optimization problem is solved by using the Complex method.

Later, Automatic synthesis of mass exchanger networks with single component targets by El-Halwagi and Manousiouthakis [3] is reported. They studied about mass by using two-stage synthesis to minimize the utility cost.

Wang and Smith[4] proposed the case of mass exchanger network to maximize savings in a water network with reuse, recycle and regeneration strategies. To design the optimum mass exchanger network that achieves the minimum wastewater flowrate, two simple design methods are presented. The first design procedure maximizes driving forces in individual processes whilst the second minimizes the number of water sources for each process. From adding regeneration process without recycle, fresh water

consumption and wastewater regeneration is reduced 60 percent and cost is also reduced 60 percent.

Thevendiraraj et al.[5] later proposed a water and wastewater minimization which carried out for a citrus plant located in Argentina. The objective of this study is primarily based on reducing the overall fresh water consumption and wastewater produced in this plant by using water pinch technology. Design options are achieved by introducing further constraints to potential re-use streams and by utilizing the maximum water re-use analysis to obtain optimized designs with improved fresh water target. Four different design options are generated considering both the maximum re-use analysis and regeneration-use analysis. After compare these design options, the maximum theoretical fresh water consumption and wastewater generation reduction is 31%.

Zheng et al.[6] later proposed Water system integration of a chemical plant which studied about mass exchanger network to minimize fresh water consumption and wastewater production in a chemical plant. After the water system integration, the fresh water consumption is reduced 25.5%, and the wastewater discharge is reduced 48%.

Relvas et al.[7] studied about a software tool for Mass-Exchange Networks which is called AquoMin. It can analyze different options to reduce fresh water consumption and minimize wastewater production. There are three available strategies to optimize the targets which are process without wastewater reuse, process with waste reuse, and process with waste regeneration reuse. These options are analyzed in two stages which are the targeting and the design. The former stage uses pinch analysis to obtain the minimum fresh water consumption and also the minimum wastewater production. And the second stage uses mass exchanger network design. The result from software shows that the regeneration reuse alternative is the one with smallest fresh water consumption.

CHAPTER 3 METHODOLOGY

This chapter describes a methodology and a work plan to achieve this work. The procedures to complete each step of the methodology are briefly outlined.

3.1 Methodology

This work focuses on water pinch analysis in order to develop a water-using system that leads to the minimization of fresh water consumption and wastewater production. There are 7 steps to complete this work as shown in Figure 3.1.

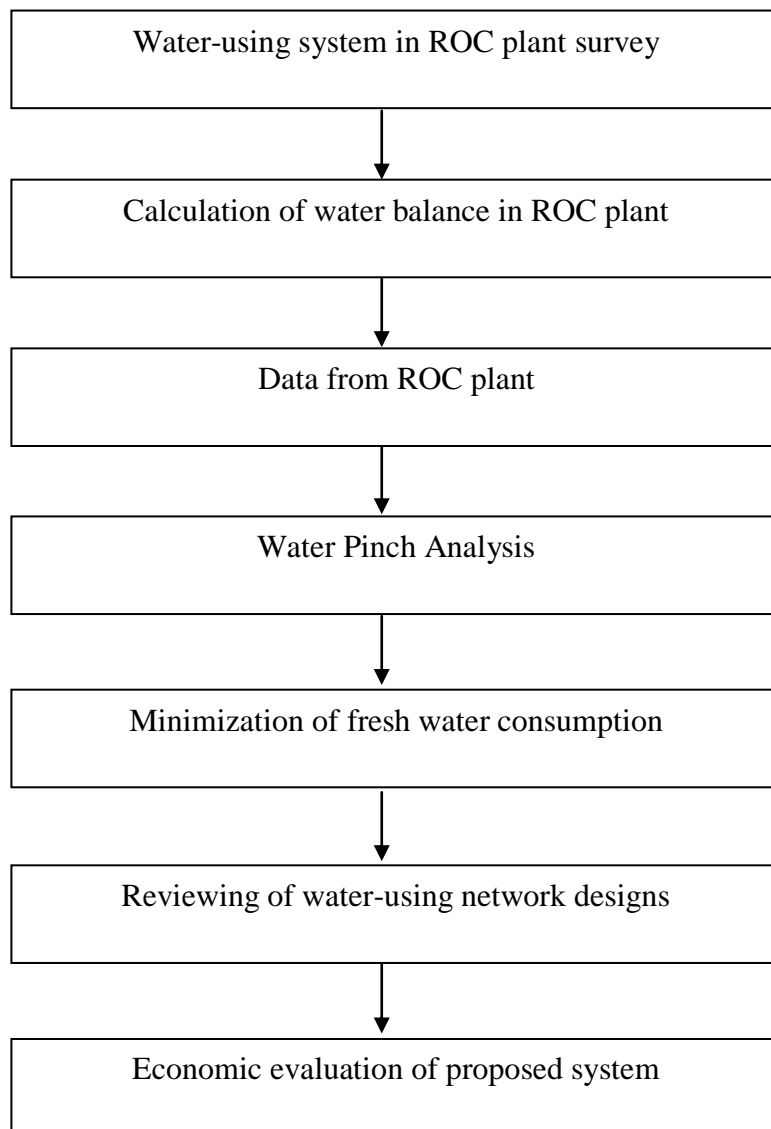


Figure 3.1 Steps of performing this project

3.1.1 Water-using system in ROC plant survey

The water-using survey need to be done firstly in this project. All of the water sources, sinks and flow diagrams of ROC water-using were indicated. The data could be collected from process flow diagrams of ROC water system such as PFD, P&ID and DCS monitor.

3.1.2 Calculation of water balance in ROC plant

After the overall process flow diagram of ROC water system was completed, the next step was performing the water balance of the process. The data of mass flowrate in every stream came from the DCS and the directed measurements in the plant.

3.1.3 Data of ROC plant

In the data extraction step, key contaminants were selected. The total mass transfer rate of contaminant (Δm_i) of each operation was calculated from the contaminant levels in the inlet streams ($C_{in,i}$) and the contaminant levels in the outlet streams ($C_{out,i}$). The method of data extraction was mentioned in Chapter two.

3.1.4 Water Pinch Analysis

The water pinch analysis is carried out to determine optimum matches between sources and sinks. In this step, the extracted data from the previous step were used to create the concentration composite curve in order to find the fresh water pinch point for single contaminant approach. Then, the minimum fresh water flowrate required for the water-using system could be calculated and preliminary block diagram of water-using network was constructed. In the water-pinch synthesis step, the required minimum fresh water and the extracted data from the water-pinch analysis step were used to create the water-using network that achieves the target of minimum water-using. In this step, the efficient water-using network was designed. The detail of the water pinch synthesis was illustrated in Chapter two.

3.1.5 Minimize fresh water consumption by Mathematical programming

Mathematical programming that was used in this project is GAMS (General Algebraic Modeling System). In this step, process modifications and regeneration options were considered that might result in lower targets. In GAMS, all sets, parameters, variable, constraints and equations were defined. After that, non-linear programs were solved using NLP.

3.1.6 Reviewing design of water-using network designs

In this step, the resulting water-using network designs were examined. It is necessary at this point to evaluate the design and determine which additional constraints should be considered. After this point, repeat steps 4-5 until a practical design has been evolved.

3.1.7 Economic evaluation of proposed system

After the water-using network was designed, the next step is the feasibility study and the economic evaluation.

3.2 Work plan

The schedule of each step for completing this work is shown in Table 3.1.

Table 3.1 Detail of work plan

Procedure	Month					
	May	Jun	Jul	Aug	Sep	Oct
Study about water pinch analysis						
Survey water-using system in ROC plant						
Calculate the water balance in ROC plant						
Extract data from ROC plant						
Apply Water Pinch Analysis						
Minimize fresh water consumption by using GAMS						
Review design of water-using network						
Evaluate economics of new system						

CHAPTER 4 RESULTS AND DISCUSSION

Before the optimal water-using network can be investigated, the existing water-using network of ROC process has to be known. This chapter therefore starts with the process description of overall process. There are 2 approaches to study, a single contaminant and multiple contaminants. For the single contaminant approach, a graphical method has been directly used to determine pinch point. On the other hand, for the multiple contaminants approach, GAMS is used to minimize fresh water consumption. The results from GAMS are shown in this chapter together with the assumptions, constraints, parameters and variables that were used to develop water-using network in the process. In addition, this chapter also includes the discussion of various constraints. From the result from GAMS, there are 6 cases of water-using network.

4.1 Process description

Firstly, the raw water from Industrial Estate Authority of Thailand (IEAT) is fed into the raw water treatment plant to remove some contaminants. This raw water treatment plant consists of clarifier, intermediate tank and sand filter.

The product from the raw water treatment plant is treated water. The treated water is divided into four main streams. The first stream is fed to the cooling tower as the make-up water. The second stream is fed to the demineralized water plant to produce the demineralized water. The third stream is fed to ROC's user which consists of the administration building, the central controlled building and any host stations in ROC's plant. The last stream is fed to downstream plant which consists of HDPE1, HDPE2, HDPE3, MMA and TPE.

In cooling tower, the make-up water is used to compensate the water that is evaporated and blown down from the cooling tower. In the cooling tower, chemical substances are added to control pH, prevent the scale and the growth of microbial. At the same time, the water is evaporated and drifted continuously. Therefore, the chemical concentration in the cooling water system is increased. Thus the system must blow some water out of the system to prevent the accumulation of chemical substances. Seventy percent of the blow down water is sent to the reverse osmosis system (RO) to regenerate the water. The permeate is returned to be reused in the cooling water system whereas the retentate (rejected RO water) is sent to the diversion box. However, thirty percent of the blow down water is sent out of the ROC's plant as the effluent.

In the demineralized water plant, the treated water is sent to remove ions and organic carbon. The product from demineralized water plant is demineralized water. The demineralized water is used as boiler feed water to produce steam. The steam in ROC's plant consists of 6 levels which are super high pressure steam (SHPS), high pressure steam (HS), medium pressure steam 1 (MS-1), medium pressure steam 2 (MS-2), low pressure steam 1 (LS-1) and low pressure steam 2 (LS-2). The steam is sent to the downstream plants (HDPE 1, HDPE 2, HDPE 3, MMA and TPE) and sent to the ROC's

users such as spent caustic system, dilution steam system, steam turbine generators, turbine pumps, heat exchangers, furnaces, stripping tower and etc. After the steam is used in the process, the condensate occurs. The condensate is divided into two types which are clean condensate and dirty condensate. The clean condensate from users of ROC's plant is recycled to be the boiler feed water of the boilers and the furnaces whereas the dirty condensate from the ROC's users is sent to treat at the condensate polisher. The dirty condensate from the downstream plants is also sent to be treated at the condensate polisher. The function of the condensate polisher is to regenerate the dirty condensate. The product of the condensate polisher is clean condensate that will be mixed with the demineralized water from the demineralized water plant and then will be used as the boiler feed water of the boilers and the furnaces.

In boiler, when the boiler feed is heated to be steam, the chemical concentration of water in boiler is increased. Therefore the system must blow some water out of the system to prevent the accumulation of chemical substances as boiler blowdown and sent to the diversion box.

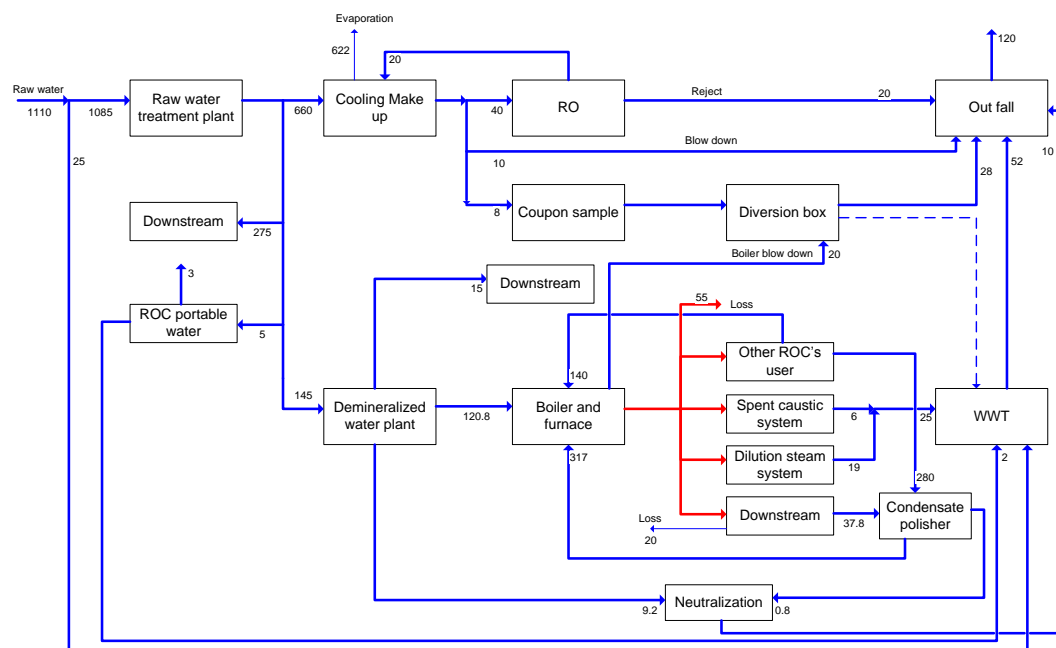


Figure 4.1 The block flow diagram with the flowrate of the water balances.

It is very important to select operations. For this project, cooling tower, spent caustic system, dilution steam system, downstream, ROC's user and boiler are selected as the operations and reverse osmosis (RO), demineralized water plant and condensate polisher are selected as the regeneration as shown in Figure 4.2. In order to maximize the possibility of water reuse from other operations for the considered operation, the highest possible inlet contaminant concentrations should be specified, which are called the limiting inlet concentrations. To minimize the water flow rate of the process, the maximum possible outlet contaminant concentrations are specified, which are called the limiting outlet concentrations. Constraints of streams and operations in the water-using network are shown in Tables 4.1a-4.1c and constraints of regenerations are shown in

Tables 4.2a-4.2b. Because the regenerations need some payment to regenerate the resin in demineralized water plant and condensate polisher, the inlet concentration of each regeneration should be limited to keep this cost low.

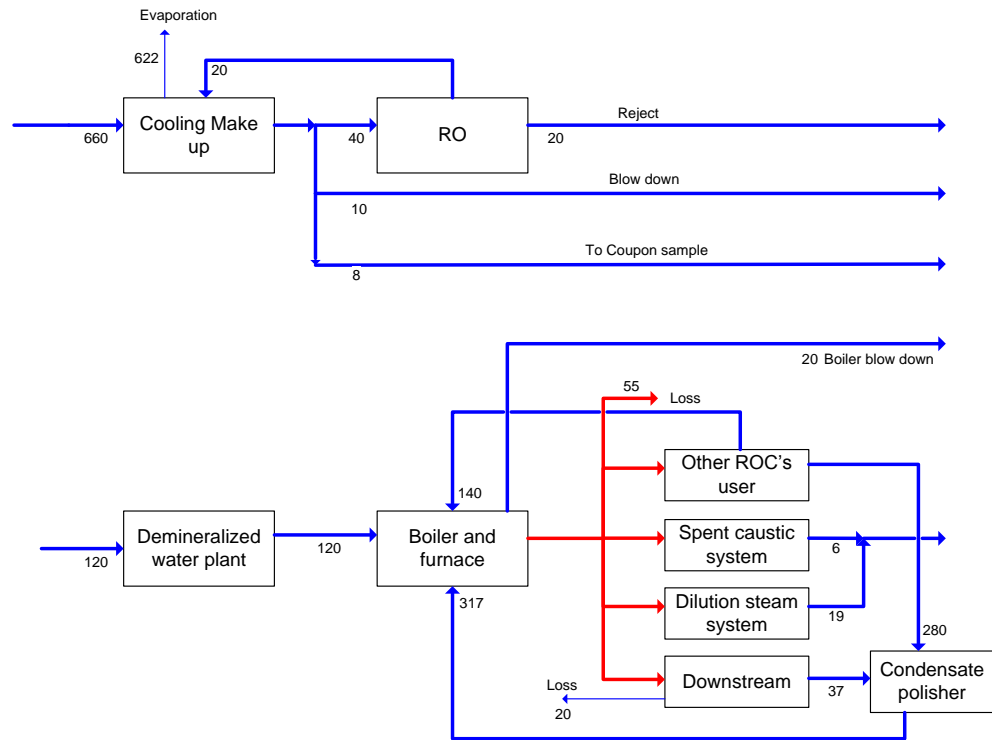


Figure 4.2 The block flow diagram of selected water-using network

Table 4.1a Limiting inlet and outlet concentration of each contaminant for each operation

Operations	Limiting inlet concentration			Limiting outlet concentration		
	Silica	TDS	COD	Silica	TDS	COD
1. cooling tower	20	124.50	15	90	1300	45
2. Spent caustic system	0.02	0.02	0.03	0.03	60000	2700
3. Dilution steam system	0.02	0.02	0.03	0.03	280	2900
4. Downstream	0.02	0.02	0.03	0.06	10	5
5. ROC's user (Dirty condensate)	0.02	0.02	0.03	0.03	10	5
6. ROC's user (Clean condensate)	0.02	0.02	0.03	0.1	15	5
7. Boiler and furnace	0.02	20	25	0.02	0	0.03

Table 4.1b Capacity and flowrate loss of each operation

Operations	Flowrate loss (ton/hr)	Capacity (ton/hr)
1. cooling tower	622	680
2. Spent caustic system	0	7
3. Dilution steam system	0	20
4. Downstream	20	65
5. ROC's user (Dirty condensate)	0	140
6. ROC's user (Clean condensate)	0	280
7. Boiler and furnace	75	600

Table 4.1c Mass load of each operation

Operations	Mass load (kg/hr)		
	Silica	TDS	COD
1. cooling tower	48	707.2	19.72
2. Spent caustic system	0.00006	341	15.72
3. Dilution steam system	0.0002	5.32	53.32
4. Downstream	0.0023	0.57	0.2
5. ROC's user (Dirty condensate)	0.0014	1.4	0.7
6. ROC's user (Clean condensate)	0.022	4.2	1.4
7. Boiler and furnace	-	-	-

Table 4.2a Capacity and removal ration of each regeneration

Regenerations	Capacity (ton/hr)	Removal ration		
		Silica	TDS	COD
1. Reverse osmosis	80	0.9	0.9	0.9
2. Demineralized water plant	220	1	1	1
3. Condensate polisher	320	0.9	0.9	0.9

Table 4.2b Limiting inlet concentration of each regeneration

Regenerations	Limiting inlet concentration (ppm)		
	Silica	TDS	COD
1. Reverse osmosis	90	1300	45
2. Demineralized water plant	20	230	15
3. Condensate polisher	1	15	5

4.2 Single Contaminant Approach

To minimize waste water by water pinch technique, it is necessary to calculate minimum fresh water flowrate to reduce the contaminant concentration of the operations in an acceptable level. A graphical method has been used to determine pinch point. According to these considerations, Silica, TDS and COD were selected as key contaminants and were analyzed separately as a single contaminant and the amount of required fresh water was calculated. For single contaminant approach, the assumptions are as follows:

- a. Contaminants concentration of fresh water is 0 ppm.
- b. There are 6 operations as shown in Table 4.3.
- c. Only amount of water is considered. Phase of water is not considered.
- d. There is not any regeneration.

Table 4.3 List of selected operations

Defined	Unit operation
Operation 1	Cooling tower
Operation 2	Spent caustic system
Operation 3	Dilution steam system
Operation 4	Downstream
Operation 5	ROC's user (Clean condensate)
Operation 6	ROC's user (Dirty condensate)

For a single contaminant system, the pinch is known as the bottleneck of the system. So, the pinch processes, including the processes with pinch concentration as the inlet or outlet concentration and the processes with their inlet and outlet concentrations across the pinch concentration, are the possible processes controlling the freshwater consumption of the system. [1]

In the first case, Silica is considered as a key contaminant. From the concentration composite curve as shown in Figure 4.3, pinch point is located at a Silica concentration of 90 ppm which is the outlet concentration of cooling tower. Similarly, from Figure 4.5 and Figure 4.7, pinch point is located at TDS concentration of 1200 ppm and COD concentration of 45 ppm which are the outlet concentration of cooling tower. Therefore, the optimal water network can be designed by investigating and debottlenecking of the cooling tower.

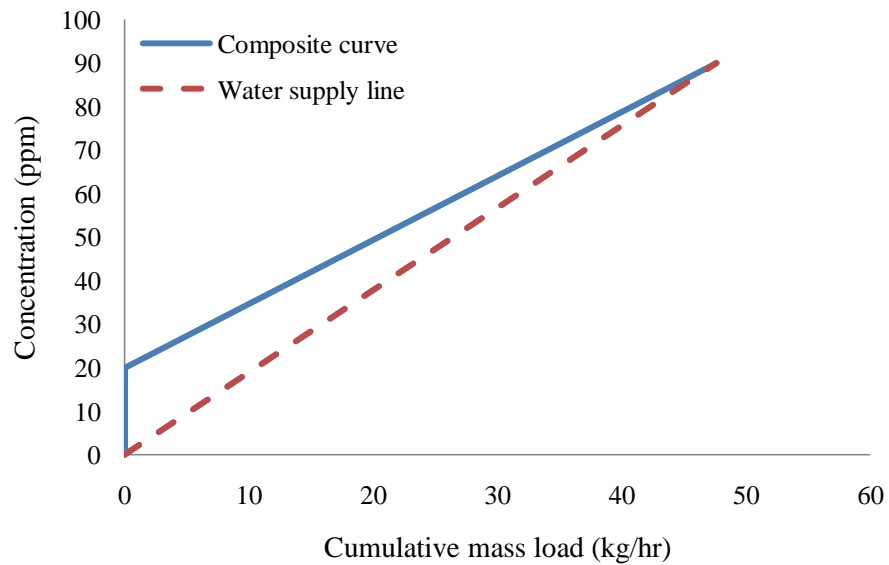


Figure 4.3 Concentration composite curve in terms of Silica

From Table 4.4, the preliminary block diagram can be constructed as Figure 4.4. Because the Silica concentration of steam system is very low so the outlet streams from operations 2, 3, 4, 5 and 6 can be reused in operation 1 as shown in Figure 4.4. In terms of TDS, discharged stream from spent caustic system cannot be reused in operation 1 because its concentration and mass load of TDS in cooling tower is very large so large amount of fresh water is needed. Finally, in terms of COD, although discharged streams from spent caustic system and dilution steam system cannot be reused in operation 1, fresh water consumption in this case is less than case of TDS because mass load in terms of COD is less than mass load in terms of TDS in cooling tower. The preliminary block diagram in terms of TDS and COD are shown in Figures 4.6 and 4.8, respectively.

Table 4.4 Concentration interval diagram in terms of Silica

Concentration (ppm)	Operation 1 680 ton/hr	Operation 2 6 ton/hr	Operation 3 19 ton/hr	Operation 4 40 ton/hr	Operation 5 140 ton/hr	Operation 6 280 ton/hr	Mass load (kg/hr)	Cumulative mass load (kg/hr)	Flowrate (ton/hr)
0.02		↑	↑	↑	↑	↑	0.00	0.00	0.00
0.03							0.00	0.00	161.67
0.06							0.01	0.01	240.83
0.10							0.02	0.03	256.50
20.00	↑						0.00	0.03	1.28
90.00							47.60	47.63	529.17

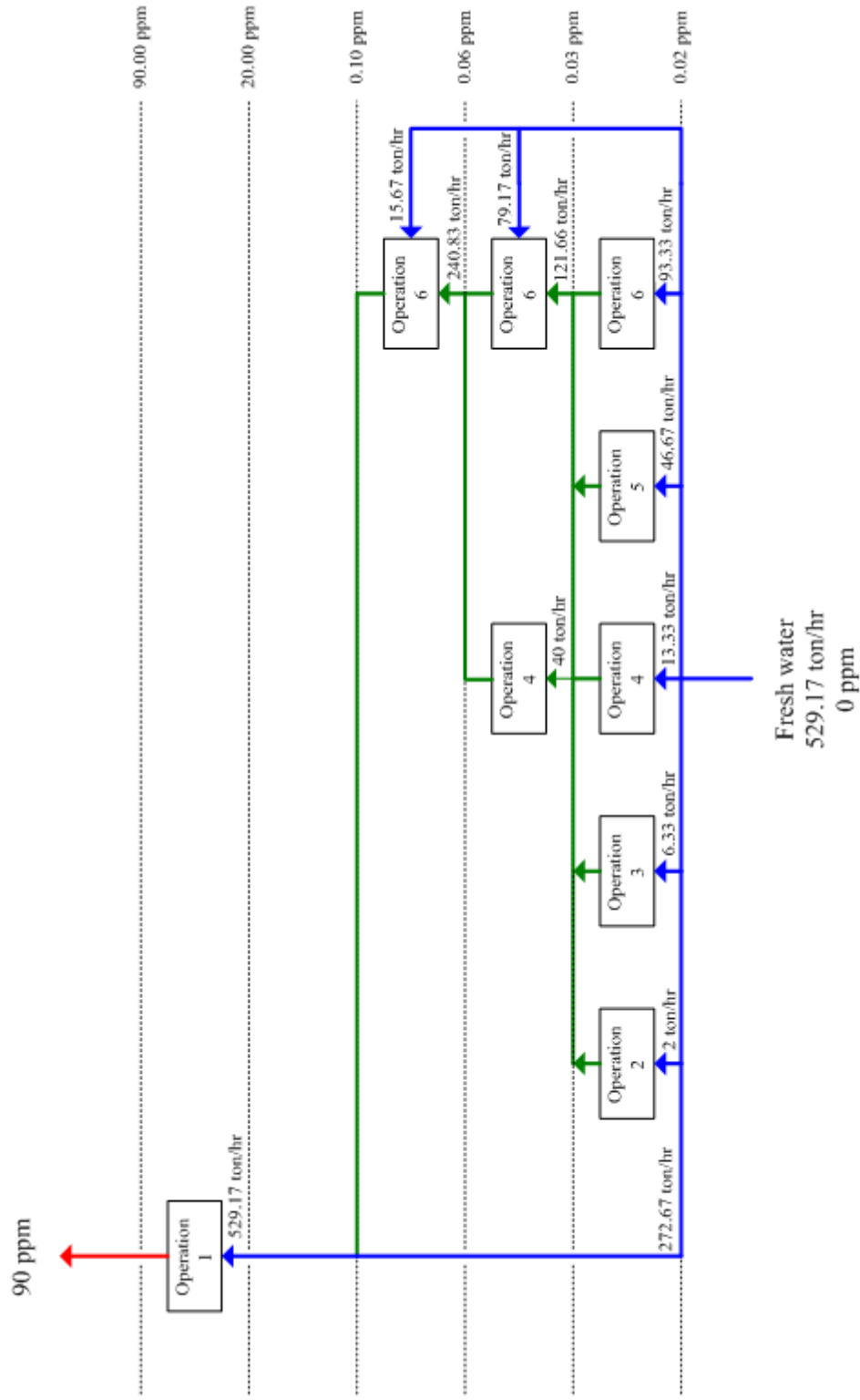
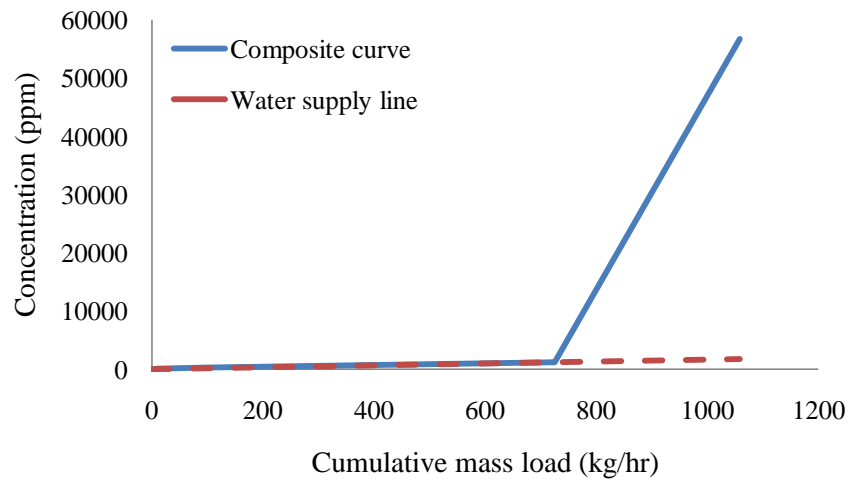
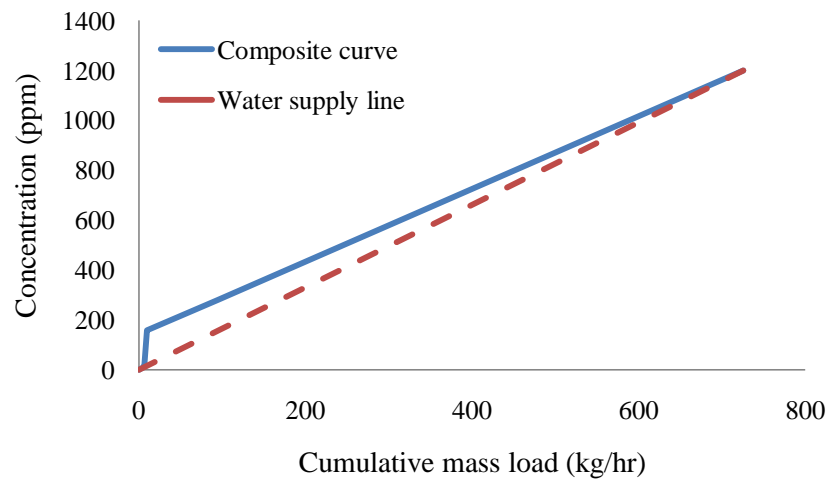


Figure 4.4 Preliminary block diagram in terms of Silica



(a) Normal concentration composite curve



(b) Expanded concentration composite curve

Figure 4.5 Concentration composite curve in terms of TDS

Table 4.5 Concentration interval diagram in terms of TDS

Concentration (ppm)	Operation 1 680 ton/hr	Operation 2 6 ton/hr	Operation 3 19 ton/hr	Operation 4 40 ton/hr	Operation 5 140 ton/hr	Operation 6 280 ton/hr	Mass load (kg/hr)	Cumulative mass load (kg/hr)	Flowrate (ton/hr)
0.02								0.00	0.00
10.00							4.84	4.84	484.03
15.00							1.53	6.37	424.35
160.00							3.63	9.99	62.44
280.00							84.60	94.59	337.82
1200.00							631.12	725.71	604.76
56671.03							332.83	1058.54	18.68

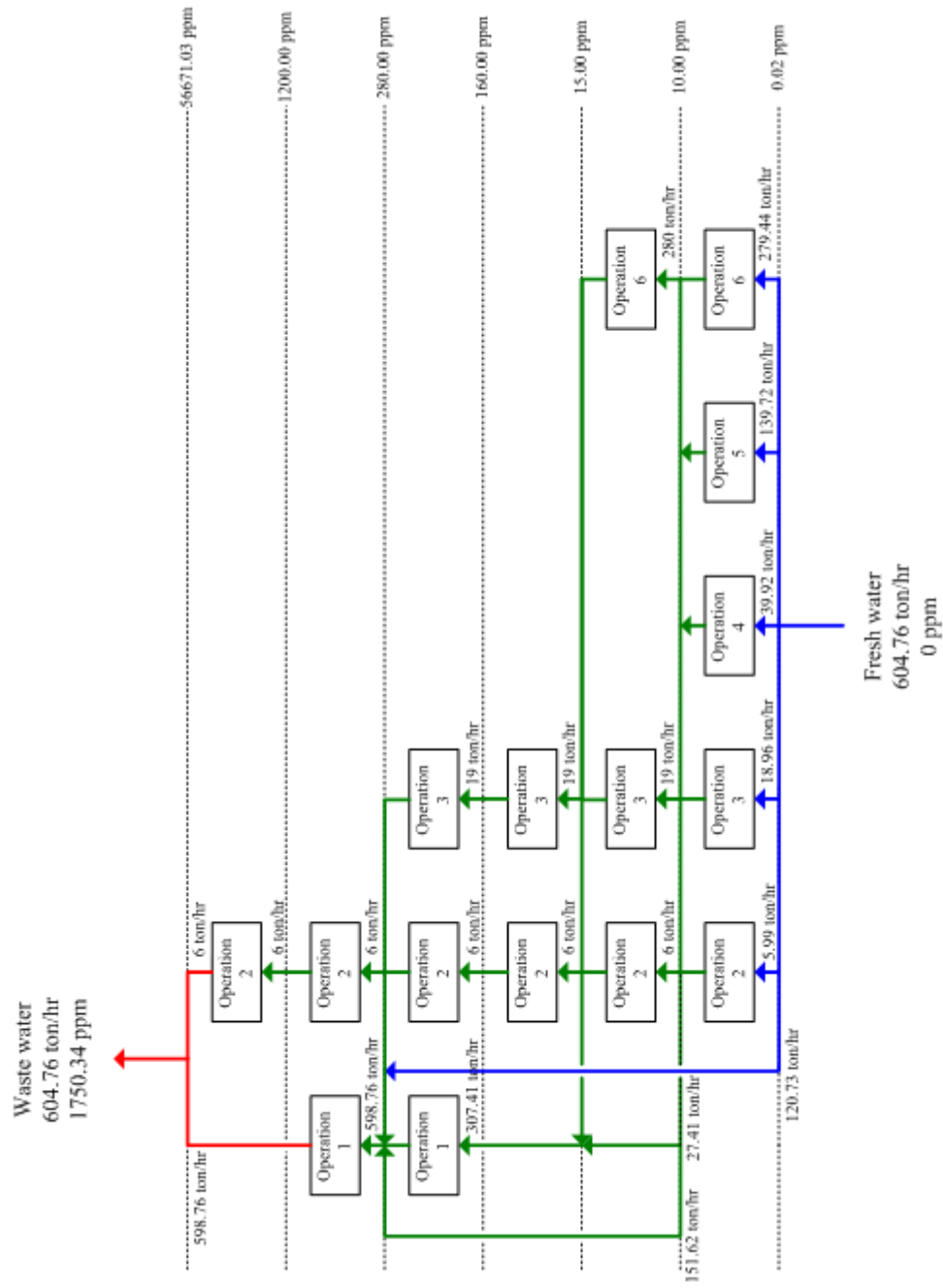
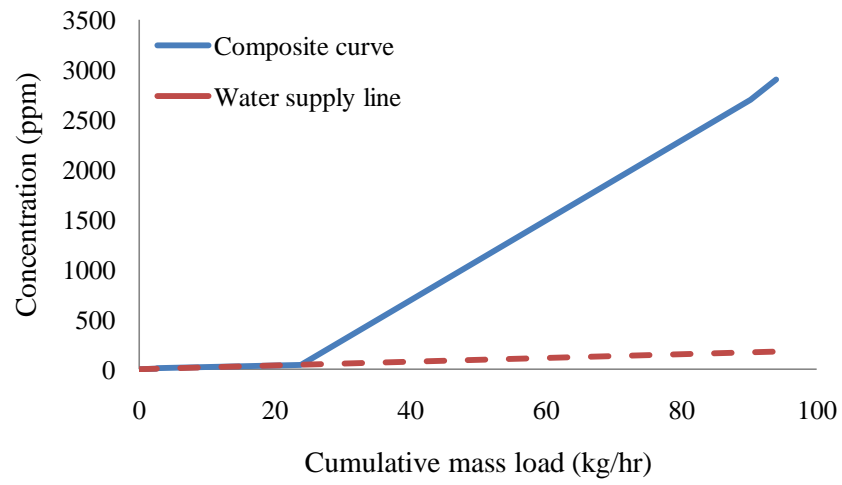
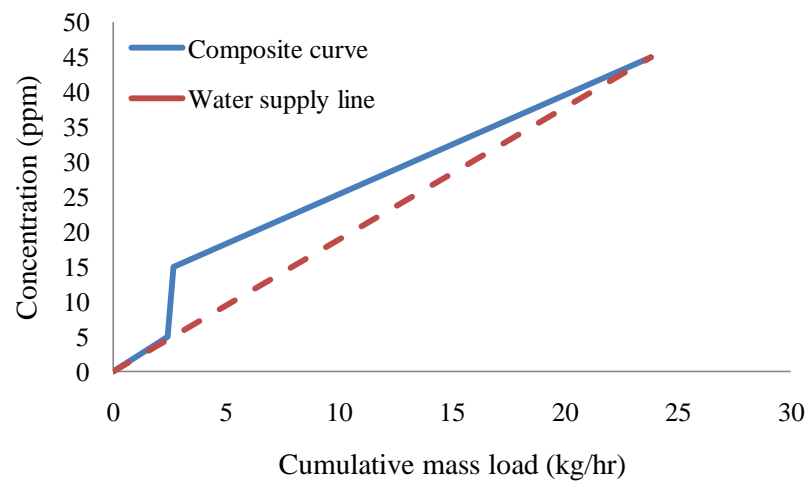


Figure 4.6 Preliminary block diagram in terms of TDS



(a) Normal concentration composite curve



(b) Expanded concentration composite curve

Figure 4.7 Concentration composite curve in term of COD

Table 4.6 Concentration interval diagram in terms of COD

Concentration (ppm)	Operation 1 680 ton/hr	Operation 2 6 ton/hr	Operation 3 19 ton/hr	Operation 4 40 ton/hr	Operation 5 140 ton/hr	Operation 6 280 ton/hr	Mass load (kg/hr)	Cumulative mass load (kg/hr)	Flowrate (ton/hr)
0.03		↑	↑	↑	↑	↑	2.41	0.00	0.00
5.00							0.25	2.41	482.09
15.00							21.15	2.66	177.36
45.00							66.38	23.81	529.12
2700.00	↑						3.80	90.19	33.40
2900.00								93.99	32.41

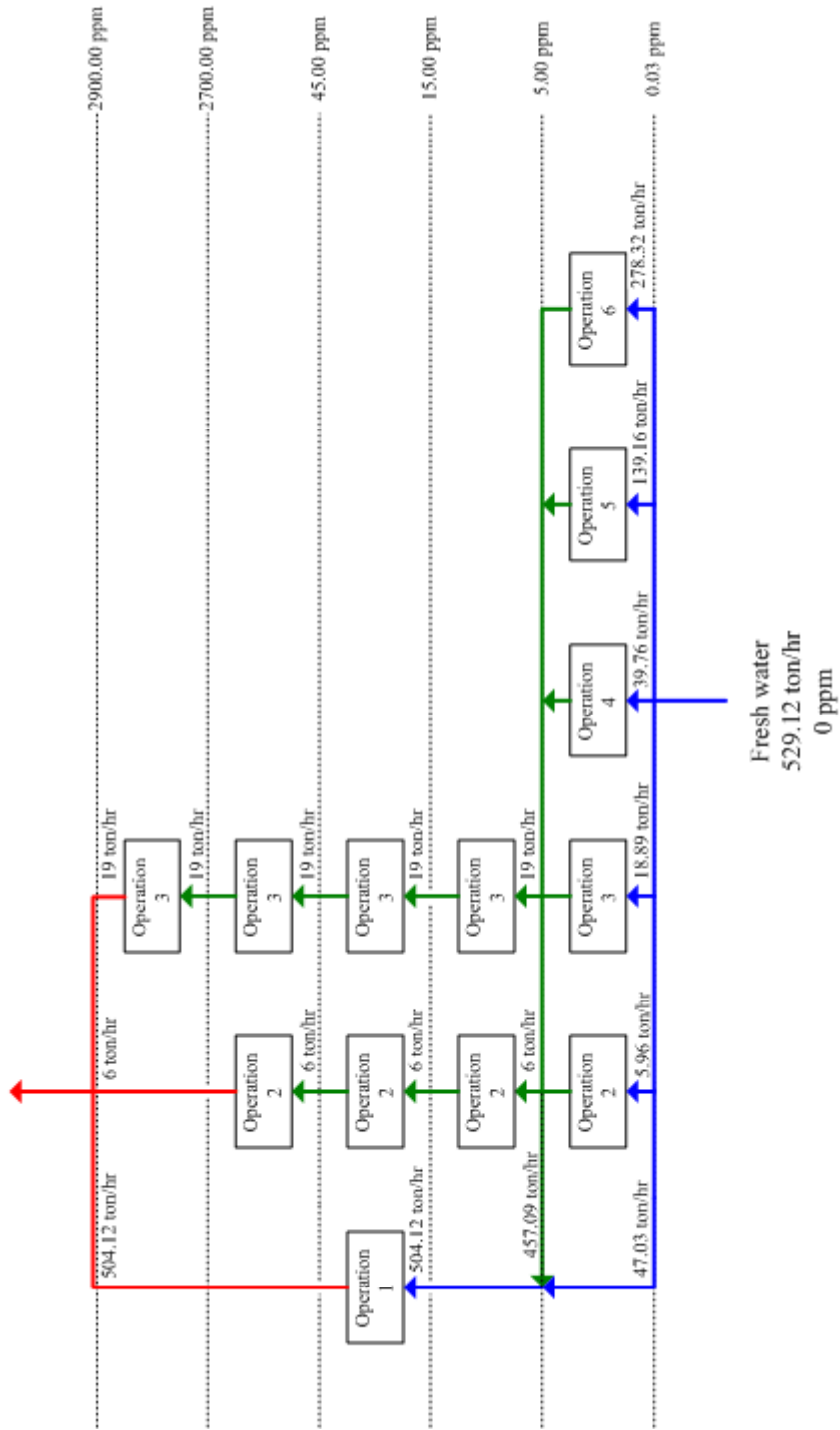


Figure 4.8 Preliminary block diagram in terms of COD

As can be seen in single contaminant approach, total required fresh water for the operations in terms of Silica, TDS and COD are 529.17, 604.76 and 529.12 ton/hr, respectively. Although, the result from this approach cannot be applied to the actual process because of the assumptions mentioned above, this approach shows that the optimal water using network can be designed by investigating and debottlenecking of the cooling tower due to the outlet concentration of this operation is the pinch point in terms of Silica, TDS and COD

4.3 Multiple Contaminants Approach

4.3.1 Model Set Up

4.3.1.1 Basic Assumption

- 1) Key contaminants are Silica, TDS and COD.
- 2) Mass load of each operation is held constant.
- 3) Water gain and loss of each operation are held constant.
- 4) Sources of water are fresh water, water from diversion box and water from boiler blowdown. The contaminant concentrations of each source in water are shown in Table 4.7.
- 5) Fresh water used in the process system is the treated water.
- 6) Water loss from the operations is pure water.
- 7) No equilibrium relation governs the distribution of contaminants in water.

Table 4.7 Concentration of each contaminant of each source of water

Sources of water	Concentration (ppm)		
	Silica	TDS	COD
1. Treated water	20	124.5	15
2. Water from diversion box	25	800	60
3. Boiler blowdown	0.5	25	25

4.3.1.2 Optimization

1) Sets

- I Operations: Operation 1, 2, 3, 4, 5C, 5D and 6
 J Contaminants: Contaminant A, B and C

2) Parameters

- $C_f(J)$ Concentration of contaminant J of fresh water in ppm
 $C_d(J)$ Concentration of contaminant J of water from diversion box in ppm
 $C_b(J)$ Concentration of contaminant J of boiler blowdown in ppm
 $M_1(J)$ Mass load of contaminant J for operation 1 in kg/hr
 $M_2(J)$ Mass load of contaminant J for operation 2 in kg/hr

M_3 (J)	Mass load of contaminant J for operation 3 in kg/hr
M_4 (J)	Mass load of contaminant J for operation 4 in kg/hr
M_{5C} (J)	Mass load of contaminant J for operation 5C in kg/hr
M_{5D} (J)	Mass load of contaminant J for operation 5D in kg/hr
$C_{in,1}^{lim}$ (J)	Limiting inlet concentration of contaminant J for operation 1
$C_{in,2}^{lim}$ (J)	Limiting inlet concentration of contaminant J for operation 2
$C_{in,3}^{lim}$ (J)	Limiting inlet concentration of contaminant J for operation 3
$C_{in,4}^{lim}$ (J)	Limiting inlet concentration of contaminant J for operation 4
$C_{in,5C}^{lim}$ (J)	Limiting inlet concentration of contaminant J for operation 5C
$C_{in,5D}^{lim}$ (J)	Limiting inlet concentration of contaminant J for operation 5D
$C_{in,6}^{lim}$ (J)	Limiting inlet concentration of contaminant J for operation 6
$C_{out,1}^{lim}$ (J)	Limiting outlet concentration of contaminant J for operation 1
$C_{out,2}^{lim}$ (J)	Limiting outlet concentration of contaminant J for operation 2
$C_{out,3}^{lim}$ (J)	Limiting outlet concentration of contaminant J for operation 3
$C_{out,4}^{lim}$ (J)	Limiting outlet concentration of contaminant J for operation 4
$C_{out,5C}^{lim}$ (J)	Limiting outlet concentration of contaminant J for operation 5C
$C_{out,5D}^{lim}$ (J)	Limiting outlet concentration of contaminant J for operation 5D
$C_{out,6}^{lim}$ (J)	Limiting outlet concentration of contaminant J for operation 6
$C_{in,R1}^{lim}$ (J)	Limiting inlet concentration of contaminant J for regeneration 1
$C_{in,R2}^{lim}$ (J)	Limiting inlet concentration of contaminant J for regeneration 2
$C_{in,R3}^{lim}$ (J)	Limiting inlet concentration of contaminant J for regeneration 3
$F_{i,loss}$	Water loss for operation i in ton/ hr
$F_{i,gain}$	Water gain for operation i in ton/ hr
R_{R1} (J)	Removal ration of contaminant J for regeneration 1
R_{R2} (J)	Removal ration of contaminant J for regeneration 2
R_{R3} (J)	Removal ration of contaminant J for regeneration 3
Capacity _i	Capacity of operation i in ton/ hr
D^{lim}	Limiting total flowrate of water from diversion box in ton/ hr
B^{lim}	Limiting total flowrate of boiler blowdown in ton/ hr

3) Variables

F_i	Flowrate of freshwater to operation i in ton/hr
D_i	Flowrate of water from diversion box to operation i in ton/hr
B_i	Flowrate of boiler blowdown to operation i in ton/hr
$X_{i,j}$	Flowrate of water from operation j to operation i in ton/hr
$X_{i,R1}$	Flowrate of water to operation i from regeneration 1
$X_{i,R2}$	Flowrate of water to operation i from regeneration 2
$X_{i,R3}$	Flowrate of water to operation i from regeneration 3
$X_{R1,i}$	Flowrate of water from operation i to regeneration 1
$X_{R2,i}$	Flowrate of water from operation i to regeneration 2

$X_{R3,i}$	Flowrate of water from operation i to regeneration 3
X_{reject}	Flowrate of water from regeneration 1 to rejected stream
$C_{\text{in},1}(\text{J})$	Inlet concentration of contaminant J for operation 1 in ppm
$C_{\text{in},2}(\text{J})$	Inlet concentration of contaminant J for operation 2 in ppm
$C_{\text{in},3}(\text{J})$	Inlet concentration of contaminant J for operation 3 in ppm
$C_{\text{in},4}(\text{J})$	Inlet concentration of contaminant J for operation 4 in ppm
$C_{\text{in},5\text{C}}(\text{J})$	Inlet concentration of contaminant J for operation 5C in ppm
$C_{\text{in},5\text{D}}(\text{J})$	Inlet concentration of contaminant J for operation 5D in ppm
$C_{\text{in},6}(\text{J})$	Inlet concentration of contaminant J for operation 6 in ppm
$C_{\text{out},1}(\text{J})$	Outlet concentration of contaminant J from operation 1 in ppm
$C_{\text{out},2}(\text{J})$	Outlet concentration of contaminant J from operation 2 in ppm
$C_{\text{out},3}(\text{J})$	Outlet concentration of contaminant J from operation 3 in ppm
$C_{\text{out},4}(\text{J})$	Outlet concentration of contaminant J from operation 4 in ppm
$C_{\text{out},5\text{C}}(\text{J})$	Outlet concentration of contaminant J from operation 5C in ppm
$C_{\text{out},5\text{D}}(\text{J})$	Outlet concentration of contaminant J from operation 5D in ppm
$C_{\text{out},6}(\text{J})$	Outlet concentration of contaminant J from operation 6 in ppm
$C_{\text{in},R1}(\text{J})$	Inlet concentration of contaminant J for regeneration 1 in ppm
$C_{\text{in},R2}(\text{J})$	Inlet concentration of contaminant J for regeneration 2 in ppm
$C_{\text{in},R3}(\text{J})$	Inlet concentration of contaminant J for regeneration 3 in ppm
$C_{\text{out},R1}(\text{J})$	Outlet concentration of contaminant J from regeneration 1 in ppm
$C_{\text{out},R2}(\text{J})$	Outlet concentration of contaminant J from regeneration 2 in ppm
$C_{\text{out},R3}(\text{J})$	Outlet concentration of contaminant J from regeneration 3 in ppm
W_i	Flowrate of wastewater from operation i in ton/hr
F_{R1}	Flowrate of freshwater to regeneration 1 in ton/hr
F_{R2}	Flowrate of freshwater to regeneration 2 in ton/hr
F_{R3}	Flowrate of freshwater to regeneration 3 in ton/hr
D_{R1}	Flowrate of water from diversion box to regeneration 1 in ton/hr
D_{R2}	Flowrate of water from diversion box to regeneration 2 in ton/hr
D_{R3}	Flowrate of water from diversion box to regeneration 3 in ton/hr
B_{R1}	Flowrate of boiler blowdown to regeneration 1 in ton/hr
B_{R2}	Flowrate of boiler blowdown to regeneration 2 in ton/hr
B_{R3}	Flowrate of boiler blowdown to regeneration 3 in ton/hr
F_{lim}	Freshwater consumption for overall process system in ton/hr

4) Constraints

i. Equality constraints

- Water mass balance for operation I

$$F_i + D_i + B_i + \sum X_{i,j} + X_{i,R1} + X_{i,R2} + X_{i,R3} + F_{i,\text{gain}} = W_i + \sum X_{j,i} + X_{R1,i} + X_{R2,i} + X_{R3,i} + F_{i,\text{loss}}$$

- Inlet concentration for operation I

$$C_{in,i} = \frac{C_f F_i + C_d D_i + C_b B_i + \sum C_j X_{i,j} + C_{R1} X_{i,R1} + C_{R2} X_{i,R2} + C_{R3} X_{i,R3} + C_{gain} F_{i,gain}}{F_i + D_i + B_i + \sum X_{i,j} + X_{i,R1} + X_{i,R2} + X_{i,R3} + F_{i,gain}}$$

- Outlet concentration for operation I

$$C_{out,i} = \frac{C_f F_i + C_d D_i + C_b B_i + \sum C_j X_{i,j} + C_{R1} X_{i,R1} + C_{R2} X_{i,R2} + C_{R3} X_{i,R3} + C_{gain} F_{i,gain} + M_i \times 1000}{F_i + D_i + B_i + \sum X_{i,j} + X_{i,R1} + X_{i,R2} + X_{i,R3} + F_{i,gain}}$$

ii. Inequality constraints

- Constraint of inlet concentration

$$C_{in,i} \leq C_{in,i}^{lim}$$

- Constraint of outlet concentration

$$C_{out,i} \leq C_{out,i}^{lim}$$

- Constraint of capacity of each operation

$$F_i + \sum X_{i,j} + X_{i,R1} + X_{i,R2} + X_{i,R3} + F_{i,gain} \leq \text{Capacity}_i$$

- Limiting flowrate of water from diversion box and boiler blowdown

$$\text{For water from diversion box} \quad \sum D_i + D_{R1} + D_{R2} + D_{R3} \leq D^{lim}$$

$$\text{For water from boiler blowdown} \quad \sum B_i + B_{R1} + B_{R2} + B_{R3} \leq B^{lim}$$

4.3.1.3 Objective Function

Mathematical optimization yields a minimum value for the freshwater flowrate subjective to constraints as defined above.

$$\text{Min } F_{lim} = \sum F_i + F_{R1} + F_{R2} + F_{R3}$$

4.3.2 Result and discussion

For the based case, in order to set up an optimization program, all the process constraints have to be embedded as follows:

- Water balance of each operation and regeneration are performed.
- Mass balance of each contaminant in the operations and regenerations are performed.

- c. The concentration of each contaminant in every stream must be less than the liming concentration.
- d. Total flowrate for each operation is not larger than its capacity.
- e. Fresh water and every discharged stream cannot be sent to the spent caustic system, dilution steam system, downstream and ROC's user because these unit need steam.

These process constraints are then added to allocate equations and will be set as constraints of a Non-linear Programming (NLP) to minimize the treated water flowrate. The specific optimization in GAMS is shown in Appendix A. For this problem, NLP-solver gives the feasible solutions. Figure 4.9 shows the conventional water-using network after improving and the concentration of each contaminant for each stream are shown in Table 4.8. This water-using network can reduce amount of treated water usage by 17.655 ton/hr or 2.26% and reduce amount of waste water generated by 17.655 ton/hr or 32.1%.

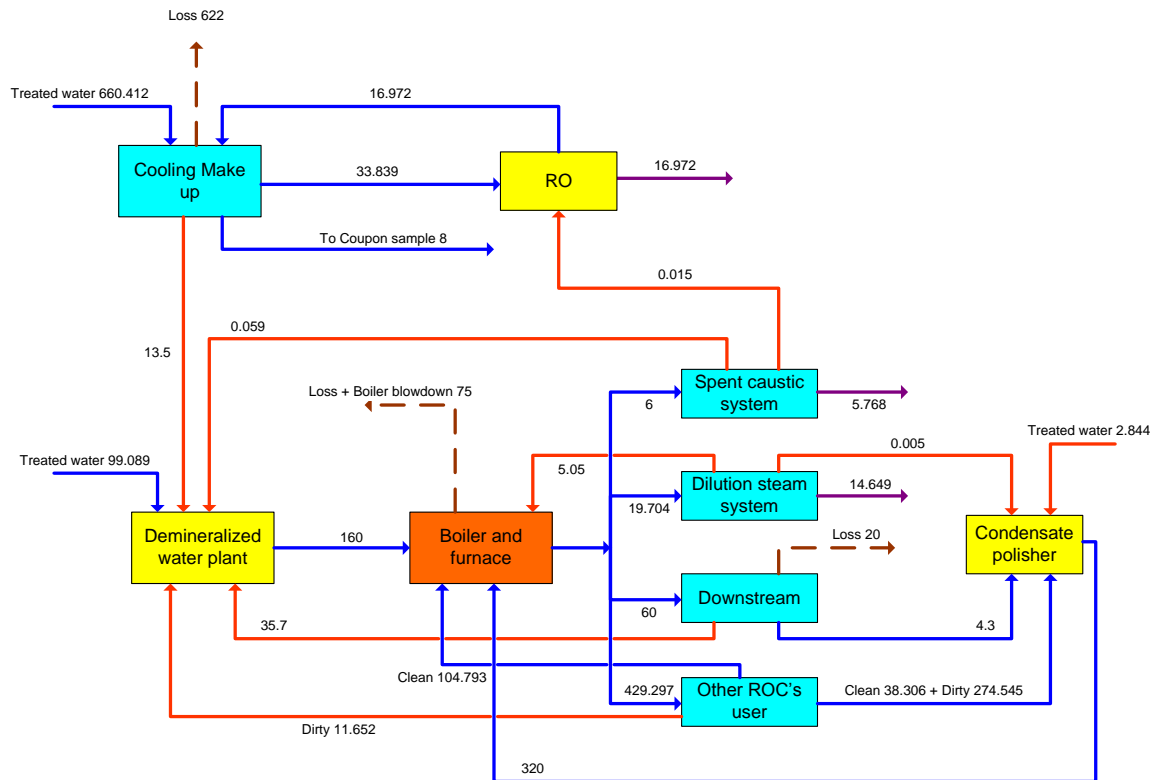


Figure 4.9 Block diagram of water-using network for case1

Table 4.8 Inlet and outlet concentration of each contaminant for each operation case1

Operation	Inlet concentration (ppm)			Outlet concentration (ppm)		
	Silica	TDS	COD	Silica	TDS	COD
1. cooling tower	19.73	124.37	14.74	90.00	1168.46	43.85
2. Spent caustic system	0.02	0.00	0.03	0.03	56833.33	2620.03
3. Dilution steam system	0.02	0.00	0.03	0.03	270.00	2706.12
4. Downstream	0.02	0.00	0.03	0.06	9.50	3.06
5. ROC's user (Dirty condensate)	0.02	0.00	0.03	0.03	9.78	4.89
6. ROC's user (Clean condensate)	0.02	0.00	0.03	0.10	14.68	4.89
7. Boiler and furnace	0.02	20.00	20.00	0.02	0.00	0.03

As shown in Figure 4.9, 13.5 ton/hr of cooling water blowdown is regenerated by fed to the demineralized water plant and 33.839 ton/hr is fed to the reverse osmosis to be regenerated before recycled to the cooling tower again. The treated water is divide into 3 streams which are fed into cooling tower, demineralized water plant and condensate polisher. Discharged stream from spent caustic system is separated to three streams which are fed to the reverse osmosis, demineralized water plant and waste water treatment plant. The amounts of water fed to the reverse osmosis and demineralized water plant are small so it is not worthwhile for investment. The discharged stream from spent caustic system should be sent to the waste water treatment plant. Discharged stream from dilution steam system is separated to three streams which are fed into condensate polisher, boiler and furnace and sent to waste water treatment plant. Since the amount of discharged stream from dilution steam system to condensate polisher is small, it is not suitable to construct new pipe line. In addition, condensate from dilution steam system is sometimes very dirty because of decoking. Therefore it is infeasible to reuse in any other units and regenerations. Furthermore, the downstream is far from demineralized water plant. It is high cost for piping investment. So all of condensate from downstream should be fed to the condensate polisher to regenerate before being recycled to furnace and boiler as the existing water-using network. For ROC's user, clean condensate can be recycled to boiler and furnace without regeneration.

After considering water-using network of case 1, some constraints should be added to this problem. For case 2, the process constraints are as follows:

- a. Water balance of each operation and regeneration are performed.
- b. Mass balance of each contaminant of the operations and regenerations are performed.
- c. The concentration of each contaminant of every stream must be less than the liming concentration.
- d. Total flowrate for each operation is not larger than its capacity.

- e. Fresh water and any discharged stream cannot be sent to the spent caustic system, dilution steam system, downstream and ROC's user because these unit need steam.
- f. Discharged from spent caustic system and dilution steam system cannot be reused in other units.
- g. All of condensate from downstream is sent to the condensate polisher.
- h. All of condensate from ROC's user is recycled to boiler and furnace.

The result of water-using network from GAMS for case 2 is shown as Figure 4.10. The amount of treated water usage can be reduced by 11.491 ton/hr or 1.47% and reduce amount of waste water generated by 11.491 ton/hr or 20.89%. The concentrations of each contaminant are shown in Table 4.9.

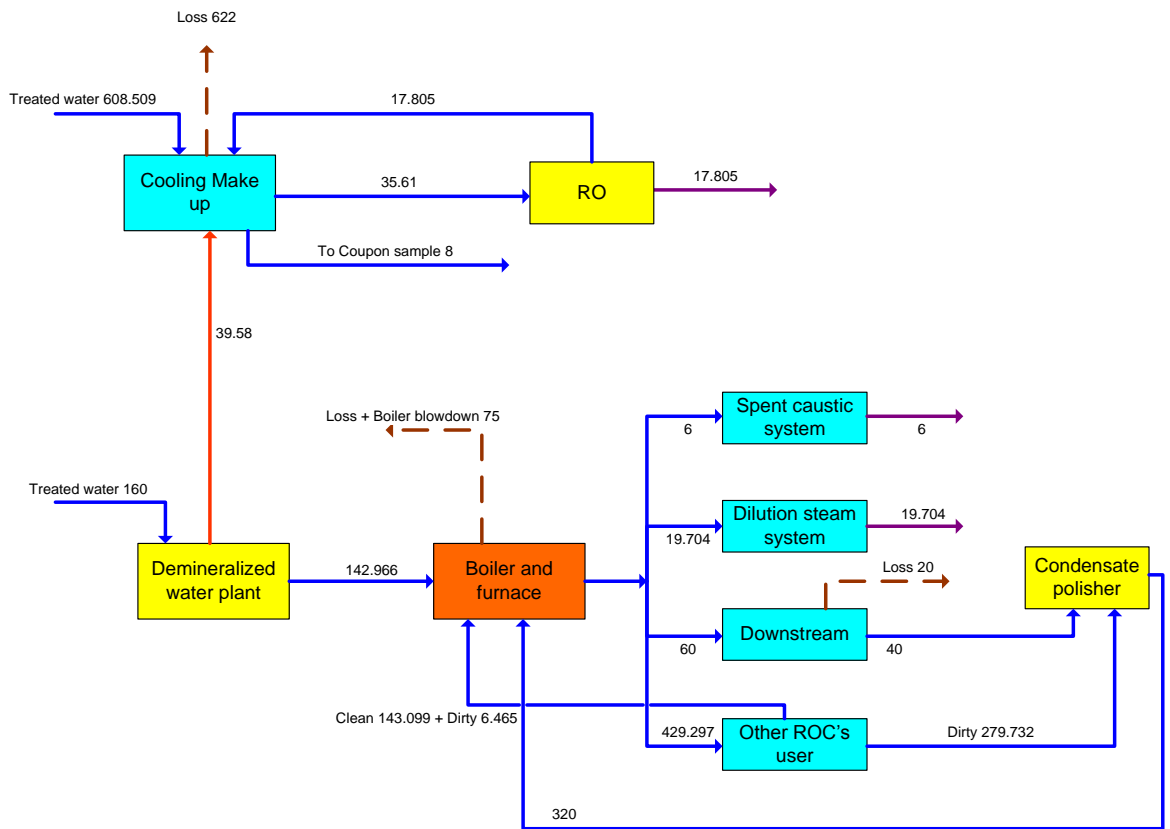


Figure 4.10 Block diagram of water-using network for case 2

Table 4.9 Inlet and outlet concentration of each contaminant for each operation case2

Operation	Inlet concentration (ppm)			Outlet concentration (ppm)		
	Silica	TDS	COD	Silica	TDS	COD
1. cooling tower	18.52	116.92	13.82	90.00	1178.96	43.44
2. Spent caustic system	0.02	0.00	0.03	0.03	56833.33	2620.03
3. Dilution steam system	0.02	0.00	0.03	0.03	270.00	2706.08
4. Downstream	0.02	0.00	0.03	0.06	9.50	3.06
5. ROC's user (Dirty condensate)	0.02	0.00	0.03	0.03	9.78	4.89
6. ROC's user (Clean condensate)	0.02	0.00	0.03	0.10	14.68	4.89
7. Boiler and furnace	0.02	3.38	1.50	0.02	0.00	0.03

The water-using network of case 1 consumes fewer amount of treated water than case 2 does but increasing of investment cost of case 1 is higher than case 2.

To reduce treated water usage, the other sources of water in the process are considered. Water from diversion box and boiler blowdown can be reused in some operations. After water from diversion box is added to the process, water-using network is shown in Figure 4.11. The constraints of case 3 are as same as the previous case but add water from diversion box as a source of water. From the water-using network of case 3, water from diversion box is fed to cooling tower, reverse osmosis and condensate polisher. In this case, the amount of treated water usage can be reduced about 45.14 ton/hr or 5.79%.

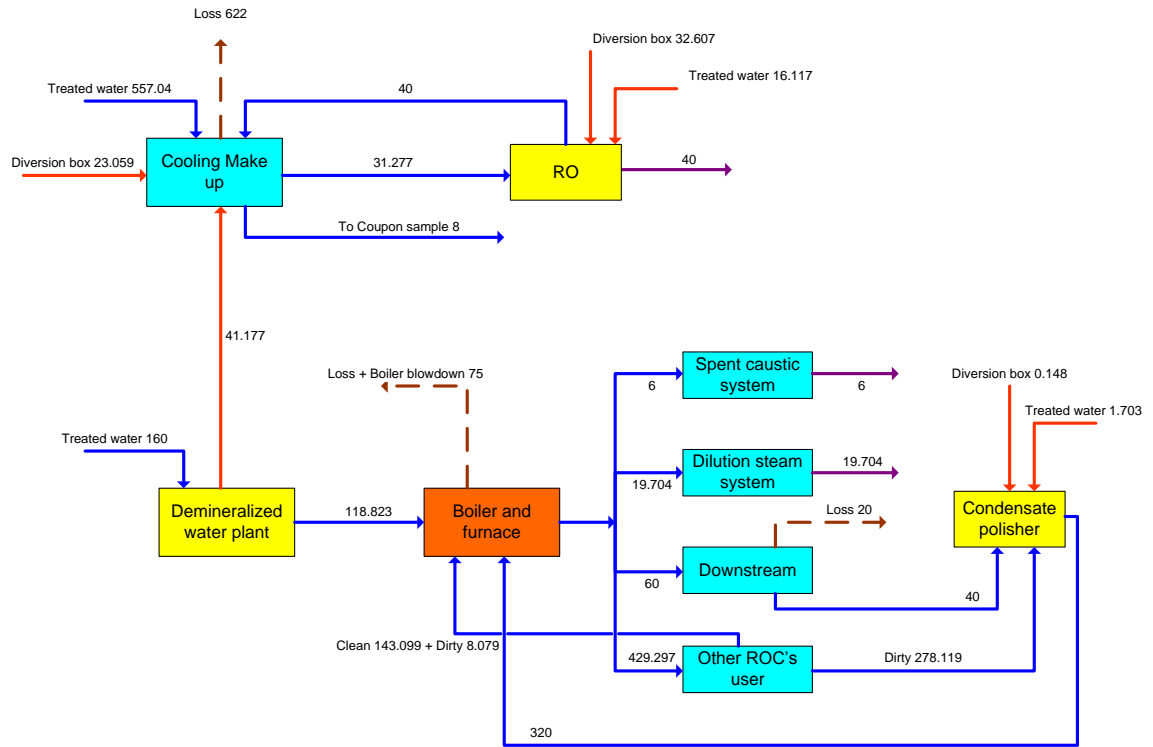


Figure 4.11 Block diagram of water-using network for case 3

Table 4.10 Inlet and outlet concentration of each contaminant for each operation case3

Operation	Inlet concentration (ppm)			Outlet concentration (ppm)		
	Silica	TDS	COD	Silica	TDS	COD
1. cooling tower	18.02	137.75	15.00	90.00	1207.20	44.82
2. Spent caustic system	0.02	0.00	0.03	0.03	56833.33	2620.03
3. Dilution steam system	0.02	0.00	0.03	0.03	270.00	2706.12
4. Downstream	0.02	0.00	0.03	0.06	9.50	3.06
5. ROC's user (Dirty condensate)	0.02	0.00	0.03	0.03	9.78	4.89
6. ROC's user (Clean condensate)	0.02	0.00	0.03	0.10	14.68	4.89
7. Boiler and furnace	0.02	3.40	1.53	0.02	0.00	0.03

Because of contact with NALGO that is water inlet of reverse osmosis must be the cooling water blowdown, water from diversion box cannot be fed to this regeneration. This brings to adding a constraint to case 3. The constraint is water from diversion box cannot be fed to the reverse osmosis. Therefore, constraints of case 4 are as follows:

- Water balance of each operation and regeneration are performed.
- Mass balance of each contaminant of the operations and regenerations are performed.

- c. The concentration of each contaminant of every stream must be less than the liming concentration.
- d. Total flowrate for each operation is not larger than its capacity.
- e. Fresh water and any discharged stream cannot be sent to the spent caustic system, dilution steam system, downstream and ROC's user because these unit need steam.
- f. Discharged from spent caustic system and dilution steam system cannot be reused in any other units.
- g. All of condensate from downstream is sent to the condensate polisher.
- h. All of condensate from ROC's user is recycled ton boiler and furnace.
- i. Water from diversion box cannot be fed to the reverse osmosis.

The result from GAMS for case 4 is shown as Figure 4.12. The amount of treated water usage of this case can be reduced 29.174 ton/hr or 3.74%.

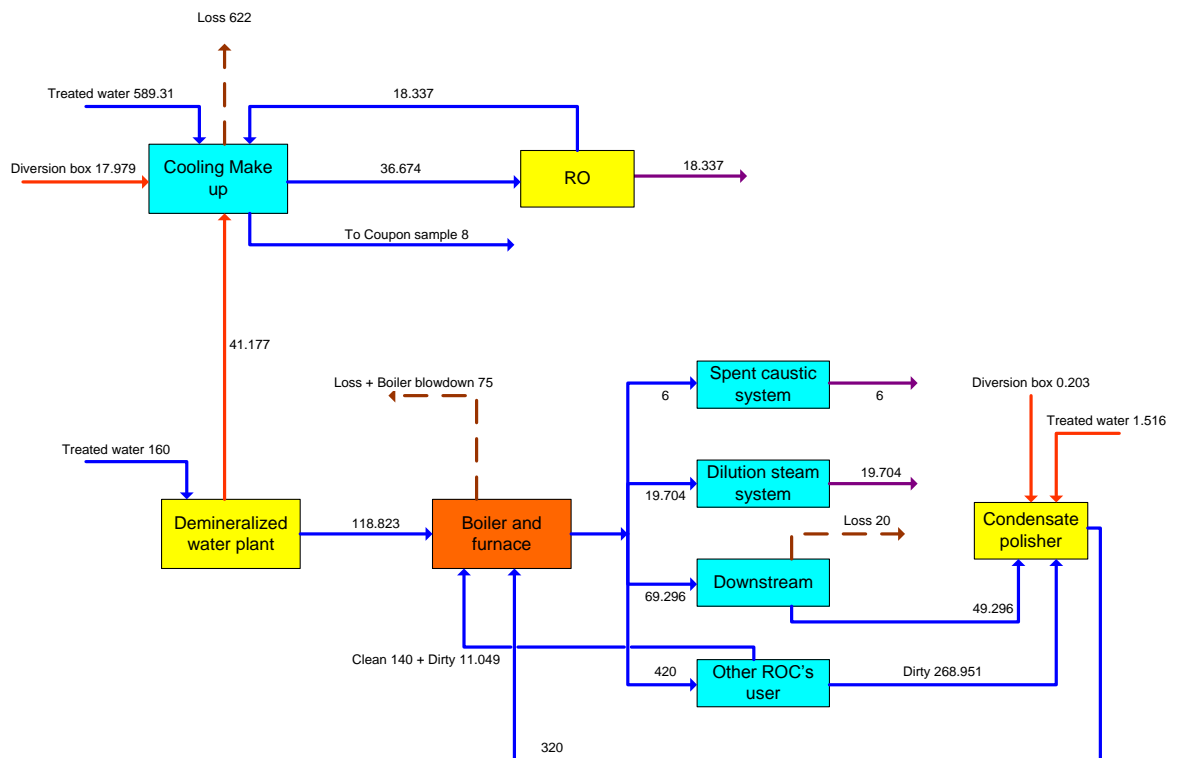


Figure 4.12 Block diagram of water-using network for case 4

Table 4.11 Inlet and outlet concentration of each contaminant for each operation case4

Operation	Inlet concentration (ppm)			Outlet concentration (ppm)		
	Silica	TDS	COD	Silica	TDS	COD
1. cooling tower	18.60	134.92	15.00	90.00	1195.70	44.58
2. Spent caustic system	0.02	0.00	0.03	0.03	56833.33	2620.03
3. Dilution steam system	0.02	0.00	0.03	0.03	270.00	2706.12
4. Downstream	0.02	0.00	0.03	0.05	8.23	2.65
5. ROC's user (Dirty condensate)	0.02	0.00	0.03	0.03	10.00	5.00
6. ROC's user (Clean condensate)	0.02	0.00	0.03	0.10	15.00	5.00
7. Boiler and furnace	0.02	20.00	3.50	0.02	1.55	0.03

When consider water from boiler blowdown, concentration of each contaminant is less when compare with treated water. Therefore, the water from boiler blowdown can be fed to demineralized water plant instead of treated water. Because the amount of boiler blowdown is about 20 ton/hr, it can save treated water 20 ton/hr. From case 2, if boiler blowdown is fed to demineralized water plant, the water-using network does not change as shown in Figure 4.13 but the amount of treated water usage can be reduce 31.491 ton/hr or 4.04%. For this case, inlet and outlet concentration of each operation and regeneration don't change except inlet concentration of demineralized water plant.

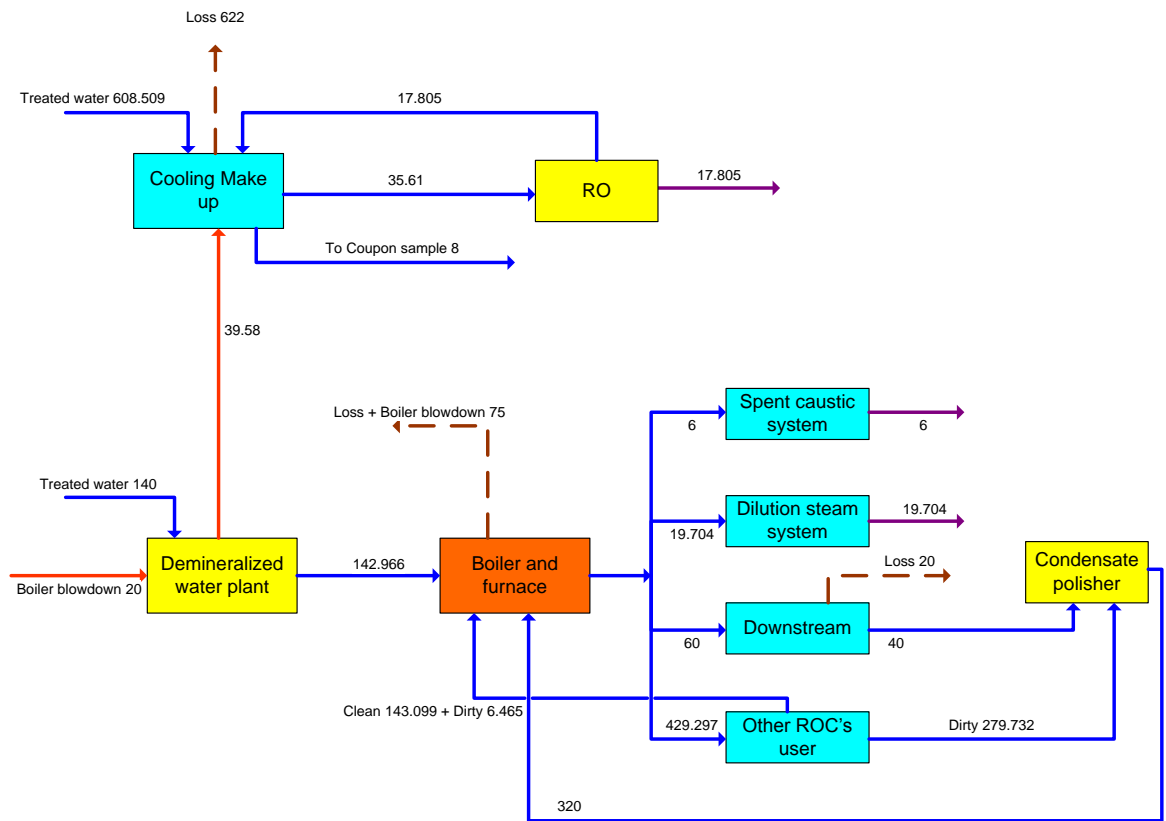


Figure 4.13 Block diagram of water-using network for case 5

To reduce more of treated water usage, all of sources of water are considered. Case 6 is modified from case 5. 8 ton/hr of water from coupon sample is fed to the reverse osmosis to be regenerated before recycled to the cooling tower. The amount of treated water usage can be reduce 35.491 ton/hr or 4.55%. Inlet and outlet concentration of each operation and regeneration are as same as case 5.

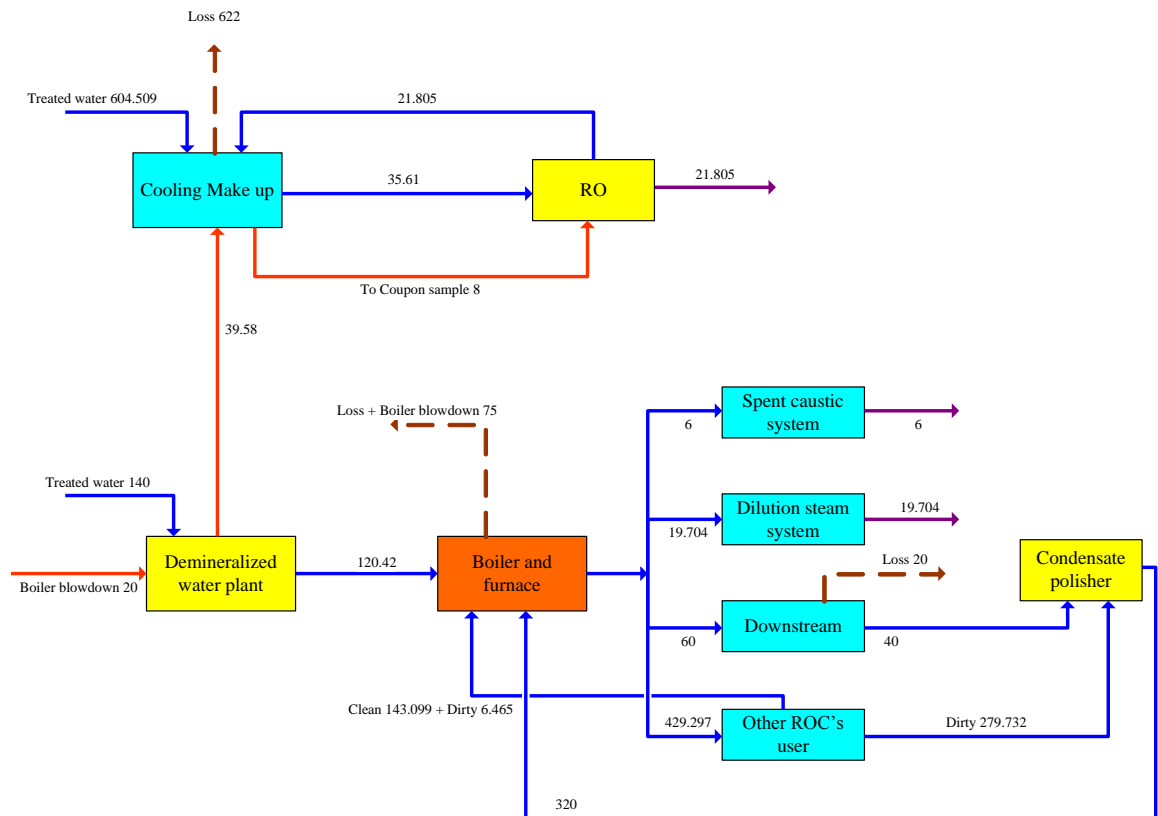


Figure 4.14 Block diagram of water-using network for case 6

4.3.3 Economic evaluation

From the result of water-using network, case 5 and case 6 are better than the others. Therefore, there are new 3 pipe lines that have to be constructed which are piping from demineralized water plant to cooling tower (piping 1), piping from boiler blowdown to demineralized water plant (piping 2) and piping from coupon sample to the reverse osmosis (piping 3). Pump is not needed in the piping 1 because there is a pump in this network. The piping 3 is expensive because coupon sample is scattered around the plant and the distance is far from the reverse osmosis. Data of each piping are shown in Table 4.12.

Table 4.12 Data of piping

	Piping 1	Piping 2	Piping 3
Distance (m)	100	400	-
Flowrate (ton/hr)	39.58	20	-
Pipe diameter (inch)	4	2	-
Pipe schedule	40	40	-
Material	Carbon steel	Carbon steel	PVC
Pipe cost (Baht)	300,000	800,000	500,000
Pump cost (Baht)	0	150,000	200,000
Electric cost (Baht/hr)	0	12.5	25

The total investment cost and the total cost saving are calculated after piping cost estimation, treated water cost reduction, treatment cost increment, piping and labor cost, pump cost and electric cost of case 5 and case 6 are investigated. Although case 6 can reduce treated water cost more than case 5, case 6 has to investment more. Cost estimations for case 5 and case 6 are shown in Table 4.13

Table 4.13 Cost estimation for water-using network of Case 5 and Case 6

	Case 5	Case 6
Treated water cost reduction (Baht/year)	350,000	390,000
Treatment cost increment (Baht/year)	1,300,000	1,300,000
Piping and labor (Baht)	2,200,000	3,200,000
Pump (Baht)	(5 kW) 150,000	(10 kW) 350,000
Electric cost (Baht/year)	99,000	300,000
Total investment cost (Baht)	2,350,000	3,550,000
Total saved cost (Baht/yr)	2,100,000	2,300,000

As above-mentioned, the decision from ROC needs to be addressed to trade-off between case 5 and case 6.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Because of high rate of water consumption about 1,100 ton/hr, the optimization of fresh water consumption is investigated. Therefore, the objectives of this work are to apply pinch analysis and optimization technique for solving the water-using minimization problem and to develop the water-using system of ROC plant in order to reduce fresh water consumption in the process system. In this work, three contaminants including Silica, Total dissolved solids (TDS) and COD have been considered to analyze the water-using network because these three contaminants are acceptable to represent other contaminants in the process system. There have been two approaches to obtain fundamental designs of the water-using systems which are conceptual graphical design (water pinch) and mathematical programming. Water pinch analysis is a simple method but it has beneficial results when applied to the water-using industries. However, it will be more difficult in case of the number of concerned contaminants increases. Hence, mathematical optimization outperforms water pinch analysis for multiple contaminants or constraints. For single contaminant approach, the key contaminants were individual analyzed as a single contaminant and the amount of required fresh water was calculated for all of them. In this stage, water pinch analysis or graphical method is obtained. Pinch points are located at Silica concentration of 90 ppm, TDS of 1200 ppm and COD of 45 ppm which are the outlet concentration of cooling tower. Therefore, the optimal water-using network can be designed by investigating and debottlenecking of cooling tower. In the next stage, three contaminants were analyzed simultaneously. Mathematical programming needs to solve the multiple contaminants approach. The optimal water-using networks are investigated by using GAMS (General Algebraic Modeling System). There are six operations that be considered which are cooling tower, spent caustic system, dilution steam system, downstream, ROC's user and boiler and furnace. There are three regenerations; the reverse osmosis, the demineralized water plant and the condensate polisher. There are six cases of water-using network in this stage. Each case has different constraints. The results show that the amount of required fresh water is reduced 17.655, 11.491, 45.14, 29.174, 31.491 and 35.491 ton/hr for cases 1 to 6, respectively. Although the water-using network of case 2 can reduce freshwater usage than other case, it is impossible to operate this case in the actual process. The water-using networks of cases 5 and 6 are considered to operate in the actual process. The suitable water-using network would be investigated after increasing of investment cost for each case is calculated.

The results show that cases 5 and 6 are better than the others. Therefore, there are 3 new pipe lines that have to be constructed. Reduced costs are 2.1 and 2.3 million baht per year for cases 5 and 6 under the total investment costs of 2.35 and 3.55 million baht, respectively.

5.2 Recommendations

5.2.1 Considering other contaminants

To make sure that the results of water-using network from GAMS can be applied in the actual process, other contaminants such as pH, suspended solid and turbidity should be considered by adding constraints of these contaminants to GAMS. The concentration of each contaminant considered in GAMS has to be measured in every stream to ensure that it is less than its limiting concentration. Although a contaminant is only concerned in any unit operation, the contaminant concentration has to be measure in every stream because the concentrations of every stream have to be used to calculate mass load for the operations.

5.2.2 Adding regenerations

Required fresh water can be reduced more if the regeneration that can regenerate wastewater from spent caustic system, dilution steam system and rejected stream from reverse osmosis is added to the process system. In addition, this can reduce waste water from process system.

5.2.3 Considering the result from GAMS

Although the total cost saving of water-using network of case 5 is close to the total cost saving of water-using network of case 6 and the investment cost of water-using network of case 6 is more than water-using network of case 5, water-using network of case 6 can reduce more discharged wastewater than water-using network of case 5. So it's up to our sponsors' decision to trade-off between water-using network of cases 5 and 6.

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APPENDIX A

GAMS input and output for case 1

GAMS input

SETS I operations /Oper1,oper2,oper3,oper4,oper5C,oper5D,oper6/

J contaminants /A, B, C/;

Parameter Cf(J) contaminant concentration of fresh water in ppm;

$$Cf('A') = 20 \quad ;$$

$$Cf('B') = 124.5 \quad ;$$

$$Cf('C') = 15 \quad ;$$

Parameter M1(J) mass load for operation 1 in kg per hr;

$$M1('A') = 47.6;$$

$$M1('B') = 707.2;$$

$$M1('C') = 19.72;$$

Parameter M2(J) mass load for operation 2 in kg per hr;

$$M2('A') = 0.00006;$$

$$M2('B') = 341;$$

$$M2('C') = 15.72;$$

Parameter M3(J) mass load for operation 3 in kg per hr;

$$M3('A') = 0.00019;$$

$$M3('B') = 5.32;$$

$$M3('C') = 53.32;$$

Parameter M4(J) mass load for operation 4 in kg per hr;

$$M4('A') = 0.002337;$$

$$M4('B') = 0.57;$$

$$M4('C') = 0.18183;$$

Parameter M5C(J) mass load for operation 5 in kg per hr;

$$M5C('A') = 0.0014;$$

$$M5C('B') = 1.4;$$

$$M5C('C') = 0.6958;$$

Parameter M5D(J) mass load for operation 5 in kg per hr;

$$M5D('A') = 0.0224;$$

$$M5D('B') = 4.2;$$

$$M5D('C') = 1.3916;$$

Parameter M6(J) mass load for operation 6 in kg per hr;

$$M6('A') = 0;$$

$$M6('B') = 0;$$

$$M6('C') = 0;$$

Parameter Climin1(J) Limiting inlet concentrations for operation 1 in ppm;

$$Climin1('A') = 20;$$

$$Climin1('B') = 160;$$

$$Climin1('C') = 15;$$

Parameter Climin2(J) Limiting inlet concentrations for operation 2 in ppm;

$$Climin2('A') = 0.02;$$

$$Climin2('B') = 0.03;$$

$$Climin2('C') = 0.03;$$

Parameter Climin3(J) Limiting inlet concentrations for operation 3 in ppm;

$$Climin3('A') = 0.02;$$

$$Climin3('B') = 0.02;$$

$$Climin3('C') = 0.03;$$

Parameter Climin4(J) Limiting inlet concentrations for operation 4 in ppm;

$$Climin4('A') = 0.02;$$

$$Climin4('B') = 0.02;$$

$$Climin4('C') = 0.03;$$

Parameter Climin5C(J) Limiting inlet concentrations for operation 5 in ppm;

$$Climin5C('A') = 0.02;$$

$$Climin5C('B') = 0.02;$$

$$\text{Climin5C('C')} = 0.03;$$

Parameter Climin5D(J) Limiting inlet concentrations for operation 5 in ppm;

$$\text{Climin5D('A')} = 0.02;$$

$$\text{Climin5D('B')} = 0.02;$$

$$\text{Climin5D('C')} = 0.03;$$

Parameter Climin6(J) Limiting inlet concentrations for operation 6 in ppm;

$$\text{Climin6('A')} = 0.02;$$

$$\text{Climin6('B')} = 20;$$

$$\text{Climin6('C')} = 25;$$

Parameter Climout1(J) Limiting outlet concentrations for operation 1 in ppm;

$$\text{Climout1('A')} = 90;$$

$$\text{Climout1('B')} = 1300;$$

$$\text{Climout1('C')} = 45;$$

Parameter Climout2(J) Limiting outlet concentrations for operation 2 in ppm;

$$\text{Climout2('A')} = 1;$$

$$\text{Climout2('B')} = 70000;$$

$$\text{Climout2('C')} = 2700;$$

Parameter Climout3(J) Limiting outlet concentrations for operation 3 in ppm;

$$\text{Climout3('A')} = 1;$$

$$\text{Climout3('B')} = 270;$$

$$\text{Climout3('C')} = 2900;$$

Parameter Climout6(J) Limiting outlet concentrations for operation 6 in ppm;

$$\text{Climout6('A')} = 0.02;$$

$$\text{Climout6('B')} = 0;$$

$$\text{Climout6('C')} = 0.03;$$

Parameter ClimR1(J) Limiting outlet concentrations for regen 1 in ppm;

$$\text{ClimR1('A')} = 90;$$

ClimR1('B') = 1300;

ClimR1('C') = 45;

Parameter ClimR2(J) Limiting outlet concentrations for regen 2 in ppm;

ClimR2('A') = 20;

ClimR2('B') = 230;

ClimR2('C') = 15;

Parameter ClimR3(J) Limiting outlet concentrations for regen 3 in ppm;

ClimR3('A') = 1;

ClimR3('B') = 15;

ClimR3('C') = 5;

Parameter Floss(I) Flowrate loss in operation i;

Floss('oper1') = 622;

Floss('oper2') = 0;

Floss('oper3') = 0;

Floss('oper4') = 20;

Floss('oper5C') = 0;

Floss('oper5D') = 0;

Floss('oper6') = 75;

Parameter Fgain(I) Flowrate gain in operation i;

Fgain('oper1') = 0;

Fgain('oper2') = 0;

Fgain('oper3') = 0;

Fgain('oper4') = 0;

Fgain('oper5C') = 0;

Fgain('oper5D') = 0;

Fgain('oper6') = 0;

Parameter R1(J) removal ration for regeneration 1;

$$R1('A') = 0.9;$$

$$R1('B') = 0.9;$$

$$R1('C') = 0.9;$$

Parameter R2(J) removal ration for regeneration 2;

$$R2('A') = 1;$$

$$R2('B') = 1;$$

$$R2('C') = 1;$$

Parameter R3(J) removal ration for regeneration 3;

$$R3('A') = 0.9;$$

$$R3('B') = 0.9;$$

$$R3('C') = 0.9;$$

Scalar RRO percent to reject /0.5/

Variables

F(I) flowrate of freshwater to operation i in ton per hr

D(I) flowrate from diversion box to operation i in ton per hr

X(I,I) flowrate to operation i from operation j in ton per hr

XTR1(I) flowrate to operation i from regeneration 1

XTR2(I) flowrate to operation i from regeneration 2

XTR3(I) flowrate to operation i from regeneration 3

XFR1(I) flowrate from operation i to regeneration 1

XFR2(I) flowrate from operation i to regeneration 2

XFR3(I) flowrate from operation i to regeneration 3

Xreject flowrate from RO to rejected stream

Cin1(J) inlet concentration to operation 1 of contaminant j in ppm

Cin2(J) inlet concentration to operation 2 of contaminant j in ppm

Cin3(J) inlet concentration to operation 3 of contaminant j in ppm

Cin4(J) inlet concentration to operation 4 of contaminant j in ppm

Cin5C(J) inlet concentration to operation 5 of contaminant j in ppm
 Cin5D(J) inlet concentration to operation 5 of contaminant j in ppm
 Cin6(J) inlet concentration to operation 6 of contaminant j in ppm
 Cout1(J) outlet concentration from operation 1 of contaminant j in ppm
 Cout2(J) outlet concentration from operation 2 of contaminant j in ppm
 Cout3(J) outlet concentration from operation 3 of contaminant j in ppm
 Cout4(J) outlet concentration from operation 4 of contaminant j in ppm
 Cout5C(J) *outlet concentration from operation 5 of contaminant j in ppm
 Cout5D(J) *outlet concentration from operation 5 of contaminant j in ppm
 Cout6(J) outlet concentration from operation 6 of contaminant j in ppm
 CinR1(J) inlet concentration to regeneration 1 of contaminant j in ppm
 CinR2(J) inlet concentration to regeneration 2 of contaminant j in ppm
 CinR3(J) inlet concentration to regeneration 3 of contaminant j in ppm
 CoutR1(J) outlet concentration from regeneration 1 of contaminant j in ppm
 CoutR2(J) outlet concentration from regeneration 2 of contaminant j in ppm
 CoutR3(J) outlet concentration from regeneration 3 of contaminant j in ppm
 W(I) wastewater flowrate from operation i in ton per hr
 FR1 flowrate of freshwater to regeneration 1 in ton per hr
 FR2 flowrate of freshwater to regeneration 2 in ton per hr
 FR3 flowrate of freshwater to regeneration 3 in ton per hr
 DR1 flowrate from diversion box to regeneration 1 in ton per hr
 DR2 flowrate from diversion box to regeneration 2 in ton per hr
 DR3 flowrate from diversion box to regeneration 3 in ton per hr
 Flim total freshwater flowrate in ton per hr;

Positive variable F, D, FR1, FR2, FR3, DR1, DR2, DR3, X, Cout1, Cout2, Cout3, Cout4, Cout5C, Cout5D, Cin1, Cin2, Cin3, Cin4, Cin5C, Cin5D, CinR1, CinR2, CinR3, W, XTR1, XTR2, XTR3, XFR1, XFR2, XFR3;

F.L('Oper1') = 6600;

F.L('Oper2') = 0;
F.L('Oper3') = 0;
F.L('Oper4') = 0;
F.L('Oper5C') = 0;
F.L('Oper5D') = 0;
F.L('Oper6') = 0;
FR1.L = 0;
FR2.L = 1120;
FR3.L = 0;
W.L('Oper1') = 0;
W.L('Oper2') = 6;
W.L('Oper3') = 19;
W.L('Oper4') = 0;
W.L('Oper5C') = 0;
W.L('Oper5D') = 0;
W.L('Oper6') = 0;
Cout1.L('A') = 90;
Cout1.L('B') = 1300;
Cout2.L('A') = 0.03;
Cout2.L('B') = 60000;
Cout3.L('A') = 0.03;
Cout3.L('B') = 280;
Cout4.L('A') = 0.06;
Cout4.L('B') = 10;
Cout5C.L('A') = 0.03;
Cout5C.L('B') = 10;
Cout5D.L('A') = 0.1;

Cout5D.L('B') = 15;
Cout6.L('A') = 0.02;
Cout6.L('B') = 0;
XFR1.L('Oper1') = 58;
XFR1.L('Oper2') = 0;
XFR1.L('Oper3') = 0;
XFR1.L('Oper4') = 0;
XFR1.L('Oper5C') = 0;
XFR1.L('Oper5D') = 0;
XFR2.L('Oper1') = 0;
XFR2.L('Oper2') = 0;
XFR2.L('Oper3') = 0;
XFR2.L('Oper4') = 0;
XFR2.L('Oper5C') = 0;
XFR2.L('Oper5D') = 0;
XFR3.L('Oper1') = 0;
XFR3.L('Oper2') = 0;
XFR3.L('Oper3') = 0;
XFR3.L('Oper4') = 0;
XFR3.L('Oper5C') = 0;
XFR3.L('Oper5D') = 280;
XTR1.L('Oper1') = 20;
XTR1.L('Oper6') = 0;
XTR2.L('Oper1') = 0;
XTR2.L('Oper6') = 120;
XTR3.L('Oper1') = 0;
XTR3.L('Oper6') = 317;

$X.L('oper2','oper6') = 6;$
 $X.L('oper3','oper6') = 19;$
 $X.L('oper4','oper6') = 57;$
 $X.L('oper5C','oper6') = 140;$
 $X.L('oper5D','oper6') = 280;$
 $Xreject.L = 38;$

Equations

Supply Define objective function

Cinlet1(J) inlet concentration to operation 1

Cinlet2(J) inlet concentration to operation 2

Cinlet3(J) inlet concentration to operation 3

Cinlet4(J) inlet concentration to operation 4

Cinlet5C(J) inlet concentration to operation 5

Cinlet5D(J) inlet concentration to operation 5

Cinlet6(J) inlet concentration to operation 6

Cinlim1(J) constraint associated with inlet to operation 1

Cinlim2(J) constraint associated with inlet to operation 2

Cinlim3(J) constraint associated with inlet to operation 3

Cinlim4(J) constraint associated with inlet to operation 4

Cinlim5C(J) constraint associated with inlet to operation 5

Cinlim5D(J) constraint associated with inlet to operation 5

Cinlim6(J) constraint associated with inlet to operation 6

Coutlim1(J) constraint associated with outlet to operation 1

Coutlim2(J) constraint associated with outlet to operation 2

Coutlim3(J) constraint associated with outlet to operation 3

Coutlet1(J) constraint associated with outlet from operation 1

Coutlet2(J) constraint associated with outlet from operation 2
Coutlet3(J) constraint associated with outlet from operation 3
Coutlet4(J) constraint associated with outlet from operation 4
Coutlet5C(J) constraint associated with outlet from operation 5
Coutlet5D(J) constraint associated with outlet from operation 5
Coutlet6(J) constraint associated with outlet from operation 6
Mass1 water mass balance over operation 1
Mass2 water mass balance over operation 2
Mass3 water mass balance over operation 3
Mass4 water mass balance over operation 4
Mass5C *water mass balance over operation 5
Mass5D *water mass balance over operation 5
Mass6 water mass balance over operation 6
Masslow2 lower bound water flowrate operation 2
Masslim3 limiting water flowrate operation 3
Masslim4 limiting water flowrate operation 4
Masslow5C lower bound water flowrate operation 5C
Masslow5D lower bound water flowrate operation 5D
Masslim6 limiting water flowrate operation 6
Mass5 water mass balance over operation 5
CinletR1(J) inlet concentration to regeneration 1
CinletR2(J) inlet concentration to regeneration 2
CinletR3(J) inlet concentration to regeneration 3
CinlimR1(J) inlet concentration to regeneration 1
CinlimR2(J) inlet concentration to regeneration 2
CinlimR3(J) inlet concentration to regeneration 3
CoutletR1(J) outlet concentration from regeneration 1

CoutletR2(J) outlet concentration from regeneration 2

CoutletR3(J) outlet concentration from regeneration 3

ROreject Flowrate of RO reject

MassR1 water mass balance over regeneration 1

MassR2 water mass balance over regeneration 2

MassR3 water mass balance over regeneration 3

CapaR1 limiting load of R1

CapaR2 limiting load of R2

CapaR3 limiting load of R3

X21 flowrate from oper2 to oper1

X31 flowrate from oper3 to oper1

X41 flowrate from oper4 to oper1

X5C1 flowrate from oper5C to oper1

X5D1 flowrate from oper5D to oper1

W1 From oper1 to coupon sample

R31 flowrate from regen3 to oper1;

Supply.. Flim =e= F('Oper1')+F('Oper6')+FR1+FR2+FR3;

Cinlet1(J)..

Cin1(J)*(F('Oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5C')+X('Oper1','Oper5D')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1'))
=E=

(Cf(J)*F('Oper1')+Cout2(J)*X('Oper1','Oper2')+Cout3(J)*X('Oper1','Oper3')+Cout4(J)*X('Oper1','Oper4')+Cout5C(J)*X('Oper1','Oper5C')+Cout5D(J)*X('Oper1','Oper5D')+CoutR1(J)*XTR1('Oper1')+CoutR2(J)*XTR2('Oper1')+CoutR3(J)*XTR3('Oper1'));

Cinlet2(J).. Cin2(J)*(X('Oper2','Oper6')) =E= (Cout6(J)*X('Oper2','Oper6'));

Cinlet3(J).. Cin3(J)*(X('Oper3','Oper6')) =E= (Cout6(J)*X('Oper3','Oper6'));

Cinlet4(J).. Cin4(J)*(X('Oper4','Oper6')) =E= (Cout6(J)*X('Oper4','Oper6'));

Cinlet5C(J).. Cin5C(J)*(X('Oper5C','Oper6')) =E= (Cout6(J)*X('Oper5C','Oper6'));

Cinlet5D(J).. Cin5D(J)*(X('Oper5D','Oper6')) =E= (Cout6(J)*X('Oper5D','Oper6'));

Cinlet6(J)..

Cin6(J)*(F('Oper6')+X('Oper6','Oper1')+X('Oper6','Oper2')+X('Oper6','Oper3')+X('Oper6','Oper4')+X('Oper6','Oper5C')+X('Oper6','Oper5D')+XTR1('Oper6')+XTR2('Oper6')+XTR3('Oper6')) =E=
 (Cf(J)*F('Oper6')+Cout1(J)*X('Oper6','Oper1')+Cout2(J)*X('Oper6','Oper2')+Cout3(J)*X('Oper6','Oper3')+Cout4(J)*X('Oper6','Oper4')+Cout5C(J)*X('Oper6','Oper5C')+Cout5D(J)*X('Oper6','Oper5D')+CoutR1(J)*XTR1('Oper6')+CoutR2(J)*XTR2('Oper6')+CoutR3(J)*XTR3('Oper6'));

Cinlim1(J).. Cin1(J) =l= Climin1(J);

Cinlim2(J).. Cin2(J) =l= Climin2(J);

Cinlim3(J).. Cin3(J) =l= Climin3(J);

Cinlim4(J).. Cin4(J) =l= Climin4(J);

Cinlim5C(J).. Cin5C(J) =l= Climin5C(J);

Cinlim5D(J).. Cin5D(J) =l= Climin5D(J);

Cinlim6(J).. Cin6(J) =l= Climin6(J);

Coutlim1(J).. Cout1(J) =l= Climout1(J);

Coutlim2(J).. Cout2(J) =l= Climout2(J);

Coutlim3(J).. Cout3(J) =l= Climout3(J);

Coutlet1(J)..

Cout1(J)*(F('Oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5C')+X('Oper1','Oper5D')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1')) =E=
 (Cf(J)*F('Oper1')+Cout2(J)*X('Oper1','Oper2')+Cout3(J)*X('Oper1','Oper3')+Cout4(J)*X('Oper1','Oper4')+Cout5C(J)*X('Oper1','Oper5C')+Cout5D(J)*X('Oper1','Oper5D')+CoutR1(J)*XTR1('Oper1')+CoutR2(J)*XTR2('Oper1')+CoutR3(J)*XTR3('Oper1')+M1(J)*1000);

Coutlet2(J).. Cout2(J)*(X('Oper2','Oper6')) =E=
 (Cout6(J)*X('Oper2','Oper6')+M2(J)*1000);

Coutlet3(J).. Cout3(J)*(X('Oper3','Oper6')) =E=
 (Cout6(J)*X('Oper3','Oper6')+M3(J)*1000);

Coutlet4(J).. Cout4(J)*(X('Oper4','Oper6')) =E=
 (Cout6(J)*X('Oper4','Oper6')+M4(J)*1000);

Coutlet5C(J).. Cout5C(J)*(X('Oper5C','Oper6')) =E=
 (Cout6(J)*X('Oper5C','Oper6')+M5C(J)*1000);

Coutlet5D(J).. Cout5D(J)*(X('Oper5D','Oper6')) =E=
(Cout6(J)*X('Oper5D','Oper6')+M5D(J)*1000);

Coutlet6(J).. Cout6(J) =e= Climout6(J);

Mass1..

F('Oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5
C')+X('Oper1','Oper5D')+Fgain('Oper1')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper
1') =E=

W('Oper1')+X('Oper6','Oper1')+Floss('Oper1')+XFR1('Oper1')+XFR2('Oper1')+XFR3('Oper1');

Mass2.. X('Oper2','Oper6')+Fgain('Oper2') =E=

W('Oper2')+X('Oper1','Oper2')+X('Oper6','Oper2')+Floss('Oper2')+XFR1('Oper2')+XFR2('Oper2')+XFR3('Oper2');

Mass3.. X('Oper3','Oper6')+Fgain('Oper3') =E=

W('Oper3')+X('Oper1','Oper3')+X('Oper6','Oper3')+Floss('Oper3')+XFR1('Oper3')+XFR2('Oper3')+XFR3('Oper3');

Mass4.. X('Oper4','Oper6')+Fgain('Oper4') =E=

W('Oper4')+X('Oper1','Oper4')+X('Oper6','Oper4')+Floss('Oper4')+XFR1('Oper4')+XFR2('Oper4')+XFR3('Oper4');

Mass5C.. X('Oper5C','Oper6')+Fgain('Oper5C') =E=

W('Oper5C')+X('Oper1','Oper5C')+X('Oper6','Oper5C')+Floss('Oper5C')+XFR1('Oper5C')+XFR2('Oper5C')+XFR3('Oper5C');

Mass5D.. X('Oper5D','Oper6')+Fgain('Oper5D') =E=

W('Oper5D')+X('Oper1','Oper5D')+X('Oper6','Oper5D')+Floss('Oper5D')+XFR1('Oper5D')+XFR2('Oper5D')+XFR3('Oper5D');

Mass6..

F('Oper6')+X('Oper6','Oper1')+X('Oper6','Oper2')+X('Oper6','Oper3')+X('Oper6','Oper4')+X('Oper6','Oper5C')+X('Oper6','Oper5D')+Fgain('Oper6')+XTR1('Oper6')+XTR2('Oper6')+XTR3('Oper6') =E=

W('Oper6')+X('Oper2','Oper6')+X('Oper3','Oper6')+X('Oper4','Oper6')+X('Oper5C','Oper6')+X('Oper5D','Oper6')+Floss('Oper6');

Masslow2.. X('Oper2','Oper6')+Fgain('Oper2') =g= 6;

Masslim3.. X('Oper3','Oper6')+Fgain('Oper3') =l= 20;

Masslim4.. X('Oper4','Oper6')+Fgain('Oper4') =g= 60;

Masslow5C.. X('Oper5C','Oper6')+Fgain('Oper5C') =g= 140;

Masslow5D.. X('Oper5D','Oper6')+Fgain('Oper5D') =g= 280;

Masslim6..

$$F('Oper6')+X('Oper6','Oper1')+X('Oper6','Oper2')+X('Oper6','Oper3')+X('Oper6','Oper4')+X('Oper6','Oper5C')+X('Oper6','Oper5D')+Fgain('Oper6')+XTR1('oper6')+XTR2('oper6')+XTR3('oper6') = I = 590;$$

$$\text{Mass5.. } (X('Oper5C','Oper6')+Fgain('Oper5C')) * 2 = E = X('Oper5D','Oper6')+Fgain('Oper5D');$$

CinletR1(J)..

$$\begin{aligned} \text{CinR1(J)} * (XFR1('Oper1')+XFR1('Oper2')+XFR1('Oper3')+XFR1('Oper4')+XFR1('Oper5C')+XFR1('Oper5D')+FR1) = E = \\ (\text{Cout1(J)} * XFR1('Oper1') + \text{Cout2(J)} * XFR1('Oper2') + \text{Cout3(J)} * XFR1('Oper3') + \text{Cout4(J)} * XFR1('Oper4') + \text{Cout5C(J)} * XFR1('Oper5C') + \text{Cout5D(J)} * XFR1('Oper5D') + \text{Cf(J)} * FR1); \end{aligned}$$

CinletR2(J)..

$$\begin{aligned} \text{CinR2(J)} * (XFR2('Oper1')+XFR2('Oper2')+XFR2('Oper3')+XFR2('Oper4')+XFR2('Oper5C')+XFR2('Oper5D')+FR2) = E = \\ (\text{Cout1(J)} * XFR2('Oper1') + \text{Cout2(J)} * XFR2('Oper2') + \text{Cout3(J)} * XFR2('Oper3') + \text{Cout4(J)} * XFR2('Oper4') + \text{Cout5C(J)} * XFR2('Oper5C') + \text{Cout5D(J)} * XFR2('Oper5D') + \text{Cf(J)} * FR2); \end{aligned}$$

CinletR3(J)..

$$\begin{aligned} \text{CinR3(J)} * (XFR3('Oper1')+XFR3('Oper2')+XFR3('Oper3')+XFR3('Oper4')+XFR3('Oper5C')+XFR3('Oper5D')+FR3) = E = \\ (\text{Cout1(J)} * XFR3('Oper1') + \text{Cout2(J)} * XFR3('Oper2') + \text{Cout3(J)} * XFR3('Oper3') + \text{Cout4(J)} * XFR3('Oper4') + \text{Cout5C(J)} * XFR3('Oper5C') + \text{Cout5D(J)} * XFR3('Oper5D') + \text{Cf(J)} * FR3); \end{aligned}$$

$$\text{CinlimR1(J).. } \text{CinR1(J)} = I = \text{ClimR1(J)};$$

$$\text{CinlimR2(J).. } \text{CinR2(J)} = I = \text{ClimR2(J)};$$

$$\text{CinlimR3(J).. } \text{CinR3(J)} = I = \text{ClimR3(J)};$$

$$\text{CoutletR1(J).. } \text{CoutR1(J)} = E = (1 - R1(J)) * \text{CinR1(J)};$$

$$\text{CoutletR2(J).. } \text{CoutR2(J)} = E = (1 - R2(J)) * \text{CinR2(J)};$$

$$\text{CoutletR3(J).. } \text{CoutR3(J)} = E = (1 - R3(J)) * \text{CinR3(J)};$$

RReject.. Xreject = e =

$$\text{RRO} * (\text{FR1} + \text{XFR1('oper1')} + \text{XFR1('oper2')} + \text{XFR1('oper3')} + \text{XFR1('oper4')} + \text{XFR1('oper5C')} + \text{XFR1('oper5D')});$$

MassR1.. XTR1('oper1')+XTR1('oper6')+Xreject = E =

$$(\text{XFR1('oper1')} + \text{XFR1('oper2')} + \text{XFR1('oper3')} + \text{XFR1('oper4')} + \text{XFR1('oper5C')} + \text{XFR1('oper5D')} + \text{FR1});$$

MassR2.. XTR2('oper1')+XTR2('oper6') =E=
 (XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2('oper5D'))+FR2;

MassR3.. XTR3('oper1')+XTR3('oper6') =E=
 (XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3('oper5D'))+FR3;

CapaR1..
 (XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1('oper5D'))+FR1 =l= 80;

CapaR2..
 (XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2('oper5D'))+FR2 =l= 160;

CapaR3..
 (XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3('oper5D'))+FR3 =l= 320;

X21.. X('oper1','oper2') =e=0;

X31.. X('oper1','oper3') =e=0;

X41.. X('oper1','oper4') =e=0;

X5C1.. X('oper1','oper5C') =e=0;

X5D1.. X('oper1','oper5D') =e=0;

R31.. XTR3('oper1') =e= 0;

W1.. w('oper1') =e= 8;

Model Super /All/;

Solve Super using NLP minimizing Flim;

Display

Flim.L,F.L,FR1.L,FR2.L,FR3.L,W.L,X.L,XFR1.L,XTR1.L,XFR2.L,XTR2.L,XFR3.L,
 XTR3.L,Xreject.L,Cin1.L,Cout1.L,Cin2.L,Cout2.L,Cin3.L,Cout3.L,Cin4.L,Cout4.L,Ci
 n5C.L,Cout5C.L,Cin5D.L,Cout5D.L,Cin6.L,Cout6.L,CinR1.L,CoutR1.L,CinR2.L,Cout
 R2.L,CinR3.L,CoutR3.L;

GAMS Output

```

**** REPORT SUMMARY :      0  NONOPT
                             0  INFEASIBLE
                             0  UNBOUNDED
                             0  ERRORS

      495 VARIABLE Flim.L      =    762.344  total freshwater flow
                                rate in ton per hr

----  495 VARIABLE F.L  flowrate of freshwater to operation i in ton per hr
Oper1 660.412

      495 VARIABLE FR1.L      =     0.000  flowrate of freshwate
                                r to regeneration 1 i
                                n ton per hr

----  495 VARIABLE FR2.L      =    99.089  flowrate of freshwate
                                r to regeneration 2 i
                                n ton per hr

----  495 VARIABLE FR3.L      =     2.844  flowrate of freshwate
                                r to regeneration 3 i
                                n ton per hr

----  495 VARIABLE W.L  wastewater flowrate from operation i in ton per hr
Oper1 8.000,  oper2 5.768,  oper3 14.649

----  495 VARIABLE X.L  flowrate to operation i from operation j in ton per hr
      oper2   oper3   oper5C   oper6
oper2                6.000
oper3               19.704
oper4               60.000
oper5C              143.099
oper5D              286.198

```

oper6 0.157 5.050 104.793

---- 495 VARIABLE XFR1.L flowrate from operation i to regeneration 1

Oper1 33.839, oper2 0.015

---- 495 VARIABLE XTR1.L flowrate to operation i from regeneration 1

Oper1 16.927

---- 495 VARIABLE XFR2.L flowrate from operation i to regeneration 2

Oper1 13.500, oper2 0.059, oper4 35.700, oper5D 11.652

---- 495 VARIABLE XTR2.L flowrate to operation i from regeneration 2

oper6 160.000

---- 495 VARIABLE XFR3.L flowrate from operation i to regeneration 3

oper3 0.005, oper4 4.300, oper5C 38.306, oper5D 274.545

---- 495 VARIABLE XTR3.L flowrate to operation i from regeneration 3

oper6 320.000

495 VARIABLE Xreject.L = 16.927 flowrate from RO to r
ejected stream

---- 495 VARIABLE Cin1.L inlet concentration to operation 1 of contaminant j

in ppm

A 19.725, B 124.371, C 14.738

---- 495 VARIABLE Cout1.L outlet concentration from operation 1 of contaminant j
in ppm

A 90.000, B 1168.456, C 43.852

---- 495 VARIABLE Cin2.L inlet concentration to operation 2 of contaminant j in
ppm

A 0.020, C 0.030

---- 495 VARIABLE Cout2.L outlet concentration from operation 2 of contaminant j
in ppm

A 0.030, B 56833.333, C 2620.030

---- 495 VARIABLE Cin3.L inlet concentration to operation 3 of contaminant j in
ppm

A 0.020, C 0.030

---- 495 VARIABLE Cout3.L outlet concentration from operation 3 of contaminant j in ppm

A 0.030, B 270.000, C 2706.120

---- 495 VARIABLE Cin4.L inlet concentration to operation 4 of contaminant j in ppm

A 0.020, C 0.030

---- 495 VARIABLE Cout4.L outlet concentration from operation 4 of contaminant j in ppm

A 0.059, B 9.500, C 3.060

---- 495 VARIABLE Cin5C.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 495 VARIABLE Cout5C.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.030, B 9.783, C 4.892

---- 495 VARIABLE Cin5D.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 495 VARIABLE Cout5D.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.098, B 14.675, C 4.892

---- 495 VARIABLE Cin6.L inlet concentration to operation 6 of contaminant j in ppm

A 0.020, B 20.000, C 25.000

---- 495 VARIABLE Cout6.L outlet concentration from operation 6 of contaminant j in ppm

A 0.020, C 0.030

---- 495 VARIABLE CinR1.L inlet concentration to regeneration 1 of contaminant j in ppm

A 89.960, B 1193.272, C 45.000

---- 495 VARIABLE CoutR1.L outlet concentration from regeration 1 of contaminant j in ppm

A 8.996, B 119.327, C 4.500

---- 495 VARIABLE CinR2.L inlet concentration to regeration 2 of contaminant j in ppm

A 20.000, B 199.949, C 15.000

---- 495 VARIABLE CoutR2.L outlet concentration from regeration 2 of contaminant j in ppm

(ALL 0.000)

---- 495 VARIABLE CinR3.L inlet concentration to regeration 3 of contaminant j in ppm

A 0.266, B 15.000, C 5.000

---- 495 VARIABLE CoutR3.L outlet concentration from regeration 3 of contaminant j in ppm

A 0.027, B 1.500, C 0.500

APPENDIX B

GAMS input and output for case 2

GAMS input

SETS I operations /Oper1,oper2,oper3,oper4,oper5C,oper5D,oper6/

J contaminants /A, B, C/;

Parameter Cf(J) contaminant concentration of fresh water in ppm;

$$Cf('A') = 20 \quad ;$$

$$Cf('B') = 124.5 \quad ;$$

$$Cf('C') = 15 \quad ;$$

Parameter M1(J) mass load for operation 1 in kg per hr;

$$M1('A') = 47.6;$$

$$M1('B') = 707.2;$$

$$M1('C') = 19.72;$$

Parameter M2(J) mass load for operation 2 in kg per hr;

$$M2('A') = 0.00006;$$

$$M2('B') = 341;$$

$$M2('C') = 15.72;$$

Parameter M3(J) mass load for operation 3 in kg per hr;

$$M3('A') = 0.00019;$$

$$M3('B') = 5.32;$$

$$M3('C') = 53.32;$$

Parameter M4(J) mass load for operation 4 in kg per hr;

$$M4('A') = 0.002337;$$

$$M4('B') = 0.57;$$

$$M4('C') = 0.18183;$$

Parameter M5C(J) mass load for operation 5 in kg per hr;

$$M5C('A') = 0.0014;$$

$$M5C('B') = 1.4;$$

$$M5C('C') = 0.6958;$$

Parameter M5D(J) mass load for operation 5 in kg per hr;

$$M5D('A') = 0.0224;$$

$$M5D('B') = 4.2;$$

$$M5D('C') = 1.3916;$$

Parameter M6(J) mass load for operation 6 in kg per hr;

$$M6('A') = 0;$$

$$M6('B') = 0;$$

$$M6('C') = 0;$$

Parameter Climin1(J) Limiting inlet concentrations for operation 1 in ppm;

$$Climin1('A') = 20;$$

$$Climin1('B') = 160;$$

$$Climin1('C') = 15;$$

Parameter Climin2(J) Limiting inlet concentrations for operation 2 in ppm;

$$Climin2('A') = 0.02;$$

$$Climin2('B') = 0.03;$$

$$Climin2('C') = 0.03;$$

Parameter Climin3(J) Limiting inlet concentrations for operation 3 in ppm;

$$Climin3('A') = 0.02;$$

$$Climin3('B') = 0.02;$$

$$Climin3('C') = 0.03;$$

Parameter Climin4(J) Limiting inlet concentrations for operation 4 in ppm;

$$Climin4('A') = 0.02;$$

$$Climin4('B') = 0.02;$$

$$Climin4('C') = 0.03;$$

Parameter Climin5C(J) Limiting inlet concentrations for operation 5 in ppm;

$$Climin5C('A') = 0.02;$$

$$Climin5C('B') = 0.02;$$

$$\text{Climin5C('C')} = 0.03;$$

Parameter Climin5D(J) Limiting inlet concentrations for operation 5 in ppm;

$$\text{Climin5D('A')} = 0.02;$$

$$\text{Climin5D('B')} = 0.02;$$

$$\text{Climin5D('C')} = 0.03;$$

Parameter Climin6(J) Limiting inlet concentrations for operation 6 in ppm;

$$\text{Climin6('A')} = 0.02;$$

$$\text{Climin6('B')} = 20;$$

$$\text{Climin6('C')} = 25;$$

Parameter Climout1(J) Limiting outlet concentrations for operation 1 in ppm;

$$\text{Climout1('A')} = 90;$$

$$\text{Climout1('B')} = 1300;$$

$$\text{Climout1('C')} = 45;$$

Parameter Climout2(J) Limiting outlet concentrations for operation 2 in ppm;

$$\text{Climout2('A')} = 1;$$

$$\text{Climout2('B')} = 70000;$$

$$\text{Climout2('C')} = 2700;$$

Parameter Climout3(J) Limiting outlet concentrations for operation 3 in ppm;

$$\text{Climout3('A')} = 1;$$

$$\text{Climout3('B')} = 270;$$

$$\text{Climout3('C')} = 2900;$$

Parameter Climout6(J) Limiting outlet concentrations for operation 6 in ppm;

$$\text{Climout6('A')} = 0.02;$$

$$\text{Climout6('B')} = 0;$$

$$\text{Climout6('C')} = 0.03;$$

Parameter ClimR1(J) Limiting outlet concentrations for regen 1 in ppm;

$$\text{ClimR1('A')} = 90;$$

ClimR1('B') = 1300;

ClimR1('C') = 45;

Parameter ClimR2(J) Limiting outlet concentrations for regen 2 in ppm;

ClimR2('A') = 20;

ClimR2('B') = 230;

ClimR2('C') = 15;

Parameter ClimR3(J) Limiting outlet concentrations for regen 3 in ppm;

ClimR3('A') = 1;

ClimR3('B') = 15;

ClimR3('C') = 5;

Parameter Floss(I) Flowrate loss in operation i;

Floss('oper1') = 622;

Floss('oper2') = 0;

Floss('oper3') = 0;

Floss('oper4') = 20;

Floss('oper5C') = 0;

Floss('oper5D') = 0;

Floss('oper6') = 75;

Parameter Fgain(I) Flowrate gain in operation i;

Fgain('oper1') = 0;

Fgain('oper2') = 0;

Fgain('oper3') = 0;

Fgain('oper4') = 0;

Fgain('oper5C') = 0;

Fgain('oper5D') = 0;

Fgain('oper6') = 0;

Parameter R1(J) removal ration for regeneration 1;

$$R1('A') = 0.9;$$

$$R1('B') = 0.9;$$

$$R1('C') = 0.9;$$

Parameter R2(J) removal ration for regeneration 2;

$$R2('A') = 1;$$

$$R2('B') = 1;$$

$$R2('C') = 1;$$

Parameter R3(J) removal ration for regeneration 3;

$$R3('A') = 0.9;$$

$$R3('B') = 0.9;$$

$$R3('C') = 0.9;$$

Scalar RRO percent to reject /0.5/

Variables

F(I) flowrate of freshwater to operation i in ton per hr

D(I) flowrate from diversion box to operation i in ton per hr

X(I,I) flowrate to operation i from operation j in ton per hr

XTR1(I) flowrate to operation i from regeneration 1

XTR2(I) flowrate to operation i from regeneration 2

XTR3(I) flowrate to operation i from regeneration 3

XFR1(I) flowrate from operation i to regeneration 1

XFR2(I) flowrate from operation i to regeneration 2

XFR3(I) flowrate from operation i to regeneration 3

Xreject flowrate from RO to rejected stream

Cin1(J) inlet concentration to operation 1 of contaminant j in ppm

Cin2(J) inlet concentration to operation 2 of contaminant j in ppm

Cin3(J) inlet concentration to operation 3 of contaminant j in ppm

Cin4(J) inlet concentration to operation 4 of contaminant j in ppm

Cin5C(J) *inlet concentration to operation 5 of contaminant j in ppm

Cin5D(J) *inlet concentration to operation 5 of contaminant j in ppm

Cin6(J) inlet concentration to operation 6 of contaminant j in ppm

Cout1(J) outlet concentration from operation 1 of contaminant j in ppm

Cout2(J) outlet concentration from operation 2 of contaminant j in ppm

Cout3(J) outlet concentration from operation 3 of contaminant j in ppm

Cout4(J) outlet concentration from operation 4 of contaminant j in ppm

Cout5C(J) *outlet concentration from operation 5 of contaminant j in ppm

Cout5D(J) *outlet concentration from operation 5 of contaminant j in ppm

Cout6(J) outlet concentration from operation 6 of contaminant j in ppm

CinR1(J) inlet concentration to regeneration 1 of contaminant j in ppm

CinR2(J) inlet concentration to regeneration 2 of contaminant j in ppm

CinR3(J) inlet concentration to regeneration 3 of contaminant j in ppm

CoutR1(J) outlet concentration from regeneration 1 of contaminant j in ppm

CoutR2(J) outlet concentration from regeneration 2 of contaminant j in ppm

CoutR3(J) outlet concentration from regeneration 3 of contaminant j in ppm

W(I) wastewater flowrate from operation i in ton per hr

FR1 flowrate of freshwater to regeneration 1 in ton per hr

FR2 flowrate of freshwater to regeneration 2 in ton per hr

FR3 flowrate of freshwater to regeneration 3 in ton per hr

DR1 flowrate from diversion box to regeneration 1 in ton per hr

DR2 flowrate from diversion box to regeneration 2 in ton per hr

DR3 flowrate from diversion box to regeneration 3 in ton per hr

Flim total freshwater flowrate in ton per hr;

Positive variable F, D, FR1, FR2, FR3, DR1, DR2, DR3, X, Cout1, Cout2, Cout3, Cout4, Cout5C, Cout5D, Cin1, Cin2, Cin3, Cin4, Cin5C, Cin5D, CinR1, CinR2, CinR3, W, XTR1, XTR2, XTR3, XFR1, XFR2, XFR3;

F.L('Oper1') = 6600;
F.L('Oper2') = 0;
F.L('Oper3') = 0;
F.L('Oper4') = 0;
F.L('Oper5C') = 0;
F.L('Oper5D') = 0;
F.L('Oper6') = 0;
FR1.L = 0;
FR2.L = 1120;
FR3.L = 0;
W.L('Oper1') = 0;
W.L('Oper2') = 6;
W.L('Oper3') = 19;
W.L('Oper4') = 0;
W.L('Oper5C') = 0;
W.L('Oper5D') = 0;
W.L('Oper6') = 0;
Cout1.L('A') = 90;
Cout1.L('B') = 1300;
Cout2.L('A') = 0.03;
Cout2.L('B') = 60000;
Cout3.L('A') = 0.03;
Cout3.L('B') = 280;
Cout4.L('A') = 0.06;
Cout4.L('B') = 10;
Cout5C.L('A') = 0.03;
Cout5C.L('B') = 10;

Cout5D.L('A') = 0.1;
Cout5D.L('B') = 15;
Cout6.L('A') = 0.02;
Cout6.L('B') = 0;
XFR1.L('Oper1') = 58;
XFR1.L('Oper2') = 0;
XFR1.L('Oper3') = 0;
XFR1.L('Oper4') = 0;
XFR1.L('Oper5C') = 0;
XFR1.L('Oper5D') = 0;
XFR2.L('Oper1') = 0;
XFR2.L('Oper2') = 0;
XFR2.L('Oper3') = 0;
XFR2.L('Oper4') = 0;
XFR2.L('Oper5C') = 0;
XFR2.L('Oper5D') = 0;
XFR3.L('Oper1') = 0;
XFR3.L('Oper2') = 0;
XFR3.L('Oper3') = 0;
XFR3.L('Oper4') = 0;
XFR3.L('Oper5C') = 0;
XFR3.L('Oper5D') = 280;
XTR1.L('Oper1') = 20;
XTR1.L('Oper6') = 0;
XTR2.L('Oper1') = 0;
XTR2.L('Oper6') = 120;
XTR3.L('Oper1') = 0;

XTR3.L('Oper6') = 317;
X.L('oper2','oper6') = 6;
X.L('oper3','oper6') = 19;
X.L('oper4','oper6') = 57;
X.L('oper5C','oper6') = 140;
X.L('oper5D','oper6') = 280;
Xreject.L = 38;

Equations

Supply Define objective function

Cinlet1(J) inlet concentration to operation 1

Cinlet2(J) inlet concentration to operation 2

Cinlet3(J) inlet concentration to operation 3

Cinlet4(J) inlet concentration to operation 4

Cinlet5C(J) inlet concentration to operation 5

Cinlet5D(J) inlet concentration to operation 5

Cinlet6(J) inlet concentration to operation 6

Cinlim1(J) constraint associated with inlet to operation 1

Cinlim2(J) constraint associated with inlet to operation 2

Cinlim3(J) constraint associated with inlet to operation 3

Cinlim4(J) constraint associated with inlet to operation 4

Cinlim5C(J) constraint associated with inlet to operation 5

Cinlim5D(J) constraint associated with inlet to operation 5

Cinlim6(J) constraint associated with inlet to operation 6

Coutlim1(J) constraint associated with outlet to operation 1

Coutlim2(J) constraint associated with outlet to operation 2

Coutlim3(J) constraint associated with outlet to operation 3

Coutlet1(J) constraint associated with outlet from operation 1

Coutlet2(J) constraint associated with outlet from operation 2

Coutlet3(J) constraint associated with outlet from operation 3

Coutlet4(J) constraint associated with outlet from operation 4

Coutlet5C(J) constraint associated with outlet from operation 5

Coutlet5D(J) constraint associated with outlet from operation 5

Coutlet6(J) constraint associated with outlet from operation 6

Mass1 water mass balance over operation 1

Mass2 water mass balance over operation 2

Mass3 water mass balance over operation 3

Mass4 water mass balance over operation 4

Mass5C water mass balance over operation 5

Mass5D water mass balance over operation 5

Mass6 water mass balance over operation 6

Masslow2 lower bound water flowrate operation 2

Masslim3 limiting water flowrate operation 3

Masslim4 limiting water flowrate operation 4

Masslow5C lower bound water flowrate operation 5C

Masslow5D lower bound water flowrate operation 5D

Masslim6 limiting water flowrate operation 6

Mass5 water mass balance over operation 5

CinletR1(J) inlet concentration to regeneration 1

CinletR2(J) inlet concentration to regeneration 2

CinletR3(J) inlet concentration to regeneration 3

CinlimR1(J) inlet concentration to regeneration 1

CinlimR2(J) inlet concentration to regeneration 2

CinlimR3(J) inlet concentration to regeneration 3

CoutletR1(J) outlet concentration from regeneration 1

CoutletR2(J) outlet concentration from regeneration 2

CoutletR3(J) outlet concentration from regeneration 3

ROreject Flowrate of RO reject

MassR1 water mass balance over regeneration 1

MassR2 water mass balance over regeneration 2

MassR3 water mass balance over regeneration 3

CapaR1 limiting load of R1

CapaR2 limiting load of R2

CapaR3 limiting load of R3

X21 flowrate from oper2 to oper1

X31 flowrate from oper3 to oper1

X41 flowrate from oper4 to oper1

X5C1 flowrate from oper5C to oper1

X5D1 flowrate from oper5D to oper1

X5C6 flowrate from oper5C to oper6

W1 From oper1 to coupon sample

X4R3 flowrate from oper4 to R3

X1R2 flowrate from oper1 to R2

FR33 fresh water flowrate to R3

X2W from oper2 to waste

X3W from oper3 to waste

R31 flowrate from regen3 to oper1;

Supply.. Flim =e= F('Oper1')+F('Oper6')+FR1+FR2+FR3;

Cinlet1(J)..

Cin1(J)*(F('Oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5C')+X('Oper1','Oper5D')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1'))

=E=

(Cf(J)*F('Oper1')+Cout2(J)*X('Oper1','Oper2')+Cout3(J)*X('Oper1','Oper3')+Cout4(J)*

$X('Oper1','Oper4')+Cout5C(J)*X('Oper1','Oper5C')+Cout5D(J)*X('Oper1','Oper5D')+CoutR1(J)*XTR1('Oper1')+CoutR2(J)*XTR2('Oper1')+CoutR3(J)*XTR3('Oper1');$

$Cinlet2(J).. Cin2(J)*(X('Oper2','Oper6')) =E= (Cout6(J)*X('Oper2','Oper6'));$

$Cinlet3(J).. Cin3(J)*(X('Oper3','Oper6')) =E= (Cout6(J)*X('Oper3','Oper6'));$

$Cinlet4(J).. Cin4(J)*(X('Oper4','Oper6')) =E= (Cout6(J)*X('Oper4','Oper6'));$

$Cinlet5C(J).. Cin5C(J)*(X('Oper5C','Oper6')) =E= (Cout6(J)*X('Oper5C','Oper6'));$

$Cinlet5D(J).. Cin5D(J)*(X('Oper5D','Oper6')) =E= (Cout6(J)*X('Oper5D','Oper6'));$

$Cinlet6(J)..$

$Cin6(J)*(F('Oper6')+X('Oper6','Oper1')+X('Oper6','Oper2')+X('Oper6','Oper3')+X('Oper6','Oper4')+X('Oper6','Oper5C')+X('Oper6','Oper5D')+XTR1('Oper6')+XTR2('Oper6')+XTR3('Oper6')) =E=$

$(Cf(J)*F('Oper6')+Cout1(J)*X('Oper6','Oper1')+Cout2(J)*X('Oper6','Oper2')+Cout3(J)*X('Oper6','Oper3')+Cout4(J)*X('Oper6','Oper4')+Cout5C(J)*X('Oper6','Oper5C')+Cout5D(J)*X('Oper6','Oper5D')+CoutR1(J)*XTR1('Oper6')+CoutR2(J)*XTR2('Oper6')+CoutR3(J)*XTR3('Oper6'));$

$Cinlim1(J).. Cin1(J) =I= Climin1(J);$

$Cinlim2(J).. Cin2(J) =I= Climin2(J);$

$Cinlim3(J).. Cin3(J) =I= Climin3(J);$

$Cinlim4(J).. Cin4(J) =I= Climin4(J);$

$Cinlim5C(J).. Cin5C(J) =I= Climin5C(J);$

$Cinlim5D(J).. Cin5D(J) =I= Climin5D(J);$

$Cinlim6(J).. Cin6(J) =I= Climin6(J);$

$Coutlim1(J).. Cout1(J) =I= Climout1(J);$

$Coutlim2(J).. Cout2(J) =I= Climout2(J);$

$Coutlim3(J).. Cout3(J) =I= Climout3(J);$

$Coutlet1(J)..$

$Cout1(J)*(F('Oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5C')+X('Oper1','Oper5D')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1')) =E=$

$(Cf(J)*F('Oper1')+Cout2(J)*X('Oper1','Oper2')+Cout3(J)*X('Oper1','Oper3')+Cout4(J)*X('Oper1','Oper4')+Cout5C(J)*X('Oper1','Oper5C')+Cout5D(J)*X('Oper1','Oper5D')+CoutR1(J)*XTR1('Oper1')+CoutR2(J)*XTR2('Oper1')+CoutR3(J)*XTR3('Oper1')+M1(J)*1000);$

Coutlet2(J).. Cout2(J)*(X('Oper2','Oper6')) =E=
(Cout6(J)*X('Oper2','Oper6')+M2(J)*1000);

Coutlet3(J).. Cout3(J)*(X('Oper3','Oper6')) =E=
(Cout6(J)*X('Oper3','Oper6')+M3(J)*1000);

Coutlet4(J).. Cout4(J)*(X('Oper4','Oper6')) =E=
(Cout6(J)*X('Oper4','Oper6')+M4(J)*1000);

Coutlet5C(J).. Cout5C(J)*(X('Oper5C','Oper6')) =E=
(Cout6(J)*X('Oper5C','Oper6')+M5C(J)*1000);

Coutlet5D(J).. Cout5D(J)*(X('Oper5D','Oper6')) =E=
(Cout6(J)*X('Oper5D','Oper6')+M5D(J)*1000);

Coutlet6(J).. Cout6(J) =e= Climout6(J);

Mass1..

F('Oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5
C')+X('Oper1','Oper5D')+Fgain('Oper1')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper
1') =E=

W('Oper1')+X('Oper6','Oper1')+Floss('Oper1')+XFR1('Oper1')+XFR2('Oper1')+XFR3('Op
er1');

Mass2.. X('Oper2','Oper6')+Fgain('Oper2') =E=

W('Oper2')+X('Oper1','Oper2')+X('Oper6','Oper2')+Floss('Oper2')+XFR1('Oper2')+XF
R2('Oper2')+XFR3('Oper2');

Mass3.. X('Oper3','Oper6')+Fgain('Oper3') =E=

W('Oper3')+X('Oper1','Oper3')+X('Oper6','Oper3')+Floss('Oper3')+XFR1('Oper3')+XF
R2('Oper3')+XFR3('Oper3');

Mass4.. X('Oper4','Oper6')+Fgain('Oper4') =E=

W('Oper4')+X('Oper1','Oper4')+X('Oper6','Oper4')+Floss('Oper4')+XFR1('Oper4')+XF
R2('Oper4')+XFR3('Oper4');

Mass5C.. X('Oper5C','Oper6')+Fgain('Oper5C') =E=

W('Oper5C')+X('Oper1','Oper5C')+X('Oper6','Oper5C')+Floss('Oper5C')+XFR1('Oper5
C')+XFR2('Oper5C')+XFR3('Oper5C');

Mass5D.. X('Oper5D','Oper6')+Fgain('Oper5D') =E=

W('Oper5D')+X('Oper1','Oper5D')+X('Oper6','Oper5D')+Floss('Oper5D')+XFR1('Oper5
D')+XFR2('Oper5D')+XFR3('Oper5D');

Mass6..

F('Oper6')+X('Oper6','Oper1')+X('Oper6','Oper2')+X('Oper6','Oper3')+X('Oper6','Oper4'
) +X('Oper6','Oper5C')+X('Oper6','Oper5D')+Fgain('Oper6')+XTR1('Oper6')+XTR2('Op
er6')+XTR3('Oper6') =E=

$W('Oper6')+X('Oper2','Oper6')+X('Oper3','Oper6')+X('Oper4','Oper6')+X('Oper5C','Oper6')+X('Oper5D','Oper6')+Floss('Oper6');$

Masslow2.. $X('Oper2','Oper6')+Fgain('Oper2') = g = 6;$

Masslim3.. $X('Oper3','Oper6')+Fgain('Oper3') = l = 20;$

Masslim4.. $X('Oper4','Oper6')+Fgain('Oper4') = e = 60;$

Masslow5C.. $X('Oper5C','Oper6')+Fgain('Oper5C') = g = 140;$

Masslow5D.. $X('Oper5D','Oper6')+Fgain('Oper5D') = g = 280;$

Masslim6..

$F('Oper6')+X('Oper6','Oper1')+X('Oper6','Oper2')+X('Oper6','Oper3')+X('Oper6','Oper4')+X('Oper6','Oper5C')+X('Oper6','Oper5D')+Fgain('Oper6')+XTR1('oper6')+XTR2('oper6')+XTR3('oper6') = l = 590;$

Mass5.. $(X('Oper5C','Oper6')+Fgain('Oper5C'))*2 = e = X('Oper5D','Oper6')+Fgain('Oper5D');$

CinletR1(J)..

$CinR1(J)*(XFR1('Oper1')+XFR1('Oper2')+XFR1('Oper3')+XFR1('Oper4')+XFR1('Oper5C')+XFR1('Oper5D')+FR1) = E = (Cout1(J)*XFR1('Oper1')+Cout2(J)*XFR1('Oper2')+Cout3(J)*XFR1('Oper3')+Cout4(J)*XFR1('Oper4')+Cout5C(J)*XFR1('Oper5C')+Cout5D(J)*XFR1('Oper5D')+Cf(J)*FR1);$

CinletR2(J)..

$CinR2(J)*(XFR2('Oper1')+XFR2('Oper2')+XFR2('Oper3')+XFR2('Oper4')+XFR2('Oper5C')+XFR2('Oper5D')+FR2) = E = (Cout1(J)*XFR2('Oper1')+Cout2(J)*XFR2('Oper2')+Cout3(J)*XFR2('Oper3')+Cout4(J)*XFR2('Oper4')+Cout5C(J)*XFR2('Oper5C')+Cout5D(J)*XFR2('Oper5D')+Cf(J)*FR2);$

CinletR3(J)..

$CinR3(J)*(XFR3('Oper1')+XFR3('Oper2')+XFR3('Oper3')+XFR3('Oper4')+XFR3('Oper5C')+XFR3('Oper5D')+FR3) = E = (Cout1(J)*XFR3('Oper1')+Cout2(J)*XFR3('Oper2')+Cout3(J)*XFR3('Oper3')+Cout4(J)*XFR3('Oper4')+Cout5C(J)*XFR3('Oper5C')+Cout5D(J)*XFR3('Oper5D')+Cf(J)*FR3);$

CinlimR1(J).. $CinR1(J) = l = ClimR1(J);$

CinlimR2(J).. $CinR2(J) = l = ClimR2(J);$

CinlimR3(J).. $CinR3(J) = l = ClimR3(J);$

CoutletR1(J).. $CoutR1(J) = E = (1-R1(J))*CinR1(J);$

CoutletR2(J).. CoutR2(J) =E= (1-R2(J))*CinR2(J);

CoutletR3(J).. CoutR3(J) =E= (1-R3(J))*CinR3(J);

ROreject.. Xreject =e=

RRO*(FR1+XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1('oper5D')));

MassR1.. XTR1('oper1')+XTR1('oper6')+Xreject =E=

(XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1('oper5D'))+FR1;

MassR2.. XTR2('oper1')+XTR2('oper6') =E=

(XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2('oper5D'))+FR2;

MassR3.. XTR3('oper1')+XTR3('oper6') =E=

(XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3('oper5D'))+FR3;

CapaR1..

(XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1('oper5D'))+FR1 =l= 80;

CapaR2..

(XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2('oper5D'))+FR2 =l= 160;

CapaR3..

(XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3('oper5D'))+FR3 =l= 320;

X21.. X('oper1','oper2') =e=0;

X31.. X('oper1','oper3') =e=0;

X41.. X('oper1','oper4') =e=0;

X5C1.. X('oper1','oper5C') =e=0;

X5D1.. X('oper1','oper5D') =e=0;

X5C6.. X('oper6','oper5C') =g=143.098;

R31.. XTR3('oper1') =e= 0;

W1.. W('oper1') =e= 8;

X4R3.. XFR2('oper4') =e= 0;

X1R2.. XFR2('oper1') =e= 0;

FR33.. FR3 =e= 0;

X2W.. W('oper2') =g= 6;

X3W.. W('oper3') =g= 19.704;

Model Super /All/;

Solve Super using NLP minimizing Flim;

Display

Flim.L,F.L,FR1.L,FR2.L,FR3.L,W.L,X.L,XFR1.L,XTR1.L,XFR2.L,XTR2.L,XFR3.L,
XTR3.L,Xreject.L,Cin1.L,Cout1.L,Cin2.L,Cout2.L,Cin3.L,Cout3.L,Cin4.L,Cout4.L,Ci
n5C.L,Cout5C.L,Cin5D.L,Cout5D.L,Cin6.L,Cout6.L,CinR1.L,CoutR1.L,CinR2.L,Cout
R2.L,CinR3.L,CoutR3.L;

GAMS Output

```

**** REPORT SUMMARY :      0  NONOPT
                             0  INFEASIBLE
                             0  UNBOUNDED
                             0  ERRORS

      509 VARIABLE Flim.L      =  768.509 total freshwater flowrate in ton
per hr

---- 509 VARIABLE F.L flowrate of freshwater to operation i in ton per hr
Oper1 608.509

      509 VARIABLE FR1.L      =   0.000 flowrate of freshwater to
regeneration 1 in ton per hr

---- 509 VARIABLE FR2.L      =  160.000 flowrate of freshwater to
regeneration 2 in ton per hr

---- 509 VARIABLE FR3.L      =   0.000 flowrate of freshwater to
regeneration 3 in ton per hr

---- 509 VARIABLE W.L wastewater flowrate from operation i in ton per hr
Oper1 8.000, oper2 6.000, oper3 19.704

---- 509 VARIABLE X.L flowrate to operation i from operation j in ton per hr
      Oper1  oper5C  oper5D  oper6
oper2                6.000
oper3                19.704
oper4                60.000
oper5C               143.099
oper5D               286.197
oper6  0.017  143.098  6.465

---- 509 VARIABLE XFR1.L flowrate from operation i to regeneration 1
Oper1 35.610

---- 509 VARIABLE XTR1.L flowrate to operation i from regeneration 1

```

Oper1 17.805

---- 509 VARIABLE XFR2.L flowrate from operation i to regeneration 2

(ALL 0.000)

---- 509 VARIABLE XTR2.L flowrate to operation i from regeneration 2

Oper1 39.580, oper6 120.420

---- 509 VARIABLE XFR3.L flowrate from operation i to regeneration 3

Oper1 0.267, oper4 40.000, oper5C 6.666667E-4

oper5D 279.732

---- 509 VARIABLE XTR3.L flowrate to operation i from regeneration 3

oper6 320.000

509 VARIABLE Xreject.L = 17.805 flowrate from RO to rejected stream

---- 509 VARIABLE Cin1.L inlet concentration to operation 1 of contaminant j in ppm

A 18.517, B 116.923, C 13.823

---- 509 VARIABLE Cout1.L outlet concentration from operation 1 of contaminant j in ppm

A 90.000, B 1178.955, C 43.438

---- 509 VARIABLE Cin2.L inlet concentration to operation 2 of contaminant j in ppm

A 0.020, C 0.030

---- 509 VARIABLE Cout2.L outlet concentration from operation 2 of contaminant j in ppm

A 0.030, B 56833.333, C 2620.030

---- 509 VARIABLE Cin3.L inlet concentration to operation 3 of contaminant j in ppm

A 0.020, C 0.030

---- 509 VARIABLE Cout3.L outlet concentration from operation 3 of contaminant j in ppm

---- 509 VARIABLE Cin4.L inlet concentration to operation 4 of contaminant j in ppm

A 0.020, C 0.030

---- 509 VARIABLE Cout4.L outlet concentration from operation 4 of contaminant j in ppm

A 0.059, B 9.500, C 3.060

---- 509 VARIABLE Cin5C.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 509 VARIABLE Cout5C.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.030, B 9.783, C 4.892

---- 509 VARIABLE Cin5D.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 509 VARIABLE Cout5D.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.098, B 14.675, C 4.892

---- 509 VARIABLE Cin6.L inlet concentration to operation 6 of contaminant j in ppm

A 0.020, B 3.381, C 1.496

---- 509 VARIABLE Cout6.L outlet concentration from operation 6 of contaminant j in ppm

A 0.020, C 0.030

---- 509 VARIABLE CinR1.L inlet concentration to regeneration 1 of contaminant j in ppm

A 90.000, B 1178.955, C 43.438

---- 509 VARIABLE CoutR1.L outlet concentration from regeneration 1 of contaminant j in ppm

A 9.000, B 117.895, C 4.344

---- 509 VARIABLE CinR2.L inlet concentration to regeration 2 of contaminant j in ppm

A 20.000, B 124.500, C 15.000

---- 509 VARIABLE CoutR2.L outlet concentration from regeration 2 of contaminant j in ppm

(ALL 0.000)

---- 509 VARIABLE CinR3.L inlet concentration to regeration 3 of contaminant j in ppm

A 0.168, B 15.000, C 4.696

---- 509 VARIABLE CoutR3.L outlet concentration from regeration 3 of contaminant j in ppm

A 0.017, B 1.500, C 0.470

APPENDIX C

GAMS input and output for case 3

GAMS input

SETS I operations /Oper1,oper2,oper3,oper4,oper5C,oper5D,oper6/

J contaminants /A, B, C/;

Parameter Cf(J) contaminant concentration of fresh water in ppm;

$$Cf('A') = 20 \quad ;$$

$$Cf('B') = 124.5 \quad ;$$

$$Cf('C') = 15 \quad ;$$

Parameter Cd(J) contaminant concentration of fresh water in ppm;

$$Cd('A') = 25;$$

$$Cd('B') = 800;$$

$$Cd('C') = 60;$$

Parameter M1(J) mass load for operation 1 in kg per hr;

$$M1('A') = 47.6;$$

$$M1('B') = 707.2;$$

$$M1('C') = 19.72;$$

Parameter M2(J) mass load for operation 2 in kg per hr;

$$M2('A') = 0.00006;$$

$$M2('B') = 341;$$

$$M2('C') = 15.72;$$

Parameter M3(J) mass load for operation 3 in kg per hr;

$$M3('A') = 0.00019;$$

$$M3('B') = 5.32;$$

$$M3('C') = 53.32;$$

Parameter M4(J) mass load for operation 4 in kg per hr;

$$M4('A') = 0.002337;$$

$$M4('B') = 0.57;$$

$$M4('C') = 0.18183;$$

Parameter M5C(J) mass load for operation 5 in kg per hr;

$$M5C('A') = 0.0014;$$

$$M5C('B') = 1.4;$$

$$M5C('C') = 0.6958;$$

Parameter M5D(J) mass load for operation 5 in kg per hr;

$$M5D('A') = 0.0224;$$

$$M5D('B') = 4.2;$$

$$M5D('C') = 1.3916;$$

Parameter M6(J) mass load for operation 6 in kg per hr;

$$M6('A') = 0;$$

$$M6('B') = 0;$$

$$M6('C') = 0;$$

Parameter Climin1(J) Limiting inlet concentrations for operation 1 in ppm;

$$Climin1('A') = 20;$$

$$Climin1('B') = 160;$$

$$Climin1('C') = 15;$$

Parameter Climin2(J) Limiting inlet concentrations for operation 2 in ppm;

$$Climin2('A') = 0.02;$$

$$Climin2('B') = 0.03;$$

$$Climin2('C') = 0.03;$$

Parameter Climin3(J) Limiting inlet concentrations for operation 3 in ppm;

$$Climin3('A') = 0.02;$$

$$Climin3('B') = 0.02;$$

$$Climin3('C') = 0.03;$$

Parameter Climin4(J) Limiting inlet concentrations for operation 4 in ppm;

$$Climin4('A') = 0.02;$$

$$Climin4('B') = 0.02;$$

$$\text{Climin4('C')} = 0.03;$$

Parameter Climin5C(J) Limiting inlet concentrations for operation 5 in ppm;

$$\text{Climin5C('A')} = 0.02;$$

$$\text{Climin5C('B')} = 0.02;$$

$$\text{Climin5C('C')} = 0.03;$$

Parameter Climin5D(J) Limiting inlet concentrations for operation 5 in ppm;

$$\text{Climin5D('A')} = 0.02;$$

$$\text{Climin5D('B')} = 0.02;$$

$$\text{Climin5D('C')} = 0.03;$$

Parameter Climin6(J) Limiting inlet concentrations for operation 6 in ppm;

$$\text{Climin6('A')} = 0.02;$$

$$\text{Climin6('B')} = 20;$$

$$\text{Climin6('C')} = 25;$$

Parameter Climout1(J) Limiting outlet concentrations for operation 1 in ppm;

$$\text{Climout1('A')} = 90;$$

$$\text{Climout1('B')} = 1300;$$

$$\text{Climout1('C')} = 45;$$

Parameter Climout2(J) Limiting outlet concentrations for operation 2 in ppm;

$$\text{Climout2('A')} = 1;$$

$$\text{Climout2('B')} = 70000;$$

$$\text{Climout2('C')} = 2700;$$

Parameter Climout3(J) Limiting outlet concentrations for operation 3 in ppm;

$$\text{Climout3('A')} = 1;$$

$$\text{Climout3('B')} = 270;$$

$$\text{Climout3('C')} = 2900;$$

Parameter Climout6(J) Limiting outlet concentrations for operation 6 in ppm;

$$\text{Climout6('A')} = 0.02;$$

Climout6('B') = 0;

Climout6('C') = 0.03;

Parameter ClimR1(J) Limiting outlet concentrations for regen 1 in ppm;

ClimR1('A') = 90;

ClimR1('B') = 1300;

ClimR1('C') = 45;

Parameter ClimR2(J) Limiting outlet concentrations for regen 2 in ppm;

ClimR2('A') = 20;

ClimR2('B') = 230;

ClimR2('C') = 15;

Parameter ClimR3(J) Limiting outlet concentrations for regen 3 in ppm;

ClimR3('A') = 1;

ClimR3('B') = 15;

ClimR3('C') = 5;

Parameter Floss(I) Flowrate loss in operation i;

Floss('oper1') = 622;

Floss('oper2') = 0;

Floss('oper3') = 0;

Floss('oper4') = 20;

Floss('oper5C') = 0;

Floss('oper5D') = 0;

Floss('oper6') = 75;

Parameter Fgain(I) Flowrate gain in operation i;

Fgain('oper1') = 0;

Fgain('oper2') = 0;

Fgain('oper3') = 0;

Fgain('oper4') = 0;

$$F_{\text{gain}}(\text{'oper5C'}) = 0;$$

$$F_{\text{gain}}(\text{'oper5D'}) = 0;$$

$$F_{\text{gain}}(\text{'oper6'}) = 0;$$

Parameter R1(J) removal ration for regeneration 1;

$$R1(\text{'A'}) = 0.9;$$

$$R1(\text{'B'}) = 0.9;$$

$$R1(\text{'C'}) = 0.9;$$

Parameter R2(J) removal ration for regeneration 2;

$$R2(\text{'A'}) = 1;$$

$$R2(\text{'B'}) = 1;$$

$$R2(\text{'C'}) = 1;$$

Parameter R3(J) removal ration for regeneration 3;

$$R3(\text{'A'}) = 0.9;$$

$$R3(\text{'B'}) = 0.9;$$

$$R3(\text{'C'}) = 0.9;$$

Scalar RRO percent to reject /0.5/

Variables

F(I) flowrate of freshwater to operation i in ton per hr

D(I) flowrate from diversion box to operation i in ton per hr

X(I,I) flowrate to operation i from operation j in ton per hr

XTR1(I) flowrate to operation i from regeneration 1

XTR2(I) flowrate to operation i from regeneration 2

XTR3(I) flowrate to operation i from regeneration 3

XFR1(I) flowrate from operation i to regeneration 1

XFR2(I) flowrate from operation i to regeneration 2

XFR3(I) flowrate from operation i to regeneration 3

Xreject flowrate from RO to rejected stream

Cin1(J) inlet concentration to operation 1 of contaminant j in ppm

Cin2(J) inlet concentration to operation 2 of contaminant j in ppm

Cin3(J) inlet concentration to operation 3 of contaminant j in ppm

Cin4(J) inlet concentration to operation 4 of contaminant j in ppm

Cin5C(J) inlet concentration to operation 5 of contaminant j in ppm

Cin5D(J) inlet concentration to operation 5 of contaminant j in ppm

Cin6(J) inlet concentration to operation 6 of contaminant j in ppm

Cout1(J) outlet concentration from operation 1 of contaminant j in ppm

Cout2(J) outlet concentration from operation 2 of contaminant j in ppm

Cout3(J) outlet concentration from operation 3 of contaminant j in ppm

Cout4(J) outlet concentration from operation 4 of contaminant j in ppm

Cout5C(J) *outlet concentration from operation 5 of contaminant j in ppm

Cout5D(J) *outlet concentration from operation 5 of contaminant j in ppm

Cout6(J) outlet concentration from operation 6 of contaminant j in ppm

CinR1(J) inlet concentration to regeneration 1 of contaminant j in ppm

CinR2(J) inlet concentration to regeneration 2 of contaminant j in ppm

CinR3(J) inlet concentration to regeneration 3 of contaminant j in ppm

CoutR1(J) outlet concentration from regeneration 1 of contaminant j in ppm

CoutR2(J) outlet concentration from regeneration 2 of contaminant j in ppm

CoutR3(J) outlet concentration from regeneration 3 of contaminant j in ppm

W(I) wastewater flowrate from operation i in ton per hr

FR1 flowrate of freshwater to regeneration 1 in ton per hr

FR2 flowrate of freshwater to regeneration 2 in ton per hr

FR3 flowrate of freshwater to regeneration 3 in ton per hr

DR1 flowrate from diversion box to regeneration 1 in ton per hr

DR2 flowrate from diversion box to regeneration 2 in ton per hr

DR3 flowrate from diversion box to regeneration 3 in ton per hr

Flim total freshwater flowrate in ton per hr;

Positive variable F, D, FR1, FR2, FR3, DR1,DR2,DR3, X, Cout1, Cout2, Cout3, Cout4, Cout5C, Cout5D, Cin1, Cin2, Cin3, Cin4, Cin5C, Cin5D, CinR1, CinR2, CinR3, W, XTR1, XTR2, XTR3, XFR1, XFR2, XFR3;

F.L('Oper1') = 6600;

F.L('Oper2') = 0;

F.L('Oper3') = 0;

F.L('Oper4') = 0;

F.L('Oper5C') = 0;

F.L('Oper5D') = 0;

F.L('Oper6') = 0;

FR1.L = 0;

FR2.L = 1120;

FR3.L = 0;

W.L('Oper1') = 0;

W.L('Oper2') = 6;

W.L('Oper3') = 19;

W.L('Oper4') = 0;

W.L('Oper5C') = 0;

W.L('Oper5D') = 0;

W.L('Oper6') = 0;

Cout1.L('A') = 90;

Cout1.L('B') = 1300;

Cout2.L('A') = 0.03;

Cout2.L('B') = 60000;

Cout3.L('A') = 0.03;

Cout3.L('B') = 280;

Cout4.L('A') = 0.06;
Cout4.L('B') = 10;
Cout5C.L('A') = 0.03;
Cout5C.L('B') = 10;
Cout5D.L('A') = 0.1;
Cout5D.L('B') = 15;
Cout6.L('A') = 0.02;
Cout6.L('B') = 0;
XFR1.L('Oper1') = 58;
XFR1.L('Oper2') = 0;
XFR1.L('Oper3') = 0;
XFR1.L('Oper4') = 0;
XFR1.L('Oper5C') = 0;
XFR1.L('Oper5D') = 0;
*XFR1.L('Oper6') = 0;
XFR2.L('Oper1') = 0;
XFR2.L('Oper2') = 0;
XFR2.L('Oper3') = 0;
XFR2.L('Oper4') = 0;
XFR2.L('Oper5C') = 0;
XFR2.L('Oper5D') = 0;
XFR3.L('Oper1') = 0;
XFR3.L('Oper2') = 0;
XFR3.L('Oper3') = 0;
XFR3.L('Oper4') = 0;
XFR3.L('Oper5C') = 0;
XFR3.L('Oper5D') = 280;

$X_{TR1}.L('Oper1') = 20;$
 $X_{TR1}.L('Oper6') = 0;$
 $X_{TR2}.L('Oper1') = 0;$
 $X_{TR2}.L('Oper6') = 120;$
 $X_{TR3}.L('Oper1') = 0;$
 $X_{TR3}.L('Oper6') = 317;$
 $X.L('oper2','oper6') = 6;$
 $X.L('oper3','oper6') = 19;$
 $X.L('oper4','oper6') = 57;$
 $X.L('oper5C','oper6') = 140;$
 $X.L('oper5D','oper6') = 280;$
 $X_{reject}.L = 38;$

Equations

Supply Define objective function

Cinlet1(J) inlet concentration to operation 1

Cinlet2(J) inlet concentration to operation 2

Cinlet3(J) inlet concentration to operation 3

Cinlet4(J) inlet concentration to operation 4

Cinlet5C(J) inlet concentration to operation 5

Cinlet5D(J) inlet concentration to operation 5

Cinlet6(J) inlet concentration to operation 6

Cinlim1(J) constraint associated with inlet to operation 1

Cinlim2(J) constraint associated with inlet to operation 2

Cinlim3(J) constraint associated with inlet to operation 3

Cinlim4(J) constraint associated with inlet to operation 4

Cinlim5C(J) constraint associated with inlet to operation 5

Cinlim5D(J) constraint associated with inlet to operation 5

Cinlim6(J) constraint associated with inlet to operation 6

Coutlim1(J) constraint associated with outlet to operation 1

Coutlim2(J) constraint associated with outlet to operation 2

Coutlim3(J) constraint associated with outlet to operation 3

Coutlet1(J) constraint associated with outlet from operation 1

Coutlet2(J) constraint associated with outlet from operation 2

Coutlet3(J) constraint associated with outlet from operation 3

Coutlet4(J) constraint associated with outlet from operation 4

Coutlet5C(J) constraint associated with outlet from operation 5

Coutlet5D(J) constraint associated with outlet from operation 5

Coutlet6(J) constraint associated with outlet from operation 6

Mass1 water mass balance over operation 1

Mass2 water mass balance over operation 2

Mass3 water mass balance over operation 3

Mass4 water mass balance over operation 4

Mass5C *water mass balance over operation 5

Mass5D *water mass balance over operation 5

Mass6 water mass balance over operation 6

Masslow2 lower bound water flowrate operation 2

Masslim3 limiting water flowrate operation 3

Masslim4 limiting water flowrate operation 4

Masslow5C lower bound water flowrate operation 5C

Masslow5D lower bound water flowrate operation 5D

Masslim6 limiting water flowrate operation 6

Mass5 water mass balance over operation 5

CinletR1(J) inlet concentration to regeneration 1

CinletR2(J) inlet concentration to regeneration 2
 CinletR3(J) inlet concentration to regeneration 3
 CinlimR1(J) inlet concentration to regeneration 1
 CinlimR2(J) inlet concentration to regeneration 2
 CinlimR3(J) inlet concentration to regeneration 3
 CoutletR1(J) outlet concentration from regeneration 1
 CoutletR2(J) outlet concentration from regeneration 2
 CoutletR3(J) outlet concentration from regeneration 3
 ROreject Flowrate of RO reject
 MassR1 water mass balance over regeneration 1
 MassR2 water mass balance over regeneration 2
 MassR3 water mass balance over regeneration 3
 CapaR1 limiting load of R1
 CapaR2 limiting load of R2
 CapaR3 limiting load of R3
 X21 flowrate from oper2 to oper1
 X31 flowrate from oper3 to oper1
 X41 flowrate from oper4 to oper1
 X5C1 flowrate from oper5C to oper1
 X5D1 flowrate from oper5D to oper1
 X26 flowrate from oper2 to oper6
 X36 flowrate from oper3 to oper6
 W1 from oper1 to coupon sample
 R31 flowrate from regen3 to oper1;

Supply.. Flim =e= F('Oper1')+F('Oper6')+FR1+FR2+FR3;

Cinlet1(J)..

$Cin1(J) * (F('Oper1') + D('oper1') + X('Oper1', 'Oper2') + X('Oper1', 'Oper3') + X('Oper1', 'Oper4') + X('Oper1', 'Oper5C') + X('Oper1', 'Oper5D') + XTR1('Oper1') + XTR2('Oper1') + XTR3('Oper1')) = E =$

$(Cf(J) * F('Oper1') + Cd(J) * D('oper1') + Cout2(J) * X('Oper1', 'Oper2') + Cout3(J) * X('Oper1', 'Oper3') + Cout4(J) * X('Oper1', 'Oper4') + Cout5C(J) * X('Oper1', 'Oper5C') + Cout5D(J) * X('Oper1', 'Oper5D') + CoutR1(J) * XTR1('Oper1') + CoutR2(J) * XTR2('Oper1') + CoutR3(J) * XTR3('Oper1'));$

Cinlet2(J).. $Cin2(J) * (X('Oper2', 'Oper6')) = E = (Cout6(J) * X('Oper2', 'Oper6'));$

Cinlet3(J).. $Cin3(J) * (X('Oper3', 'Oper6')) = E = (Cout6(J) * X('Oper3', 'Oper6'));$

Cinlet4(J).. $Cin4(J) * (X('Oper4', 'Oper6')) = E = (Cout6(J) * X('Oper4', 'Oper6'));$

Cinlet5C(J).. $Cin5C(J) * (X('Oper5C', 'Oper6')) = E = (Cout6(J) * X('Oper5C', 'Oper6'));$

Cinlet5D(J).. $Cin5D(J) * (X('Oper5D', 'Oper6')) = E = (Cout6(J) * X('Oper5D', 'Oper6'));$

Cinlet6(J)..

$Cin6(J) * (F('Oper6') + D('oper6') + X('Oper6', 'Oper1') + X('Oper6', 'Oper2') + X('Oper6', 'Oper3') + X('Oper6', 'Oper4') + X('Oper6', 'Oper5C') + X('Oper6', 'Oper5D') + XTR1('Oper6') + XTR2('Oper6') + XTR3('Oper6')) = E =$

$(Cf(J) * F('Oper6') + Cd(J) * D('oper6') + Cout1(J) * X('Oper6', 'Oper1') + Cout2(J) * X('Oper6', 'Oper2') + Cout3(J) * X('Oper6', 'Oper3') + Cout4(J) * X('Oper6', 'Oper4') + Cout5C(J) * X('Oper6', 'Oper5C') + Cout5D(J) * X('Oper6', 'Oper5D') + CoutR1(J) * XTR1('Oper6') + CoutR2(J) * XTR2('Oper6') + CoutR3(J) * XTR3('Oper6'));$

Cinlim1(J).. $Cin1(J) = I = Climin1(J);$

Cinlim2(J).. $Cin2(J) = I = Climin2(J);$

Cinlim3(J).. $Cin3(J) = I = Climin3(J);$

Cinlim4(J).. $Cin4(J) = I = Climin4(J);$

Cinlim5C(J).. $Cin5C(J) = I = Climin5C(J);$

Cinlim5D(J).. $Cin5D(J) = I = Climin5D(J);$

Cinlim6(J).. $Cin6(J) = I = Climin6(J);$

Coutlim1(J).. $Cout1(J) = I = Climout1(J);$

Coutlim2(J).. $Cout2(J) = I = Climout2(J);$

Coutlim3(J).. $Cout3(J) = I = Climout3(J);$

Coutlet1(J)..

$Cout1(J) * (F('Oper1') + D('oper1') + X('Oper1', 'Oper2') + X('Oper1', 'Oper3') + X('Oper1', 'Oper4') + X('Oper1', 'Oper5C') + X('Oper1', 'Oper5D') + XTR1('Oper1') + XTR2('Oper1') + XTR3('Oper1')) = E =$

$r4)+X('Oper1','Oper5C')+X('Oper1','Oper5D')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1')) =E=$
 $(Cf(J)*F('Oper1')+Cd(J)*D('oper1')+Cout2(J)*X('Oper1','Oper2')+Cout3(J)*X('Oper1','Oper3')+Cout4(J)*X('Oper1','Oper4')+Cout5C(J)*X('Oper1','Oper5C')+Cout5D(J)*X('Oper1','Oper5D')+CoutR1(J)*XTR1('Oper1')+CoutR2(J)*XTR2('Oper1')+CoutR3(J)*XTR3('Oper1')+M1(J)*1000);$

$Coutlet2(J).. Cout2(J)*(X('Oper2','Oper6')) =E=$
 $(Cout6(J)*X('Oper2','Oper6')+M2(J)*1000);$

$Coutlet3(J).. Cout3(J)*(X('Oper3','Oper6')) =E=$
 $(Cout6(J)*X('Oper3','Oper6')+M3(J)*1000);$

$Coutlet4(J).. Cout4(J)*(X('Oper4','Oper6')) =E=$
 $(Cout6(J)*X('Oper4','Oper6')+M4(J)*1000);$

$Coutlet5C(J).. Cout5C(J)*(X('Oper5C','Oper6')) =E=$
 $(Cout6(J)*X('Oper5C','Oper6')+M5C(J)*1000);$

$Coutlet5D(J).. Cout5D(J)*(X('Oper5D','Oper6')) =E=$
 $(Cout6(J)*X('Oper5D','Oper6')+M5D(J)*1000);$

$Coutlet6(J).. Cout6(J) =e= Climout6(J);$

Mass1..

$F('Oper1')+D('oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5C')+X('Oper1','Oper5D')+Fgain('Oper1')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1') =E=$
 $W('Oper1')+X('Oper6','Oper1')+Floss('Oper1')+XFR1('Oper1')+XFR2('Oper1')+XFR3('Oper1');$

Mass2.. $X('Oper2','Oper6')+Fgain('Oper2') =E=$

$W('Oper2')+X('Oper1','Oper2')+X('Oper6','Oper2')+Floss('Oper2')+XFR1('Oper2')+XFR2('Oper2')+XFR3('Oper2');$

Mass3.. $X('Oper3','Oper6')+Fgain('Oper3') =E=$

$W('Oper3')+X('Oper1','Oper3')+X('Oper6','Oper3')+Floss('Oper3')+XFR1('Oper3')+XFR2('Oper3')+XFR3('Oper3');$

Mass4.. $X('Oper4','Oper6')+Fgain('Oper4') =E=$

$W('Oper4')+X('Oper1','Oper4')+X('Oper6','Oper4')+Floss('Oper4')+XFR1('Oper4')+XFR2('Oper4')+XFR3('Oper4');$

Mass5C.. $X('Oper5C','Oper6')+Fgain('Oper5C') =E=$

$W('Oper5C')+X('Oper1','Oper5C')+X('Oper6','Oper5C')+Floss('Oper5C')+XFR1('Oper5C')+XFR2('Oper5C')+XFR3('Oper5C');$

$$\text{Mass5D.. } X(\text{'Oper5D'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5D'}) =E= \\ W(\text{'Oper5D'})+X(\text{'Oper1'},\text{'Oper5D'})+X(\text{'Oper6'},\text{'Oper5D'})+\text{Floss}(\text{'Oper5D'})+\text{XFR1}(\text{'Oper5D'})+\text{XFR2}(\text{'Oper5D'})+\text{XFR3}(\text{'Oper5D'});$$

Mass6..

$$\text{F}(\text{'Oper6'})+\text{D}(\text{'oper6'})+X(\text{'Oper6'},\text{'Oper1'})+X(\text{'Oper6'},\text{'Oper2'})+X(\text{'Oper6'},\text{'Oper3'})+X(\text{'Oper6'},\text{'Oper4'})+X(\text{'Oper6'},\text{'Oper5C'})+X(\text{'Oper6'},\text{'Oper5D'})+\text{Fgain}(\text{'Oper6'})+\text{XTR1}(\text{'Oper6'})+\text{XTR2}(\text{'Oper6'})+\text{XTR3}(\text{'Oper6'}) =E= \\ W(\text{'Oper6'})+X(\text{'Oper2'},\text{'Oper6'})+X(\text{'Oper3'},\text{'Oper6'})+X(\text{'Oper4'},\text{'Oper6'})+X(\text{'Oper5C'},\text{'Oper6'})+X(\text{'Oper5D'},\text{'Oper6'})+\text{Floss}(\text{'Oper6'});$$

$$\text{Masslow2.. } X(\text{'Oper2'},\text{'Oper6'})+\text{Fgain}(\text{'Oper2'}) =g= 6;$$

$$\text{Masslim3.. } X(\text{'Oper3'},\text{'Oper6'})+\text{Fgain}(\text{'Oper3'}) =l= 20;$$

$$\text{Masslim4.. } X(\text{'Oper4'},\text{'Oper6'})+\text{Fgain}(\text{'Oper4'}) =g= 60;$$

$$\text{Masslow5C.. } X(\text{'Oper5C'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5C'}) =g= 140;$$

$$\text{Masslow5D.. } X(\text{'Oper5D'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5D'}) =g= 280;$$

Masslim6..

$$\text{F}(\text{'Oper6'})+\text{D}(\text{'oper6'})+X(\text{'Oper6'},\text{'Oper1'})+X(\text{'Oper6'},\text{'Oper2'})+X(\text{'Oper6'},\text{'Oper3'})+X(\text{'Oper6'},\text{'Oper4'})+X(\text{'Oper6'},\text{'Oper5C'})+X(\text{'Oper6'},\text{'Oper5D'})+\text{Fgain}(\text{'Oper6'})+\text{XTR1}(\text{'oper6'})+\text{XTR2}(\text{'oper6'})+\text{XTR3}(\text{'oper6'}) =l= 590;$$

$$\text{Mass5.. } (X(\text{'Oper5C'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5C'}))*2 =e= \\ X(\text{'Oper5D'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5D'});$$

CinletR1(J)..

$$\text{CinR1}(J)*(XFR1(\text{'Oper1'})+XFR1(\text{'Oper2'})+XFR1(\text{'Oper3'})+XFR1(\text{'Oper4'})+XFR1(\text{'Oper5C'})+XFR1(\text{'Oper5D'})+\text{FR1}+\text{DR1}) =E= \\ (\text{Cout1}(J)*XFR1(\text{'Oper1'})+\text{Cout2}(J)*XFR1(\text{'Oper2'})+\text{Cout3}(J)*XFR1(\text{'Oper3'})+\text{Cout4}(J)*XFR1(\text{'Oper4'})+\text{Cout5C}(J)*XFR1(\text{'Oper5C'})+\text{Cout5D}(J)*XFR1(\text{'Oper5D'})+\text{Cf}(J)*\text{FR1}+\text{Cd}(J)*\text{DR1});$$

CinletR2(J)..

$$\text{CinR2}(J)*(XFR2(\text{'Oper1'})+XFR2(\text{'Oper2'})+XFR2(\text{'Oper3'})+XFR2(\text{'Oper4'})+XFR2(\text{'Oper5C'})+XFR2(\text{'Oper5D'})+\text{FR2}+\text{DR2}) =E= \\ (\text{Cout1}(J)*XFR2(\text{'Oper1'})+\text{Cout2}(J)*XFR2(\text{'Oper2'})+\text{Cout3}(J)*XFR2(\text{'Oper3'})+\text{Cout4}(J)*XFR2(\text{'Oper4'})+\text{Cout5C}(J)*XFR2(\text{'Oper5C'})+\text{Cout5D}(J)*XFR2(\text{'Oper5D'})+\text{Cf}(J)*\text{FR2}+\text{Cd}(J)*\text{DR2});$$

CinletR3(J)..

$$\text{CinR3}(J)*(XFR3(\text{'Oper1'})+XFR3(\text{'Oper2'})+XFR3(\text{'Oper3'})+XFR3(\text{'Oper4'})+XFR3(\text{'Oper5C'})+XFR3(\text{'Oper5D'})+\text{FR3}+\text{DR3}) =E= \\ (\text{Cout1}(J)*XFR3(\text{'Oper1'})+\text{Cout2}(J)*XFR3(\text{'Oper2'})+\text{Cout3}(J)*XFR3(\text{'Oper3'})+\text{Cout4}(J)$$

*XFR3('Oper4')+Cout5C(J)*XFR3('Oper5C')+Cout5D(J)*XFR3('Oper5D')+Cf(J)*FR3
+Cd(J)*DR3);

CinlimR1(J).. CinR1(J) =I= ClimR1(J);

CinlimR2(J).. CinR2(J) =I= ClimR2(J);

CinlimR3(J).. CinR3(J) =I= ClimR3(J);

CoutletR1(J).. CoutR1(J) =E= (1-R1(J))*CinR1(J);

CoutletR2(J).. CoutR2(J) =E= (1-R2(J))*CinR2(J);

CoutletR3(J).. CoutR3(J) =E= (1-R3(J))*CinR3(J);

ROreject.. Xreject =e=

RRO*(FR1+DR1+XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1
('oper5C')+XFR1('oper5D')));

MassR1.. XTR1('oper1')+XTR1('oper6')+Xreject =E=

(XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1(
'oper5D'))+FR1+DR1;

MassR2.. XTR2('oper1')+XTR2('oper6') =E=

(XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2(
'oper5D'))+FR2+DR2;

MassR3.. XTR3('oper1')+XTR3('oper6') =E=

(XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3(
'oper5D'))+FR3+DR3;

CapaR1..

(XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1(
'oper5D'))+FR1+DR1 =I= 80;

CapaR2..

(XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2(
'oper5D'))+FR2+DR2 =I= 160;

CapaR3..

(XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3(
'oper5D'))+FR3+DR3 =I= 320;

X21.. X('oper1','oper2') =e=0;

X31.. X('oper1','oper3') =e=0;

X41.. X('oper1','oper4') =e=0;

X5C1.. X('oper1','oper5C') =e=0;

X5D1.. X('oper1','oper5D') =e=0;

X26.. X('oper6','oper2') =e=0;

X36.. X('oper6','oper3') =e=0;

R31.. XTR3('oper1') =e= 0;

W1.. W('oper1') =e= 8;

Model Super /All/;

Solve Super using NLP minimizing Flim;

Display

Flim.L,F.L,D.L,FR1.L,FR2.L,FR3.L,DR1.L,DR2.L,DR3.L,W.L,X.L,XFR1.L,XTR1.L,
XFR2.L,XTR2.L,XFR3.L,XTR3.L,Xreject.L,Cin1.L,Cout1.L,Cin2.L,Cout2.L,Cin3.L,C
out3.L,Cin4.L,Cout4.L,Cin5C.L,Cout5C.L,Cin5D.L,Cout5D.L,Cin6.L,Cout6.L,CinR1.
L,CoutR1.L,CinR2.L,CoutR2.L,CinR3.L,CoutR3.L;

GAMS Output

```

**** REPORT SUMMARY :      0  NONOPT
                             0  INFEASIBLE
                             0  UNBOUNDED
                             0  ERRORS

      501 VARIABLE Flim.L      =  734.860 total freshwater flowrate in ton
per hr

----  501 VARIABLE F.L flowrate of freshwater to operation i in ton per hr
Oper1 557.040

----  501 VARIABLE D.L flowrate from diversion box to operation i in ton per hr
Oper1 23.059

      501 VARIABLE FR1.L      =  16.117 flowrate of freshwater to
regeneration 1 in ton per hr

----  501 VARIABLE FR2.L      =  160.000 flowrate of freshwater to
regeneration 2 in ton per hr

----  501 VARIABLE FR3.L      =  1.703 flowrate of freshwater to
regeneration 3 in ton per hr

----  501 VARIABLE DR1.L      =  32.607 flowrate from diversion box to
regeneration 1 in ton per hr

----  501 VARIABLE DR2.L      =  0.000 flowrate from diversion box to
regeneration 2 in ton per hr

----  501 VARIABLE DR3.L      =  0.148 flowrate from diversion box to
regeneration 3 in ton per hr

----  501 VARIABLE W.L wastewater flowrate from operation i in ton per hr
Oper1 8.000, oper2 6.000, oper3 19.673

----  501 VARIABLE X.L flowrate to operation i from operation j in ton per hr
      oper5C   oper5D   oper6
oper2                6.000
oper3                19.704
oper4                60.000

```

oper5C 143.099

oper5D 286.198

oper6 143.099 8.079

---- 501 VARIABLE XFR1.L flowrate from operation i to regeneration 1
Oper1 31.277

---- 501 VARIABLE XTR1.L flowrate to operation i from regeneration 1
Oper1 40.000

---- 501 VARIABLE XFR2.L flowrate from operation i to regeneration 2
(ALL 0.000)

---- 501 VARIABLE XTR2.L flowrate to operation i from regeneration 2
Oper1 41.177, oper6 118.823

---- 501 VARIABLE XFR3.L flowrate from operation i to regeneration 3
oper3 0.030, oper4 40.000, oper5D 278.119

---- 501 VARIABLE XTR3.L flowrate to operation i from regeneration 3
oper6 320.000

501 VARIABLE Xreject.L = 40.000 flowrate from RO to rejected
stream

---- 501 VARIABLE Cin1.L inlet concentration to operation 1 of contaminant j in
ppm
A 18.018, B 137.751, C 15.000

---- 501 VARIABLE Cout1.L outlet concentration from operation 1 of contaminant j
in ppm
A 90.000, B 1207.197, C 44.821

---- 501 VARIABLE Cin2.L inlet concentration to operation 2 of contaminant j in
ppm
A 0.020, C 0.030

---- 501 VARIABLE Cout2.L outlet concentration from operation 2 of contaminant j
in ppm
A 0.030, B 56833.331, C 2620.030

---- 501 VARIABLE Cin3.L inlet concentration to operation 3 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout3.L outlet concentration from operation 3 of contaminant j in ppm

A 0.030, B 270.000, C 2706.120

---- 501 VARIABLE Cin4.L inlet concentration to operation 4 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout4.L outlet concentration from operation 4 of contaminant j in ppm

A 0.059, B 9.500, C 3.060

---- 501 VARIABLE Cin5C.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout5C.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.030, B 9.783, C 4.892

---- 501 VARIABLE Cin5D.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout5D.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.098, B 14.675, C 4.892

---- 501 VARIABLE Cin6.L inlet concentration to operation 6 of contaminant j in ppm

A 0.020, B 3.387, C 1.525

---- 501 VARIABLE Cout6.L outlet concentration from operation 6 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE CinR1.L inlet concentration to regeration 1 of contaminant j in ppm

A 49.405, B 823.111, C 45.000

---- 501 VARIABLE CoutR1.L outlet concentration from regeration 1 of contaminant j in ppm

A 4.940, B 82.311, C 4.500

---- 501 VARIABLE CinR2.L inlet concentration to regeration 2 of contaminant j in ppm

A 20.000, B 124.500, C 15.000

---- 501 VARIABLE CoutR2.L outlet concentration from regeration 2 of contaminant j in ppm

(ALL 0.000)

---- 501 VARIABLE CinR3.L inlet concentration to regeration 3 of contaminant j in ppm

A 0.211, B 15.000, C 5.000

---- 501 VARIABLE CoutR3.L outlet concentration from regeration 3 of contaminant j in ppm

A 0.021, B 1.500, C 0.500

APPENDIX D

GAMS input and output for case 4

GAMS input

SETS I operations /Oper1,oper2,oper3,oper4,oper5C,oper5D,oper6/

J contaminants /A, B, C/;

Parameter Cf(J) contaminant concentration of fresh water in ppm;

$$Cf('A') = 20 \quad ;$$

$$Cf('B') = 124.5 \quad ;$$

$$Cf('C') = 15 \quad ;$$

Parameter Cd(J) contaminant concentration of fresh water in ppm;

$$Cd('A') = 25;$$

$$Cd('B') = 800;$$

$$Cd('C') = 60;$$

Parameter M1(J) mass load for operation 1 in kg per hr;

$$M1('A') = 47.6;$$

$$M1('B') = 707.2;$$

$$M1('C') = 19.72;$$

Parameter M2(J) mass load for operation 2 in kg per hr;

$$M2('A') = 0.00006;$$

$$M2('B') = 341;$$

$$M2('C') = 15.72;$$

Parameter M3(J) mass load for operation 3 in kg per hr;

$$M3('A') = 0.00019;$$

$$M3('B') = 5.32;$$

$$M3('C') = 53.32;$$

Parameter M4(J) mass load for operation 4 in kg per hr;

$$M4('A') = 0.002337;$$

$$M4('B') = 0.57;$$

$$M4('C') = 0.18183;$$

Parameter M5C(J) mass load for operation 5 in kg per hr;

$$M5C('A') = 0.0014;$$

$$M5C('B') = 1.4;$$

$$M5C('C') = 0.6958;$$

Parameter M5D(J) mass load for operation 5 in kg per hr;

$$M5D('A') = 0.0224;$$

$$M5D('B') = 4.2;$$

$$M5D('C') = 1.3916;$$

Parameter M6(J) mass load for operation 6 in kg per hr;

$$M6('A') = 0;$$

$$M6('B') = 0;$$

$$M6('C') = 0;$$

Parameter Climin1(J) Limiting inlet concentrations for operation 1 in ppm;

$$Climin1('A') = 20;$$

$$Climin1('B') = 160;$$

$$Climin1('C') = 15;$$

Parameter Climin2(J) Limiting inlet concentrations for operation 2 in ppm;

$$Climin2('A') = 0.02;$$

$$Climin2('B') = 0.03;$$

$$Climin2('C') = 0.03;$$

Parameter Climin3(J) Limiting inlet concentrations for operation 3 in ppm;

$$Climin3('A') = 0.02;$$

$$Climin3('B') = 0.02;$$

$$Climin3('C') = 0.03;$$

Parameter Climin4(J) Limiting inlet concentrations for operation 4 in ppm;

$$Climin4('A') = 0.02;$$

$$Climin4('B') = 0.02;$$

$$\text{Climin4('C')} = 0.03;$$

Parameter Climin5C(J) Limiting inlet concentrations for operation 5 in ppm;

$$\text{Climin5C('A')} = 0.02;$$

$$\text{Climin5C('B')} = 0.02;$$

$$\text{Climin5C('C')} = 0.03;$$

Parameter Climin5D(J) Limiting inlet concentrations for operation 5 in ppm;

$$\text{Climin5D('A')} = 0.02;$$

$$\text{Climin5D('B')} = 0.02;$$

$$\text{Climin5D('C')} = 0.03;$$

Parameter Climin6(J) Limiting inlet concentrations for operation 6 in ppm;

$$\text{Climin6('A')} = 0.02;$$

$$\text{Climin6('B')} = 20;$$

$$\text{Climin6('C')} = 25;$$

Parameter Climout1(J) Limiting outlet concentrations for operation 1 in ppm;

$$\text{Climout1('A')} = 90;$$

$$\text{Climout1('B')} = 1300;$$

$$\text{Climout1('C')} = 45;$$

Parameter Climout2(J) Limiting outlet concentrations for operation 2 in ppm;

$$\text{Climout2('A')} = 1;$$

$$\text{Climout2('B')} = 70000;$$

$$\text{Climout2('C')} = 2700;$$

Parameter Climout3(J) Limiting outlet concentrations for operation 3 in ppm;

$$\text{Climout3('A')} = 1;$$

$$\text{Climout3('B')} = 270;$$

$$\text{Climout3('C')} = 2900;$$

Parameter Climout6(J) Limiting outlet concentrations for operation 6 in ppm;

$$\text{Climout6('A')} = 0.02;$$

Climout6('B') = 0;

Climout6('C') = 0.03;

Parameter ClimR1(J) Limiting outlet concentrations for regen 1 in ppm;

ClimR1('A') = 90;

ClimR1('B') = 1300;

ClimR1('C') = 45;

Parameter ClimR2(J) Limiting outlet concentrations for regen 2 in ppm;

ClimR2('A') = 20;

ClimR2('B') = 230;

ClimR2('C') = 15;

Parameter ClimR3(J) Limiting outlet concentrations for regen 3 in ppm;

ClimR3('A') = 1;

ClimR3('B') = 15;

ClimR3('C') = 5;

Parameter Floss(I) Flowrate loss in operation i;

Floss('oper1') = 622;

Floss('oper2') = 0;

Floss('oper3') = 0;

Floss('oper4') = 20;

Floss('oper5C') = 0;

Floss('oper5D') = 0;

Floss('oper6') = 75;

Parameter Fgain(I) Flowrate gain in operation i;

Fgain('oper1') = 0;

Fgain('oper2') = 0;

Fgain('oper3') = 0;

Fgain('oper4') = 0;

$$F_{\text{gain}}(\text{'oper5C'}) = 0;$$

$$F_{\text{gain}}(\text{'oper5D'}) = 0;$$

$$F_{\text{gain}}(\text{'oper6'}) = 0;$$

Parameter R1(J) removal ration for regeneration 1;

$$R1(\text{'A'}) = 0.9;$$

$$R1(\text{'B'}) = 0.9;$$

$$R1(\text{'C'}) = 0.9;$$

Parameter R2(J) removal ration for regeneration 2;

$$R2(\text{'A'}) = 1;$$

$$R2(\text{'B'}) = 1;$$

$$R2(\text{'C'}) = 1;$$

Parameter R3(J) removal ration for regeneration 3;

$$R3(\text{'A'}) = 0.9;$$

$$R3(\text{'B'}) = 0.9;$$

$$R3(\text{'C'}) = 0.9;$$

Scalar RRO percent to reject /0.5/

Variables

F(I) flowrate of freshwater to operation i in ton per hr

D(I) flowrate from diversion box to operation i in ton per hr

X(I,I) flowrate to operation i from operation j in ton per hr

XTR1(I) flowrate to operation i from regeneration 1

XTR2(I) flowrate to operation i from regeneration 2

XTR3(I) flowrate to operation i from regeneration 3

XFR1(I) flowrate from operation i to regeneration 1

XFR2(I) flowrate from operation i to regeneration 2

XFR3(I) flowrate from operation i to regeneration 3

Xreject flowrate from RO to rejected stream

Cin1(J) inlet concentration to operation 1 of contaminant j in ppm

Cin2(J) inlet concentration to operation 2 of contaminant j in ppm

Cin3(J) inlet concentration to operation 3 of contaminant j in ppm

Cin4(J) inlet concentration to operation 4 of contaminant j in ppm

Cin5C(J) inlet concentration to operation 5 of contaminant j in ppm

Cin5D(J) inlet concentration to operation 5 of contaminant j in ppm

Cin6(J) inlet concentration to operation 6 of contaminant j in ppm

Cout1(J) outlet concentration from operation 1 of contaminant j in ppm

Cout2(J) outlet concentration from operation 2 of contaminant j in ppm

Cout3(J) outlet concentration from operation 3 of contaminant j in ppm

Cout4(J) outlet concentration from operation 4 of contaminant j in ppm

Cout5C(J) outlet concentration from operation 5 of contaminant j in ppm

Cout5D(J) outlet concentration from operation 5 of contaminant j in ppm

Cout6(J) outlet concentration from operation 6 of contaminant j in ppm

CinR1(J) inlet concentration to regeneration 1 of contaminant j in ppm

CinR2(J) inlet concentration to regeneration 2 of contaminant j in ppm

CinR3(J) inlet concentration to regeneration 3 of contaminant j in ppm

CoutR1(J) outlet concentration from regeneration 1 of contaminant j in ppm

CoutR2(J) outlet concentration from regeneration 2 of contaminant j in ppm

CoutR3(J) outlet concentration from regeneration 3 of contaminant j in ppm

W(I) wastewater flowrate from operation i in ton per hr

FR1 flowrate of freshwater to regeneration 1 in ton per hr

FR2 flowrate of freshwater to regeneration 2 in ton per hr

FR3 flowrate of freshwater to regeneration 3 in ton per hr

DR1 flowrate from diversion box to regeneration 1 in ton per hr

DR2 flowrate from diversion box to regeneration 2 in ton per hr

DR3 flowrate from diversion box to regeneration 3 in ton per hr

Flim total freshwater flowrate in ton per hr;

Positive variable F, D, FR1, FR2, FR3, DR1,DR2,DR3, X, Cout1, Cout2, Cout3, Cout4, Cout5C, Cout5D, Cin1, Cin2, Cin3, Cin4, Cin5C, Cin5D, CinR1, CinR2, CinR3, W, XTR1, XTR2, XTR3, XFR1, XFR2, XFR3;

F.L('Oper1') = 6600;

F.L('Oper2') = 0;

F.L('Oper3') = 0;

F.L('Oper4') = 0;

F.L('Oper5C') = 0;

F.L('Oper5D') = 0;

F.L('Oper6') = 0;

FR1.L = 0;

FR2.L = 1120;

FR3.L = 0;

W.L('Oper1') = 0;

W.L('Oper2') = 6;

W.L('Oper3') = 19;

W.L('Oper4') = 0;

W.L('Oper5C') = 0;

W.L('Oper5D') = 0;

W.L('Oper6') = 0;

Cout1.L('A') = 90;

Cout1.L('B') = 1300;

Cout2.L('A') = 0.03;

Cout2.L('B') = 60000;

Cout3.L('A') = 0.03;

Cout3.L('B') = 280;

Cout4.L('A') = 0.06;
Cout4.L('B') = 10;
Cout5C.L('A') = 0.03;
Cout5C.L('B') = 10;
Cout5D.L('A') = 0.1;
Cout5D.L('B') = 15;
Cout6.L('A') = 0.02;
Cout6.L('B') = 0;
XFR1.L('Oper1') = 58;
XFR1.L('Oper2') = 0;
XFR1.L('Oper3') = 0;
XFR1.L('Oper4') = 0;
XFR1.L('Oper5C') = 0;
XFR1.L('Oper5D') = 0;
XFR2.L('Oper1') = 0;
XFR2.L('Oper2') = 0;
XFR2.L('Oper3') = 0;
XFR2.L('Oper4') = 0;
XFR2.L('Oper5C') = 0;
XFR2.L('Oper5D') = 0;
XFR3.L('Oper1') = 0;
XFR3.L('Oper2') = 0;
XFR3.L('Oper3') = 0;
XFR3.L('Oper4') = 0;
XFR3.L('Oper5C') = 0;
XFR3.L('Oper5D') = 280;
XTR1.L('Oper1') = 20;

$XTR1.L('Oper6') = 0;$
 $XTR2.L('Oper1') = 0;$
 $XTR2.L('Oper6') = 120;$
 $XTR3.L('Oper1') = 0;$
 $XTR3.L('Oper6') = 317;$
 $X.L('oper2','oper6') = 6;$
 $X.L('oper3','oper6') = 19;$
 $X.L('oper4','oper6') = 57;$
 $X.L('oper5C','oper6') = 140;$
 $X.L('oper5D','oper6') = 280;$
 $Xreject.L = 38;$

Equations

Supply Define objective function

Cinlet1(J) inlet concentration to operation 1

Cinlet2(J) inlet concentration to operation 2

Cinlet3(J) inlet concentration to operation 3

Cinlet4(J) inlet concentration to operation 4

Cinlet5C(J) inlet concentration to operation 5

Cinlet5D(J) inlet concentration to operation 5

Cinlet6(J) inlet concentration to operation 6

Cinlim1(J) constraint associated with inlet to operation 1

Cinlim2(J) constraint associated with inlet to operation 2

Cinlim3(J) constraint associated with inlet to operation 3

Cinlim4(J) constraint associated with inlet to operation 4

Cinlim5C(J) constraint associated with inlet to operation 5

Cinlim5D(J) constraint associated with inlet to operation 5

Cinlim6(J) constraint associated with inlet to operation 6

Coutlim1(J) constraint associated with outlet to operation 1

Coutlim2(J) constraint associated with outlet to operation 2

Coutlim3(J) constraint associated with outlet to operation 3

Coutlet1(J) constraint associated with outlet from operation 1

Coutlet2(J) constraint associated with outlet from operation 2

Coutlet3(J) constraint associated with outlet from operation 3

Coutlet4(J) constraint associated with outlet from operation 4

Coutlet5C(J) constraint associated with outlet from operation 5

Coutlet5D(J) constraint associated with outlet from operation 5

Coutlet6(J) constraint associated with outlet from operation 6

Mass1 water mass balance over operation 1

Mass2 water mass balance over operation 2

Mass3 water mass balance over operation 3

Mass4 water mass balance over operation 4

Mass5C *water mass balance over operation 5

Mass5D *water mass balance over operation 5

Mass6 water mass balance over operation 6

Masslow2 lower bound water flowrate operation 2

Masslim3 limiting water flowrate operation 3

Masslim4 limiting water flowrate operation 4

Masslow5C lower bound water flowrate operation 5C

Masslow5D lower bound water flowrate operation 5D

Masslim6 limiting water flowrate operation 6

Mass5 water mass balance over operation 5

CinletR1(J) inlet concentration to regeneration 1

CinletR2(J) inlet concentration to regeneration 2

CinletR3(J) inlet concentration to regeneration 3
 CinlimR1(J) inlet concentration to regeneration 1
 CinlimR2(J) inlet concentration to regeneration 2
 CinlimR3(J) inlet concentration to regeneration 3
 CoutletR1(J) outlet concentration from regeneration 1
 CoutletR2(J) outlet concentration from regeneration 2
 CoutletR3(J) outlet concentration from regeneration 3
 ROreject Flowrate of RO reject
 MassR1 water mass balance over regeneration 1
 MassR2 water mass balance over regeneration 2
 MassR3 water mass balance over regeneration 3
 CapaR1 limiting load of R1
 CapaR2 limiting load of R2
 CapaR3 limiting load of R3
 X21 flowrate from oper2 to oper1
 X31 flowrate from oper3 to oper1
 X41 flowrate from oper4 to oper1
 X5C1 flowrate from oper5C to oper1
 X5D1 flowrate from oper5D to oper1
 X26 flowrate from oper2 to oper6
 X36 flowrate from oper3 to oper6
 W1 from oper1 to coupon sample
 DR11 Diversion box to R1
 Dlim limiting flowrate of diversion box
 R31 flowrate from regen3 to oper1;

Supply.. Flim =e= F('Oper1')+F('Oper6')+FR1+FR2+FR3;

Cinlet1(J)..

$Cin1(J) * (F('Oper1') + D('oper1') + X('Oper1', 'Oper2') + X('Oper1', 'Oper3') + X('Oper1', 'Oper4') + X('Oper1', 'Oper5C') + X('Oper1', 'Oper5D') + XTR1('Oper1') + XTR2('Oper1') + XTR3('Oper1')) = E =$

$(Cf(J) * F('Oper1') + Cd(J) * D('oper1') + Cout2(J) * X('Oper1', 'Oper2') + Cout3(J) * X('Oper1', 'Oper3') + Cout4(J) * X('Oper1', 'Oper4') + Cout5C(J) * X('Oper1', 'Oper5C') + Cout5D(J) * X('Oper1', 'Oper5D') + CoutR1(J) * XTR1('Oper1') + CoutR2(J) * XTR2('Oper1') + CoutR3(J) * XTR3('Oper1'));$

Cinlet2(J).. $Cin2(J) * (X('Oper2', 'Oper6')) = E = (Cout6(J) * X('Oper2', 'Oper6'));$

Cinlet3(J).. $Cin3(J) * (X('Oper3', 'Oper6')) = E = (Cout6(J) * X('Oper3', 'Oper6'));$

Cinlet4(J).. $Cin4(J) * (X('Oper4', 'Oper6')) = E = (Cout6(J) * X('Oper4', 'Oper6'));$

Cinlet5C(J).. $Cin5C(J) * (X('Oper5C', 'Oper6')) = E = (Cout6(J) * X('Oper5C', 'Oper6'));$

Cinlet5D(J).. $Cin5D(J) * (X('Oper5D', 'Oper6')) = E = (Cout6(J) * X('Oper5D', 'Oper6'));$

Cinlet6(J)..

$Cin6(J) * (F('Oper6') + D('oper6') + X('Oper6', 'Oper1') + X('Oper6', 'Oper2') + X('Oper6', 'Oper3') + X('Oper6', 'Oper4') + X('Oper6', 'Oper5C') + X('Oper6', 'Oper5D') + XTR1('Oper6') + XTR2('Oper6') + XTR3('Oper6')) = E =$

$(Cf(J) * F('Oper6') + Cd(J) * D('oper6') + Cout1(J) * X('Oper6', 'Oper1') + Cout2(J) * X('Oper6', 'Oper2') + Cout3(J) * X('Oper6', 'Oper3') + Cout4(J) * X('Oper6', 'Oper4') + Cout5C(J) * X('Oper6', 'Oper5C') + Cout5D(J) * X('Oper6', 'Oper5D') + CoutR1(J) * XTR1('Oper6') + CoutR2(J) * XTR2('Oper6') + CoutR3(J) * XTR3('Oper6'));$

Cinlim1(J).. $Cin1(J) = I = Climin1(J);$

Cinlim2(J).. $Cin2(J) = I = Climin2(J);$

Cinlim3(J).. $Cin3(J) = I = Climin3(J);$

Cinlim4(J).. $Cin4(J) = I = Climin4(J);$

Cinlim5C(J).. $Cin5C(J) = I = Climin5C(J);$

Cinlim5D(J).. $Cin5D(J) = I = Climin5D(J);$

Cinlim6(J).. $Cin6(J) = I = Climin6(J);$

Coutlim1(J).. $Cout1(J) = I = Climout1(J);$

Coutlim2(J).. $Cout2(J) = I = Climout2(J);$

Coutlim3(J).. $Cout3(J) = I = Climout3(J);$

Coutlet1(J)..

$Cout1(J) * (F('Oper1') + D('oper1') + X('Oper1', 'Oper2') + X('Oper1', 'Oper3') + X('Oper1', 'Oper4') + X('Oper1', 'Oper5C') + X('Oper1', 'Oper5D') + XTR1('Oper1') + XTR2('Oper1') + XTR3('Oper1')) = E =$

$r4)+X('Oper1','Oper5C')+X('Oper1','Oper5D')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1')) =E=$
 $(Cf(J)*F('Oper1')+Cd(J)*D('oper1')+Cout2(J)*X('Oper1','Oper2')+Cout3(J)*X('Oper1','Oper3')+Cout4(J)*X('Oper1','Oper4')+Cout5C(J)*X('Oper1','Oper5C')+Cout5D(J)*X('Oper1','Oper5D')+CoutR1(J)*XTR1('Oper1')+CoutR2(J)*XTR2('Oper1')+CoutR3(J)*XTR3('Oper1')+M1(J)*1000);$

$Coutlet2(J).. Cout2(J)*(X('Oper2','Oper6')) =E=$
 $(Cout6(J)*X('Oper2','Oper6')+M2(J)*1000);$

$Coutlet3(J).. Cout3(J)*(X('Oper3','Oper6')) =E=$
 $(Cout6(J)*X('Oper3','Oper6')+M3(J)*1000);$

$Coutlet4(J).. Cout4(J)*(X('Oper4','Oper6')) =E=$
 $(Cout6(J)*X('Oper4','Oper6')+M4(J)*1000);$

$Coutlet5C(J).. Cout5C(J)*(X('Oper5C','Oper6')) =E=$
 $(Cout6(J)*X('Oper5C','Oper6')+M5C(J)*1000);$

$Coutlet5D(J).. Cout5D(J)*(X('Oper5D','Oper6')) =E=$
 $(Cout6(J)*X('Oper5D','Oper6')+M5D(J)*1000);$

$Coutlet6(J).. Cout6(J) =e= Climout6(J);$

Mass1..

$F('Oper1')+D('oper1')+X('Oper1','Oper2')+X('Oper1','Oper3')+X('Oper1','Oper4')+X('Oper1','Oper5C')+X('Oper1','Oper5D')+Fgain('Oper1')+XTR1('Oper1')+XTR2('Oper1')+XTR3('Oper1') =E=$
 $W('Oper1')+X('Oper6','Oper1')+Floss('Oper1')+XFR1('Oper1')+XFR2('Oper1')+XFR3('Oper1');$

Mass2.. $X('Oper2','Oper6')+Fgain('Oper2') =E=$

$W('Oper2')+X('Oper1','Oper2')+X('Oper6','Oper2')+Floss('Oper2')+XFR1('Oper2')+XFR2('Oper2')+XFR3('Oper2');$

Mass3.. $X('Oper3','Oper6')+Fgain('Oper3') =E=$

$W('Oper3')+X('Oper1','Oper3')+X('Oper6','Oper3')+Floss('Oper3')+XFR1('Oper3')+XFR2('Oper3')+XFR3('Oper3');$

Mass4.. $X('Oper4','Oper6')+Fgain('Oper4') =E=$

$W('Oper4')+X('Oper1','Oper4')+X('Oper6','Oper4')+Floss('Oper4')+XFR1('Oper4')+XFR2('Oper4')+XFR3('Oper4');$

Mass5C.. $X('Oper5C','Oper6')+Fgain('Oper5C') =E=$

$W('Oper5C')+X('Oper1','Oper5C')+X('Oper6','Oper5C')+Floss('Oper5C')+XFR1('Oper5C')+XFR2('Oper5C')+XFR3('Oper5C');$

$$\text{Mass5D.. } X(\text{'Oper5D'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5D'}) =E= \\ W(\text{'Oper5D'})+X(\text{'Oper1'},\text{'Oper5D'})+X(\text{'Oper6'},\text{'Oper5D'})+\text{Floss}(\text{'Oper5D'})+\text{XFR1}(\text{'Oper5D'})+\text{XFR2}(\text{'Oper5D'})+\text{XFR3}(\text{'Oper5D'});$$

Mass6..

$$\text{F}(\text{'Oper6'})+\text{D}(\text{'oper6'})+X(\text{'Oper6'},\text{'Oper1'})+X(\text{'Oper6'},\text{'Oper2'})+X(\text{'Oper6'},\text{'Oper3'})+X(\text{'Oper6'},\text{'Oper4'})+X(\text{'Oper6'},\text{'Oper5C'})+X(\text{'Oper6'},\text{'Oper5D'})+\text{Fgain}(\text{'Oper6'})+\text{XTR1}(\text{'Oper6'})+\text{XTR2}(\text{'Oper6'})+\text{XTR3}(\text{'Oper6'}) =E= \\ W(\text{'Oper6'})+X(\text{'Oper2'},\text{'Oper6'})+X(\text{'Oper3'},\text{'Oper6'})+X(\text{'Oper4'},\text{'Oper6'})+X(\text{'Oper5C'},\text{'Oper6'})+X(\text{'Oper5D'},\text{'Oper6'})+\text{Floss}(\text{'Oper6'});$$

$$\text{Masslow2.. } X(\text{'Oper2'},\text{'Oper6'})+\text{Fgain}(\text{'Oper2'}) =g= 6;$$

$$\text{Masslim3.. } X(\text{'Oper3'},\text{'Oper6'})+\text{Fgain}(\text{'Oper3'}) =l= 20;$$

$$\text{Masslim4.. } X(\text{'Oper4'},\text{'Oper6'})+\text{Fgain}(\text{'Oper4'}) =g= 60;$$

$$\text{Masslow5C.. } X(\text{'Oper5C'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5C'}) =g= 140;$$

$$\text{Masslow5D.. } X(\text{'Oper5D'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5D'}) =g= 280;$$

Masslim6..

$$\text{F}(\text{'Oper6'})+\text{D}(\text{'oper6'})+X(\text{'Oper6'},\text{'Oper1'})+X(\text{'Oper6'},\text{'Oper2'})+X(\text{'Oper6'},\text{'Oper3'})+X(\text{'Oper6'},\text{'Oper4'})+X(\text{'Oper6'},\text{'Oper5C'})+X(\text{'Oper6'},\text{'Oper5D'})+\text{Fgain}(\text{'Oper6'})+\text{XTR1}(\text{'oper6'})+\text{XTR2}(\text{'oper6'})+\text{XTR3}(\text{'oper6'}) =l= 590;$$

$$\text{Mass5.. } (X(\text{'Oper5C'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5C'}))*2 =e= \\ X(\text{'Oper5D'},\text{'Oper6'})+\text{Fgain}(\text{'Oper5D'});$$

CinletR1(J)..

$$\text{CinR1}(J)*(XFR1(\text{'Oper1'})+XFR1(\text{'Oper2'})+XFR1(\text{'Oper3'})+XFR1(\text{'Oper4'})+XFR1(\text{'Oper5C'})+XFR1(\text{'Oper5D'})+\text{FR1}+\text{DR1}) =E= \\ (\text{Cout1}(J)*XFR1(\text{'Oper1'})+\text{Cout2}(J)*XFR1(\text{'Oper2'})+\text{Cout3}(J)*XFR1(\text{'Oper3'})+\text{Cout4}(J)*XFR1(\text{'Oper4'})+\text{Cout5C}(J)*XFR1(\text{'Oper5C'})+\text{Cout5D}(J)*XFR1(\text{'Oper5D'})+\text{Cf}(J)*\text{FR1}+\text{Cd}(J)*\text{DR1});$$

CinletR2(J)..

$$\text{CinR2}(J)*(XFR2(\text{'Oper1'})+XFR2(\text{'Oper2'})+XFR2(\text{'Oper3'})+XFR2(\text{'Oper4'})+XFR2(\text{'Oper5C'})+XFR2(\text{'Oper5D'})+\text{FR2}+\text{DR2}) =E= \\ (\text{Cout1}(J)*XFR2(\text{'Oper1'})+\text{Cout2}(J)*XFR2(\text{'Oper2'})+\text{Cout3}(J)*XFR2(\text{'Oper3'})+\text{Cout4}(J)*XFR2(\text{'Oper4'})+\text{Cout5C}(J)*XFR2(\text{'Oper5C'})+\text{Cout5D}(J)*XFR2(\text{'Oper5D'})+\text{Cf}(J)*\text{FR2}+\text{Cd}(J)*\text{DR2});$$

CinletR3(J)..

$$\text{CinR3}(J)*(XFR3(\text{'Oper1'})+XFR3(\text{'Oper2'})+XFR3(\text{'Oper3'})+XFR3(\text{'Oper4'})+XFR3(\text{'Oper5C'})+XFR3(\text{'Oper5D'})+\text{FR3}+\text{DR3}) =E= \\ (\text{Cout1}(J)*XFR3(\text{'Oper1'})+\text{Cout2}(J)*XFR3(\text{'Oper2'})+\text{Cout3}(J)*XFR3(\text{'Oper3'})+\text{Cout4}(J)$$

*XFR3('Oper4')+Cout5C(J)*XFR3('Oper5C')+Cout5D(J)*XFR3('Oper5D')+Cf(J)*FR3
+Cd(J)*DR3);

CinlimR1(J).. CinR1(J) =I= ClimR1(J);

CinlimR2(J).. CinR2(J) =I= ClimR2(J);

CinlimR3(J).. CinR3(J) =I= ClimR3(J);

CoutletR1(J).. CoutR1(J) =E= (1-R1(J))*CinR1(J);

CoutletR2(J).. CoutR2(J) =E= (1-R2(J))*CinR2(J);

CoutletR3(J).. CoutR3(J) =E= (1-R3(J))*CinR3(J);

ROreject.. Xreject =e=

RRO*(FR1+DR1+XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1
('oper5C')+XFR1('oper5D')));

MassR1.. XTR1('oper1')+XTR1('oper6')+Xreject =E=

(XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1(
'oper5D'))+FR1+DR1;

MassR2.. XTR2('oper1')+XTR2('oper6') =E=

(XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2(
'oper5D'))+FR2+DR2;

MassR3.. XTR3('oper1')+XTR3('oper6') =E=

(XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3(
'oper5D'))+FR3+DR3;

CapaR1..

(XFR1('oper1')+XFR1('oper2')+XFR1('oper3')+XFR1('oper4')+XFR1('oper5C')+XFR1(
'oper5D'))+FR1+DR1 =I= 80;

CapaR2..

(XFR2('oper1')+XFR2('oper2')+XFR2('oper3')+XFR2('oper4')+XFR2('oper5C')+XFR2(
'oper5D'))+FR2+DR2 =I= 160;

CapaR3..

(XFR3('oper1')+XFR3('oper2')+XFR3('oper3')+XFR3('oper4')+XFR3('oper5C')+XFR3(
'oper5D'))+FR3+DR3 =I= 320;

X21.. X('oper1','oper2') =e=0;

X31.. X('oper1','oper3') =e=0;

X41.. X('oper1','oper4') =e=0;

X5C1.. X('oper1','oper5C') =e=0;

X5D1.. X('oper1','oper5D') =e=0;

X26.. X('oper6','oper2') =e=0;

X36.. X('oper6','oper3') =e=0;

R31.. XTR3('oper1') =e= 0;

W1.. W('oper1') =e= 8;

DR11.. DR1 =e= 0;

Dlim.. D('oper1')+D('oper6')+DR1+DR2+DR3 =l= 30;

Model Super /All/;

Solve Super using NLP minimizing Flim;

Display

Flim.L,F.L,D.L,FR1.L,FR2.L,FR3.L,DR1.L,DR2.L,DR3.L,W.L,X.L,XFR1.L,XTR1.L,
XFR2.L,XTR2.L,XFR3.L,XTR3.L,Xreject.L,Cin1.L,Cout1.L,Cin2.L,Cout2.L,Cin3.L,C
out3.L,Cin4.L,Cout4.L,Cin5C.L,Cout5C.L,Cin5D.L,Cout5D.L,Cin6.L,Cout6.L,CinR1.
L,CoutR1.L,CinR2.L,CoutR2.L,CinR3.L,CoutR3.L;

GAMS Output

```

**** REPORT SUMMARY :      0  NONOPT
                             0  INFEASIBLE
                             0  UNBOUNDED
                             0  ERRORS

      501 VARIABLE Flim.L      =  750.826 total freshwater flowrate in ton
per hr

----  501 VARIABLE F.L flowrate of freshwater to operation i in ton per hr
Oper1 589.310

----  501 VARIABLE D.L flowrate from diversion box to operation i in ton per hr
Oper1 17.979

      501 VARIABLE FR1.L      =  0.000 flowrate of freshwater to
regeneration 1 in ton per hr

----  501 VARIABLE FR2.L      =  160.000 flowrate of freshwater to
regeneration 2 in ton per hr

----  501 VARIABLE FR3.L      =  1.516 flowrate of freshwater to
regeneration 3 in ton per hr

----  501 VARIABLE DR1.L      =  0.000 flowrate from diversion box to
regeneratio 1 in ton per hr

----  501 VARIABLE DR2.L      =  0.000 flowrate from diversion box to
regeneration 2 in ton per hr

----  501 VARIABLE DR3.L      =  0.203 flowrate from diversion box to
regeneratio 3 in ton per hr

----  501 VARIABLE W.L wastewater flowrate from operation i in ton per hr
Oper1 8.000, oper2 6.000, oper3 19.671

----  501 VARIABLE X.L flowrate to operation i from operation j in ton per hr
      oper5C   oper5D   oper6
oper2                6.000
oper3                19.704
oper4                69.296

```

oper5C 140.000

oper5D 280.000

oper6 140.000 11.049

---- 501 VARIABLE XFR1.L flowrate from operation i to regeneration 1

Oper1 36.674

---- 501 VARIABLE XTR1.L flowrate to operation i from regeneration 1

Oper1 18.337

---- 501 VARIABLE XFR2.L flowrate from operation i to regeneration 2

(ALL 0.000)

---- 501 VARIABLE XTR2.L flowrate to operation i from regeneration 2

Oper1 41.049, oper6 118.951

---- 501 VARIABLE XFR3.L flowrate from operation i to regeneration 3

oper3 0.033, oper4 49.296, oper5D 268.951

---- 501 VARIABLE XTR3.L flowrate to operation i from regeneration 3

oper6 320.000

501 VARIABLE Xreject.L = 18.337 flowrate from RO to rejected stream

---- 501 VARIABLE Cin1.L inlet concentration to operation 1 of contaminant j in ppm

A 18.601, B 134.915, C 15.000

---- 501 VARIABLE Cout1.L outlet concentration from operation 1 of contaminant j in ppm

A 90.000, B 1195.703, C 44.580

---- 501 VARIABLE Cin2.L inlet concentration to operation 2 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout2.L outlet concentration from operation 2 of contaminant j in ppm

A 0.030, B 56833.333, C 2620.030

---- 501 VARIABLE Cin3.L inlet concentration to operation 3 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout3.L outlet concentration from operation 3 of contaminant j in ppm

A 0.030, B 270.000, C 2706.120

---- 501 VARIABLE Cin4.L inlet concentration to operation 4 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout4.L outlet concentration from operation 4 of contaminant j in ppm

A 0.054, B 8.226, C 2.654

---- 501 VARIABLE Cin5C.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout5C.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.030, B 10.000, C 5.000

---- 501 VARIABLE Cin5D.L *inlet concentration to operation 5 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE Cout5D.L *outlet concentration from operation 5 of contaminant j in ppm

A 0.100, B 15.000, C 5.000

---- 501 VARIABLE Cin6.L inlet concentration to operation 6 of contaminant j in ppm

A 0.020, B 3.467, C 1.551

---- 501 VARIABLE Cout6.L outlet concentration from operation 6 of contaminant j in ppm

A 0.020, C 0.030

---- 501 VARIABLE CinR1.L inlet concentration to regeration 1 of contaminant j in ppm

A 90.000, B 1195.703, C 44.580

---- 501 VARIABLE CoutR1.L outlet concentration from regeration 1 of contaminant j in ppm

A 9.000, B 119.570, C 4.458

---- 501 VARIABLE CinR2.L inlet concentration to regeration 2 of contaminant j in ppm

A 20.000, B 124.500, C 15.000

---- 501 VARIABLE CoutR2.L outlet concentration from regeration 2 of contaminant j in ppm

(ALL 0.000)

---- 501 VARIABLE CinR3.L inlet concentration to regeration 3 of contaminant in ppm

A 0.203, B 15.000, C 5.000

---- 501 VARIABLE CoutR3.L outlet concentration from regeration 3 of contaminant j in ppm

A 0.020, B 1.500, C 0.500

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