TOWARDS MACROSCOPIC WATER INTEGRATION FOR ZERO LIQUID DISCHARGE IN INDUSTRIAL COMPLEXES

A THESIS

by

ZAKARYA AZHAR OTHMAN OTHMAN

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Chair of Committee,	Patrick Linke
Co-Chair of Committee,	Mahmoud El-Halwagi
Committee Member,	Eyad Masad
Head of Department,	Nazmul Karim

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ABSTRACT

The increasing environmental pressures to minimize wastewater discharge from industrial plants to the environment have led to the emergence of policies and regulations that promote Zero-Liquid Discharge (ZLD) solutions. These systems are typically associated with high capital and operating cost and pose a significant economic burden to implementing industries. ZLD solutions are explored as End-of-Pipe treatment options to eliminate liquid discharges. Instead, ZLD options should be explored in the context of overall water integration of industrial facilities to achieve desired reductions in water footprints through efficient reuse together whilst achieving ZLD.

In this work, we propose a systematic approach to screen sustainable and low cost strategies that will assist in targeting water integration for Zero Liquid Discharge (ZLD) in industrial parks. The approach expands an Eco-Industrial Park (EIP) representation for water integration to include different possible ZLD options. A mixed integer non-linear programming (MINLP) model for water integration in industrial parks is developed to screen the representation. The optimization model represents a decision support tool that can help the designer in quickly evaluate potential reuse and recycle scenarios with ZLD. The model is formulated to allow streams to be reused internally and externally in each plant, recycled in a shared centralized and decentralized treatment and in ZLD systems, and utilized for a number of options that can constitute ZLD including beneficial usage and/or ZLD processing. The default objective is to achieve ZLD at minimum total annual cost.

A case study of an industrial park with three plants has been solved and analyzed in a number of scenarios to illustrate the usefulness of the proposed model.

DEDICATION

To my family.

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All praises are due to Allah, the Most Gracious, the Ever Merciful for blessing me with the ability to complete my research work.

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1. INTRODUCTION

Practically all processing facilities use water and in many cases produce liquid discharges. End of pipe treatment is widely used in chemical processing facilities, in which several wastewater streams are merged and passed over a series of treatment steps, thus eventually maintaining all pollutant concentrations of the outlet stream below the imposed disposal limits. However, increased environmental concerns towards continuous wastewater discharge into the sea, and its impact on marine life instigated more effective water management strategies within chemical processing industries and in many cases setting ZLD as a primary goal [1].

Targeting for Zero Liquid Discharge (ZLD) to the environment was in the beginning a technique for reducing fresh water consumption in industrial complexes where water is scarce or expensive. Today, ZLD is an emerging regulatory requirement for industrial water management in some countries, which aims at eliminating water discharges from industrial complexes.

Drivers for ZLD are many, one of these drivers are the difficulties of implementing the conventional disposal options such as discharge to surface water, deep well injection, discharge to sewer etc.. These difficulties are related to the more ever restricted regulations and permitting requirements as well as the high cost associated to line with these new regulations. The second driver is the growing environmental and resources conservation concerns as high quality fresh water is a scarce resource and there is a growing concern for quality and quantity of water supply. ZLD will reduce the environmental footprint especially if salts recovery is taken into account. Thirdly, the economical driver, as ZLD will push toward sustainability and benefits of water reuse and recycle techniques. Fourthly, ZLD will reduce the public perception toward industrial wastewater impacts as public has the perception that the discharge wastewater is kind of hazardous and toxic waste.

Water integration approaches so far have been developed under the assumption of water treatment to meet effluent discharge regulations. ZLD technologies exist that eliminate waste water streams and produce pure water streams for potential reuse in the facility or industrial complex as well as solid waste such as salts. Besides processing for the recovery of water and solids, ZLD options may include the reuse of water in beneficial applications such as beautification. The industries are challenged to seek sustainable and low cost strategies that will assist in achieving ZLD in response to emerging environmental regulations.

Therefore, in an attempt to seek sustainable and low cost strategies that will assist in achieving ZLD in response to the emerging environmental regulations for the industries located in complexes, the following work is proposed and mainly includes:

A. Preparing a representative case study: This will include data presentation for the considered plants in industrial complex, contaminants, fresh water sources, process sources, process sinks, existing local EOPT, candidate decentralized end of pipe treatment options, candidate centralized treatment options, candidate centralized and decentralized ZLD systems, available beneficial uses sinks, candidate evaporation pond, and data on the shortest distances between all fresh water sources, process sources, process sinks, existing local end of pipe treatment, decentralized treatment, decentralized ZLD systems, centralized treatment, centralized ZLD system, beneficial uses sinks and evaporation pond.

B. Formulation a model to optimize water integration in industrial complexes to achieve ZLD at minimum cost: Preparing a formulation that defines the network configuration and satisfies plants facilities and constraints. The model is formulated to allow streams to be reused internally and externally, recycled in a shared centralized and decentralized treatment and ZLD systems, utilized for beneficial usage and/or evaporated in evaporation ponds. The model objective is to achieve ZLD at minimum total annual cost, which comprises the costs of fresh water, centralized, decentralized treatment, centralized and decentralized ZLD systems, beneficial usage, evaporation ponds and piping cost.

2. LITERATURE REVIEW

Significant savings in fresh water requirements and discharges can typically be achieved through water integration in terms of reuse, regeneration reuse and recycling. Over the past three decades, many water integration methodologies have been developed and implemented in various chemical processing industries. Much of the work initially started within the context of a single plant. One of early efforts in this area were presented by Takama et al., who identify optimal connections of water streams in an oil refinery plant, in order to reduce freshwater consumption [2]. El-Halwagi and Manousiouthak have systematized mass exchanger network design and have provided the foundation for water integration approaches [3, 4]. Focusing specifically on water integration, Wang and Smith introduced a graphical pinch analysis method for targeting minimum fresh and waste water requirements within a single process [5, 6]. Their methodology distinguishes three cases: reuse, regeneration reuse and regeneration recycle. Since then, many modified graphical representations have been proposed for the design of water networks within single plants, many of which utilize the concept of wastewater reuse and recycle [7-11]. This was accompanied by an increasing number of contributions based on mathematical programming techniques that can better address multi-contaminant problems to determine reuse strategies and treatment options considering cost objectives in design [12-18]. These design methods assume a discharge flow that meets an environmental discharge regulation based on water quality.

ZLD has been defined as the complete elimination of wastewater discharge, by means of a closed water circuit where effluent discharge into environment from any processing facility is eliminated [12, 19]. Goldblatt et al. and Koppol et al. [12, 20] list the main reason for pursuing ZLD as minimization of the freshwater consumption which might bring about economic benefits and provide a good environmental performance reputation for the entities involved. Mickley [21] compare between high recovery treatment systems such as membranes and ZLD systems for different water qualities and quantities. Furthermore, the cost and performance trends together with some regulatory issues correspond to ZLD technologies are highlighted. Goldblatt et al. [20] discuss different technologies for ZLD and proposed an approach for wastewater management that starts with the minimization of wastewater generated, followed by a segregation step for all wastewater streams that would allow for their direct reuse. Moreover, their approach involves the possibility of introducing a wastewater treatment stage that would enable recycle, in case direct reuse does not meet quality specifications of the sinks, and includes evaporation as a final processing stage for untreated unutilized wastewater. Few in-plant water integration approaches address the issue of Zero Liquid Discharge. Alves et al. [22] considered photochemical wastewater treatment technologies, together with hybrid systems of water and air cooling to reach near ZLD for an industrial polypropylene plant. Deng et al. [23] target the optimum inlet and outlet concentration of regeneration for ZLD in fixed mass load systems using a graphical method for single contaminant cases. Foo et al. [24] propose a water cascade analysis method for targeting a water threshold for single contaminant problems. Bagajewicza and Faria [15, 25] utilize mathematical programming techniques for developing a zero net water balance by implementing ZLD within a given process, in both single and multiple contaminant problems. Most of the proposed approaches consider the case of water integration for an existing plant.

Beyond the level of an individual process, techniques exist for managing water resources within eco-industrial parks that address the resulting inter-plant water integration problems. Eco-industrial parks (EIPs) can be defined as a community of industries located near to each other, sharing and managing common utilities and resources such as water, material and energy to ensure a better environmental, economic, and social performance [26]. Olesen and Polley [27] presented the first work on this topic, from a water integration perspective, through a pinch analysis technique. Liao et al. [28] developed a MINLP model for targeting freshwater consumption in multiple plants and proposed a MILP model for individual plants with single contaminants and constant flowrates problems. Efforts of Chew et al. [29] elaborate the development of MILP and MINLP models for two schemes of inter-plant water integration respectively, direct and indirect integration scenarios. A new concept for centralized utility hub with regeneration units was introduced for indirect networks; however, the work does not consider wastewater discharge limits to the environment. Chew et al. [30] developed an approach that acts as a tool for decision making in investigating indirect inter-plant water integration schemes. Lovelady and El-Halwagi [31] proposed a water integration approach for eco-industrial park. The approach allows direct reuse and recycle based on a source-interceptor-sink network representation, and utilizes a cost function as an objective. Rubio-Castro et al. [32] proposed a mathematical programming formulation that can handle multi-contaminants problems, in which wastewater reuse both internally (within each plant) and externally (with other plants) is considered, in addition to integrating a centralized treatment facility, as one of the wastewater treatment options. Alnouri et al. [33] present a spatially constrained representation that considers the location of plants, corridors and barriers to find the shortest possible linking options between sources and sinks. Bishnu et al. [34] presented source sink water mapping model for planning over multi-period. Most of the proposed approaches consider the case of water integration among existing plants through introducing more treatment to maintain discharge quality. The inter-plant integration with zero liquid effluent discharge has not been considered so far.

The paper proposes a first approach to inter-plant water integration for zero liquid effluent discharge. An optimization model is developed to support decision-making with respect to the selection of cost effective designs for interplant water integration within industrial complexes, which considers direct wastewater reuse options as well as treatment options including local end-of-pipe treatment facilities and decentralized ZLD systems together with centralized treatment facilities, centralized ZLD system and centralized evaporation ponds. The approach is capable of determining optimal water flows that can be used as feed for alternative ZLD water use options such as uses in the industrial sector (e.g. cooling towers) or in the municipal sector (e.g. landscape greening, recreational purposes). The representation and model development is explained in the next section followed by a case study illustrated throw-out a number of scenarios.

3. AN INTEGRATED APPROACH FOR ZERO LIQUID DISCHARGE IN INDUSTRIAL COMPLEXES

3.1 Problem statement

The paper deals with the inter-plant water integration with ZLD to environment in industrial complexes by means of direct reuse and recycle with an objective of minimization total annual cost. Figure 1 shows a schematic of an industrial complex with sources, sinks, end-of-pipe-treatment (EOPT) and effluent discharge to the sea. The problem addressed here is to determine optimal ZLD strategies to achieve lowest cost ZLD strategies for the industrial complex through optimal combinations of regeneration, reuse and ZLD options. Figure 2 shows the high-level structural options considered in this problem, which include the upgrading of the existing end of pipe treatment as well as addressing of centralized treatment, centralized evaporation ponds, centralized and decentralized ZLD system together with beneficial uses sinks such as irrigation. The problem addressed in this work is stated as follows:

Given is a number of plants in industrial complex, the contaminants to be considered in the study, the fresh water (flowrates, water quality, cost), process sources (flowrates, water quality), the process sinks (required flowrates, water quality constraints), the existing local EOPT options (efficiencies, constraints, operating cost), candidate decentralized end of pipe treatment options (efficiencies, constraints, fixed and operating cost), candidate centralized treatment options (efficiencies, constraints, fixed and operating cost), candidate centralized and decentralized ZLD systems (efficiencies, constraints, fixed and operating cost), available beneficial uses sinks (upper bounds on flowrates, water quality constraints), candidate evaporation pond (constraints, fixed and operating cost), and data on the shortest distances between all fresh water sources, process sources, process sinks, existing local end of pipe treatment, decentralized treatment, decentralized ZLD systems, centralized treatment, centralized ZLD system, beneficial uses sinks and evaporation pond. The goal is to determine the cost optimal ZLD network in terms of connections and flowrates between sources, sinks and regenerations facilities together with the utilization of existence EOPT, and the implementation of centralized and decentralized treatment with ZLD systems and evaporation pond.

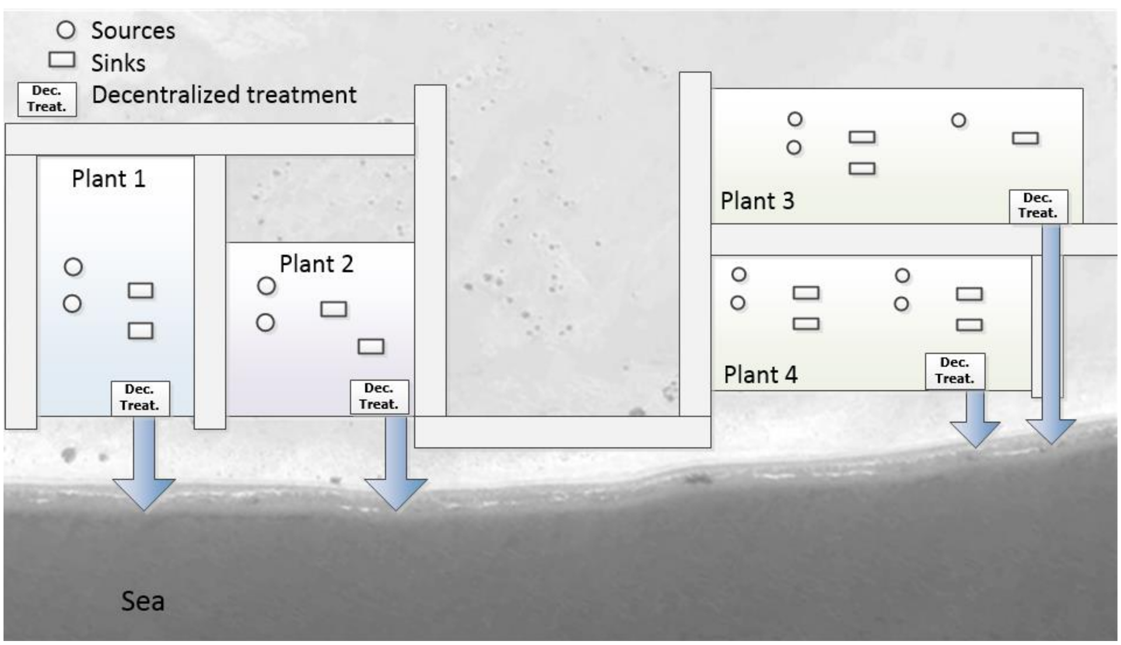

Figure 1: Industrial complex representation with effluent discharge to sea

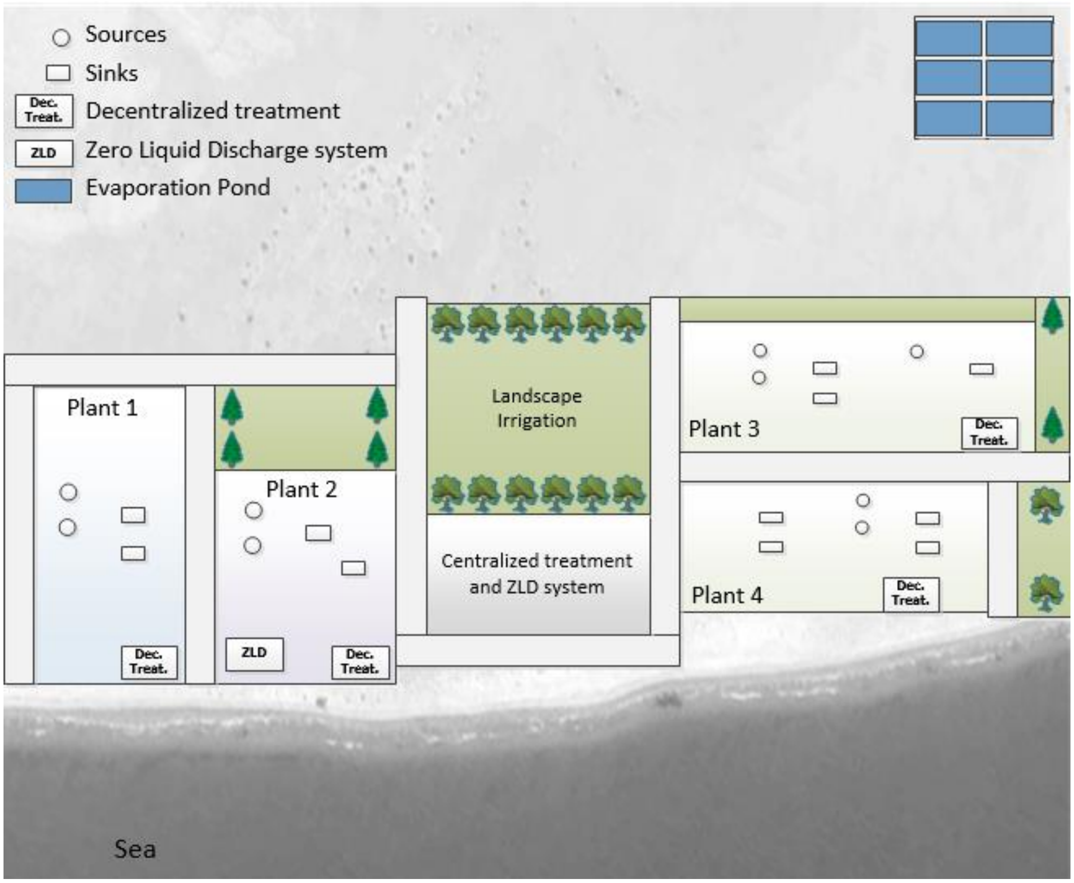

Figure 2: Industrial complex representation with ZLD to sea

3.2 Synthesis representation and optimization model

The problem stated in the previous section poses a network optimization challenge, in which optimal connections between sources and sinks, the existence and utilization of treatment and ZLD options need to be determined from the set of feasible combinations of design options. Figure 3 illustrates the superstructure that is optimized in this work. It consists of the basic elements of processing plants, fresh water source, process water sources, process and beneficial use (ZLD option) sinks, locally existing end of pipe treatment and inter-plants treatment interceptors. This consists of the possibility of having centralized and decentralized treatment stages, as well as implementing ZLD options. Figure 4 elaborates the possible connections for the centralized and decentralized treatment. The network optimization problem is formulated as a mixed integer nonlinear program (MINLP) to screen the various treatment options and selecting the optimal treatment for every single stage associated with centralized treatment. The developed model is an extension of the formulation proposed by Rubio-Castro et al. [32]. Future work will look into introducing water mains together with implementing the combinations of centralized and decentralized treatment and ZLD options.

We define the following sets as a basis for our model formulation:

- $W_w = \{w|\ set\ of$ fresh water source $w\}$
- $S_{i_{n=x}} = \{i_{n=x}|\ set\ of$ process sources i at network $n = x\}$
- $U_{j_{n=x}} = \{j_{n=x}|\ set\ of$ process sink j at network $n = x$ $\}$
- $E_{e_{n=x_t}} = \{e_{n=x_t}|\ set\ of$ decentralized treatment e at stage $t\ in$ network $n = x\}$
- $I_{r_t} = \{r_t|\ set\ of$ centralized tratment options r at stage $t\}$
- $Z_{z_{n=x}} = \{z_{n=x}|\ set\ of\ de$centralized ZLD systems $z\ in$ network $n = x\}$
- $Z_z = \{z|\ set\ of$ centralized ZLD systems z $\}$
- $B_b = \{b|\ set\ of$ beneficial use sinks $b\}$
- $V_v = \{v|\ set\ of$ evaporation pond sinks $v\}$
- $D_d = \{d|\ set\ of\ environmental\ weastwater\ discharge\ sinks\ d\}$
- $L = \{l|\ set\ of$ contaminants$\}$

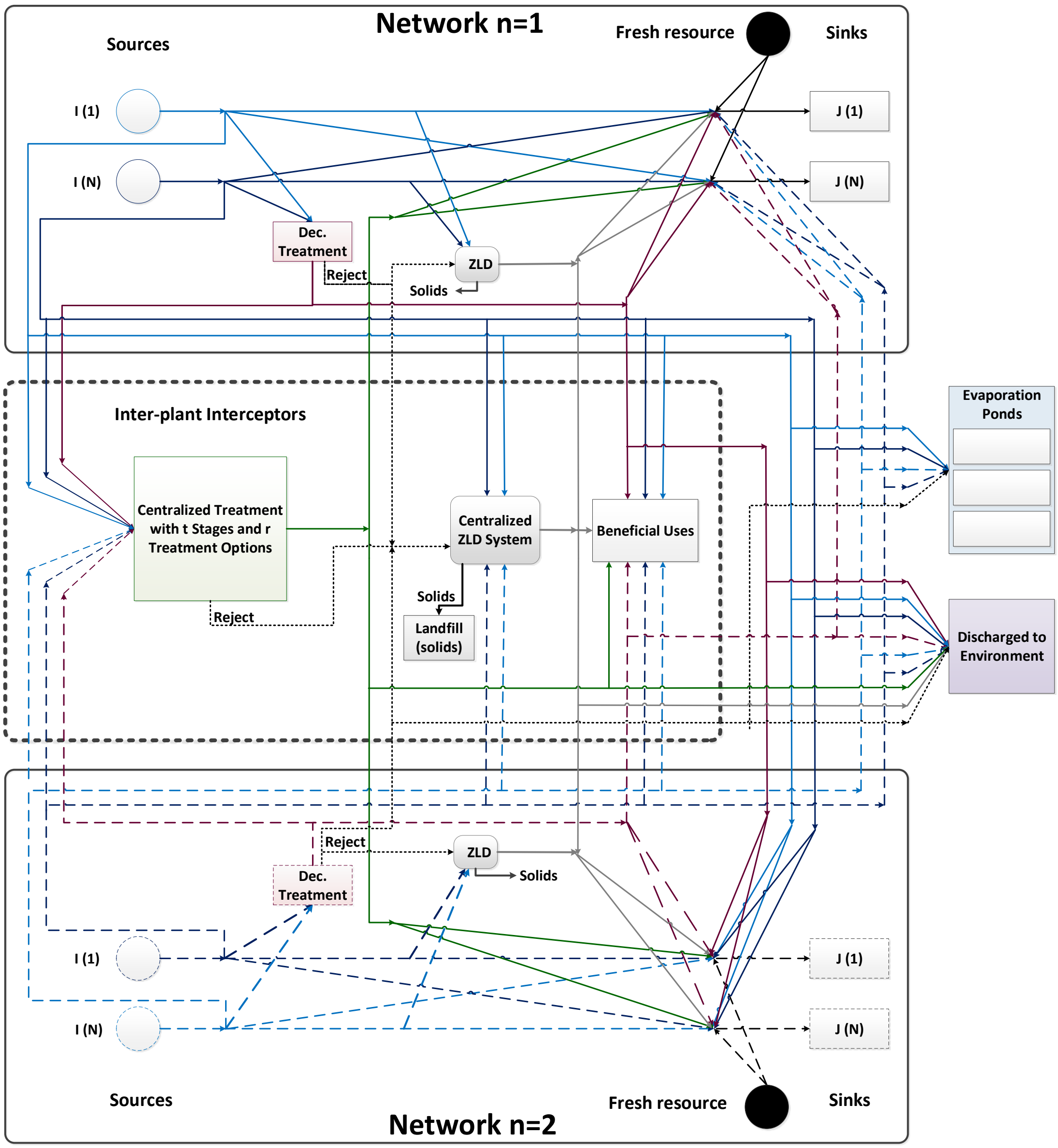

Figure 3: Superstructure for water integration in industrial parks with zero liquid discharge

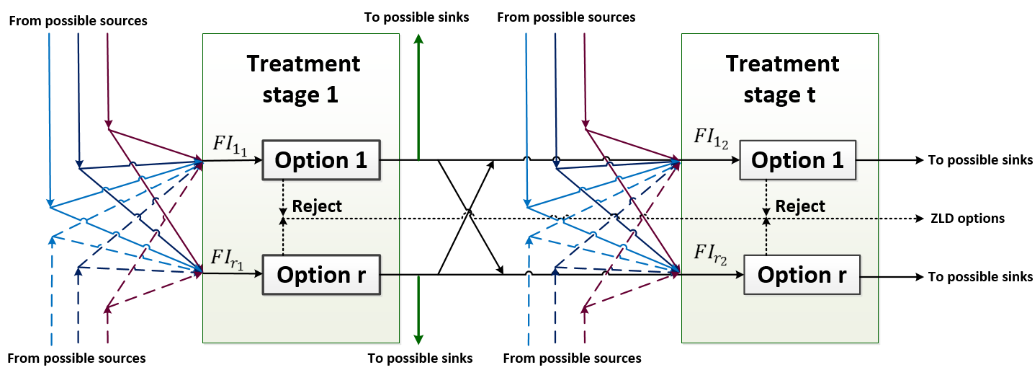

Figure 4: Centralized and Decentralized treatment possible connections

The optimization model consists of an objective function, equality and inequality constraints and will be developed over the following sections. Figure 3 and Figure 4 illustrate the main variables of the model.

1. Fresh water source mass balance: Fresh water source FW_w is formulated to be accessible to any process sink $fws_{w,j_{n=x}}$ at any network $n = x$.

$$FW_w = \sum_{j_{n=x}=1}^{J_{n=x}} fws_{w,j_{n=x}} \qquad w_w \in W_w \tag{1}$$

2. Process sources mass balance: The effluent from any process source $FS_{i_{n=x}}$ at a network $n = x$ can be divided and utilized in process sinks $fss_{i_{n=x},j_{n=x}}$ at the same network $n = x$, utilized in process sinks $fss_{i_{n=x},j_{n\neq x}}$ at other networks $n \neq x$, sent to end of pipe treatment $fse_{i_{n=x},e_{n=x_t}}$ stage t at the same network $n = x$, sent to end of pipe treatment $fse_{i_{n=x},e_{n\neq x_t}}$ stage t at other networks $n \neq x$, sent to centralized treatment $fsi_{i_{n=x},r_t}$ stage t, sent to decentralized ZLD system $fsz_{i_{n=x},z_{n=x}}$ at the same network $n = x$, sent to decentralized ZLD system $fsz_{i_{n=x},z_{n\neq x}}$ at other networks $n \neq x$, sent to centralized ZLD system $fsz_{i_{n=x},z}$,

sent to evaporation pond $fsv_{i_{n=x},v}$ stage t, utilized for beneficial uses $fsb_{i_{n=x},b}$ and/or discharge to environment $fsd_{i_{n=x},d}$.

$$FS_{i_{n=x}} = \sum_{j_{n=x}=1}^{J_{n=x}} fss_{i_{n=x},j_{n=x}} + \sum_{j_{n\neq x}=1}^{J_{n\neq x}} fss_{i_{n=x},j_{n\neq x}} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} fse_{i_{n=x},e_{n=x_t}} + \sum_{e_{n\neq x_t}=1}^{E_{n\neq x_t}} fse_{i_{n=x},e_{n\neq x_t}} + \sum_{r_t=1}^{R_t} fsi_{i_{n=x},r_t} + \sum_{z_{n=x}=1}^{Z_{n=x}} fsz_{i_{n=x},z_{n=x}} + \sum_{z_{n\neq x}=1}^{Z_{n\neq x}} fsz_{i_{n=x},z_{n\neq x}} + \sum_{z=1}^{Z} fsz_{i_{n=x},z} + \sum_{v=1}^{V} fsv_{i_{n=x},v} + \sum_{b=1}^{B} fsb_{i_{n=x},b} + \sum_{d=1}^{D} fsd_{i_{n=x},d}\,, \quad i_{n=x} \in I_{n=x} \tag{2}$$

3. Process sinks mass balance: The inlet flowrate to any process sink $FU_{j_{n=x}}$ in a network $n = x$ is the combination of flowrates from all the different types of fresh water sources considered $fws_{w,j_{n=x}}$, process sources $fss_{i_{n=x},j_{n=x}}$ at the same network $n = x$, process sources $fss_{i_{n\neq x},j_{n=x}}$ at other networks $n \neq x$, from end of pipe treatment $fes_{e_{n=x_t},j_{n=x}}$ stage t at the same network $n = x$, from end of pipe treatment $fes_{e_{n\neq x_t},j_{=x}}$ stage t at another network $n \neq x$, from centralized treatment $fis_{r_{t=NT},j_{n=x}}$, from decentralized ZLD system $fzs_{z_{n=x_i},j_{n=x}}$ at the same network $n = x$, from decentralized ZLD system $fzs_{z_{n\neq x},j_{n=x}}$ at other networks $n \neq x$ and from centralized ZLD system $fzs_{z,j_{n=x}}$.

$$FU_{j_{n=x}} = \sum_{w=1}^{W} fws_{w,j_{n=x}} + \sum_{i_{n=x}=1}^{I_{n=x}} fss_{i_{n=x},j_{n=x}} + \sum_{i_{n\neq x}=1}^{I_{n\neq x}} fss_{i_{n\neq x},j_{n=x}} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} fes_{e_{n=x_t},j_{n=x}} + \sum_{e_{n\neq x_t}=1}^{E_{n\neq x_t}} fes_{e_{n\neq x_t},j_{n=x}} + \sum_{r_t=1}^{R_t} fis_{r_t,j_{n=x}} + \sum_{z_{n=x}=1}^{Z_{n=x}} fzs_{z_{n=x},j_{n=x}} + \sum_{z_{n\neq x}=1}^{z_{n\neq x}} fzs_{z_{n\neq x},j_{n=x}} + \sum_{z=1}^{Z} fzs_{z,j_{n=x}}\,, \; j_{n=x} \in J_{n=x} \tag{3}$$

The total flowrate $FU_{j_{n=x}}$ received by each process sink at network $n = x$ and its pollutant concentration $cu_{j_{n=x},l}$ are restricted to a maximum allowable flowrate capacity, associated with each sink. The flowrate capacity constraints are provided by Equation (3). While Equation (4) details the pollutant concentration constraint for each sink, where $cw_{w,l}$ is the fresh water pollutant concentration, $cs_{i_{n=x},l}$ is the process sources pollutant concentration at the same network $n = x$, $cs_{i_{n\neq x},l}$ is the process sources pollutant concentration at other networks $n \neq x$, $ce^{out}_{e_{n=x_t},l}$ is the outlet pollutant concentration of end of pipe treatment of stage t at the same network $n = x$, $ce^{out}_{e_{n\neq x_t},l}$ is the outlet pollutant concentration of end of pipe treatment of stage t at other networks $n \neq x$, $ci^{out}_{r_t,l}$ is the outlet pollutant concentration of stage t of the centralized treatment, $ci^{out}_{z_{n=x},l}$ is the outlet pollutant concentration of the decentralized ZLD system at the same network $n = x$, $ci^{out}_{z_{n\neq x},l}$ is the outlet pollutant concentration of the decentralized ZLD system at other networks $n \neq x$ and $ci^{out}_{z,l}$ is the outlet pollutant concentration of the centralized ZLD system.

$$\sum_{w=1}^{W} cw_{w,l} \;\; fws_{w,j_{n=x}} +$$

$$\sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l} \;\; fss_{i_{n=x},j_{n=x}} + \sum_{i_{n\neq x}=1}^{I_{n\neq x}} cs_{i_{n\neq x},l} \;\; fss_{i_{n\neq x},j_{n=x}} +$$

$$\sum_{e_{n=x_t}=1}^{E_{n=x_t}} ce^{out}_{e_{n=x_t},l} \; fes_{e_{n=x_t},j_{n=x}} + \sum_{e_{n\neq x_t}=1}^{E_{n\neq x_t}} ce^{out}_{e_{n\neq x_t},l} \;\; fes_{e_{n\neq x_t},j_{n=x}} +$$

$$\sum_{r_t=1}^{R_t} ci^{out}_{r_t,l} \;\; fis_{r_t,j_{n=x}} + \sum_{z_{n=x}=1}^{Z_{n=x}} ci^{out}_{z_{n=x_i},l} \;\; fzs_{z_{n=x},j_{n=x}} \; +$$

$$\sum_{z_{n\neq x}=1}^{Z_{n\neq x}} ci_{z_{n\neq x},l}^{out} \quad fzs_{z_{n\neq x},j_{n=x}} + \sum_{z=1}^{Z} ci_{z,l}^{out} \quad fzs_{z,j_{n=x}} \leq$$

$$cu_{j_{n=x},l} FU_{j_{n=x}} \qquad j_{n=x} \in J_{n=x} \ ; \quad l \in L \tag{4}$$

4. Mass balance in the interceptors of local decentralized treatment for each plant (network): The local decentralized treatment systems are formulated in to series of treatment stages. It is assumed that the first stages are the existing ones that allow wastewater streams to be treated to certain disposal limits that have been imposed while the following treatment stages could provide an additional treatment or substitute of the existing ones. The inlet flowrate to any decentralized treatment $FE_{e_{n=x_t}}$ stage t in a network $n = x$ equals all flowrates from process sources at the same network, flowrates from process sources at other networks and from decentralized treatment stage $t - 1$.

$$FE_{e_{n=x_t}} = \sum_{i_{n=x}=1}^{I_{n=x}} fse_{i_{n=x},e_{n=x_t}} + \sum_{i_{n\neq x}=1}^{I_{n\neq x}} fse_{i_{n\neq x},e_{n=x_t}} +$$

$$\sum_{e_{n=x_{t-1}}=1}^{E_{n=x_{t-1}}} fee_{e_{n=x_{t-1}},e_{e_{n=x_t}}}, \quad e_{n=x_{t=y}} \in E_{n=x_{t=y}} \tag{5}$$

Equation (6) provides the pollutants concentration balance of the inlet concentrations.

$$ce_{e_{n=x_t},l}^{in} FE_{e_{n=x_t}} = \sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l} \quad fse_{i_{n=x},e_{n=x_t}} +$$

$$\sum_{i_{n\neq x}=1}^{I_{n\neq x}} cs_{i_{n\neq x},l} \quad fse_{i_{n\neq x},e_{n=x_t}} +$$

$$\sum_{e_{n=x_{t-1}}=1}^{E_{n=x_{t-1}}} ce_{e_{n=x_{t-1}},l}^{out} \quad fee_{e_{n=x_{t-1}},e_{e_{n=x_t}}}, \qquad l \in L; \quad i_{n=x} \in I_{n=x}; \ e_{n=x_{t=y}} \in$$

$$E_{n=x_{t=y}} \tag{6}$$

Where $ce^{out}_{e_{n=x_{t-1}},l}$ is the given outlet pollutant concentration of decentralized treatment of stage $t-1$ at the same network $n=x$, while $ce^{in}_{e_{n=x_t},l}$ is the variable inlet pollutant concentration to the decentralized treatment of stage t and it is constrained with a specified upper $ce^{in,max}_{e_{n=x_t},l}$ and lower $ce^{in,min}_{e_{n=x_t},l}$ inlet concentrations limits for various decentralized treatment options as following:

$$ce^{in,max}_{e_{n=x_t},l} \ll ce^{in}_{e_{n=x_t},l} \ll ce^{in,min}_{e_{n=x_t},l} \qquad (7)$$

5. Flowrates distribution in the interceptors of decentralized treatment: The presented formulation takes into account two types of treatments, the treatment with single outlet treated effluent and the treatment with two outlet effluents, treated effluent and concentrated effluent.

   The treated effluent from decentralized treatment stage t at a network $n=x$, which is equal to the inlet flowrate to treatment times percentage recovery $PR_{e_{n=x_t}}$ of raw effluent, can be divided and utilized in process sinks $fes_{e_{n=x_t},j_{n=x}}$ at the same network $n=x$, utilized in process sinks $fes_{e_{n=x_t},j_{n\neq x}}$ at other networks $n\neq x$, sent to decentralized treatment $fes_{e_{n=x_t},e_{n=x_{t+1}}}$ stage $t+1$ at the same network $n=x$, sent to centralized treatment $fei_{e_{n=x_t},r_t}$ stage t, utilized for beneficial uses $feb_{e_{n=x_t},b}$ and/or discharge to environment $fed_{e_{n=x_t},d}$.

$$FE_{e_{n=x_t}}\,PR_{e_{n=x_t}} = \sum_{j_{n=x}=1}^{J_{n=x}} fes_{e_{n=x_t},j_{n=x}} + \sum_{j_{n\neq x}=1}^{J_{n\neq x}} fes_{e_{n=x_t},j_{n\neq x}} + \sum_{e_{n=x_{t+1}}=1}^{E_{n=x_{t+1}}} fee_{e_{n=x_t},e_{n=x_{t+1}}} + \sum_{r_t=1}^{R_t} fei_{e_{n=x_t},r_t} + \sum_{b=1}^{B} feb_{e_{n=x_t},b} + \sum_{d=1}^{D} fed_{e_{n=x_t},d}, \quad e_{n=x_t}\in E_{n=x_t} \qquad (8)$$

In order to reduce the computational load a little bit for obtaining the solution, recycling between various treatment stages are not allowed.

The concentrated effluent from decentralized treatment $FE_{e_{n=x_{t_C}}}$ stage t at a network $n = x$ is formulated to be sent to decentralized ZLD system $fez_{e_{n=x_{t_C}},z_{n=x}}$ at the same network $n = x$, sent to decentralized ZLD system $fez_{e_{n=x_{t_C}},z_{n\neq x}}$ at other networks $n \neq x$, sent to centralized ZLD system $fez_{e_{n=x_{t_C}},z}$, sent to evaporation pond $fev_{e_{n=x_{t_C}},v}$ stage t, and/or discharge to environment $fed_{e_{n=x_{t_C}},d}$.

$$FE_{e_{n=x_{t_C}}} = FE_{e_{n=x_t}} \left(1 - PR_{e_{n=x_t}}\right) = \sum_{z_{n=x}=1}^{Z_{n=x}} fez_{e_{n=x_{t_C}},z_{n=x}} + \sum_{z_{n\neq x}=1}^{z_{n\neq x}} fez_{e_{n=x_{t_C}},z_{n\neq x}} + \sum_{z=1}^{Z} fez_{e_{n=x_{t_C}},z} + \sum_{v=1}^{V} fev_{e_{n=x_{t_C}},v} + \sum_{d=1}^{D} fed_{e_{n=x_{t_C}},d}, \quad e_{n=x_{t_C}} \in E_{n=x_{t_C}} \tag{9}$$

6. Interceptor balances of local decentralized treatment: Given the discharge concentration for the end-of-pipe effluent after treatment at any stage, $ce^{out}_{e_{n=x_t},l}$ and the treatment percentage recovery $PR_{e_{n=x_t}}$, the contaminant load can be calculated by Equation (10) and the discharge concentration for the concentrated end-of-pipe effluent $ce^{out}_{e_{n=x_{t_C}},l}$ can be calculated by Equation (11) where treatment inlet concentrations $ce^{out}_{e_{n=x_t},l}$ are variables.

$$cim_{e_{n=x_t},l} = (ce^{in}_{e_{n=x_t},l} - ce^{out}_{e_{n=x_t},l})FE_{e_{n=x_t}}, \quad e_{n=x_t} \in E_{n=x_t}; \;\; l \in L \tag{10}$$

$$ci^{out}_{e_{n=x_{t_C}},l} = \frac{(ce^{in}_{e_{n=x_t},l} - PR_{e_{n=x_t}} \;\; ce^{out}_{e_{n=x_t},l})}{\left(1 - PR_{e_{n=x_t}}\right)} \tag{11}$$

7. Mass balance in the centralized treatment: Centralized treatment is formulated in a smeller way to the decentralized decentralized treatment. It consist of several stages, where each stage uses same or different treatment process to remove or reduce the concentration of different pollutants in the water streams. The flowrate to the centralized treatment FI_{r_t} stage t is a combination of flowrates from process sources $fsi_{i_{n=x},r_t}$ at a network $n = x$ from decentralized treatment $fei_{e_{n=x_t},r_t}$ at network $n = x$ and/or from centralized treatment fii_{r_{t-1},r_t} stage $t - 1$.

$$FI_{r_t} = \sum_{i_{n=x}=1}^{I_{n=x}} fsi_{i_{n=x},r_t} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} fei_{e_{n=x_t},r_t} + \sum_{r_{t-1}=1}^{R_{t-1}} fii_{r_{t-1},r_t}, \quad r_t \in R_t \tag{12}$$

To estimate the inlet pollutants concentrations variable $ci_{r_t,l}^{in}$ at any treatment stage t of the centralized treatment, a component balance shown in Equation (13) is needed.

$$ci_{r_t,l}^{in} FI_{r_t} = \sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l} fsi_{i_{n=x},r_t} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} ce_{e_{n=x_t},l}^{out} fei_{e_{n=x_{t=y}},r_t} + \sum_{r_{t-1}=1}^{R_{t-1}} ci_{r_{t-1},l}^{out} \; fii_{r_{t-1},r_t}, \quad l \in L; \quad r_{t=1} \in R_{t=1} \tag{13}$$

Where, $cs_{i_{n=x},l}$ is the process sources pollutant concentration at network $n = x$ and $ce_{e_{n=x_t},l}^{out}$ is the outlet pollutant concentration of decentralized treatment at network $n = x$. while $ci_{r_t,l}^{in}$ is the variable inlet pollutant concentration to the centralized treatment of stage t and it is constrained with a specified upper $ci_{r_t,l}^{in,max}$ and lower $ci_{r_t,l}^{in,min}$ inlet concentrations limits for various centralized treatment options as following:

$$ci_{r_t,l}^{in,max} \ll ci_{r_t,l}^{in} \ll ci_{r_t,l}^{in,min} \quad (14)$$

8. Flowrate distribution in the centralized treatment interceptors: Similarly to decentralized treatment, the presented formulation takes into account two types of treatments, the treatment with single outlet treated effluent, and the treatment with two outlet effluents, treated effluent and concentrated effluent. The outlet treated effluent from any treatment stage at the centralized treatment can be divided and utilized in process sinks $fis_{r_t,j_{n=x}}$ at any network $n = x$, sent to centralized treatment $fii_{r_t,r_{t+1}}$ stage $t + 1$, utilized for beneficial uses $feb_{e_{n=x_t},b}$, and/or discharge to environment $fid_{r_{t_C},d}$.

$$FI_{r_t}\, PR_{r_t} = \sum_{j_{n=x}=1}^{J_{n=x}} fis_{r_t,j_{n=x}} + \sum_{r_{t+1}=1}^{R_{t+1}} fii_{r_t,r_{t+1}} + \sum_{b=1}^{B} fib_{r_t,b} + \sum_{d=1}^{D} fid_{r_t,d}, \quad r_t \in R_t \quad (15)$$

Where PR_{r_t} is a given the treatment percentage recovery for treatment stage t. In order to reduce the computational load a little bit for obtaining the solution, recycling between various treatment stages are not allowed.

The concentrated effluent from the centralized treatment $FI_{r_{t_C}}$stage t is formulated to be sent to centralized ZLD system $fiz_{r_{t_C},z}$, sent to evaporation pond $fiv_{r_{t_C},v}$ stage t, and/or discharge to environment $fid_{r_{t_C},d}$.

$$FI_{r_{t_C}} = FI_{r_t}\left(1 - PR_{r_t}\right) = \sum_{z=1}^{Z} fiz_{r_{t_C},z} + \sum_{v=1}^{V} fiv_{r_{t_C},v} + \sum_{d=1}^{D} fid_{r_{t_C},d}, \quad r_{t_C} \in R_{t_C} \quad (16)$$

9. Centralized treatment interceptor balances: Given the discharge concentration for the centralized treatment effluent after treatment at any stage, $ci_{r_t,l}^{out}$ and the treatment percentage recovery PR_{r_t}, the load of each treatment stage $cim_{r_t,l}$ can be obtained through Equation (17). While the discharge concentration for the centralized treatment concentrated effluent $ci_{r_{t_C},l}^{out}$ can be calculated by Equation (18) where treatment inlet concentrations $ci_{r_t,l}^{in}$ are variables.

$$cim_{r_t,l} = (ci_{r_t,l}^{in} - ci_{r_t,l}^{out})FI_{r_t}, \quad r_t \in R_t;\ t \in T\ ;\ \ l \in L \tag{17}$$

$$ci_{r_{t_C},l}^{out} = \frac{(ci_{r_t,l}^{in} - PR_{r_t}\ \ ci_{r_t,l}^{out})}{(1 - PR_{r_t})} \tag{18}$$

10. Mass balance for Decentralized ZLD system: With the assumption of ZLD system is capable of removing or reducing the contaminants concentration to desired level $ci_{z_{n=x},l}^{out}$. The ZLD system is designed to accept flow from process sources $fsz_{i_{n=x},z_{n=x}}$ at same network $n = x$, from process sources $fsz_{i_{n\neq x},z_{n=x}}$ at other networks $n = x$, from decentralized treatment concentrated effluent $fez_{e_{n=x_{t_C}},z_{n=x}}$ at the same network $n = x$ and/or from decentralized treatment concentrated effluent $fez_{e_{n\neq x_{t_C}},z_{n=x}}$ at other networks $n = x$.

11. $FZ_{z_{n=x}} = \sum_{i_{n=x}=1}^{I_{n=x}} fsz_{i_{n=x},z_{n=x}} + \sum_{i_{n\neq x}=1}^{I_{n\neq x}} fsz_{i_{n\neq x},z_{n=x}} +$

$$\sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} fez_{e_{n=x_{t_C}},z_{n=x}} + \sum_{e_{n\neq x_{t_C}}=1}^{E_{n\neq x_{t_C}}} fez_{e_{n\neq x_{t_C}},z_{n=x}}, \qquad z_{n=x} \in Z_{n=x} \tag{19}$$

The inlet pollutants concentration constraint can be determined by the following equations:

$$cz^{in}_{z_{n=x},l}\ FZ_{z_{n=x}} = \sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l}\ \ fsz_{i_{n=x},z_{n=x}} + \sum_{i_{n\neq x}=1}^{I_{n\neq x}} cs_{i_{n\neq x},l}\ \ fsz_{i_{n\neq x},z_{n=x}} + \sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} ce^{out}_{e_{n=x_{t_C}},l} fez_{e_{n=x_{t_C}},z_{n=x}} + \sum_{e_{n\neq x_{t_C}}=1}^{E_{n\neq x_{t_C}}} ce^{out}_{e_{n\neq x_{t_C}},l} fez_{e_{n\neq x_{t_C}},z_{n=x}}\ , l \in L \tag{20}$$

$$cz^{in,max}_{z_{n=x},l} \ll cz^{in}_{z_{n=x},l} \ll cz^{in,min}_{z_{n=x},l} \tag{21}$$

12. Flowrate distribution in the Decentralized ZLD system: The treated effluent from decentralized ZLD system at network $n = x$, which is equal to the raw effluent processed in ZLD system times percentage recovery $PR_{z_{n=x}}$ of raw effluent, can be segregated and utilized in process sinks $fzs_{z_{n=x},j_{n=x}}$ at the same network $n = x$, utilized in process sinks $fzs_{z_{n=x},j_{n\neq x}}$ at other networks $n \neq x$, and/or utilized for beneficial uses $fzb_{z_{n=x},b}$.

$$PR_{z_{n=x}}\ \ FZ_{z_{n=x}} = \sum_{j_{n=x}=1}^{j_{n=x}} fzs_{z_{n=x},j_{n=x}} + \sum_{j_{n\neq x}=1}^{j_{n\neq x}} fzs_{z_{n=x},j_{n\neq x}} + \sum_{b=1}^{B} fzb_{z_{n=x},b}\ , z_{n=x} \in Z_{n=x} \tag{22}$$

With given pollutants concentration $ci^{out}_{z_{n=x},l}$ in the recovered water stream from that particular ZLD system, the produced solids/sludge load can be calculated as following:

$$cim_{z_{n=x},l} = \sum_{z_{n=x}=1}^{Z_{n=x}} (cz^{in}_{z_{n=x},l} - ci^{out}_{z_{n=x},l}) FZ_{z_{n=x}}\ , \quad l \in L \tag{23}$$

13. Mass balance for Centralized ZLD system: Centralized ZLD system has formulated in quite similar way to the decentralized ZLD system where it is designed to accept flow from process sources $fsz_{i_{n=x},z}$ at any network $n = x$, from decentralized treatment concentrated effluent $fez_{e_{n=x_{t_C}},z}$ of stage t at any

network $n = x$ and/or from treatment concentrated effluent of stage t at the centralized treatment $fiz_{r_{t_C},z}$.

$$FZ_z = \sum_{i_{n=x}=1}^{I_{n=x}} fsz_{i_{n=x},z} + \sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} fez_{e_{n=x_{t_C}},z} + \sum_{r_{t_C}=1}^{R_{t_C}} fiz_{r_{t_C},z}\,, \qquad z \in Z \tag{24}$$

The inlet pollutants concentration constraint can be determined by the following equation:

$$cz_{z,l}^{in}\, FZ_z \;=\; \sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l}\;\; fsz_{i_{n=x},z} + \sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} ce_{e_{n=x_{t_C}},l}^{out} fez_{e_{n=x_{t_C}},z} + \sum_{r_{t_C}=1}^{R_{t_C}} ci_{r_{t_C},l}^{out}\;\; fiz_{r_{t_C},z}\,, \qquad l \in L \tag{25}$$

$$cz_{z,l}^{in} \ll cz_{z,l}^{in} \ll cz_{z,l}^{in} \tag{26}$$

14. Flowrate distribution in the interceptors of the Centralized ZLD system: The treated effluent from centralized ZLD system can be segregated and directed to process sinks $fzs_{z,j_{n=x}}$ at any network $n = x$, and/or utilized for beneficial uses $fzb_{z_{n=x},b}$.

$$PR_z \;\; FZ_z = \sum_{j_{n=x}=1}^{j_{n=x}} fzs_{z,j_{n=x}} + \sum_{b=1}^{B} fzb_{z,b}\,, \quad z_{n=x} \in Z_{n=x} \tag{27}$$

Where PR_z is centralized ZLD system percentage recovery of raw effluent. With given pollutants concentration $ci_{z,l}^{out}$ in the recovered water stream from that particular ZLD system, the produced solids/sludge load can be calculated as following:

$$cim_{z,l} \;= \sum_{z=1}^{Z} (cz_{z,l}^{in} - ci_{z,l}^{out}) FZ_{z_{n=x}}\,, \quad l \in L \tag{28}$$

15. Mass balance for Beneficial Uses: Beneficial usage of water is introduced in this model to act as an additional sink for extra water to be used beneficial in industrial and/or urban sector such as water for cooling towers and for irrigation, respectively. Equation (29) shows the possible sources of water that can be supplied to beneficial uses, while Equation (30) represents the pollutants concentration constraint of the inlet flowrate to beneficial uses.

$$FB_b = \sum_{i_{n=x}=1}^{I_{n=x}} fsb_{i_{n=x},b} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} feb_{e_{n=x_t},b} + \sum_{r_t=1}^{R_t} fib_{r_t,b} + \sum_{z_{n=x}=1}^{Z_{n=x}} fzb_{z_{n=x},b} + \sum_{z=1}^{Z} fzb_{z,b}\,, \quad b \in \mathrm{B} \tag{29}$$

$$cb_{b,l}^{in}\ FB_b \leq \sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l}\ \ fsb_{i_{n=x},b} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} ce_{e_{n=x_t},l}^{out}\ feb_{e_{n=x_t},b} + \sum_{r_t=1}^{R_t} ci_{r_t,l}^{out}\ fib_{r_t,b} + \sum_{z_{n=x}=1}^{Z_{n=x}} ci_{z_{n=x},l}^{out}\ \ fzb_{z_{n=x},b} + \sum_{z=1}^{Z} ci_{z,l}^{out}\ \ fzb_{z,b}\,, \quad b \in \mathrm{B} \tag{30}$$

16. Mass balance in the mixer prior to Evaporation Ponds: Evaporation pond has been considered in this work to act as an alternative option to the thermal processing of liquids to solids through the centralized and decentralized ZLD systems. Equation (31) shows the possible sources of water that can be supplied to evaporation ponds, while Equation (32) and (33) represents the pollutants concentration constraint of the inlet flowrate to evaporation pond if needed.

$$FV_v = \sum_{i_{n=x}=1}^{I_{n=x}} fsv_{i_{n=x},v} + \sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} fev_{e_{n=x_{t_C}},v} + \sum_{r_{t_C}=1}^{R_{t_C}} fiv_{r_{t_C},v} \quad v \in \mathrm{V} \tag{31}$$

$$cv_{v,l}^{in}\ FV_v \leq \sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l}\ fsv_{i_{n=x},v} + \sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} ce_{e_{n=x_t},l}^{out}\ fev_{e_{n=x_{t_C}},v} +$$

$$\sum_{r_{t_C}=1}^{R_{t_C}} ci_{t_C,l}^{out}\ fiv_{r_{t_C},v} \quad v \in \mathrm{V} \tag{32}$$

$$cv_{v,l}^{in} \ll cz_{z,l}^{in,max} \quad v \in \mathrm{V} \tag{33}$$

17. Mass balance for wastewater discharged to environment: Although the main purpose of this work is to eliminate the wastewater discharged to the environment, or to sea as in the scope of this work, the discharged to the environment option has still been considered in the presented formulation to give a better understanding for the cost variation as approaching to the ZLD goal. Possible sources of water that can be supplied to evaporation pond and the pollutants concentration constraint of the inlet flowrate to evaporation pond as follows.

$$FD_d = \sum_{i_{n=x}=1}^{I_{n=x}} fsd_{i_{n=x},d} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} fed_{e_{n=x_t},d} + \sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} fed_{e_{n=x_{t_C}},d} +$$

$$\sum_{r_t=1}^{R_t} fid_{r_t,d} + \sum_{r_{t_C}=1}^{R_{t_C}} fid_{r_{t_C},d} \quad v \in \mathrm{V} \tag{34}$$

$$cd_{d,l}^{in}\ FD_d \leq \sum_{i_{n=x}=1}^{I_{n=x}} cs_{i_{n=x},l}\ fsd_{i_{n=x},d} + \sum_{e_{n=x_t}=1}^{E_{n=x_t}} ce_{e_{n=x_t},l}^{out}\ fed_{e_{n=x_t},d} +$$

$$\sum_{e_{n=x_{t_C}}=1}^{E_{n=x_{t_C}}} ce_{e_{n=x_{t_C}},l}^{out}\ fed_{e_{n=x_{t_C}},d} + \sum_{r_t=1}^{R_t} ci_{t,l}^{out}\ fid_{r_t,d} +$$

$$\sum_{r_{t_C}=1}^{R_{t_C}} ci_{t_C,l}^{out}\ fid_{r_{t_C},d}\,, \quad v \in \mathrm{V} \tag{35}$$

18. Existence of connecting pipes: The determination of the existence of pipeline connections between various sources and sinks is determined through Equation (36).

$$fNM_{\mathrm{n,m}} - M_{fNM_{\mathrm{n,m}}}^{max} x_{\mathrm{n,m}} \leq 0\,, \qquad n \in \mathrm{N}\,;\ m \in \mathrm{M} \tag{36}$$

where $x_{\mathrm{n,m}}$ is a general binary variable term to describe the existence of pipeline between fresh water sources, process sources, process sinks, decentralized treatment, centralized treatment, centralized and decentralized ZLD system beneficial uses sinks, evaporation pond and discharge to environment while $M_{fNM_{\mathrm{n,m}}}^{max}$ is the corresponded flowrate upper boundaries.

19. Feasibility of flows: All flows that are not included in the proposed superstructure are set to zero. An example of such flows is $fes_{e_{n=x_{t_C}},j_{n=x}}$ the flow from the decentralized treatment concentrated stream at stage t in network $\mathrm{n} = \mathrm{x}$ to process sink at network $\mathrm{n} = \mathrm{x}$.

20. Objective function: The objective function in this work is minimization of the total annual cost, TAC, which consist of fresh water annual cost, WC, decentralized treatment annual cost, EC, centralized regeneration (treatment) annual cost, RC, centralized ZLD system annual cost, ZC_C, decentralized ZLD system annual cost, ZC_D, beneficial usage annual cost, BC, evaporation pond annual cost, VC, and piping annual cost, PC.

$$Minimize\ TAC \tag{37}$$

$$TAC = WC + EC + RC + ZC_C + ZC_D + BC + VC + PC \tag{38}$$

21. Fresh water annual cost (WC): The fresh water cost is determined through the following equation:

$$WC = Hy \sum_{w=1}^{W} \sum_{j_{n=x}=1}^{J_{n=x}} CUW_w\, fws_{w,j_{n=x}} \tag{39}$$

Where Hy is the plant operating hours per year, and CUW_w is unit cost of fresh water per ton.

22. Decentralized treatment annual cost (EC): The annual cost has been formulated to account for the capital cost and operating cost. The capital cost $CAPEX_{E_{n=x_t}}$ is a linear function based on the size of inlet flow to treatment while the operating cost has formulated to be either as a function of mass removed of contaminants $OPEX_{E_{n=x_{t_m}}}$ or as a function of flow size that goes into the treatment $OPEX_{E_{n=x_{t_f}}}$ as shown in the following equation,

$$EC = \sum_{e_{n=x_t}=1}^{E_{n=x_t}} \left(CAPEX_{e_{n=x_t}} AF_{e_{n=x_t}} + OPEX_{E_{n=x_{t_m}}} x_{e_{n=x_t}} + OPEX_{E_{n=x_{t_f}}} \left(1 - x_{e_{n=x_t}}\right)\right), \; e_{n=x_t} \in E_{n=x_t} \tag{40}$$

$$CAPEX_{E_{n=x_t}} = CU_{e_{n=x_t}} FE_{e_{n=x_t}} + y_{e_{n=x_t}} \tag{41}$$

$$FE_{e_{n=x_t}} - M_{e_{n=x_t}}^{max} y_{e_{n=x_t}} \leq 0 \,, \; e_{n=x_t} \in E_{n=x_t} \tag{42}$$

$$OPEX_{E_{n=x_{t_m}}} = Hy \sum_{e_{n=x_t}=1}^{E_{n=x_t}} CUM_{e_{n=x_t}} \, cim_{e_{n=x_t},l} \,, \qquad e_{n=x_t} \in E_{n=x_t}; \quad l \in L \tag{43}$$

$$OPEX_{E_{n=x_{t_f}}} = Hy \, CUF_{e_{n=x_t}} \, FE_{e_{n=x_t}} \tag{44}$$

Where $CU_{e_{n=x_t}}$ is the capital unit cost per flow size for stage t of decentralized treatment in network $n = x$, $AF_{e_{n=x_t}}$ is the annualized factor for that treatment, $CUM_{e_{n=x_t}}$ is the operating unit cost per mass removed for that treatment, and $CUF_{e_{n=x_t}}$ is the operating unit cost per ton of flow enters that treatment,

$x_{e_{n=x_t}}$ is a manually adjusted binary input based on treatment techniques to define the operating cost and $y_{e_{n=x_t}}$ is a linear relationship interception for the capital cost. It is worth noting here that the capital cost for the existing treatment stages of the local decentralized treatment should not be considered as the facility already exist.

23. Centralized regeneration (treatment) annual cost (RC): The annual cost for centralized treatment is formulated in a similar way to that of decentralized treatment as follows,

$$RC = \sum_{r_t=1}^{R_t} \left(CAPEX_{r_t} \, AF_{r_t} + OPEX_{r_{t_m}} x_{r_t} + OPEX_{r_{t_f}} \left(1 - x_{r_t}\right) \right), \; r_t \in R_t \tag{45}$$

$$CAPEX_{r_t} = CU_{r_t} FI_{r_t} + y_{r_t} \tag{46}$$

$$FI_{r_t} - M_{r_t}^{max} y_{r_t} \leq 0 \,, \; r_t \in R_t \tag{47}$$

$$OPEX_{r_{t_m}} = Hy \sum_{r_t=1}^{R_t} CUM_{r_t} \, cim_{r_t,l} \,, \quad r_{n=x_t} \in R_t; \quad l \in L \tag{48}$$

$$OPEX_{r_{t_f}} = Hy \, CUF_{r_t} \, FI_{r_t} \tag{49}$$

24. Centralized and decentralized ZLD systems annual cost (ZC): Centralized and decentralized ZLD systems annual cost estimations is formulated in an identical manner, both involve capital and operating cost and are based on the size of inlet flow to the ZLD system. Equation (50) shows the centralized ZLD system annual cost and Equation (52) shows the decentralized ZLD systems annual cost,

$$ZC_C = \sum_{z=1}^{Z} (CU_z FE_z + y_z) \, AF_z + Hy \sum_{z=1}^{Z} CUF_z \; FZ_z, \quad z \in Z \tag{50}$$

$$FZ_z - M_z^{max} y_z \leq 0 \,, \; z \in Z \tag{51}$$

$$ZC_D = \sum_{z_{n=x}=1}^{Z_{n=x}} \left(CU_{z_{n=x}} FZ_{z_{n=x}} + y_{z_{n=x}}\right) AF_{z_{n=x}} +$$

$$Hy \sum_{z_{n=x}=1}^{Z_{n=x}} CUF_{z_{n=x}} \; FZ_{z_{n=x}}, \quad z_{n=x} \in Z_{n=x} \tag{52}$$

$$FZ_{z_{n=x}} - M_{z_{n=x}}^{max} y_{z_{n=x}} \leq 0 \,, \; z_{n=x} \in Z_{n=x} \tag{53}$$

Where in Equations (50) and (52), the first part corresponds to the capital cost and the second part corresponds to the operating cost.

25. Beneficial usage annual cost (BC): Since there are many ways to use the surplus treated water beneficially, such as water for cooling towers and for irrigation, the costing for beneficial usage is quite variable from case to case. The following is a general expression could be used to account for the beneficial usage capital and operating annual cost,

$$BC = \sum_{b=1}^{B} CU_b \, FE_b AF_b + Hy \sum_{b=1}^{B} CUF_b \, FE_b, \quad b \in B \tag{54}$$

26. Evaporation pond annual cost (VC): Evaporation pond costing is influenced generally by the required area for evaporation which can be roughly estimated through the following general expression [35],

$$REA = 0.000247105 \frac{FV_v - EEV}{EV - \Pr(1 - C_{EEV})} \tag{55}$$

Where REA is the required evaporation area, FV_v is the inlet flowrate to evaporation ponds, EV is the evaporation rate, Pr is the precipitation rate, EEV is the enhanced evaporation rate and C_{EEV} is the enhanced evaporation coefficient. However, the actual pond area cover the dike and contingency zones which could be counted too in the following expression,

$$TA = 1.25 * REA \tag{56}$$

Where TA is the total area for evaporation pond plus contingency factor. For evaporation pond with area range of 10 to 100 acres, the total unit area capital cost $TUACC$ is calculated as fallowing [36],

$$TUACC = 5406 + 465 * LT + 1.07 * LC + 0.931 * LCC + 217.5 * DH \quad (57)$$

Where LT is the liner thickness, LC is the land cost, LCC is the land clearance cost and DH is the dike height. Annual capital cost is then obtained through multiplying together these two expressions with the evaporation pond annualized factor.

$$VC = TUACC * TA * AF_v \quad (58)$$

27. Piping annual cost (PC): With the assumption of utilization of existing piping connections between freshwater sources and process sinks does not incur additional costs. The capital and operational Piping costs is determined by the general equation (59) and the detailed equation (60) which is developed based on [29, 32, 37] works which are linear approximations of Figures presented by [38] where the pipeline cross sectional area is based on flow size.

$$PC_{N,M} = D_{N,M} \sum_{n=1}^{N} \sum_{m=1}^{M} \frac{p \ fNM_{n,m}}{3600\rho v} + q \ x_{n,m} \ , \qquad n \in \mathrm{N} \ ; \ m \in \mathrm{M} \quad (59)$$

$$PC = AF_p \Big(PC_{i_{n=x},j_{n=x}} + PC_{i_{n=x},j_{n\neq x}} + PC_{i_{n=x},e_{n=x_t}} + PC_{i_{n=x},e_{n\neq x_t}} + PC_{i_{n=x},r_t} +$$

$$PC_{i_{n=x},z_{n=x}} + PC_{i_{n=x},z_{n\neq x}} + PC_{i_{n=x},z} + PC_{i_{n=x},v} + PC_{i_{n=x},b} + PC_{i_{n=x},d} +$$

$$PC_{e_{n=x_t},j_{n=x}} + PC_{e_{n=x_t},j_{n\neq x}} + PC_{e_{n=x_t},e_{n=x_{t+1}}} + PC_{e_{n=x_t},r_t} + PC_{e_{n=x_t},b} +$$

$$PC_{e_{n=x_t},d} + PC_{e_{n=x_{t_C}},z_{n=x}} + PC_{e_{n=x_{t_C}},z_{n\neq x}} + PC_{e_{n=x_{t_C}},z} + PC_{e_{n=x_{t_C}},v} +$$

$$PC_{e_{n=x_{t_C}},d} + PC_{r_t,j_{n=x}} + PC_{r_t,r_{t+1}} + PC_{r_t,b} + PC_{r_t,d} + PC_{r_t,z} + PC_{r_t,v} + PC_{r_{t_C},d} +$$

$$PC_{z_{n=x},j_{n=x}} + PC_{z_{n=x},j_{n\neq x}} + PC_{z_{n=x},b} + PC_{z,j_{n=x}} + PC_{z,b}\Big) \quad (60)$$

Where $PC_{N,M}$ is a general term to describe the pipeline cost for connections if exist between fresh water sources, process sources, process sinks, decentralized treatment, centralized treatment, centralized and decentralized ZLD system beneficial uses sinks, evaporation pond and discharge to environment, AF_p is an annualization factor, D is the length of the pipe connection between various types of sources and sinks, ρ is the water density, v is the velocity, q and p are cost parameter for cross plant pipeline, the slope and interception of linear approximation. Worth noting here that in many cases, evaporation pond is quite far away from the sources/treatment, which will lead to huge pipeline cost if it is associated for every stream that goes to evaporation pond. To avoid this, all streams could be directed first to an imaginary mixer where they get merge into one line and directed to evaporation pond. That could be implemented through the use of binary variable to account for existence of evaporation ponds option as shown in below equation.

$$FV_v - M_v^{max} y_v \leq 0\,,\ \ v \in V \quad (61)$$

With an objective of minimization of the total annual cost, Equation (37), the model will act as a decision-making tool for the selection of cost effective designs for interplant water allocation within industrial complexes.

3.3 Illustrative example

An illustrative case study has been carried out to show the implementation of the presented MINLP model. Overall, the aim is to identify optimum layout changes for a given industrial complex, that seeks the lowest total annual cost for retrofitting's and operations in order to be compliant with the new emerging constraint of ZLD to environment (sea). The model is implemented and solved using Lindo "What'sBest! Version 12.0 (32 Bit)" Global solver [39].

The analyzed case study shown in Figure 5 represent an industrial complex that consist of three different plants, each of which is associated with two different process sources and two different process sinks. Table 1 presents water flowrates passing through each plant, as well as the contaminant concentrations; three different contaminants are assumed in this case study.

It has been assumed that each of the industrial plants has its own local end-of-pipe treatment facility that is eventually capable to maintain all pollutant concentrations of the outlet stream below the imposed disposal limits. Therefore, the local end-of-pipe treatment facility has been considered as an existing treatment stage in the decentralized treatment at each of the corresponded plants. Where then, a number of treatment stages can be added to follow or replace the existing treatment stage at the decentralized treatment. Table 2 illustratively express the configuration and costing of the decentralized treatment. Each plant can have a number of treatment stages, where each stage can perform relatively different level of treatment (e.g. primary treatment stage, secondary treatment stage, etc.). Then, each stage can have a number of treatment options to be screened. These treatment

Table 1: Industrial complex case study data

Plant	Sources				
	Number	Flowrate (ton/h)	Contaminants concentration (ppm)		
			L 1	L 2	L 3
1	1	50	600	300	150
	2	70	300	250	100
2	3	80	500	150	70
	4	60	800	500	100
3	5	40	400	200	120
	6	55	1000	600	150
Plant	**Sinks**				
	Number	**Flowrate (ton/h)**	**Contaminants concentration (ppm)**		
			L 1	**L 2**	**L 3**
1	1	50	150	80	20
	2	70	60	40	15
2	3	80	40	30	25
	4	60	80	40	10
3	5	40	100	90	5
	6	55	150	100	30

options are associated with different recovery percentages, cost parameters and treatment performances. In similar way, Table 3 presents the treatment stages with their associated treatment options to be screened for the centralized treatment.

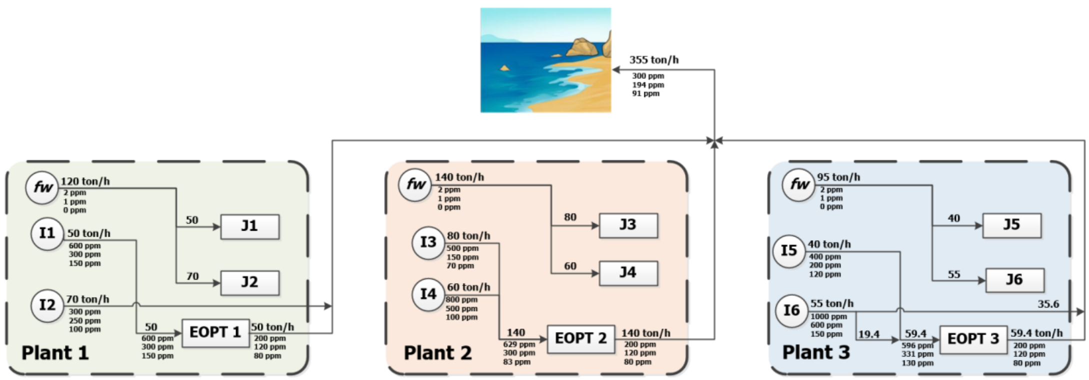

Figure 5: Industrial complex layout without inter-plant integration

It should be pointed out that the costing parameters for some treatment options listed in Table 2 and Table 3 are set up to be same as some earlier presented work, such as the case of the second option of the second stage of the decentralized treatment in all of the three plants. They all are set up to be similar to earlier presented work for reverse osmosis treatment [40]. While the costing of other treatment options are artificial and set up in a comparable way based on the treatment performance for the purpose of illustrating the usefulness of the developed model.

Table 2: Decentralized treatment Costing parameters

Plant	**Treatment options**	**Recovery (%)**	**Capital unit cost per flow size (US$/ton/h)**	**Operating unit cost per flow size (US$/ton)**	**Operating unit cost for mass removed of contaminant L (US$/kg)**		**Inlet Con. Constraint (ppm)**	**Outlet Con. (ppm)**
1	Stage 1 (Existing EOPT)	100	0	-	L 1	0.10	2000<C<200	200
					L 2	0.30	2000<C<150	150
					L 3	0.40	500<C<80	80
	Stage 2 (option 1)	95	20000	0.100	L 1	-	500<C<200	120
					L 2	-	500<C<150	110
					L 3	-	500<C<80	100
	Stage 2 (option 2)	95	31700	0.132	L 1	-	400<C<200	100
					L 2	-	400<C<150	80
					L 3	-	400<C<80	70

Table 2 Continued

Plant	**Treatment options**	**Recovery (%)**	**Capital unit cost per flow size (US$/ton/h)**	**Operating unit cost per flow size (US$/ton)**	**Operating unit cost for mass removed of contaminant L (US$/kg)**		**Inlet Con. Constraint (ppm)**	**Outlet Con. (ppm)**
2	Stage 1 (Existing EOPT)	100	0	-	L 1	0.12	2000<C<200	200
					L 2	0.25	2000<C<150	150
					L 3	0.30	500<C<80	80
	Stage 2 (option 1)	95	18000	0.150	L 1	-	500<C<200	120
					L 2	-	500<C<150	110
					L 3	-	500<C<80	100
	Stage 2 (option 2)	95	31700	0.132	L 1	-	400<C<200	100
					L 2	-	400<C<150	80
					L 3	-	400<C<80	70

Table 2 Continued

Plant	Treatment options	Recovery (%)	Capital unit cost per flow size (US$/ton/h)	Operating unit cost per flow size (US$/ton)	Operating unit cost for mass removed of contaminant L (US$/kg)		Inlet Con. Constraint (ppm)	Outlet Con. (ppm)
3	Stage 1 (Existing EOPT)	100	0	-	L 1	0.14	2000<C<200	200
					L 2	0.40	2000<C<150	150
					L 3	0.35	500<C<80	80
	Stage 2 (option 1)	95	22000	-	L 1	0.15	500<C<200	120
					L 2	0.25	500<C<150	110
					L 3	0.30	500<C<80	100
	Stage 2 (option 2)	95	31700	0.132	L 1	-	400<C<200	100
					L 2	-	400<C<150	80
					L 3	-	400<C<80	70

Table 3: Centralized treatment costing parameters

Treatment options	Recovery (%)	Capital unit cost per flow size (US$/ton/h)	Operating unit cost per flow size (US$/ton)	Operating unit cost for mass removed of contaminant L (US$/kg)		Inlet Con. Constraint (ppm)	Outlet Con. (ppm)
Stage 1 (option 1)	100	18000	-	L 1	0.12	2000<C<180	180
				L 2	0.30	2000<C<140	140
				L 3	0.30	2000<C<70	70
Stage 1 (option 2)	100	22000	-	L 1	0.14	2000<C<140	140
				L 2	0.40	2000<C<130	130
				L 3	0.35	200<C<80	80

Table 3 Continued

Treatment options	**Recovery (%)**	**Capital unit cost per flow size (US$/ton/h)**	**Operating unit cost per flow size (US$/ton)**	**Operating unit cost for mass removed of contaminant L (US$/kg)**		**Inlet Con. Constraint (ppm)**	**Outlet Con. (ppm)**
Stage 2 (option 1)	95	25000	0.125	L 1	-	500<C<120	120
				L 2	-	500<C<110	110
				L 3	-	500<C<80	80
Stage 2 (option 2)	95	30000	0.130	L 1	-	500<C<100	100
				L 2	-	500<C<80	80
				L 3	-	500<C<60	60

Zero liquid discharge options considered in this work include ZLD treatment systems, evaporation ponds and beneficial usage of treated wastewater. ZLD systems are end-of-pipe treatment systems that consist of brine concentrator and crystallizer. Table 4 displays the capital and operating costing associated with ZLD systems as reported in earlier work [40, 41],assuming that brine concentrator has a reject of 5 % and it get processed in a crystallizer. In addition, Table 4 present the assumed treatment performances and the recovery percentages for the centralized and decentralized ZLD systems.

Table 4: Centralized and Decentralized ZLD systems costing parameters.

ZLD System options	**Recovery (%)**	**Capital unit cost per flow size (US$/ton/h)**	**Operating unit cost per flow size (US$/ton)**	**Inlet Con. Constraint for of contaminant L (ppm)**		**Outlet Con. (ppm)**
Decentralized ZLD system	95	74500	1.1	L 1	40000<C<5	5
				L 2	40000<C<4	4
				L 3	40000<C<3	3
Centralized ZLD system	95	67050	1.1	L 1	40000<C<5	5
				L 2	40000<C<4	4
				L 3	40000<C<3	3

The second ZLD option considered in this work is the solar evaporation ponds, which is widely used method for removing water and recovering salts from a concentrate wastewater. However, salt recovery has not been analyzed in this work. For costing of evaporation ponds, a material with liner thickness of 60 mils and dike height of 8 feet are used [41]. A unit land cost of $0 per acre has been applied for different scenarios with land clearing costs of $1000 per acre. An estimated lake evaporation rate of 38 inches per year (1.207E-04 m^3/h) and precipitation rate of 8 inches per year (2.540E-05 m^3/h) have been used to estimate the number of evaporation ponds needed [35], with an area of 100 acres for a single pond. Inlet flows concentration constrains to evaporation ponds are presented in Table 5.

Table 5: Water qualities

Water Quality	**Contaminants concentration (ppm)**		
	L 1	**L 2**	**L 3**
Fresh Water	2	1	0
Treated water for irrigation	100	75	50
Wastewater to evaporation Pond	10000	8000	5000
Wastewater discharged to sea	300	200	100

The third ZLD option considered in this work is the beneficial usage of surplus treated wastewater. The cost for this option will vary depend on the applied practice. In the work, the surplus treated wastewater is used for irrigation. To evaluate and compare this option with others, the cost of installing lawn irrigation systems has been consider. The applied cost rate is 7.53 $\$/m^2$ of the irrigated area [42], which accounts for the material and manpower needed with the assumption of providing the lawn with one inch of water per week (1.51E-04 m/h) [43].

With the information provided above, the parameters Hy, v and ρ are 8000 h/year, 1m/s and 1000 kg/m3, respectively [32]. Pipeline costs is a linear approximation with $p = 4936.2$ and $q = 170.7$ for data presented in literature for carbon steel pipes, which covers the cost of pipes supply, installation and required fittings [37]. In addition, the resulted capital costs associated with all considered treatment options, ZLD option and piping have been annualized over ten years with annualized factor AF =0.117/year. The assumed distances for different connections between process sources, process sinks, treatment options and ZLD options are presented in Table 6.

Table 6: Lengths of the pipeline connections

Description	**Assumed distance (meters)**
Distance between all possible points within the same plant	100
Distance between all possible points and irrigation sink	100
Distance between all possible points across plants	500
Distance between all possible points and Evaporation ponds option	5000

Before any integration, Figure 5 presents the industrial complex with a discharge of 355 ton/h to sea. This case study has been cost wise evaluated in Table 7 for two different fresh water prices, 0.13 $/ton and 1.1 $/ton. The obvious cost difference between the two cases shown in Table 7 gives a first impression that minimizing liquid discharge to sea may not only be a regulatory requirement, but it may be a requirement for cost reduction in some cases where fresh water is expensive. Appendixes A and B shows the network connection configuration for case study A and B, respectively.

Table 7: Case study cost estimation for two different fresh water prices

Case study cost estimation	**A**	**B**
Fresh water price ($/ton)	0.13	1.1
Total Annual Cost ($/year)	601,558	3,356,358
Fresh water cost ($/year)	369,200	3,124,000
Existing treatment in plant 1 (EOPT) ($/year)	48,800	48,800
Existing treatment in plant 1 (EOPT) ($/year)	108,960	108,960

In the following sections, water reuse, recycle and ZLD options highlighted in this work have been implemented to achieve ZLD to sea in five different scenarios for the same industrial complex case study. The first scenario applies Inter-plant Water Integration only. The second scenario applies Inter-plant Water Integration with maximum discharge of 50 m^3/h to sea. The third scenario applies Inter-plant Water Integration with and all ZLD options to achive ZLD to sea. The forth scenario applies Inter-plant Water Integration with achieving ZLD to sea without the utilization of evaporation ponds option. The fifth scenario applies Inter-plant Water Integration with achieving ZLD to sea and consider the presence of highly polluted streams. Table 8 displays the detailed optimal cost estimations for the analyzed five scenarios where each scenario has been solved twice to account for both fresh water prices, 0.13 $/ton and 1.1 $/ton and refer to them with A and B characters in Table 8. Furthermore, Table 9 shows the total fresh water consumption, flow to irrigation, flow to evaporation ponds and water discharged to sea for the corresponded scenarios. Appendixes C to L shows the obtained network connections for all the developed scenarios (1-A to 5-A and 1-B to 5-B).

For the first three scenarios, the impact of implementing ZLD regulation is analyzed through applying no constraint, 50 ton/h constraint and 0 ton/h constraint on the water discharge to the sea for the first, second and third scenarios respectively, while allowing all other centralized and decentralized reuse, recycle and ZLD options. The obtained results are sketched in Figure 6. From the figure, it is quite clear that scenarios associated with low fresh water prices (1-A, 2-A and 3-A) are significantly affected by the enforcing of ZLD to sea constraint. While scenarios associated with high fresh water prices (1-B, 2-B and 3-B) are lightly affected as these scenarios from the start are consuming the least possible amounts of fresh water as shown in Table 9, and therefore the impact on those scenarios is minimal.

Table 8: Scenarios cost estimations

Scenarios		**1-A**	**1-B**	**2-A**	**2-B**	**3-A**	**3-B**	**4-A**	**4-B**	**5-A**	**5-B**
Fresh water price ($/ton)		0.13	1.1	0.13	1.1	0.13	1.1	0.13	1.1	0.13	1.1
Total Annual Cost ($/year)		504,904	1,755,971	1,269,527	1,755,971	1,477,258	1,769,296	1,755,433	1,878,643	2,169,073	2,228,145
Fresh water cost ($/year)		303,524	176,000	112,297	176,000	112,297	176,000	63,456	78,289	59,063	15,653
Treatment in plant 1 ($/year)	Stage 1 (EOPT)	51,184	48,800	43,225	48,800	25,923	48,800	69,283	49,962	70,994	69,210
	Stage 2 (option 1)	0	477,463	722,281	477,463	722,281	477,463	884,110	496,523	383,373	375,523
	Stage 2 (option 2)	0	0	0	0	0	0	0	0	0	0
Treatment in plant 2 ($/year)	Stage 1 (EOPT)	141,613	84,463	38,300	84,463	12,303	79,081	70,478	83,390	147,456	148,798
	Stage 2 (option 1)	0	0	0	0	0	0	0	0	422,093	63,533
	Stage 2 (option 2)	0	0	0	0	0	0	0	0	0	0
Treatment in plant 3 ($/year)	Stage 1 (EOPT)	0	3,536	0	3,536	0	3,536	0	3,536	85,523	88,582
	Stage 2 (option 1)	0	0	0	0	0	0	0	0	189,797	124,296
	Stage 2 (option 2)	0	107,165	0	107,165	0	107,165	0	107,165	0	157,794
Centralized treatment ($/year)	Stage 1 (option 1)	0	0	0	0	0	0	0	0	0	0
	Stage 1 (option 2)	0	0	0	0	0	0	0	0	0	0
	Stage 2 (option 1)	0	0	0	0	0	0	0	0	0	0
	Stage 2 (option 2)	0	722,708	0	722,708	0	722,708	172,649	699,882	0	514,755

Table 8: Continued

Scenarios		1-A	1-B	2-A	2-B	3-A	3-B	4-A	4-B	5-A	5-B
Decentralized ZLD systems ($/year)	System at Plant 1	0	0	0	0	0	0	246,481	138,426	106,881	104,692
	System at Plant 2	0	0	0	0	0	0	0	0	111,790	16,827
	System at Plant 3	0	0	0	0	0	0	0	19,687	400,541	403,214
Centralized ZLD system ($/year)		0	0	0	0	0	0	33,215	134,647	0	99,031
Beneficial use (irrigation) ($/year)		0	0	0	0	0	0	177,300	23,736	162,013	0
Evaporation ponds ($/year)		0	80,530	280,515	80,530	522,429	96,766	0	0	0	0
piping cost ($/year)		8,584	55,305	72,909	55,305	82,024	57,778	38,462	43,400	29,548	46,236

Table 9: Flows beyond the industrial complex for various scenarios

Scenarios	**1-A**	**1-B**	**2-A**	**2-B**	**3-A**	**3-B**	**4-A**	**4-B**	**5-A**	**5-B**
Fresh water (ton/h)	291.8	20.0	108.0	20.0	108.0	20.0	61.0	8.9	56.8	1.8
flow to irrigation (ton/h)	0	0	0	0	0	0	60.2	8.1	55.0	0
flow to Evaporation ponds (ton/h)	0	16.6	58.0	16.6	108.0	20.0	0	0	0	0
Waste discharge (ton/h)	291.8	3.4	50.0	3.4	0	0	0	0	0	0

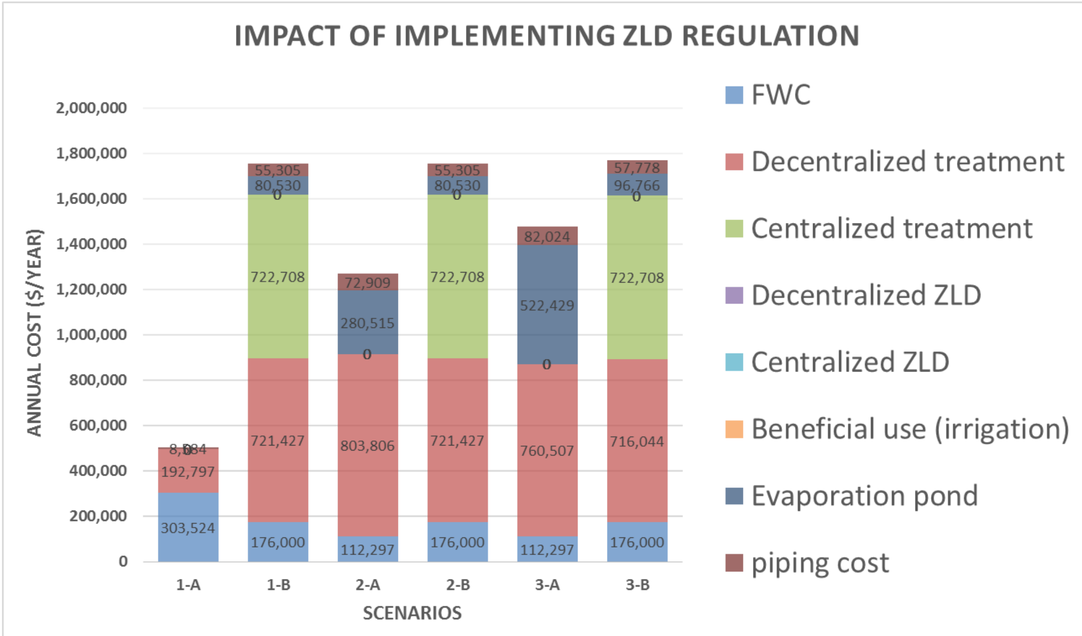

Figure 6: Impact of implementing ZLD regulation

It is observed from Figure 6, that as ZLD to sea constraint is applied, there is a rising trend for evaporation ponds as an alternative to discharge to sea. That is mainly because evaporation ponds option is designed in this work with relaxed inlet concentration constraints as shown in Table 5 and does not require the quality of treated water as the case for irrigation option. Scenarios 4-A and 4-B have been solved to see the impact on total annual cost for the case where evaporation pond is not considered as an option. Figure 7 compares scenarios 3 and 4, with and without evaporation ponds option respectively, and the results clearly shows the positive effect that evaporation ponds option will have in cutting some cost instead of spending considerable additional amounts for irrigation and ZLD treatment systems. In addition, scenario 4-A that is associated with lower fresh water cost trend to use surplus treated water in irrigation while scenario 4-B that is associated with higher fresh water cost trend to utilize the ZLD treatment system to recycle back water to process to minimize the purchase of additional quantities of fresh water in case surplus water is used for irrigation.

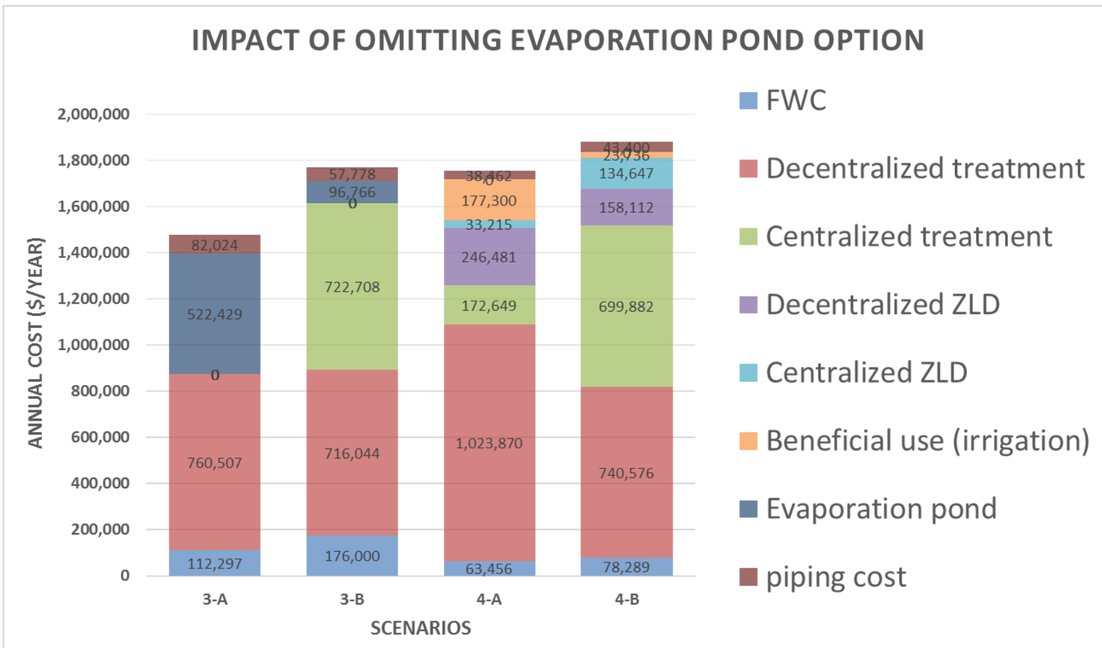

Figure 7: Impact of omitting evaporation pond option

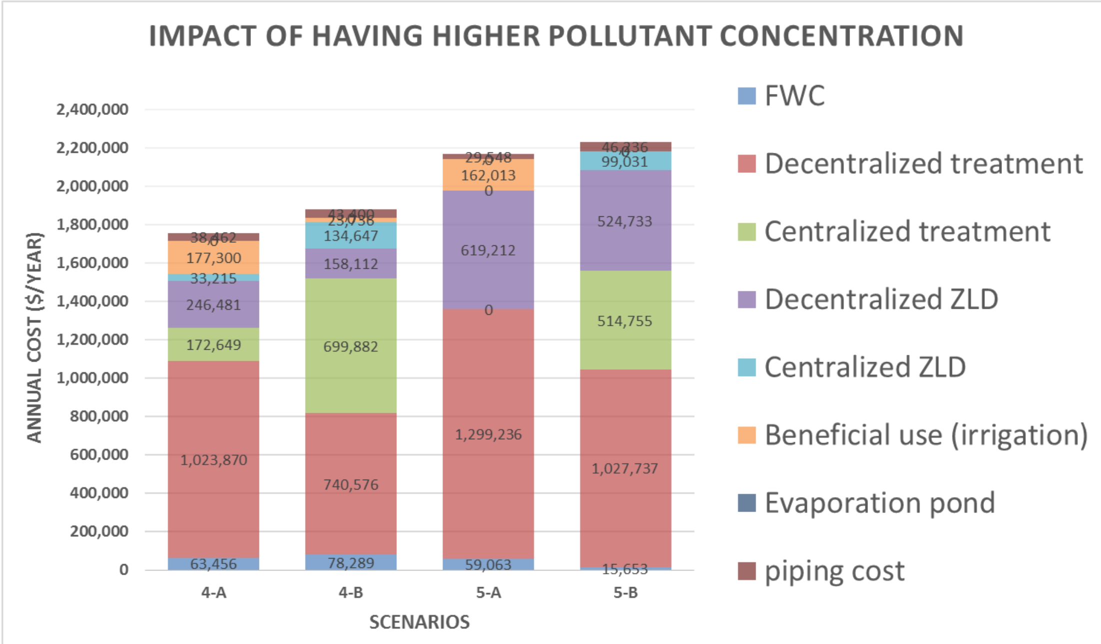

Figure 8: Impact of having higher pollutant concentration

A small change has been applied to the case study in scenario 5-A and 5-B to study the effect of having contaminants with very high concentrations, which are even higher than the maximum inlet concentration constrains for treatment options listed in Table 2 and Table 3. The modification has been made on the contaminant concentration L1 to be 5000 ppm instead of 1000 ppm for source 6 in plant 3 in the case study presented in Table 1. The results shows that this highly contaminated stream will be partially mix with other streams to lower its contamination level and being able to enter possible treatments options at their maximum inlet concentration, while the remain portion of that stream is then forced to be processed in the expensive ZLD treatment option. Figure 8 present the cost wise impact of having such highly polluted streams on the overall total annual cost. For the purpose of illustration, scenarios 4 and 5 does not consider evaporation ponds as an available option to have a representative picture to what extent ZLD systems are utilized in such cases.

Taking a look at the connectivity side after applying the proposed inter-plant integration methods on the studied case study, Figure 9 shows the industrial complex layout after applying Inter-Plant Integration (scenario 1-A). This scenario is associated with minimum total annual cost. Although in this scenario there is no constrain toward discharging to sea and the considered price of fresh water is relatively cheap, 0.13 $/ton, the discharge rate is reduced compared to the original case presented in Figure 5. The achieved cost saving and less discharging to sea are mainly due to the full utilization of the concept of reuse and recycle internally and externally across plants. Existing decentralized treatment options (EOPT) is utilized in plant 1 and plant 2 without the need for additional treatment stages at these plants. Furthermore, there is no need for using EOPT in plant 3, as it is associated with relatively higher operating cost as shown in Table 2.

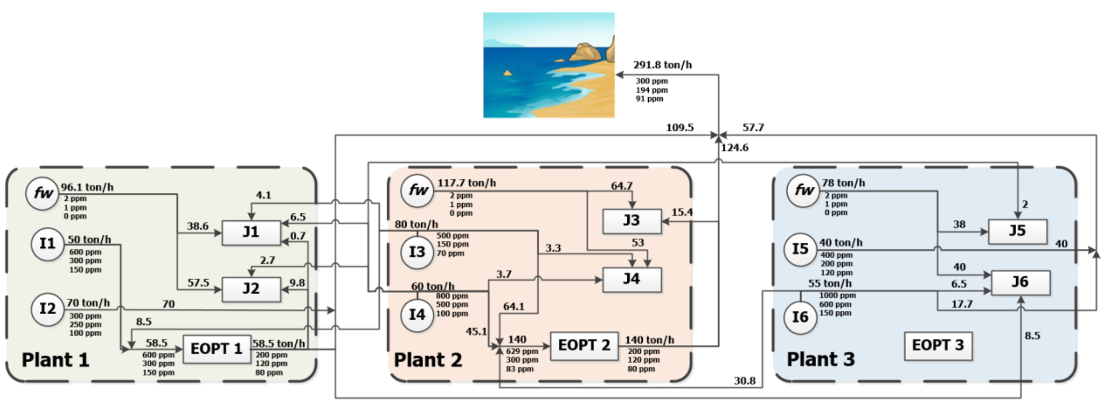

Figure 9: (Scenario 1-A) industrial complex layout with inter-plant integration without ZLD to sea constraint

Looking at more complicated layouts, scenario 4-B is presented in Figure 10. In this scenario, ZLD to sea constraint has been applied with enabling all proposed reuse, recycle and ZLD options except evaporation pond option. As shown in Figure 10, existing EOPT options is utilized in all plants. In addition, a second decentralized treatment stage is required in plant 1 and plant 3 accompanied by decentralized ZLD systems to treat the reject concentrated flows produced. For the centralized treatment, the stage 2 treatment option 2 is selected for this scenario together with centralized ZLD system. A small surplus quantities of treated water is utilized for irrigation purpose.

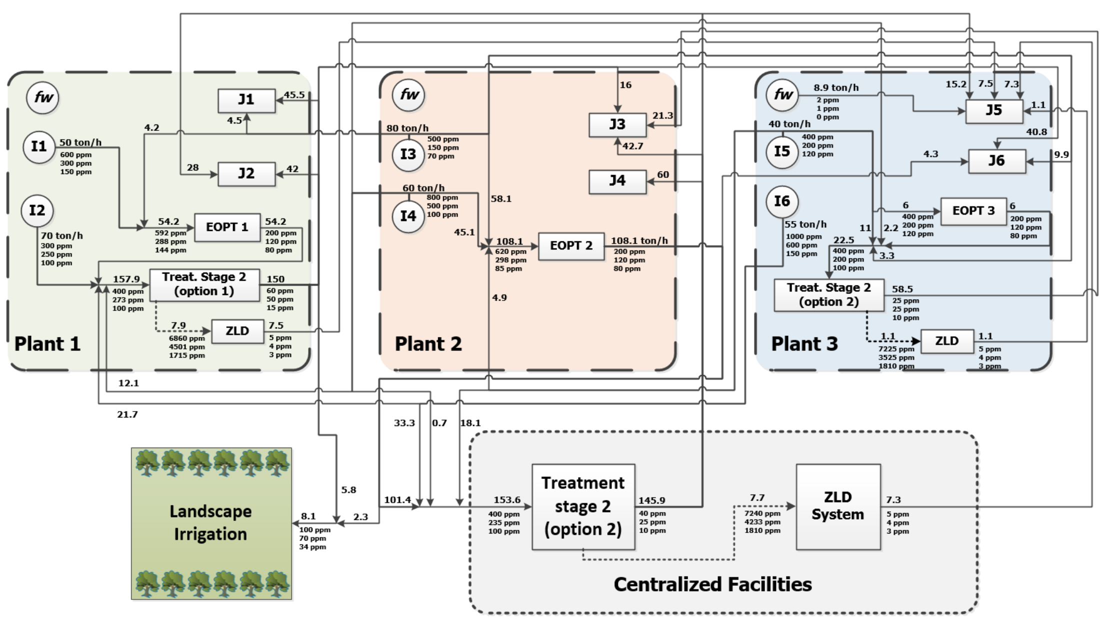

Figure 10: (Scenario 4-B) industrial complex layout with inter-plant integration with ZLD to sea constraint

4. CONCLUSION

This work presents the first approach to optimize water integration in industrial complexes to achieve ZLD to sea at minimum cost. The proposed model takes into account direct reuse of water across facilities, wastewater recycle in centralized and decentralized treatment and Zero liquid discharge options, that includes ZLD treatment systems, evaporation ponds and beneficial usage of treated wastewater. A case study of a small industrial complex consisting of three plants with three contaminants has been solved in a number of scenarios to demonstration the effectiveness of the proposed model. The main motivation has been to show the cost wise impact of implementing the regulation of ZLD to sea for scenarios where fresh water is expensive and for scenarios where fresh water is relatively cheap. It was found that when fresh water is available at low prices, there will be a significant cost impact as we approach toward the goal of ZLD to sea. While a minimal cost impact was observed for scenarios associated with higher fresh water prices, as these cases once inter-plant integration is implemented, they trend to consume the least possible amounts of fresh water in both cases, when ZLD regulation is strictly applied and when it is relaxed. Evaporation ponds option has been evaluated as a ZLD option and found that it will result in considerable cost saving as ZLD regulation is enforced, especially for scenarios associated with lower fresh water prices. Furthermore, it was found that highly contaminated streams will have great impact on cost as large portion of these streams will be forced to be processed in the expensive ZLD treatment systems. Future efforts will look into considering wastewater mains alongside with implementing the proposed model.

NOMENCLATURE

Concentrations

$cw_{w,l}$	Concentration of pollutant l from a source of the type of fresh water w (ppm)
$cs_{i_{n=x},l}$	Concentration of pollutant l from process source i at network $n = x$ (ppm)
$cs_{i_{n\neq x},l}$	Concentration of pollutant l from process source i at network $n \neq x$ (ppm)
$cu_{j_{n=x},l}$	Concentration of pollutant l to process sink j at network $n = x$ (ppm)
$ce^{in}_{e_{n=x_t},l}$	Inlet concentration of pollutant l to decentralized treatment e stage t at network $n = x$ (ppm)
$ce^{out}_{e_{n=x_t},l}$	Treated flow outlet concentration of pollutant l from decentralized treatment e stage t at network $n = x$ (ppm)
$ce^{out}_{e_{n=x_{t_C}},l}$	Concentrated flow outlet concentration of pollutant l from decentralized treatment e stage t at network $n = x$ (ppm)
$ci^{in}_{r_t,l}$	Inlet concentration of pollutant l to centralized treatment r_t stage t (ppm)
$ci^{out}_{r_t,l}$	Treated flow outlet concentration of pollutant l from stage t in centralized treatment $\mathrm{r_t}$ (ppm)

$ci_{r_{t_C},l}^{out}$ Concentrated flow outlet concentration of pollutant l from stage t in centralized treatment $\mathrm{r_t}$ (ppm)

$cz_{z_{n=x},l}^{in}$ Inlet concentration of pollutant l to decentralized ZLD system z at network $n = x$ (ppm)

$ci_{z_{n=x},l}^{out}$ Outlet concentration of pollutant l from decentralized ZLD system z at network $n = x$ (ppm)

$cz_{z,l}^{in}$ Inlet concentration of pollutant l to centralized ZLD system z_j (ppm)

$ci_{z,l}^{out}$ Outlet concentration of pollutant l from centralized ZLD system z_j (ppm)

$cb_{b,l}^{in}$ Inlet concentration of pollutant l to beneficial usage b (ppm)

$cv_{v,l}^{in}$ Inlet concentration of pollutant l to evaporation pond v (ppm)

$cd_{d,l}^{in}$ Discharge to environment inlet concentration of pollutant l (ppm)

Mass load

$cim_{e_{n=x_t},l}$ Load of pollutant l in decentralized treatment e stage t at network $n = x$ (Kg/h)

$cim_{r_t,l}$ Load of pollutant l in centralized treatment r_t stage t (Kg/h)

$cim_{z_{n=x},l}$ Produced sludge load of pollutant l in decentralized ZLD system z at network $n = x$ (Kg/h)

$cim_{z,l}$ — Produced sludge load of pollutant l in centralized ZLD system z (Kg/h)

Flowrates

FW_w — Total flow from a source of the type of fresh water

$fws_{w,j_{n=x}}$ — Flow from a source of the type of fresh water w to process sink j at network $n = x$ (ton/h)

$FS_{i_{n=x}}$ — Flow from process sources i at network $n = x$ (ton/h)

$FU_{j_{n=x}}$ — Flow to process sink j at network $n = x$ (ton/h)

$fss_{i_{n=x},j_{n=x}}$ — Flow from a process sources i at network $n = x$ to process sink j at network $n = x$ (ton/h)

$fss_{i_{n=x},j_{n\neq x}}$ — Flow from a process sources i at network $n = x$ to process sink j at network $n \neq x$ (ton/h)

$fse_{i_{n=x},e_{n=x_t}}$ — Flow from a process sources i at network $n = x$ to decentralized treatment e stage t at network $n = x$ (ton/h)

$fse_{i_{n=x},e_{n\neq x_t}}$ — Flow from a process sources i at network $n = x$ to decentralized treatment e stage t at network $n \neq x$ (ton/h)

$fsi_{i_{n=x},r_t}$ — Flow from a process sources i at network $n = x$ to stage t in centralized treatment i_{r_t} (ton/h)

$fsz_{i_{n=x},z_{n=x}}$ — Flow from a process sources i at network $n = x$ to decentralized ZLD system z at network $n = x$ (ton/h)

$fsz_{i_{n=x},z_{n\neq x}}$	Flow from a process sources i at network $n = x$ to decentralized ZLD system z at network $n \neq x$ (ton/h)
$fsz_{i_{n=x},z}$	Flow from a process sources i at network $n = x$ to centralized ZLD system z (ton/h)
$fsv_{i_{n=x},v}$	Flow from a process sources i at network $n = x$ to evaporation pond v (ton/h)
$fsb_{i_{n=x},b}$	Flow from a process sources i at network $n = x$ to beneficial usage b (ton/h)
$fsd_{i_{n=x},d}$	Flow from a process sources i at network $n = x$ to discharge to environment (ton/h)
$FE_{e_{n=x_t}}$	Flow to decentralized treatment e stage t at network $n = x$ (ton/h)
$fes_{e_{n=x_t},j_{n=x}}$	Flow from decentralized treatment e stage t at network $n = x$ to process sink j at network $n = x$ (ton/h)
$fes_{e_{n=x_t},j_{n\neq x}}$	Flow from decentralized treatment e stage t at network $n = x$ to process sink j at network $n \neq x$ (ton/h)
$fee_{e_{n=x_t},e_{n=x_{t+1}}}$	Flow from decentralized treatment e stage t at network $n = x$ to decentralized treatment e stage $t + 1$ at network $n = x$ (ton/h)
$fei_{e_{n=x_t},r_t}$	Flow from decentralized treatment e stage t at network $n = x$ to stage t in centralized treatment i_{r_t} (ton/h)

$feb_{e_{n=x_t},b}$	Flow from decentralized treatment e stage t at network $n = x$ to beneficial usage b (ton/h)
$fed_{e_{n=x_t},d}$	Flow from decentralized treatment e stage t at network $n = x$ to discharge to environment (ton/h)
$fez_{e_{n=x_{t_C}},z_{n=x}}$	Concentrated flow from decentralized treatment e stage t at network $n = x$ to decentralized ZLD system z at network $n = x$ (ton/h)
$fez_{e_{n=x_{t_C}},z_{n\neq x}}$	Concentrated flow from decentralized treatment e stage t at network $n = x$ to decentralized ZLD system z at network $n \neq x$ (ton/h)
$fez_{e_{n=x_{t_C}},z}$	Concentrated flow from decentralized treatment e stage t at network $n = x$ to centralized ZLD system z (ton/h)
$fev_{e_{n=x_{t_C}},v}$	Concentrated flow from decentralized treatment e stage t at network $n = x$ to evaporation pond v (ton/h)
$fed_{e_{n=x_{t_C}},d}$	Concentrated flow from decentralized treatment e stage t at network $n = x$ to discharge to environment (ton/h)
FI_{r_t}	Flow to centralized treatment i_{r_t} (ton/h)
$fis_{r_t,j_{n=x}}$	Flow from stage t in centralized treatment i_r to process sink j at network $n = x$ (ton/h)
$fii_{r_t,r_{t+1}}l$	Flow from stage t in centralized treatment i_r to stage $t + 1$ in centralized treatment i_r (ton/h)

$fib_{r_t,b}$ Flow from stage t in centralized treatment i_r to beneficial usage b (ton/h)

$fid_{r_t,d}$ Flow from stage t in centralized treatment i_r to discharge to environment (ton/h)

$fiz_{r_{t_C},z}$ Concentrated flow from stage t in centralized treatment i_r to centralized ZLD system z (ton/h)

$fiv_{r_{t_C},v}$ Concentrated flow from stage t in centralized treatment i_r to evaporation pond v (ton/h)

$fid_{r_{t_C},d}$ Concentrated flow from stage t in centralized treatment i_r to discharge to environment (ton/h)

$FZ_{z_{n=x}}$ Flow to decentralized ZLD system z at network $n = x$ (ton/h)

$fzs_{z_{n=x},j_{n=x}}$ Flow from decentralized ZLD system z at network $n = x$ to process sink j at network $n = x$ (ton/h)

$fzs_{z_{n=x},j_{n\neq x}}$ Flow from decentralized ZLD system z at network $n = x$ to process sink j at network $n \neq x$ (ton/h)

$fzb_{z_{n=x},b}$ Flow from decentralized ZLD system z at network $n = x$ to beneficial usage b (ton/h)

FZ_z Flow to centralized ZLD system z (ton/h)

$fzs_{z,j_{n=x}}$ Flow from centralized ZLD system z to process sink j at network $n = x$ (ton/h)

$fzb_{z,b}$	Flow from centralized ZLD system z to beneficial usage b (ton/h)
FB_b	Flow to beneficial usage b (ton/h)
FV_v	Flow to evaporation pond v (ton/h)
FD_d	Flow to discharge to environment (ton/h)
	Flow rates upper limits
$M^{max}_{fxy_{x_{n=1},y_{n=2}}}$	Upper limit for the flow f in pipeline from source x at network $\mathrm{n} = 1$ to process sink y at network $\mathrm{n} = 2$ for the corresponded flows.

Binary variables

$x_{x_{n=1},y_{n=2}}$	Binary variable to determine the existence of pipeline from source x at network $\mathrm{n} = 1$ to process sink y at network $\mathrm{n} = 2$ for the corresponded connections.
$x_{e_{n=x_t}}$	Binary input for decentralized treatment e stage t at network $n = x$ to define the operating cost.
x_{r_t}	Binary input for centralized treatment r_t stage t to define the operating cost.
$y_{e_{n=x_t}}$	Binary variable for determining the existence of decentralized treatment e at stage t in network $n = x$
y_{r_t}	Binary variable for determining the existence of for centralized treatment r at stage t

y_z — Binary variable for determining the existence of centralized ZLD system z

$y_{z_{n=x}}$ — Binary variable for determining the existence of decentralized ZLD systems $z_{n=x}$ in network $n = x$

y_v — Binary variable for determining the existence of evaporation ponds option

Distance

$D_{\mathrm{n,m}}$ — Length of the pipe segments from source n to sink m.

Cost parameters

$AF_{e_{n=x_t}}$ — Annualization factor for stage t of decentralized treatment in network $n = x$ (year−1)

AF_{r_t} — Annualization factor for stage t of centralized treatment (year−1)

AF_z — Annualization factor for centralized and decentralized ZLD systems (year−1)

AF_b — Annualization factor for beneficial usage of water (year−1)

AF_v — Annualization factor for evaproration ponds (year−1)

AF_p — Annualization factor for piping (year−1)

CUW_w — Unit cost of fresh water w (US$/ton)

$CU_{e_{n=x_t}}$ — Capital unit cost per flow size for stage t of decentralized treatment in network $n = x$ (US$/ton/h)

CU_{r_t}	Capital unit cost per flow size for centralized treatment r_t stage t (US$/ton/h)
lCU_z	Capital unit cost per flow size for centralized systems (US$/ton/h)
$CU_{z_{n=x}}$	Capital unit cost per flow size for decentralized ZLD systems (US$/ton/h)
CU_b	Capital unit cost per flow size for beneficial usage of water (US$/ton/h)
$CUM_{e_{n=x_t}}$	Operating unit cost for mass removed in decentralized treatment e stage t at network $n = x$ (US$/kg)
CUM_{r_t}	Operating unit cost for mass removed in centralized treatment r_t stage t (US$/kg)
$CUF_{e_{n=x_t}}$	Operating unit cost per flow size for stage t of decentralized treatment in network $n = x$ (US$/ton)
$CUF_{r_t}l$	Operating unit cost per flow size for centralized treatment r_t stage t (US$/ton)
CUF_z	Operating unit cost per flow size for centralized ZLD system (US$/ton)
$CUF_{z_{n=x}}$	Operating unit cost per flow size for decentralized ZLD system in network $n = x$ (US$/ton)
CUF_b	Operating unit cost per flow size for beneficial usage of water (US$/ton)

$CAPEX_{e_{n=x_t}}$	Capital cost of decentralized treatment e at stage t in network $n = x$ (US$)
$OPEX_{e_{n=x_{t_m}}}$	Operating cost of decentralized treatment e at stage t in network $n = x$ as a function of mass removed of contaminants (US$/year)
$OPEX_{e_{n=x_{t_f}}}$	Total operating cost of decentralized treatment e at stage t in network $n = x$ as a function of flow size that goes into the treatment (US$/year)
$CAPEX_{r_t}$	Capital cost of centralized treatment r at stage t (US$/year)
$OPEX_{r_{t_m}}$	Operating cost of centralized treatment r at stage t as a function of mass removed of contaminants (US$/year)
$OPEX_{r_{t_f}}$	Operating cost of centralized treatment r at stage t as a function of flow size that goes into the treatment (US$/year)
Hy	Plants operating hours per year (h/year)
TAC	Total annual cost (US$/year)
WC	Fresh water annual cost (US$/year)
BC	Beneficial usage annual cost (US$/year)
EC	Decentralized treatment annual cost (US$/year)
RC	Centralized treatment annual cost (US$/year)
ZC_Cl	Centralized ZLD system annual cost (US$/year)
ZC_D	Decentralized ZLD systems annual cost (US$/year)

VC Evaporation pond annual cost (US$/year)

PC Pipeline annual cost (US$/year)

lq Cost parameter for cross-plant pipeline (linear relationship slope)

p Cost parameter for cross-plant pipeline (linear relationship interception)

Percentage recovery

$PR_{e_{n=x_t}}$ Percentage recovery of raw effluent flowing to decentralized treatment stage t in network $n = x$

PR_{r_t} Percentage recovery of raw effluent flowing to centralized treatment r_t stage t

$PR_{z_{n=x}}$ Percentage recovery of raw effluent flowing to decentralized ZLD system in network $n = x$

PR_z Percentage recovery of raw effluent flowing to centralized ZLD system

Evap. pond terms

REA Required evaporation area (acre)

EEV Enhanced evaporation rate $(\mathrm{m3/h})$

EV Evaporation rate $(\mathrm{m/h})$

Pr Precipitation rate $(\mathrm{m/h})$

C_{EEV}	Enhanced evaporation coefficient
TA	Total area for evaporation pond plus contingency factor (acre)
$TUACC$	Total unit area capital cost ($/acre)
LT	Liner thickness
LC	Land cost
LCC	Land clearance cost
DH	Dike height

Subscripts

w	Type of fresh water
$i_{n=x}$	Source i at network $n = x$
$i_{n\neq x}$	Source i at network $n \neq x$
$j_{n=x}$	Sink j at network $n = x$
$j_{n\neq x}$	Sink j at network $n \neq x$
$e_{n=x}$	Decentralized treatment e at network $n = x$
$e_{n\neq x}$	Decentralized treatment e at network $n \neq x$
r_t	Centralized treatment at stage t
t	Treatment stage
z	Centralized ZLD system
$Z_{n=x}$	Decentralized ZLD system z at network $n = x$
b	Beneficial usage of water
v	Evaporation pond

d	Environmental discharge
l	Pollutant

Symbols

ρ	Water density (ton/m^3)
v	Velocity (m/s)

Superscripts

in	Inlet
m	Removed mass
max	Upper limit
outl	Outlet

REFERENCES

1. Ministry of Energy and Industry (2011) Sustainability report. Qatar Energy & Industry Sector.

2. Takama, N., Kuriyama, T., Shiroko, K., Umeda, T. (1980) Optimal water allocation in a petroleum refinery. Comput Chem Eng 4(4):251–258.

3. El-Halwagi, M.M., Manousiouthakis, V. (1990) Automatic synthesis of mass-exchange networks with single-component targets. Chem Eng Sci 45(9):2813–2831.

4. El-Halwagi, M.M., Manousiouthakis, V. (1989) Synthesis of mass exchange networks. AIChE J 35(8):1233–1244.

5. Wang, Y.P., Smith, R. (1994a) Wastewater minimisation. Chem Eng Sci 49(7):981–1006.

6. Wang, Y.P., Smith, R. (1994b) Design of distributed effluent treatment systems. Chem Eng Sci 49(18):3127–3145.

7. Kuo, W. C. J., Smith, R. (1998) Designing for the interactions between water-use and effluent treatment. Chem Eng Res Des 76(3): 287-301.

8. El-Halwagi, M.M., Gabriel, F., Harell, D. (2003) Rigorous graphical targeting for resource conservation via material recycle/reuse networks. Ind Eng Chem Res 42(19):4319–4328.

9. Manan, Z.A., Tan, Y.L., Foo, D.C.Y. (2004) Targeting the minimum water flow rate using water cascade analysis technique. AIChE J 50(12):3169–3183.

10. Shenoy, U.V. (2007) Targeting for multiple resources. Ind Eng Chem Res 46: 3698-3708.

11. Bandyopadhyay, S. (2008) Water management in process industries incorporating regeneration and recycle through a single treatment unit. Ind Eng Chem Res 47: 1111-1119.

12. Koppol, A.P.R., Bagajewicz, M.J., Dericks, B.J., Savelski, M.J. (2004) On zero water discharge solutions in the process industry. Advances in Environmental Research 8(2): 151-171.

13. Van der Bruggen, B., Braeken,L. (2006) The challenge of zero discharge: from water balance to regeneration. Desalination 188(1-3): 177-183.

14. Faria, D.C., Bagajewicz, M.J. (2009) Profit-based grassroots design and retrofit of water networks in process plants. Computers & Chemical Engineering 33(2): 436-453.

15. Bagajewicz, M.J., Faria, D.C. (2009) On the appropriate architecture of the water/wastewater allocation problem in process plants. 19th European Symposium on Computer Aided Process Engineering.

16. Faria, D.C., Bagajewicz, M.J. (2011) Planning model for the design and/or retrofit of industrial water systems. Industrial & Engineering Chemistry Research 50(7): 3788-3797.

17. Alva-Argáez, Vallianatos, A., Kokossis, A. (1999) A multi-contaminant transshipment model for mass exchange network and wastewater minimization problems." Computers and Chemical Engineering 23(10): 1439–1453.

18. Alnouri, S., Linke, P., & El-Halwagi, M.M. (2014) Water integration in industrial zones: a spatial representation with direct recycle applications. Clean Technologies and Environmental Policy 16(8): 1637-1659..

19. Ying, L.I., Jian D.U. , Pingjing, Y.A.O. (2003) Design of water network with multiple contaminants and zero discharge. Chinese J.Chem. Eng. 11(5): 559-564.

20. Goldblatt, M.E., Eble, K.S., Feathers, J.E. (1993) Zero discharge: what, why, and how. Chemical Engineering Progress 89(4): 22-27.

21. Mickley, P.E.. (2008). Survey of High-Recovery and Zero Liquid Discharge Technologies for Water Utilities. WateReuse foundation. Alexandria, VA 22314 USA.

22. Alves, R.M.B., Guardani, R., Bresciani, A.E., Nascimento, L., Nascimento, C.A.O. (2006) Water reuse: a successful almost zero discharge case. 16th European Symposium on Computer Aided Process Engineering. C. P. W. Marquardt, Elsevier B.V.: 1845-1850.

23. Deng, C., Feng, X., Bai J. (2008) Graphically based analysis of water system with zero liquid discharge. Chemical Engineering Research and Design 86(2): 165-171.

24. Foo, D.C.Y. (2008). Flowrate targeting for threshold problems and plant-wide integration for water network synthesis. Journal of Environmental Management 88: 253–274.

25. Faria, D.C., Bagajewicz, M.J. (2009). On the appropriate modeling of process plant water systems. AIChE Journal.

26. Lowe, E.A. (2001) Eco-industrial Park handbook for asian developing countries. Oakland.

27. Olesen, S.G., Polley, G.T. (1996) Dealing with plant geography and piping constraints in water network design. Process Safety and Environmental Protection 74(4): 273-276.

28. Liao, Z.W., Wu, J.T., Jiang, B.B., Wang, J.D., Yang, Y.R. (2007) Design methodology for flexible multiple plant water networks. Ind Eng Chem Res 46(14):4954–4963.

29. Chew, I.M.L., Tan, R., Ng, D.K.S., Foo, D.C.Y., Majozi, T., Gouws, J. (2008) Synthesis of direct and indirect interplant water network. Ind Eng Chem Res 47(23):9485–9496.

30. Chew, I.M.L., Thillaivarrna, S.L., Tan, R.R., Foo D.C.Y. (2010) Analysis of inter-plant water integration with indirect integration schemes through game theory approach: Pareto optimal solution with interventions." Clean Technologies and Environmental Policy 13(1): 49-62.

31. Lovelady, E. M., El-Halwagi, M.M. (2009) Design and integration of eco-industrial parks for managing water resources. Environmental Progress & Sustainable Energy 28(2): 265-272.

32. Rubio-Castro, E., Ponce-Ortega, J.M., Serna-González, M., Jiménez-Gutiérrez, A. ,El-Halwagi, M.M (2011) A global optimal formulation for the water integration in eco-industrial parks considering multiple pollutants. Computers & Chemical Engineering 35(8): 1558-1574.

33. Alnouri, S., Linke, P., El-Halwagi, M.M. (2014) Water integration in industrial zones: a spatial representation with direct recycle applications. Clean Techn Environ Policy 2014.

34. Bishnu, S.K., Linke, P., Alnouri, S.Y., El-Halwagi, M.M. (2014) Multiperiod planning of optimal industrial city direct water reuse networks. Industrial & Engineering Chemistry Research, 53(21): 8844-8865.

35. Golder Associates Inc (2008) Evaporation Pond Design Report, Pifion Ridge Project, Montrose County, Colorado. Energy Fuels Resources Corporation

36. Michael C. Mickley, P.E. (2006) Membrane concentrate disposal: practices and regulation; p 298

37. Kim, J.K., Smith, R. (2004) Automated design of discontinuous water systems. process safety and environmental protection 82(3): 238-248.

38. IChemE (1988) A guide to capital cost estimating, 3rd edn, IChemE and The Association of Cost Engineers, London.

39. Lindo Systems, What'sBest! 12.0 - excel add-in for linear, nonlinear, and integer modeling and optimization. http://www.lindo.com/index.php?option=com_content&view=article&id=36&Itemid=21. Accessed 1 May 2014.

40. Mickley, P.E., Bjorklund, D. Shaw, W. (2013) Zero liquid discharge (ZLD): market dynamics and technology trends in brine concentrate management; BlueTech research.

41. Michael C. Mickley, P. E. (2006) Membrane Concentrate Disposal: Practices and Regulation (Second Edition) Mickley & Associates.

42. Homewyse, Cost to install a lawn irrigation system. http://www.homewyse.com/services/cost_to_install_lawn_irrigation_system.html. Accessed 25 May 2014.

43. Erickson, B., How to calculate lawn irrigation water usage and costs. http://www.todayshomeowner.com/calculating-lawn-irrigation-costs/. Accessed 25 May 2014.

APPENDIX A: CASE STUDY A

What'sBest! report for the case study A

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 05, 2014	01:27 AM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
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Total Cells 2583		
Numerics 2362		
Adjustables 30 Unlimited		
Continuous 30		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 2235		
Formulas 97		
Strings 0		
Constraints 221 Unlimited		
Globals 12 Unlimited		
Coefficients 545		

Minimum coefficient value: 2.6645352591004e-015 on <RHS>		
Minimum coefficient in formula: Sheet1!J86		
Maximum coefficient value: 39995 on <RHS>		
Maximum coefficient in formula: Sheet1!D86		
MODEL TYPE: Quadratic (Quadratic Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OBJECTIVE VALUE: 601557.5		
DIRECTION: Minimize		
SOLVER TYPE: . . .		
TRIES: 342		
INFEASIBILITY: 2.9103830456734e-011		
BEST OBJECTIVE BOUND: 601557.5		
STEPS: 0		
ACTIVE: 0		
SOLUTION TIME: 0 Hours 0 Minutes 0 Seconds		

NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-007		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		total	355	50	70	80	60	40	55	50	0	0	140	0	0	59.375	0	0	0	0	0	0	0	0	0	0
Sinks	1	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	80	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	60	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	40	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	55	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	140	0	0	0	80	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	59.375	0	0	0	0	0	40	19.375	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	355	0	0	70	0	0	0	35.625	50	0	0	140	0	0	59.375	0	0	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment		L1			L2			L3			Tretment reject L1	Tretment reject L2	Tretment reject L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	600	200	20	300	120	9	150	80	3.5	8200	3720	1480
	T1A	60	60	0	50	50	0	15	15	0	60	50	15
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	628.571429	200	60	300	120	25.2	82.85714	80	0.4	8771.429	3720	137.1429
	T2A	60	60	0	50	50	0	15	15	0	60	50	15
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	595.789474	200	23.5	330.5263	120	12.5	129.7895	80	2.95625	8115.789	4330.526	1075.789
	T3A	70	70	0	45	45	0	20	20	0	70	45	20
	T3B	25	25	0	25	25	0	10	10	0	25	25	10
Cent. T	CT1A	180	180	0	100	100	0	70	70	0	180	100	70
	CT1B	125	125	0	80	80	0	40	40	0	125	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	40	40	0	25	25	0	10	10	0	40	25	10

APPENDIX B: CASE STUDY B

What'sBest! report for the case study B

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 05, 2014	01:29 AM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
--		
Total Cells 2583		
Numerics 2362		
Adjustables 30 Unlimited		
Continuous 30		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 2235		
Formulas 97		
Strings 0		
Constraints 221 Unlimited		
Globals 12 Unlimited		
Coefficients 545		

Minimum coefficient value: 2.6645352591004e-015 on <RHS>		
Minimum coefficient in formula: Sheet1!J86		
Maximum coefficient value: 39995 on <RHS>		
Maximum coefficient in formula: Sheet1!D86		
MODEL TYPE: Quadratic (Quadratic Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OBJECTIVE VALUE: 3356357.5		
DIRECTION: Minimize		
SOLVER TYPE: . . .		
TRIES: 321		
INFEASIBILITY: 4.3655745685101e-010		
BEST OBJECTIVE BOUND: 3356357.5		
STEPS: 0		
ACTIVE: 0		
SOLUTION TIME: 0 Hours 0 Minutes 0 Seconds		

NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-007		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	355	50	70	80	60	40	55	50	0	0	140	0	0	59.375	0	0	0	0	0	0	0	0	0	0
Sinks	1	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	80	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	60	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	40	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	55	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	140	0	0	0	80	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	59.375	0	0	0	0	0	40	19.375	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	355	0	0	70	0	0	0	35.625	50	0	0	140	0	0	59.375	0	0	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment		L1			L2			L3			Tretment reject L1	Tretment reject L2	Tretment reject L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	600	200	20	300	120	9	150	80	3.5	8200	3720	1480
	T1A	60	60	0	50	50	0	15	15	0	60	50	15
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	628.571429	200	60	300	120	25.2	82.85714	80	0.4	8771.429	3720	137.1429
	T2A	60	60	0	50	50	0	15	15	0	60	50	15
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	595.789474	200	23.5	330.5263	120	12.5	129.7895	80	2.95625	8115.789	4330.526	1075.789
	T3A	70	70	0	45	45	0	20	20	0	70	45	20
	T3B	25	25	0	25	25	0	10	10	0	25	25	10
Cent. T	CT1A	180	180	0	100	100	0	70	70	0	180	100	70
	CT1B	125	125	0	80	80	0	40	40	0	125	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	40	40	0	25	25	0	10	10	0	40	25	10

APPENDIX C: CASE STUDY SCENARIO 1-A

What'sBest! report for the case study 1-A

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 05, 2014	01:24 AM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		

Total Cells 2867		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 221 Unlimited		
Globals 454 Unlimited		
Coefficients 5441		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 504904.1801308		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 115724		
INFEASIBILITY: 5.6388671509922e-011		
BEST OBJECTIVE BOUND: 504904.17518035		
STEPS: 1		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 0 Minutes 25 Seconds		
NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-007		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	291.8497	50	70	80	60	40	55	58.51537	0	0	140	0	0	0	0	0	0	0	0	0	0	0	0	0
Sinks	1	50	38.60624	0	0	4.148416	6.499186	0	0	0.746153	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	57.5386	0	0	0	2.654405	0	0	9.806994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	80	64.64646	0	0	0	0	0	0	0	0	0	15.35353535	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	60	53.02047	0	0	3.265102	3.714428	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	40	38	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	55	40.03789	0	0	0	0	0	6.471879	0	0	0	8.490227363	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	58.51537	0	50	0	8.515374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	140	0	0	0	64.07111	45.13198	0	30.79691	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	291.8497	0	0	70	0	0	40	17.73121	47.96223	0	0	116.1562373	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	585.4476	200	22.55461	278.1714	120	9.255461	138.3581035	80	3.414846	7908.953	3283.429	1247.162071
	T1A	60	60	0	50	50	0	15	15	0	60	50	15
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	706.7004	200	70.93805	361.82	120	33.8548	97.26937421	80	2.417712	10334.01	4956.401	425.3874843
	T2A	60	60	0	50	50	0	15	15	0	60	50	15
	T2B	400	45	0	30	30	0	10	10	0	7145	30	10
Plant 3	EOPT(3)	1000	200	0	120	120	0	80	80	0	16200	120	80
	T3A	70	70	0	45	45	0	20	20	0	70	45	20
	T3B	400	25	0	25	25	0	10	10	0	7525	25	10
Cent. T	CT1A	180	180	0	100	100	0	70	70	0	180	100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	40	40	0	25	25	0	10	10	0	40	25	10

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	5	5	4	4	3	3
zld2	5	5	4	4	3	3
zld3	5	5	4	4	3	3
CZLD	5	5	4	4	3	3

APPENDIX D: CASE STUDY SCENARIO 1-B

What'sBest! report for the case study 1-B

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 05, 2014	01:48 AM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		

Total Cells 2867		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 221 Unlimited		
Globals 454 Unlimited		
Coefficients 5441		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 1755970.7390301		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 489576		
INFEASIBILITY: 1.1641532182693e-010		
BEST OBJECTIVE BOUND: 1739352.368486		
STEPS: 103		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 3 Minutes 53 Seconds		
NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-002		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	20	50	70	80	60	40	55	50	144.244	0	111.1928146	0	0	5.972377753	0	21.33333333	0	0	0	150.6667	0	0	0	0
Sinks	1	50	0	0	0	4.545455	0	0	0	0	45.45455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0
	3	80	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	21.33333333	0	0	0	42.66667	0	0	0	0
	4	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0
	5	40	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0
	6	55	0	0	0	9.868421	0	0	0	0	40.78947	0	4.342105263	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	151.8358	0	0	69.46865	0	12.36716	0	20	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	111.1928	0	0	0	62.24159	45.26348	3.687737873	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	5.972378	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	22.45614	0	0	0	3.344532	2.150056	10.98917507	0	0	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	158.5965	0	0	0	0	0.219298	17.93859649	35	0	0	0	105.4385965	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	16.64442	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	3.355578	0	0	0.531352	0	0	1.412112818	0	0	0	0	1.412112818	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	7.59179	0	0	0	0	1.122807	0	7.929825
ZLD	zld1	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0
	EP	7.59179	0	0	0	0	1.122807	0	7.929825
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	600	200	20	300	120	9	150	80	3.5	8200	3720	1480
	T1A	400	60	51.62418	273.6558	50	33.95895	100	15	12.90604	6860	4523.115	1715
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	618.8051	200	46.56812	294.1335	120	19.36239	83.87042332	80	0.430363	8576.102	3602.669	157.4084665
	T2A	400	60	0	240	50	0	97.5	15	0	6860	3850	1665
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	400	200	1.194476	200	120	0.47779	120	80	0.238895	4200	1720	880
	T3A	499.2002	70	0	45	45	0	20	20	0	8654.004	45	20
	T3B	400	25	8.421053	200	25	3.929825	100	10	2.021053	7525	3525	1810
Cent. T	CT1A	180	180	0	100	100	0	70	70	0	180	100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	400	40	57.09474	235.5033	25	33.38509	100	10	14.27368	7240	4235.066	1810

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	5	5	4	4	3	3
zld2	5	5	4	4	3	3
zld3	5	5	4	4	3	3
CZLD	5	5	4	4	3	3

APPENDIX E: CASE STUDY SCENARIO 2-A

What'sBest! report for the case study 2-A

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 05, 2014	12:40 AM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		

Total Cells 2867		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 221 Unlimited		
Globals 454 Unlimited		
Coefficients 5441		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 1269486.9578054		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 239167		
INFEASIBILITY: 2.619344741106e-010		
BEST OBJECTIVE BOUND: 1269486.9575515		
STEPS: 1		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 1 Minutes 17 Seconds

NON-DEFAULT SETTINGS:

Global Solver Options / Strategy / Global Solver: On

Global Solver Options / Tolerance / Optimality: 1.000000e-007

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	107.9781	50	70	80	60	40	55	93.56262	218.205	0	34.48496241	0	0	0	0	0	0	0	0	0	0	0	0	0
Sinks	1	50	0	0	0	4.545455	0	0	0	0	45.45455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	21.31148	0	0	0	0	0	0	4.918033	43.77049	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	80	40	0	0	0	0	0	0	0	34.85714	0	5.142857143	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	60	20	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	40	26.66667	0	0	0	0	0	0	0	13.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	55	0	0	0	9.868421	0	0	0	0	40.78947	0	4.342105263	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	93.56262	0	23.0485	0	65.58612	0	4.92799363	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	229.6895	0	26.9515	70	0	35.58704	0	8.506331	88.64458	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	34.48496	0	0	0	0	24.41296	10.07200637	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	57.97814	0	0	0	0	0	0	46.49367	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	50	0	0	0	0	0	25	0	0	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	11.48447	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0
	EP	11.48447	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	519.3672	200	29.88084	189.585	120	6.510553	92.34096902	80	1.154653	6587.345	1511.7	326.8193804
	T1A	400	60	78.09442	257.3915	50	47.63565	100	15	19.5236	6860	4197.831	1715
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	683.1722	200	16.66217	412.3791	120	10.08268	105.8413904	80	0.891139	9863.444	5967.583	596.8278075
	T2A	60	60	0	50	50	0	100	15	0	60	50	1715
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	1000	200	0	120	120	0	80	80	0	16200	120	80
	T3A	70	70	0	45	45	0	20	20	0	70	45	20
	T3B	25	25	0	25	25	0	10	10	0	25	25	10
Cent. T	CT1A	1000	180	0	100	100	0	70	70	0	16580	100	70
	CT1B	800	125	0	80	80	0	150	40	0	13625	80	2240
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	40	40	0	25	25	0	10	10	0	40	25	10

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	5	5	4	4	3	3
zld2	5	5	4	4	3	3
zld3	5	5	4	4	3	3
CZLD	5	5	4	4	3	3

APPENDIX F: CASE STUDY SCENARIO 2-B

What'sBest! report for the case study 2-B

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 04, 2014	11:31 PM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
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Total Cells 2867		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 221 Unlimited		
Globals 454 Unlimited		
Coefficients 5441		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 1755970.7390301		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 811592		
INFEASIBILITY: 6.7152683413951e-010		
BEST OBJECTIVE BOUND: 1739353.1840936		
STEPS: 199		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 7 Minutes 53 Seconds		
NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-002		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	20	50	70	80	60	40	55	50	144.244	0	111.1928146	0	0	5.972377753	0	21.33333333	0	0	0	150.6667	0	0	0	0
Sinks	1	50	0	0	0	4.545455	0	0	0	0	45.45455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0
	3	80	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	21.33333333	0	0	0	42.66667	0	0	0	0
	4	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0
	5	40	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0
	6	55	0	0	0	9.868421	0	0	0	0	40.78947	0	4.342105263	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	151.8358	0	0	69.46865	0	12.36716	0	20	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	111.1928	0	0	0	62.24159	45.26348	3.687737873	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	5.972378	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	22.45614	0	0	0	3.344532	2.150056	10.98917507	0	0	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	158.5965	0	0	0	0	0.219298	17.93859649	35	0	0	0	105.4385965	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	16.64442	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	3.355578	0	0	0.531352	0	0	1.412112818	0	0	0	0	1.412112818	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	7.59179	0	0	0	0	1.122807	0	7.929825
ZLD	zld1	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0
	EP	7.59179	0	0	0	0	1.122807	0	7.929825
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	600	200	20	300	120	9	150	80	3.5	8200	3720	1480
	T1A	400	60	51.62418	273.6558	50	33.95895	100	15	12.90604	6860	4523.115	1715
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	618.8051	200	46.56812	294.1335	120	19.36239	83.87042332	80	0.430363	8576.102	3602.669	157.4084665
	T2A	60	60	0	50	50	0	15	15	0	60	50	15
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	400	200	1.194476	200	120	0.47779	120	80	0.238895	4200	1720	880
	T3A	70	70	0	189.2434	45	0	20	20	0	70	2929.867	20
	T3B	400	25	8.421053	200	25	3.929825	100	10	2.021053	7525	3525	1810
Cent. T	CT1A	1000	180	0	100	100	0	70	70	0	16580	100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	60.05076	50	0	20	20	0	80	251.0152	20.00000001
	CT2B	400	40	57.09474	235.5033	25	33.38509	100	10	14.27368	7240	4235.066	1810

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	5	5	4	4	3	3
zld2	5	5	4	4	3	3
zld3	5	5	4	4	3	3
CZLD	5	5	4	4	3	3

APPENDIX G: CASE STUDY SCENARIO 3-A

What'sBest! report for the case study 3-A

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 04, 2014	11:04 PM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
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Total Cells 2867		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 221 Unlimited		
Globals 454 Unlimited		
Coefficients 5441		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 1477257.5623544		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 1279778		
INFEASIBILITY: 4.3655745685101e-011		
BEST OBJECTIVE BOUND: 1477257.5620587		
STEPS: 1		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 2 Minutes 8 Seconds		
NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-007		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	107.9781	50	70	80	60	40	55	81.01026	218.205	0	9.484962406	0	0	0	0	0	0	0	0	0	0	0	0	0
Sinks	1	50	0	0	0	4.545455	0	0	0	0	45.45455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	21.31148	0	0	0	0	0	0	4.918033	43.77049	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	80	40	0	0	0	0	0	0	0	34.85714	0	5.142857143	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	60	20	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	40	26.66667	0	0	0	0	0	0	0	13.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	55	0	0	0	9.868421	0	0	0	0	40.78947	0	4.342105263	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	81.01026	0	0	0	64.80821	0	16.2020529	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	229.6895	0	8.506331	70	0	51.29295	23.7979471	0	76.09223	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	9.484962	0	0	0	0.777913	8.70705	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	107.9781	0	41.49367	0	0	0	0	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	11.48447	0	0	0	0	0	0	0
ZLD	zld1	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0
	EP	11.48447	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment		L1			L2			L3			Treatment reject L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	480	200	22.68287	160	120	3.240411	80	80	0	5800	920	80
	T1A	400	60	78.09442	259.433	50	48.10456	97.29822542	15	18.90303	6860	4238.661	1660.964508
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	775.3954	200	5.457604	471.2946	120	3.332016	97.53953859	80	0.166362	11707.91	7145.892	430.7907718
	T2A	60	60	0	50	50	0	15	15	0	60	50	15
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	1000	200	0	120	120	0	80	80	0	16200	120	80
	T3A	70	70	0	45	45	0	20	20	0	70	45	20
	T3B	25	25	0	25	25	0	10	10	0	25	25	10
Cent. T	CT1A	1000	180	0	100	100	0	70	70	0	16580	100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	40	40	0	25	25	0	10	10	0	40	25	10

.Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	5	5	4	4	3	3
zld2	5	5	4	4	3	3
zld3	5	5	4	4	3	3
CZLD	5	5	4	4	3	3

APPENDIX H: CASE STUDY SCENARIO 3-B

What'sBest! report for the case study 3-B

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Oct 04, 2014	10:46 PM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		

Total Cells 2867		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 221 Unlimited		
Globals 454 Unlimited		
Coefficients 5441		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 1769296.2450476		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 355735		
INFEASIBILITY: 8.2246697274968e-007		
BEST OBJECTIVE BOUND: 1769296.2446906		
STEPS: 1		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 0 Minutes 58 Seconds

NON-DEFAULT SETTINGS:

Global Solver Options / Strategy / Global Solver: On

Global Solver Options / Tolerance / Optimality: 1.000000e-007

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	20	50	70	80	60	40	55	50	144.244	0	105.4883321	0	0	5.972377753	0	21.33333333	0	0	0	150.6667	0	0	0	0
Sinks	1	50	0	0	0	4.545455	0	0	0	0	45.45455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0
	3	80	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	21.33333333	0	0	0	42.66667	0	0	0	0
	4	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0
	5	40	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0
	6	55	0	0	0	9.868421	0	0	0	0	40.78947	0	4.342105263	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	120	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A		0	0	69.46865	0	12.36716	0	20	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	140	0	0	0	62.24159	42.24346	1.003275521	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	95	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B		0	0	0	3.344532	2.150056	10.98917507	0	0	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B		0	0	0.531352	0	3.239318	22.03517166	31.64442	0	0	0	101.1462268	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	30	0	0	0	0	0	0	3.355578	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	7.59179	0	0	0	0	1.122807	0	7.929825
ZLD	zld1	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0
	EP	7.59179	0	0	0	0	1.122807	0	7.929825
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	600	200	20	300	120	9	150	80	3.5	8200	3720	1480
	T1A	400	60	51.62418	273.6558	50	33.95895	100	15	12.90604	6860	4523.115	1715
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	619.1858	200	44.21921	290.6352	120	18.00003	82.48922664	80	0.262584	8583.716	3532.705	129.7845327
	T2A	60	60	0	50	50	0	15	15	0	60	50	15
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	400	200	1.194476	200	120	0.47779	120	80	0.238895	4200	1720	880
	T3A	500	70	0	45	45	0	20	20	0	8670	45	20
	T3B	400	25	8.421053	200	25	3.929825	100	10	2.021053	7525	3525	1810
Cent. T	CT1A	1000	180	0	700	100	0	70	70	0	16580	12100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	400	40	57.09474	235.0855	25	33.31882	100	10	14.27368	7240	4226.71	1810

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	5	5	4	4	3	3
zld2	5	5	4	4	3	3
zld3	5	5	4	4	3	3
CZLD	5	5	4	4	3	3

APPENDIX I: CASE STUDY SCENARIO 4-A

What'sBest! report for the case study 4-A

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Sep 29, 2014	01:23 PM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
--		
Total Cells 2868		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 222 Unlimited		
Globals 454 Unlimited		
Coefficients 5443		
Minimum coefficient value: 0.05 on Sheet1!L13		

Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 1755432.8163684		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 175417		
INFEASIBILITY: 3.9290171116591e-010		
BEST OBJECTIVE BOUND: 1755432.8160174		
STEPS: 1		
ACTIVE: 0		
SOLUTION TIME: 0 Hours 0 Minutes 35 Seconds		

NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-007		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	61.01517	50	70	80	60	40	55	120	267.0941	0	46.8053177	0	0	0	0	0	0	0	0	35.99292	13.35471	0	0	1.799646
Sinks	1	50	0	0	0	4.545455	0	0	0	0	45.45455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	11.99793	0	0	0	0	0	0	0	53.51801	0	0	0	0	0	0	0	0	0	0	4.484056	0	0	0	0
	3	80	2.350574	0	0	0	0	0	0	0	30.98621	0	0	0	0	0	0	0	0	0	0	31.50887	13.35471	0	0	1.799646
	4	60	20	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	40	26.66667	0	0	0	0	0	0	0	13.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	55	0	0	0	9.868421	0	0	0	0	40.78947	0	4.342105263	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	120	0	50	0	65.58612	0	4.413875598	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	281.1517	0	0	70	0	24.32586	31.37642584	35.44943	120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	46.80532	0	0	0	0	35.67414	0	11.13117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	37.88729	0	0	0	0	0	4.209698565	8.419397	0	0	0	25.25819139	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	14.05759	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	1.894364	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	60.21757	0	0	0	0	0	0	0	0	43.01255	0	17.20502105	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	14.05759	0	0	0	0	0	0	1.894364
ZLD	zld1	14.05759	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	1.894364
	EP	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment		L1			L2			L3			Treatment reject L1	Treatment reject L2	Treatment reject L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	537.9884	200	40.55861	214.3391	120	11.32069	105.1724482	80	3.020694	6959.769	2006.782	583.4489633
	T1A	400	60	95.59158	254.6948	50	57.55029	100	15	23.8979	6860	4143.895	1715
	T1B	400	40	0	30	30	0	10	10	0	7240	30	10
Plant 2	EOPT(2)	847.5637	200	30.30943	523.7819	120	18.89914	111.8909279	80	1.492665	13151.27	8195.637	717.8185589
	T2A	60	60	0	300	50	0	15	15	0	60	5050	15
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	1000	200	0	120	120	0	80	80	0	16200	120	80
	T3A	70	70	0	45	45	0	20	20	0	70	45	20
	T3B	25	25	0	25	25	0	10	10	0	25	25	10
Cent. T	CT1A	1000	180	0	100	100	0	150	70	0	16580	100	1670
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	50	50	0	100	20	0	80	50	1620
	CT2B	400	40	13.63942	235.5556	25	7.977379	100	10	3.409856	7240	4236.111	1810

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	6860	5	4143.895	4	1715	3
zld2	5	5	4	4	3	3
zld3	5	5	4	4	3	3
CZLD	40000	5	4236.111	4	1810	3

APPENDIX J: CASE STUDY SCENARIO 4-B

What'sBest! report for the case study 4-B

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Sep 29, 2014	01:20 PM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
--		
Total Cells 2868		
Numerics 2646		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1117		
Formulas 1092		
Strings 0		
Constraints 222 Unlimited		
Globals 454 Unlimited		
Coefficients 5443		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 1878643.2445546		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 83249		
INFEASIBILITY: 1.8189894035459e-010		
BEST OBJECTIVE BOUND: 1878643.2441789		
STEPS: 1		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 0 Minutes 43 Seconds		
NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Optimality: 1.000000e-007		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	8.896472	50	70	80	60	40	55	54.15168	150.0023	0	108.0875734	0	0	5.972377753	0	21.33333333	0	0	0	145.908	7.500116	0	1.066667	7.295401
Sinks	1	50	0	0	0	4.545455	0	0	0	0	45.45455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0
	3	80	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	21.33333333	0	0	0	42.66667	0	0	0	0
	4	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0
	5	40	8.896472	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15.24135	7.500116	0	1.066667	7.295401
	6	55	0	0	0	9.868421	0	0	0	0	40.78947	0	4.342105263	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	54.15168	0	50	0	4.151675	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	157.8972	0	0	70	0	12.08483	0	21.66067	54.15168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	108.0876	0	0	0	58.08992	45.05303	4.944623667	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	5.972378	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3B	22.45614	0	0	0	3.344532	2.150056	10.98917507	0	0	0	0	0	0	0	5.972377753	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	153.5874	0	0	0	0	0.712079	18.09382351	33.33933	0	0	0	101.4421481	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	7.894859	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	1.122807	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	7.679369	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	8.06162	0	0	0	0	0	0	0	0	5.7583	0	2.303320002	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

		plant 1		plant 2		plant 3		central treatment	
		T1A	T1B	T2A	T2B	T3A	T3B	CT2A	CT2B
	Total	7.894859	0	0	0	0	1.122807	0	7.679369
ZLD	zld1	7.894859	0	0	0	0	0	0	0
	zld2	0	0	0	0	0	0	0	0
	zld3	0	0	0	0	0	1.122807	0	0
	CZLD	0	0	0	0	0	0	0	7.679369
	EP	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	592.3332	200	21.2455	288.4999	120	9.12455	143.8665973	80	3.458483	8046.665	3489.997	1357.331946
	T1A	400	60	53.68504	272.5636	50	35.14216	100	15	13.42126	6860	4501.272	1715
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	620.4713	200	45.44772	298.1742	120	19.25842	84.79191457	80	0.517946	8609.425	3683.485	175.8382913
	T2A	60	60	0	300	50	0	15	15	0	60	5050	15
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	400	200	1.194476	200	120	0.47779	120	80	0.238895	4200	1720	880
	T3A	70	70	0	45	45	0	20	20	0	70	45	20
	T3B	400	25	8.421053	200	25	3.929825	100	10	2.021053	7525	3525	1810
Cent. T	CT1A	1000	180	0	100	100	0	70	70	0	16580	100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	400	40	55.29146	235.3804	25	32.31178	100	10	13.82286	7240	4232.608	1810

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	6860	5	4501.272	4	1715	3
zld2	5	5	4	4	3	3
zld3	7525	5	3525	4	1810	3
CZLD	7240	5	4232.608	4	1810	3

APPENDIX K: CASE STUDY SCENARIO 5-A

What'sBest! report for the case study 5-A

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Sep 29, 2014	01:13 PM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
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Total Cells 2870		
Numerics 2648		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1119		
Formulas 1092		
Strings 0		
Constraints 222 Unlimited		
Globals 454 Unlimited		
Coefficients 5443		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 2169073.0593989		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 861571		
INFEASIBILITY: 3.1650415621698e-010		
BEST OBJECTIVE BOUND: 2169064.9979009		
STEPS: 15		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 2 Minutes 14 Seconds		
NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Delta: 1.000000e-006		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	56.79142	50	70	80	60	40	55	81.27655	115.8191	0	140	121.1393	0	62.70752151	52.11847	0	0	0	0	0	5.790954	6.056966	21.70197	0
Sinks	1	50	0	0	0	0	0	0	0.852085	0	47.07148	0	2.076439444	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	10.12475	0	0	0	0	0	0	0	26.45179	0	0	0	0	0	32.52664	0	0	0	0	0	0.896828	0	0	0
	3	80	0	0	0	0	0	0	0	0	0	0	0	27.7551	0	0	19.59184	0	0	0	0	0	4.894126	6.056966	21.70197	0
	4	60	20	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0
	5	40	26.66667	0	0	0	0	0	0	0	13.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	55	0	0	0	0	0	0	0.682495	0	28.96249	0	0	14.0802	0	11.274818	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	81.27655	0	4.656627	70	0	0	0	6.619922	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	121.9148	0	0	0	0	40.63827	0	0	81.27655	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	140	0	45.34337	0	65.14887	19.36173	0	10.14603	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	127.5151	0	0	0	0	0	0	5.313128	0	0	0	122.2019512	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	62.70752	0	0	0	14.85113	0	40	7.856391	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	54.86155	0	0	0	0	0	0	3.428847	0	0	0	0	0	0	51.43270351	0	0	0	0	0	0	0	0	0	0
	T3B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	6.095741	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	6.375754	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	22.84418	0	0	0	0	0	0	20.1011	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	55.02563	0	0	0	0	0	0	0	0	0	0	15.72160939	39.30402	0	0	0	0	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	6860	5	3983.333	4	1448.333	3
zld2	6860	5	1850	4	1373.333	3
zld3	5440.68536	5	785.5201	4	288.99	3
CZLD	5	5	4	4	3	3

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	700	200	40.63827	281.372	120	13.11576	106.937148	80	2.189358	10200	3347.439	618.7429608
	T1A	400	60	41.45104	246.6667	50	23.97658	86.66666667	15	8.737229	6860	3983.333	1448.333333
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	900	200	98	279.5987	120	22.34382	105.8571725	80	3.620004	14200	3311.975	597.1434492
	T2A	400	60	43.35513	140	50	11.47636	82.91666667	15	8.660399	6860	1850	1373.333333
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	1000	200	50.16602	238.2729	120	7.416602	111.917002	80	2.001436	16200	2485.458	718.3400393
	T3A	500	70	23.59047	150	45	5.760463	84.375	20	3.531712	8670	2145	1307.5
	T3B	25	25	0	25	25	0	10	10	0	25	25	10
Cent. T	CT1A	1000	180	0	100	100	0	70	70	0	16580	100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	80	80	0	50	50	0	20	20	0	80	50	20
	CT2B	400	40	0	25	25	0	10	10	0	7240	25	10

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	6860	5	3983.333	4	1448.333	3
zld2	6860	5	1850	4	1373.333	3
zld3	5440.68536	5	785.5201	4	288.99	3
CZLD	5	5	4	4	3	3

APPENDIX L: CASE STUDY SCENARIO 5-B

What'sBest! report for the case study 5-B

What'sBest!® 12.0.1.5 (May 01, 2014) - Lib. 8.0.1694.527 - 32-bit - Status Report -		
DATE GENERATED:	Sep 29, 2014	07:48 AM
MODEL INFORMATION:		
CLASSIFICATION DATA Current Capacity Limits		
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Total Cells 2869		
Numerics 2647		
Adjustables 437 Unlimited		
Continuous 437		
Free 0		
Integers/Binaries 0/0 Unlimited		
Constants 1118		
Formulas 1092		
Strings 0		
Constraints 222 Unlimited		
Globals 454 Unlimited		
Coefficients 5443		

Minimum coefficient value: 0.05 on Sheet1!L13		
Minimum coefficient in formula: Sheet1!AC38		
Maximum coefficient value: 40000 on <RHS>		
Maximum coefficient in formula: Sheet1!D79		
MODEL TYPE: Nonlinear (Nonlinear Program)		
SOLUTION STATUS: GLOBALLY OPTIMAL		
OPTIMALITY CONDITION: SATISFIED		
OBJECTIVE VALUE: 2228145.1097116		
DIRECTION: Minimize		
SOLVER TYPE: Global		
TRIES: 40194		
INFEASIBILITY: 5.8207660913467e-011		
BEST OBJECTIVE BOUND: 2228133.732197		
STEPS: 1		
ACTIVE: 0		

SOLUTION TIME: 0 Hours 0 Minutes 23 Seconds		
NON-DEFAULT SETTINGS:		
Global Solver Options / Strategy / Global Solver: On		
Global Solver Options / Tolerance / Delta: 1.000000e-006		

Network connectivity

			Sources							plant 1			plant 2			plant 3			central treatment				ZLD			
			FW	1	2	3	4	5	6	EOPT(1)	T1A	T1B	EOPT(2)	T2A	T2B	EOPT(3)	T3A	T3B	CT1A	CT1B	CT2A	CT2B	zld1	zld2	zld3	CZLD
		Total	1.778765	50	70	80	60	40	55	79.61228	113.4475	0	140	18.23382	0	65.37035521	34.13191	31.41200513	0	0	0	107.3136	5.672375	0.911691	21.84679	5.365681
Sinks	1	50	0	0	0	0	0	0	0.852085	0	47.07148	0	2.076439444	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	0	0	0	0	0	0	0	0	23.33333	0	0	0	0	0	23.33333	0	0	0	0	23.33333	0	0	0	0
	3	80	0	0	0	0	0	0	0	0	0	0	0	7.361138	0	0	10.79858	31.41200513	0	0	0	30.42828	0	0	0	0
	4	60	1.04218	0	0	0	0	0	0	0	0	0	0	10.87268	0	0	0	0	0	0	0	41.80777	0	0.911691	0	5.365681
	5	40	0.736585	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.74425	5.672375	0	21.84679	0
	6	55	0	0	0	0	0	0	0.682495	0	43.04269	0	11.274818	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 1	EOPT(1)	79.61228	0	3.030181	70	0	0	0	6.582097	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1A	119.4184	0	0	0	0	39.80614	0	0	79.61228	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 2	EOPT(2)	140	0	46.96982	0	62.78191	20.19386	0	10.05441	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2A	19.1935	0	0	0	0	0	0	0.799729	0	0	0	18.39376631	0	0	0	0	0	0	0	0	0	0	0	0	0
	T2B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant 3	EOPT(3)	65.37036	0	0	0	17.21809	0	40	8.152262	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T3A	35.92833	0	0	0	0	0	0	2.24552	0	0	0	0	0	0	33.68280618	0	0	0	0	0	0	0	0	0	0
	T3B	33.06527	0	0	0	0	0	0	1.37772	0	0	0	0	0	0	31.68754904	0	0	0	0	0	0	0	0	0	0
Cent. T	CT1A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT1B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CT2B	112.9617	0	0	0	0	0	0	4.706738	0	0	0	108.2549762	0	0	0	0	0	0	0	0	0	0	0	0	0
ZLD	zld1	5.970921	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld2	0.959675	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	zld3	22.99662	0	0	0	0	0	0	19.54694	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CZLD	5.648086	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	BU1 (IR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Network connectivity for treatment reject streams

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	6860	5	3983.333	4	1448.333	3
zld2	6860	5	1850	4	1373.333	3
zld3	5468.21392	5	844.703	4	335.197	3
CZLD	7240	5	2325	4	1468.333	3

Treatment and treatment reject inlet and outlet pollutants concentrations

Treatment											Treatment reject		
		L1			L2			L3			L1	L2	L3
		C in	C out	cim	C in	C out	cim	C in	C out	cim	C out R	C out R	C out R
Plant 1	EOPT(1)	700	200	39.80614	280.84	120	12.80484	106.0369319	80	2.072859	10200	3336.8	600.7386377
	T1A	400	60	40.60226	246.6667	50	23.48562	86.66666667	15	8.55832	6860	3983.333	1448.333333
	T1B	40	40	0	30	30	0	10	10	0	40	30	10
Plant 2	EOPT(2)	900	200	98	283.1272	120	22.83781	106.9125317	80	3.767754	14200	3382.544	618.2506331
	T2A	400	60	6.525788	140	50	1.727415	82.91666667	15	1.303558	6860	1850	1373.333333
	T2B	45	45	0	30	30	0	10	10	0	45	30	10
Plant 3	EOPT(3)	1000	200	52.29628	236.7139	120	7.629628	110.5716158	80	1.998477	16200	2454.278	691.4323156
	T3A	500	70	15.44918	150	45	3.772474	84.375	20	2.312886	8670	2145	1307.5
	T3B	400	25	12.39948	140	25	3.802506	82.91666667	10	2.411009	7525	2325	1468.333333
Cent. T	CT1A	1000	180	0	100	100	0	70	70	0	16580	100	70
	CT1B	800	125	0	80	80	0	40	40	0	13625	80	40
	CT2A	500	80	0	50	50	0	20	20	0	8480	50	20
	CT2B	400	40	40.66622	140	25	12.9906	82.91666667	10	8.236792	7240	2325	1468.333333

Decentralized and centralized ZLD systems treatment inlet and outlet pollutants concentrations

ZLD	L1		L2		L3	
	C in	C out	C in	C out	C in	C out
zld1	6860	5	3983.333	4	1448.333	3
zld2	6860	5	1850	4	1373.333	3
zld3	5468.21392	5	844.703	4	335.197	3
CZLD	7240	5	2325	4	1468.333	3