ACS Sustainable Chemistry & Engineering

Research Article

pubs.acs.org/journal/ascecg

Synthesis of Eco-Industrial Parks Interacting with a Surrounding Watershed

Dulce Celeste López-Díaz,[†] Luis Fernando Lira-Barragán,[‡] Eusiel Rubio-Castro,[§] José María Ponce-Ortega,*[,†] and Mahmoud M. El-Halwagi[‡,⊥]

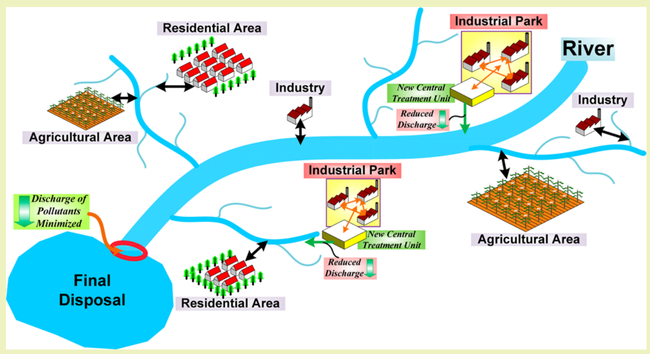
[†]Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, México

[‡]Chemical Engineering Department, Texas A&M University, College Station, Texas 77843, United States

[§]Chemical and Biochemical Sciences Department, Universidad Autónoma de Sinaloa, Culiacán, Sinaloa 80000, México

[⊥]Adjunct Faculty at the Chemical and Materials Engineering Department, King Abdulaziz University, Jeddah 21589, Saudi Arabia

ABSTRACT: Industrial facilities impacting a watershed may be clustered into groups based on their geographical locations. Water usage and discharge for each clustered group of industries may be integrated through the introduction of an eco-industrial park (EIP). This paper presents a mathematical programming model for water integration of EIPs to be synthesized with the purpose of mitigating the environmental impact of industrial effluents discharged into watersheds. The model considers the creation of multiple EIPs, their location, sizing, and tasks. To determine the effect of the discharges on the surrounding watershed, a material flow analysis (MFA) model was coupled with water recycle strategies within the industrial facilities and the associated EIPs. The MFA characterizes the interaction of individual discharges and tracks the impact of the natural (physical, chemical, and biological) phenomena within the watershed on the fate and transport of pollutants. A multiobjective optimization formulation is developed to guide the decisions for multiplant water integration while accounting for the impact on the watershed. The objective function reconciles the minimization of the environmental impact on the watershed, the minimization of the total annualized cost of the water-management system, which includes the cost of fresh water, effluent treatment, and piping and pumping associated with the eco-industrial parks. An example is presented to show the scope and capabilities of the proposed optimization approach.



KEYWORDS: *Eco-industrial parks, Material flow analysis, Water integration, Recycle and reuse networks, Sustainable watersheds*

■ INTRODUCTION

Substantial amounts of water are used in and discharged from industrial facilities. The discharged effluents are typically laden with various pollutants and may lead to major impact on the surrounding watersheds. An effective strategy in reducing water usage and discharge for industrial facilities is to synthesize recycle and reuse water networks for mass integration within the industrial facilities.[1−3] The synthesis of water networks has been extended from intraplant integration to interplant integration through the use of the concept of eco-industrial parks (EIP). In general, the EIP involves industrial symbiosis to integrate various forms of materials and energy as part of the emerging field of industrial ecology.[4−7] In the case of water integration within an EIP, adjacent industries can exchange their resources (in this case water streams) and common infrastructure (e.g., treatment units) to reduce the consumption of fresh resources and the discharge of effluents to the environment.[8−11] Figure 1 shows schematically an EIP composed of several industrial plants where it is possible to recycle wastewater streams to the same plant or to other plants. Additionally, a central treatment facility may be used to receive and treat wastewater streams to enable recycle to the participating plants. Consequently, water integration is improved in the interplant integration compared to the single-plant integration. This integration reduces the overall

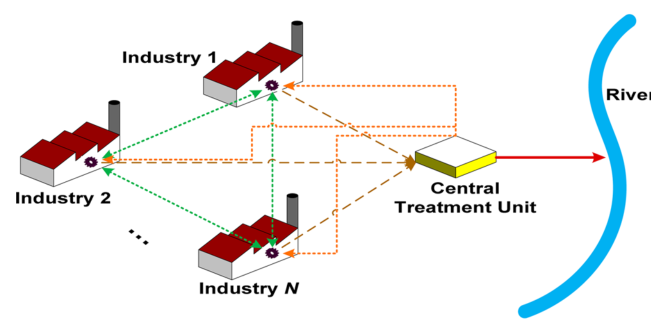


Figure 1. General configuration for an eco-industrial park.

Received: April 4, 2015
Revised: May 11, 2015
Published: May 21, 2015

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

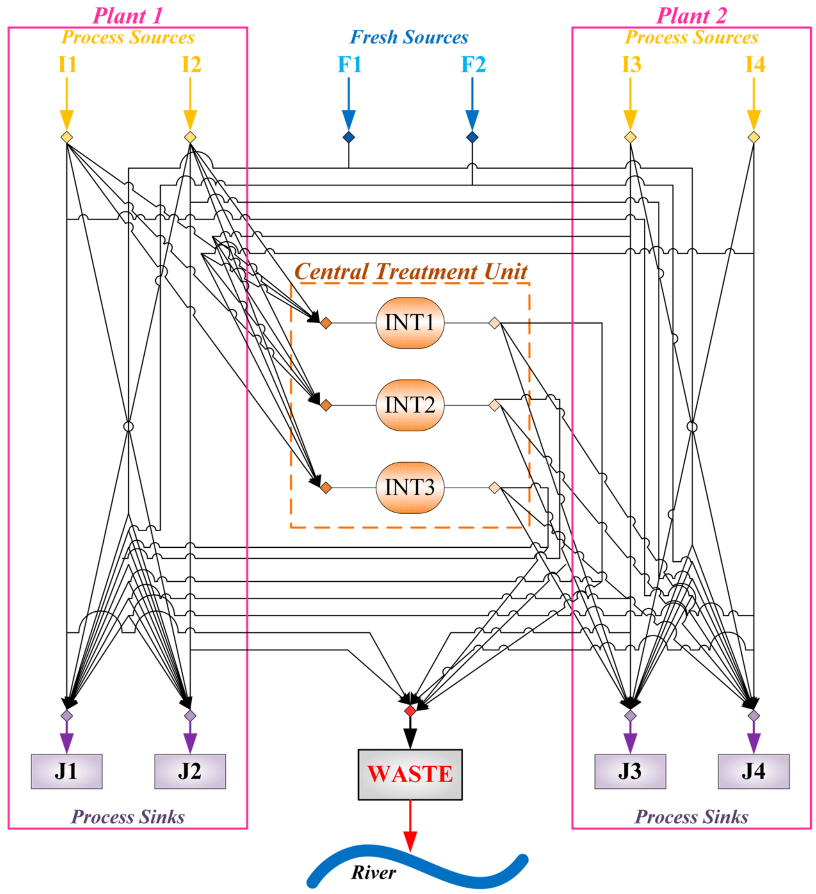


Figure 2. Superstructure for the proposed water integration in each eco-industrial park.

need of fresh water and the total wastewater discharged to the environment. Furthermore, the interplant integration allows the reduction of the capital and operating costs because of the possibility of using a shared treatment facility and/or distributed treatment units in each plant.

Several methodologies for synthesizing interplant water networks based on heuristic rules have been reported. Foo[12] included threshold problems, Bandyopadhyay et al.[13] used a decomposition algorithm, and Chew et al.[14] involved batch processes. For improving the results obtained with the heuristic rules for synthesizing interplant water networks, mathematical programming approaches have also been reported, including targeting approaches,[15] configurations that involve direct recycle networks,[16,17] including interceptors,[18−23] and involving retrofitting options,[24] and also property-based constraints have been considered.[25,26] Furthermore, different flexibility options,[27−30] multiobjective optimization approaches,[31] and fuzzy mathematical programming approaches[32−36] have been included, and these approaches have been applied to different industries.[37−39] In addition to the integration of water usage and discharge among several plants, it is important to track the impact of these discharges on the surrounding environment. Several research methods have incorporated material flow analysis (MFA) to incorporate the impact of water discharges on the surrounding.[40−48]

In spite of the valuable contributions made by the aforementioned methodologies for synthesizing and retrofitting interplant water networks, they have at least one of the following limitations: (1) Only a single eco-EIP has been considered. Because the industrial facilities may be clustered into several groups based on their proximity in a certain geographical location, the installation of multiple EIPs can offer superior results. (2) The effects of the wastewater discharges on the surrounding watershed have not been accounted for. (3) The identification of the optimal location of the retrofitted eco-industrial plant has not been included. (4) Only the economic objectives were considered without accounting for the environmental objectives including the implications of the discharged wastewaters on the surrounding watershed. (5) The interaction among the various discharges has not been considered. (6) The impact of physical, chemical, and biological natural phenomena that occur in the watershed have not been characterized.

To overcome these limitations, this paper proposes a multiobjective optimization methodology for designing a set of EIPs for water integration considering the industries located in different clusters and the interaction with the surrounding watershed. The goals are to minimize the total annualized cost and the environmental impact on the surrounding watershed while allowing retrofitting and recycle strategies and satisfying process and environmental constraints. The proposed optimization formulation is based on a new superstructure that involves the optimal selection of the industries and location for installing the eco-industrial parks. The formulation also accounts for the collective impact on water recycle, reuse, and discharge on the surrounding watershed.

■ PROBLEM STATEMENT

The addressed problem is described as follows: Given is a set of industrial plants that are installed around a watershed. These

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

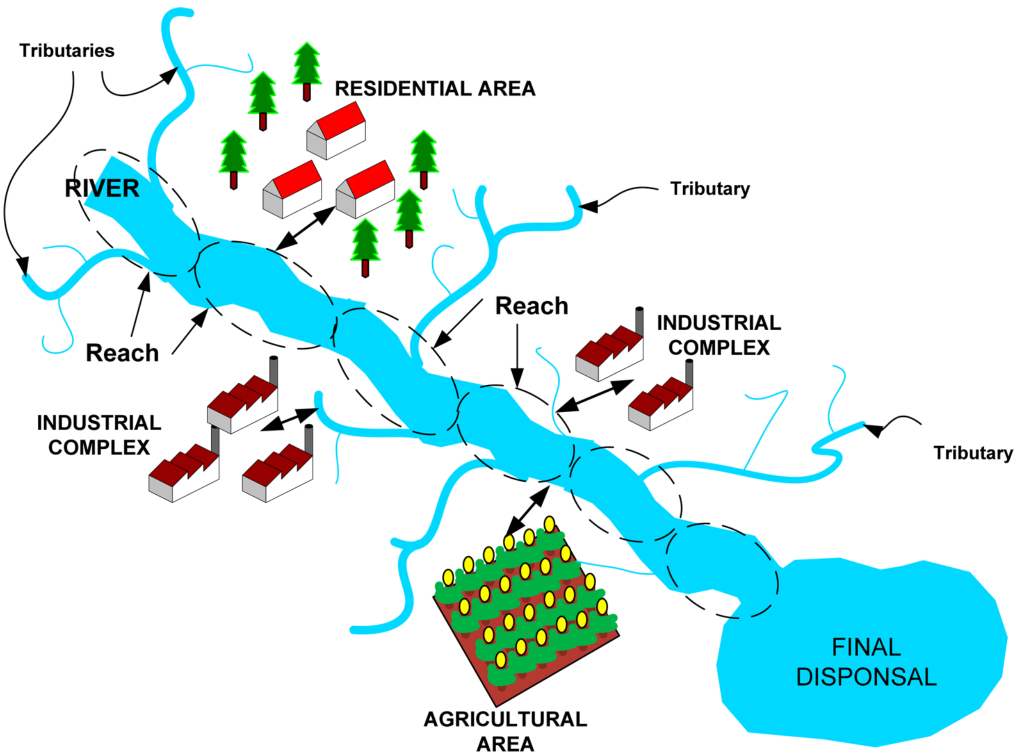


Figure 3. Watershed system interacting with several users.

plants may be grouped into a set of clusters: CLUSTER = $\{p|p = 1, 2,..., N_{\text{Clusters}}\}$. Each cluster p represents a group of plants that are located in the same geographical location and may be integrated through an EIP. The plants belonging to each group p offer a number of process sources (effluents) that are discharged to the environment. Each source, i, has a known flowrate and composition of key pollutants c. Given is also a set of fresh sources of water. Each fresh source w is available to be sent directly to the process sinks as well as a set of available interception technologies in place p to remove the considered pollutants. For each interception technology, *int*, the fixed and operating costs as well as the pollutant-removal efficiencies are known. The interception network allows reusing the process sources in a set of process sinks located in the same place. For each sink, j, the flowrate and upper limits for the inlet composition are known. The watershed receiving the industrial effluents may also receive other discharges (e.g., agricultural, residential, pluvial, etc.). For modeling the watershed, the system is divided in a set of reaches r and tributaries t. The current conditions for the watershed are given, including the flowrates and compositions for reaches and tributaries and for all the effluents and natural phenomena interacting with the watershed. Finally, the unit costs for pipe lines are given.

The problem is aimed at determining the optimal selection of industries to yield eco-industrial parks as well as their corresponding configurations, and determining the effects of the wastewater discharges in the surrounding watershed while considering as objective functions the minimization of the total annualized costs (TAC) and the minimization of the environmental impact on the surrounding watershed. The TAC is composed by the fresh sources costs, the treatment costs and piping costs. Additionally, to get a reduction in the pollutant concentrations discharged to the final disposal, this work proposes designing EIPs interacting with the watershed and consequently this process will diminish the industrial effluents coming from these facilities. To carry out this task, the proposed superstructure for water integration is shown in Figure 2. It should be noted that each process source can be sent to the process sinks in the same plant or even to other industries located in the same place, to each interceptor of the first column in the central treatment unit or finally to the wastewater stream. The fresh sources are only sent to the process sinks. Once the treatment is completed, the outlet streams are sent to the process sinks of all the industrial plants and they can be sent to the discharge stream. As can be seen, Figure 2 shows an example of a recycle/reuse superstructure for two industrial plants where each plant has two process sources and two process sinks, fresh water, and three interception units for treating one pollutant (for each component considered, there is a column of interceptors).

This work employs the MFA technique to model the watershed and to track the pollutants during their flow in the watershed until the reach the final disposal (see Figure 3). As mentioned earlier, the MFA model requires the division of the main river in several sections, which are called reaches. The main branches or channels that feed to the main waterway (e.g., river) are called tributaries. It should be noted that typically a watershed interacts with several users placed on the surrounding areas such as industrial, agricultural, and residential areas. There are several natural phenomena that change the pollutant compositions such as evaporation, filtration, and the natural degradation of the compounds through biochemical reactions.[49] In addition to constraints throughout the watershed, it is also important to limit the maximum amount of pollutants that are discharged into the final disposal of the watershed (e.g., outfall or catchment area).

■ MODEL FORMULATION

Prior to describing the proposed methodology, some subscripts, superscripts, and sets employed by the mathematical formulation are

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

defined. The index r denotes a reach, t is a tributary, and p is used to refer to the group of industrial plants in the same geographical location. It should be noted that the industries in group p can be integrated through the same EIP to be located in that geographical area. Therefore, the sources and sinks that can be integrated are the ones located in the same place p and this way there can be N_{Clusters} EIPs. The index c represents a component or pollutant, i is used to denote a process source, j is employed for the process sinks, w indicates the type of fresh water, and int denotes an interceptor. The superscripts in, out, m, and max are employed to indicate inlet, outlet and upper limit, respectively. Finally, the sets R, T, P, and C are used to denote reaches, tributaries, possible industrial parks available to be reconfigured, and compounds, respectively; whereas the sets for process sources, process sinks, and the types of fresh waters are represented by I, J, and W, respectively, as well as INT represents the interceptors.

Material Flow Analysis Technique. The material flow analysis (MFA) approach is used to track the quality of the water in the watershed before and after the retrofitting modifications. The MFA technique includes the chemical and biochemical interactions due to the natural degradation generated by the flora and fauna of the watersheds. As shown by Figure 3, the MFA model makes a subdivision of the watershed in reaches and tributaries. Then, the mathematical expressions required by this approach correspond to water and pollutant balances in each section of the system; these are described below.

Overall Balance for Each Reach. The flowrate leaving the reach r (Q_r) must be equal to the flowrate entering in the same reach r (Q_{r-1}), plus the precipitation (P_r), direct industrial discharges (D_r), residential discharges (H_r), the sum of all effluents entering to the reach ($FT_{r,t}$), the industrial discharges for the industries belonging to the industrial park available to be reconfigured in an eco-industrial park p associated to the reach r ($IP_{p(r)}$), and the eco-industrial discharges from the park p discharging at reach r after the reconfiguration ($EP_{p(r)}$), minus the terms of losses (owing to filtration and evaporation) (L_r) and uses (U_r) in the r section of the river, which is stated as follows:

$$Q_r = Q_{r-1} + P_r + D_r + H_r + \sum_{t=1}^{N_{t(r)}} FT_{r,t} + IP_{p(r)} + EP_{p(r)} - L_r - U_r, \quad \forall\, r \in R \tag{1}$$

where $N_{t(r)}$ refers to the total number of tributaries that are discharged to the reach r. In previous relationship, the flowrate leaving the reach $r-1$ is the same that the flowrate at the inlet for the reach r, as well as it requires to make an association between each industrial park available to be reconfigured as an eco-industrial park and the reach where the park discharges its waste stream.

Component Balance for Each Reach. For the component balance in the reaches, each term of the previous equation is multiplied by its concentration to obtain a balance in terms of mass instead of flowrate and only is incorporated the reactive term ($\int_{V=0}^{V_r} r_{c,r} dV_r$), which considers the chemical reactions that are carried out in that section of the river; usually, the chemical reactions decompose the components in the system. Thus, the component balance for each reach can be written as follows:

$$Q_r CQ_{c,r} = Q_{r-1} CQ_{c,r-1} + P_r CP_{c,r} + D_r CD_{c,r} + H_r CH_{c,r} + \sum_{t=1}^{N_{t(r)}} FT_{r,t} CT_{c,r,t} + IP_{p(r)} CIP_{c,p(r)} + EP_{p(r)} CEP_{c,p(r)} - L_r CL_{c,r} - U_r CU_{c,r} - \int_{V=0}^{V_r} r_{c,r} dV_r, \quad \forall\, c \in C, r \in R \tag{2}$$

Overall Balance for Each Tributary. According to the MFA technique, each reach can receive flowrates from several tributaries; these tributaries are channels or river branches that drag the chemical compounds from different polluted sources to the reaches or to the central river. Then, the total flowrate discharged from the tributary t to the reach r ($FT_{r,t}$) is equal to the sum of the following types of discharges: residual discharges without treatment ($S_{r,t}^{\text{untreated}}$), with treatment ($S_{r,t}^{\text{treated}}$), industrial discharges ($I_{r,t}$), pluvial discharges ($P_{r,t}$), direct discharges ($D_{r,t}$), discharges coming from industries inside the industrial parks selected to be readjusted as an eco-industrial park p discharging at tributary t of the reach r ($IP_{p(r)}$) and the wastewater stream of the eco-industrial park p discharged at tributary t of the reach r ($EP_{p(r)}$), minus the losses ($L_{r,t}$) and use or extraction ($U_{r,t}$) of water. Therefore, this balance is established as follows:

$$FT_{r,t} = S_{r,t}^{\text{untreated}} + S_{r,t}^{\text{treated}} + I_{r,t} + P_{r,t} + D_{r,t} + IP_{p(r,t)} + EP_{p(r,t)} - L_{r,t} - U_{r,t}, \quad \forall\, r \in R, t \in T \tag{3}$$

Component Balance for Each Tributary. Similarly to the case of the reaches, the following relationship is obtained multiplying each term of the previous equation by the pollutant concentrations and also it is considered the chemical reaction term:

$$FT_{r,t} CT_{c,r,t} = S_{r,t}^{\text{untreated}} CS_{c,r,t}^{\text{untreated}} + S_{r,t}^{\text{treated}} CS_{c,r,t}^{\text{treated}} + I_{r,t} CI_{c,r,t} + P_{r,t} CP_{c,r,t} + D_{r,t} CD_{c,r,t} + IP_{p(r,t)} CIP_{c,p(r,t)} + EP_{p(r,t)} CEP_{c,p(r,t)} - L_{r,t} CL_{c,r,t} - U_{r,t} CU_{c,r,t} - \int_{V=0}^{V_{r,t}} r_{c,r,t} dV_{r,t}, \quad \forall\, c \in C, r \in R, t \in T \tag{4}$$

It should be noted that to determine the current conditions (prior to the implementation of the proposed methodology), in the previous equations the values of $IP_{p(r)}$ and $CIP_{p(r)}$ associated to each industry available for the readjustment in the eco-industrial parks have values greater than zero and the terms related to the eco-industrial discharges once the reconfigurations is done ($EP_{p(r)}$ and $CEP_{p(r)}$) must be equal to zero; however, the roles are inverted after the reconfiguration in eco-industrial parks.

Reactive Terms. The terms to simulate the chemical and biochemical reactions that occur in the watersheds included in eqs 2 and 4 are described as follows:

$$\int_{V=0}^{V_r} r_{c,r} dV_r = k_c (CQ_{c,r})^{\sigma_c} V_r, \quad \forall\, c \in C, r \in R \tag{5}$$

$$\int_{V=0}^{V_{r,t}} r_{c,r,t} dV_{r,t} = k_c (CT_{c,r,t})^{\sigma_c} V_{r,t}, \quad \forall\, c \in C, r \in R, t \in T \tag{6}$$

where k_c is the kinetic constant for the compound c, σ_c is the reaction order for each component, $CQ_{c,r}$ is the concentration of the pollutants in the reach r and V_r is the volume of the reach; whereas $CT_{c,r,t}$ is the concentration for pollutant c in the tributary t that discharges in the reach r and $V_{r,t}$ is the volume of the tributary. It should be noted that the parameters k_c, σ_c, V_r, and $V_{r,t}$ should be experimentally measured.

Agricultural Discharges and Uses. The agricultural sector demands huge amounts of water for its adequate operation. Water is taken from watersheds. Also, a portion of this water is returned to the watershed mainly through filtration. In this context, this work considers a simplified way to determine the agricultural discharges and uses, which is represented as follows:

$$D_{r,t} = \alpha_{r,t} A_{r,t}, \quad \forall\, r \in R, t \in T \tag{7}$$

$$U_{r,t} = \beta_{r,t} A_{r,t}, \quad \forall\, r \in R, t \in T \tag{8}$$

where $\alpha_{r,t}$ is a known parameter for the water required per area cultivated and its units are m^3/acre s, $\beta_{r,t}$ is the discharged flowrate per area cultivated and its units also are m^3/acre s. $A_{r,t}$ is the cultivated area related to the tributary t that discharges to the reach r and its units are m^3.

Reconfiguration to Eco-Industrial Parks. The proposed model to synthesize EIPs that integrated water networks of grouped plants is based on the superstructure shown in Figure 2. Each process source in each plant can be sent directly to the process sinks, to the central treatment unit or to the waste stream; whereas the fresh water only can be received by the process sinks and finally the streams at the exit

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

of the treatment are segregated to be directed to the process sinks as well as to the wastewater stream. Notice that each treatment stage only can treat a single pollutant as well as the proposed methodology does not require a special index for each plant inside the industrial park (then the process sources and process sinks are consecutively located and it is identified previously to the optimization), but it is required the index p for the whole industrial park available to be readjusted into an eco-industrial park.

Overall Balance for Each Process Source. The flowrate of each process source i for each industrial park available for the reconfiguration p ($FS_{i,p}$) is segregated and sent to the process sinks ($fss_{i,j,p}$), to the first treatment stage ($fsi_{i,int=1,p}$) and to the waste stream ($fse_{i,p}$). This is stated as follows:

$$FS_{i,p} = \sum_{j=1}^{J} fss_{i,j,p} + \sum_{int=1}^{INT} fsi_{i,int=1,p} + fse_{i,p}, \quad \forall\ i \in I,\ p \in P \tag{9}$$

Overall Balance for Each Process Sink. The flowrate at the inlet of each process sink j in each industrial park p ($FU_{j,p}$) is given and it must be provided by the flowrates coming from process sources ($fss_{i,j,p}$), the exit of the interception network ($fis_{int=NT,j,p}$) and fresh water ($fws_{w,j,p}$), which is established as follows:

$$FU_{j,p} = \sum_{i=1}^{I} fss_{i,j,p} + \sum_{int=NT}^{INT} fis_{int=NT,j,p} + \sum_{w=1}^{W} fws_{w,j,p}, \quad \forall\ j \in J,\ p \in P \tag{10}$$

Component Balance for Each Process Sink. Each term of the previous balance is multiplied by its concentration for each pollutant as follows:

$$FU_{j,p}cu_{c,j,p} \geq \sum_{i=1}^{I} fss_{i,j,p}cs_{c,i,p} + \sum_{int=NT}^{INT} fis_{int=NT,j,p}ci^{out}_{c,int=NT,p} + \sum_{w=1}^{W} fws_{w,j,p}cw_{c,w,p}, \quad \forall\ c \in C,\ j \in J,\ p \in P \tag{11}$$

where $cu_{c,j,p}$ is the pollutant concentration in each process sink, $cs_{c,i,p}$ is the component concentration in each process source, $ci^{out}_{c,int=NT,p}$ represents the pollutant concentration at the outlet of the interception network and finally the pollutant concentration in each fresh water is represented by $cw_{c,w,p}$.

Overall Balance at the Inlet of the Interceptors. The flowrate entering to the first stage of the interception network ($FI_{int=1,p}$) is provided by the process sources ($fsi_{i,int,p}$):

$$FI_{int,p} = \sum_{i=1}^{I} fsi_{i,int,p}, \quad \forall\ int = 1,\ p \in P \tag{12}$$

Component Balance at the Inlet of the Interceptors. A component balance at the inlet of the interception network is required to determine the pollutant concentration at this point ($ci^{in}_{c,int,p}$). This relationship is written as follows:

$$FI_{int,p}ci^{in}_{c,int,p} = \sum_{i=1}^{I} fsi_{i,int,p}cs_{c,i,p}, \quad \forall\ c \in C,\ int \in INT;\ p \in P \tag{13}$$

Overall Mass Balances in the Interception Network after Stage 1. According to the proposed model, only a pollutant is treated in each stage of the interception network, then the number of stages required is the same than the number of pollutants. This way, the inlet flowrate to any stage of the interception network, excluding the first one ($FI_{int\neq 1,p}$), is supplied by the sum of the outlet flows from the previous stage of the interception network ($fii_{int=int-1,p}$). This is stated as follows:

$$FI_{int,p} = \sum_{int=int-1}^{int=NT} fii_{int,p}, \quad \forall\ int \neq 1,\ p \in P \tag{14}$$

It should be noted that the flowrate at the exit of the last stage is split and sent to the process sinks ($fis_{int=NT,p}$) and to the environment ($fie_{int=NT,p}$):

$$FI_{int,p} = \sum_{j=1}^{J} fis_{int,j,p} + fie_{int,p}, \quad \forall\ int = NT,\ p \in P \tag{15}$$

Similarly, the following relationship is used to determine the concentration in the inner stages:

$$FI_{int,p}ci^{in}_{c,int,p} = \sum_{int=int-1}^{int=NT} fii_{int,p}ci^{out}_{c,int,p}, \quad \forall\ c \in C,\ int \neq 1,\ p \in P \tag{16}$$

where $ci^{in}_{c,int,p}$ represents the pollutant concentration at the inlet of the interceptor int and $ci^{out}_{c,int,p}$ is the outlet pollutant concentration in the interceptor int.

It is important to remark that a fictitious interceptor is placed at the end of each treatment stage with the purpose to implement a bypass; this interceptor has a cost equal to zero and it cannot remove any pollutant.

Interception Balances. This work considers a given conversion factor ($RR_{c,int}$) that models the efficiency of each available technology int to remove the pollutant c. This factor can be fixed prior to the optimization process and it is useful to determine the pollutant concentration at the outlet of each interceptor ($ci^{out}_{c,int,p}$):

$$ci^{out}_{c,int,p} = ci^{in}_{c,int,p}(1 - RR_{c,int}), \quad \forall\ c \in C,\ int \in INT,\ p \in P \tag{17}$$

Additionally, to calculate the operating cost of the system it is needed to know the removed pollutant load ($cim_{c,int,p}$), which is carried out by the following relationship:

$$cim_{c,int,p} = FI_{int,p}(ci^{in}_{c,int,p} - ci^{out}_{c,int,p}), \quad \forall\ c \in C,\ int \in INT,\ p \in P \tag{18}$$

Overall Balance at the Mixer Prior to the Wastewater Stream. The flowrate discharged to the environment by the reconfigured eco-industrial park (FE_p) is supplied by the portions of flowrates coming from the process sources ($fse_{i,p}$) and from the exit of the interception network ($fie_{int,p}$):

$$EP_p = \sum_{i=1}^{I} fse_{i,p} + \sum_{int=1}^{INT} fie_{int,p}, \quad \forall\ p \in P \tag{19}$$

Component Balance at the Mixer Prior to the Wastewater Stream. This equation is obtained multiplying each term of the previous balance times its concentration:

$$EP_pCEP_{c,p} = \sum_{i=1}^{I} fse_{i,p}cs_{c,i,p} + \sum_{int=NT}^{NT} fie_{int,p}ci^{out}_{c,int,p}, \quad \forall\ c \in C,\ p \in P \tag{20}$$

It should be noted that the flowrate (EP_p) and the pollutant concentration ($CEP_{c,p}$) discharged to the environment are related to the MFA technique owing that this wastewater stream impacts the surrounding watershed.

Environmental Constraints through the Watershed. There are also needed environmental constraints for the pollutant concentrations through the watershed depending on the required use in each reach:

$$CEP_{c,p} \leq CEP^{max}_{c,p}, \quad \forall\ c \in C,\ p \in P \tag{21}$$

Pipelines. This work also considers the pipeline costs in the mathematical formulation. Notice that this is an important factor for eco-industrial parks (where the involved distances to transport the flowrates are significant). In this regard, the first step consists of

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

determining the existence of the required pipeline; to carry out this task, the flowrate in the pipeline must be greater than a minimum value and lower than a maximum value. Thus, the following relationships determine the existence of the required pipelines between process sources and sinks:

$$M^{min}_{fss_{i,j,p}} x^1_{i,j,p} \le fss_{i,j,p} \le M^{max}_{fss_{i,j,p}} x^1_{i,j,p}, \quad \forall\, i \in I,\, j \in J,\, p \in P \tag{22}$$

where $x^1_{i,j,p}$ is a binary variable used to model the existence of the pipeline between process sources and sinks in the eco-industrial park p.

For the pipeline among the process sources and the interception network in each eco-industrial park:

$$M^{min}_{fsi_{i,int,p}} x^2_{i,int,p} \le fsi_{i,\text{int},p} \le M^{max}_{fsi_{i,int,p}} x^2_{i,int,p}, \quad \forall\, i \in I,\, int = 1,\, p \in P \tag{23}$$

where $x^2_{i,int,p}$ is the associated binary variable.

Once the treatment is carried out in the central unit, it must consider the pipeline at the exit of the interception network to the process sinks:

$$M^{min}_{fis_{int,j,p}} x^3_{int,j,p} \le fis_{int,j,p} M^{max}_{fis_{int,j,p}} x^3_{int,j,p}, \quad \forall\, int = NT,\, j \in J,\, p \in P \tag{24}$$

where $x^3_{int,j,p}$ is the binary variable related to this case.

Also, the pipeline between the outlet of the treatment unit and the mixer prior to the wastewater stream is considered:

$$M^{min}_{fie_{int,p}} x^4_{int,p} \le fie_{int,p} \le M^{max}_{fie_{int,p}} x^4_{int,p}, \quad \forall\, int = NT,\, p \in P \tag{25}$$

where $x^4_{int,p}$ is the binary variable to determine the existence of pipeline among the interception network and the wastewater stream. In previous relationships, M^{min} represents the minimum value of the flowrate required to consider its existence, M^{max} is an upper value for the flowrate associated to each section of the pipes.

Economic Objective Function. The economic objective function consists of minimizing the total annual cost (TAC), which is constituted by the fresh water cost (FWC), treatment costs (TC), and pipeline costs (PC); then, each component of the TAC is described as follows.

Fresh Water Cost. The cost for the fresh water provided to the system can be obtained through the following expression:

$$FWC = H_Y Dsh \sum_{p=1}^{P} \sum_{j=1}^{J} \sum_{w=1}^{W} CU_w f\, ws_{w,j,p} \tag{26}$$

where H_Y is the operating hours for the eco-industrial parks, Dsh represents the conversion of seconds into hours and CU_w is the cost for the fresh water w.

Treatment Cost. The cost function for interceptors includes fixed and variable costs as follows:

$$TC = K_F \sum_{p=1}^{P} \sum_{int=1}^{INT} CU_{int} z^{treat}_{int,p} + H_Y \sum_{p=1}^{P} \sum_{int=1}^{INT} \sum_{c=1}^{C} CUM_{c,int} cim_{c,int,p} \tag{27}$$

where K_F is a factor used to annualize the investment, CU_{int} is the fixed charge for the interceptor int, $z^{treat}_{int,p}$ represents the binary variable for the interceptors and $CUM_{c,int}$ is the unit cost for the mass removed of the pollutant c for each interceptor.

It should be noted that a couple of restrictions are needed to activate the binary variables for the interceptors:

$$M^{min}_{FI_{int,p}} z^{treat}_{int,p} \le FI_{int,p} \le M^{max}_{FI_{int,p}} z^{treat}_{int,p}, \quad \forall\, int \in INT,\, p \in P \tag{28}$$

Piping Cost. The cost for each pipeline segment is determined as follows:[16]

$$\begin{aligned} PC = K_F \sum_{p=1}^{P} \Bigg[& cpp \sum_{i=1}^{I} \sum_{j=1}^{J} \frac{D^1_{i,j,p} fss_{i,j,p}}{3600 \rho v} + x^1_{i,j} D^1_{i,j,p} CUP \\ & + cpp \sum_{int=1}^{INT=1} \sum_{i=1}^{I} \frac{D^2_{i,int,p} fsi_{i,int,p}}{3600 \rho v} + x^2_{i,int} D^2_{i,int,p} CUP \\ & + cpp \sum_{int=NT}^{INT=NT} \sum_{j=1}^{J} \frac{D^3_{int,j,p} fis_{int,j,p}}{3600 \rho v} + x^3_{int,j} D^3_{int,j,p} CUP \\ & + cpp \sum_{int=NT}^{INT=NT} \frac{D^4_{int,p} fie_{int,p}}{3600 \rho v} + x^4_{int} D^4_{int,p} CUP \Bigg] \end{aligned} \tag{29}$$

where D represents the length of each pipe segment, ρ is the density, v is the velocity, cpp is a parameter for cross-plant pipeline cost and finally CUP represents the unit cost.

Finally, the TAC is equal to the sum of the previous terms:

$$TAC = FWC + TC + PC \tag{30}$$

Environmental Objective Function. The environmental objective function accounts for the sustainability of the final disposal at the end of the watershed, which is determined by the minimization of the pollutants discharged to catchment area to ensure the natural degradation of the pollutants:

$$EOF = CQ_c^{\text{final}} \tag{31}$$

where CQ_c^{final} represents the target values for the concentration of the pollutants discharged to the final disposal. In this context, these values must be determined prior to the optimization process. Then, if it is desired to generate sustainable systems, the maximum concentration for each pollutant that can be decomposed at the final disposal through natural interaction has to be quantified and set as target.

Multiobjective Optimization. The problem is formulated as a multiobjective optimization formulation, where one objective is minimizing the TAC and the other one is minimizing the EOF, which is stated as follows:

$$\text{objective function} = \min TAC;\ \min EOF \tag{32}$$

It should be noted that the objective functions contradict each other. Owing to obtain an adequate environmental performance (EOF), in other words low values for the pollutant compositions, it is necessary to increase the treatment in the EIPs in order to reduce their polluted discharges; consequently the costs augment. While low values for the total annual cost are associated to lower levels for treatment of discharges, which conducts to discharge higher values for the concentrations of the pollutants; this scheme yields low costs and high levels for the pollutants discharged to the final disposal.

It is important to remark that most of the nonlinearities included in the mathematical model formulation are bilinear terms. In this context, equation (2) presents the product $Q_r CQ_{c,r}$, relationship (4) contains $FT_{r,t} CT_{c,r,t}$, expressions (5) and (6) consider the reaction order σ_c for the unknown concentrations $CQ_{c,r}$ and $CT_{c,r,t}$, respectively. Whereas, constraint 11 includes the term $fis_{int=NT,j,p} ci^{out}_{c,int=NT,p}$, eqs (13) and (16) involve the product $FI_{int,p} ci^{in}_{c,int,p}$, in relationship (18) all the symbols accounted are unknown variables ($cim_{c,int,p}$, $FI_{int,p}$, $ci^{in}_{c,int,p}$ and $ci^{out}_{c,int,p}$) and finally constraint (20) considers the term $EP_p CEP_{c,p}$. It should be noticed that all the previous symbols are optimization variables (with exception of the exponent σ_c).

To solve this multiobjective optimization formulation, the epsilon constraint optimization approach was implemented to obtain Pareto solutions that compensate the contradicting objectives.[50−53] It should be noted that the model formulation corresponds to a multiobjective mixed-integer nonlinear programming problem. The software GAMS[54] was used to solve this problem using the algorithm DICOPT in a computer with an Intel Core i7-3612QM CPU processor at 2.10 GHz and 6.00 GB of RAM. Finally, it should be mentioned that the problem is solved employing a deterministic mathematical programming method owing to the large number of degrees of freedom

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

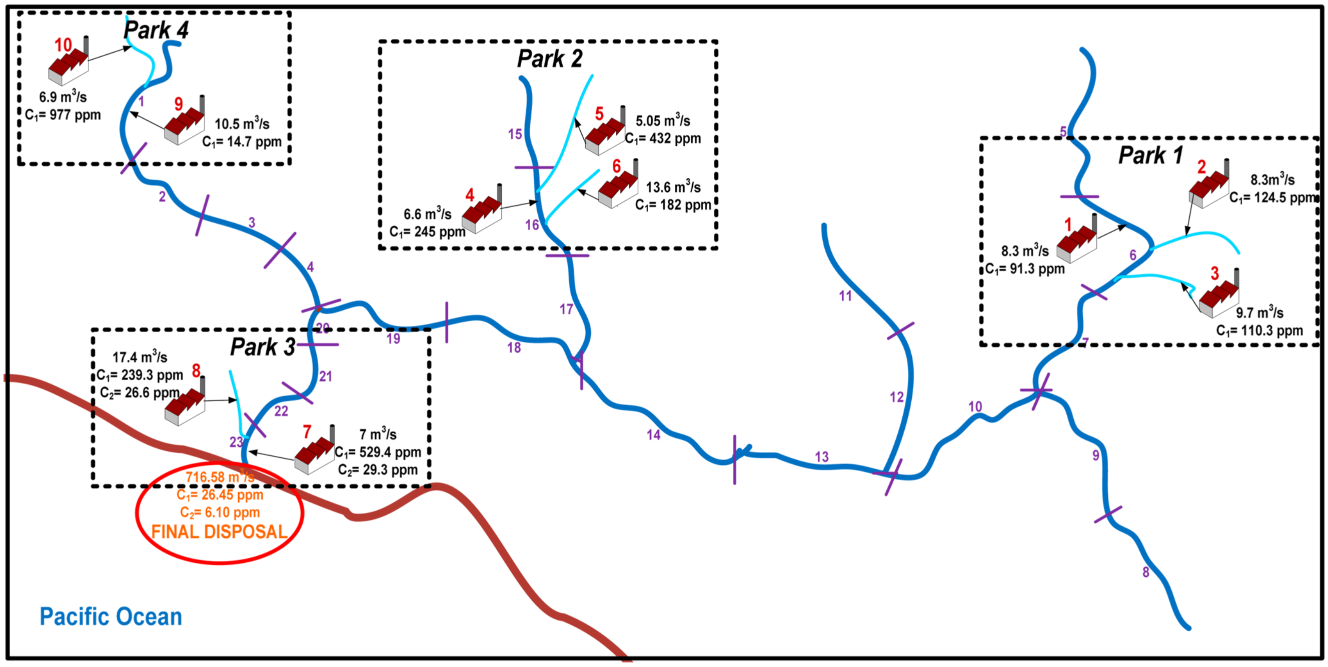


Figure 4. Industrial parks located at Balsas watershed.

generated by the model, which complicates the use of multiobjective stochastic optimization algorithms.

RESULTS AND DISCUSSION

A case study is solved to show the capabilities of the proposed optimization approach. This example considers the Balsas watershed, which is one of the most important watersheds in Mexico and covers 117 305 km^2. This system is impacted by several wastewater effluents (such as industrial, agricultural, residential discharges and wastewater streams from power plants); however, the most polluted discharges are the industrial effluents. Additionally, as can be seen in Figure 4, the Balsas watershed has been divided in 23 reaches, where there are four industrial parks available to be reconfigured as eco-industrial parks with the purpose to reduce the pollutant concentrations at the final disposal. Notice that parks 1 and 2 are composed of three industrial plants, whereas parks 3 and 4 contain two industrial plants each one; giving a total of ten industries available to participate in the implementation of the methodology. In this context, this example considers two pollutants where the pollutant 1 is the most toxic compound.

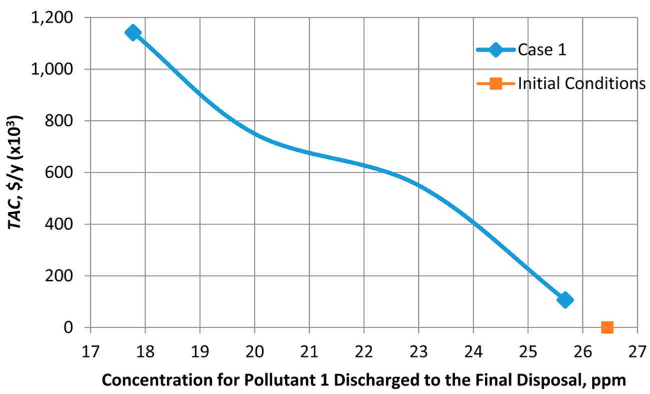


Figure 5. Pareto curve for Case 1.

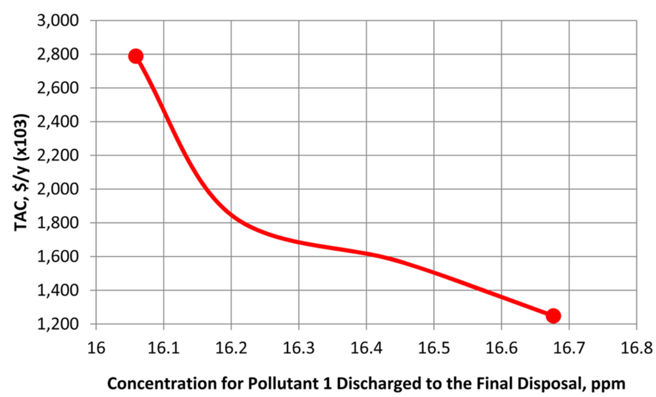


Figure 6. Pareto curve for Case 2.

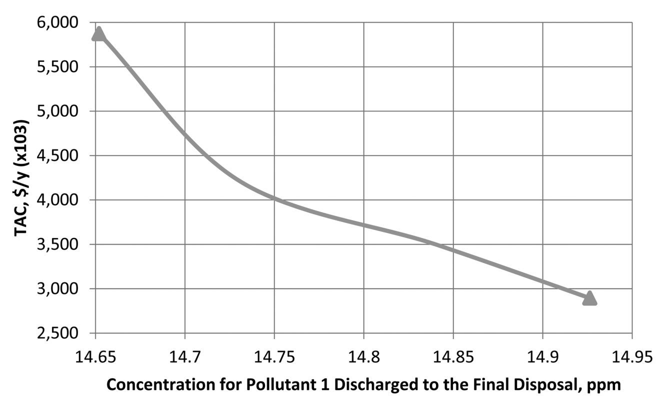


Figure 7. Pareto curve for Case 3.

Also, Figure 4 shows the flowrates and the pollutant concentrations discharged by each individual plant (it should be noted that the information is the result of the sum of all the process sources for each industry, which are discharged to the environment without any treatment) as well as the current conditions for the final disposal (prior to the implementation of

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

Table 1. Sources and Sinks for Each Plant

	sinks				sources			
plant	process sink	flowrate (m^3/s)	pollutant composition 1 (ppm)	pollutant composition 2 (ppm)	process source	flowrate (m^3/s)	pollutant composition 1 (ppm)	pollutant composition 2 (ppm)
1	1	2.22	70		1	3.33	80	
	2	3.33	80		2	2.22	110	
	3	2.78	100		3	2.78	90	
2	4	3.61	90		4	3.61	125	
	5	2.50	110		5	1.67	95	
	6	4.17	120		6	3.06	140	
3	7	3.06	115		7	2.64	120	
	8	4.44	85		8	3.19	115	
	9	2.22	125		9	3.89	100	
4	10	0.56	0		10	0.56	100	
	11	1.85	50		11	1.85	80	
	12	2.78	50		12	2.78	100	
	13	1.16	80		13	1.16	800	
	14	0.28	400		14	0.28	800	
5	15	0.56	0		15	0.56	100	
	16	1.85	50		16	1.85	80	
	17	0.43	80		17	0.43	400	
	18	1.19	100		18	2.02	800	
	19	0.19	400		19	0.19	1000	
6	20	0.56	0		20	0.56	100	
	21	2.22	25		21	2.22	50	
	22	1.39	25		22	1.39	125	
	23	1.11	50		23	1.11	800	
	24	8.33	100		24	8.33	150	
7	25	2.78	3	20	25	2.78	35	600
	26	3.61	1	80	26	3.61	30	500
	27	0.69	3	0	27	0.69	3	400
8	28	8.33	2	15	28	8.33	30	0
	29	5.56	8	70	29	5.56	35	400
	30	3.47	2	30	30	3.47	5	550
9	31	3.75	5		31	2.78	10	
	32	4.33	12		32	4.17	15	
	33	5.42	9		33	3.61	18	
10	34	4.17	100		34	2.22	800	
	35	5.83	50		35	2.08	1.2	
	36	3.94	130		36	2.64	950	

the methodology), which receives 716.58 m^3/s with a concentration of 26.45 and 6.10 ppm for pollutants 1 and 2, respectively. The complete data for the sources and sinks for the considered plants are presented in Table 1. To model this watershed, we employ information taken from CONAGUA[55] (this is an annual report published by the Mexican commission of water). Furthermore, making an experimental study, the pollutant degradation follows a kinetic of first order with the next constants: $k_1 = 4.0284 \times 10^{-6}\ s^{-1}$ and $k_2 = 1.492 \times 10^{-6}\ s^{-1}$. Moreover, the parameters D, K_F, H_Y, CU_{int}, CUP, ρ, and υ are 100 m, 0.231/y, 8,000 h/y, 12,600 US$, 250 US$, 1,000 kg/m^3, and 1 m/s, respectively. The interceptors considered can operate with efficiencies (RR) of 0.6 and 0.8 and their costs (CUM) are 1.46 and 2.06 $/kg removed, respectively. The fresh water has a unit cost of 0.13 US$/ton.

It should be noted that the pollutant concentrations at the final disposal have high values that put at risk the aquatic life at the Pacific Ocean. Hence, it is required to implement a strategy to decrease the pollutant concentrations at this point. The discussion of the results includes several cases to solve the above-described problem. In this context, Case 1 analyzes the solution when only one industrial park is reconfigured as an eco-industrial park, Case 2 visualizes the possible solution involving two readjusted eco-industrial parks, Case 3 allows three reconfigurations and Case 4 presents the solution when all the industrial parks can be readjusted. According to each case, the generated solutions are different; however, if a greater number of industrial parks are reconfigured, the costs increase but the values for the environmental objective are reduced. In this context, Figures 5, 6, and 7 show the Pareto curves for the set of solutions for the Cases 1, 2, and 3, respectively. Notice that Case 4 corresponds to the specific solution where all the industrial parks are reconfigured. Also, notice the different scales and values in Pareto curves. The following discussion considers the extreme cases for each Pareto frontier; nevertheless, intermediate solutions can be selected by the decision-makers.

Case 1. This case includes constraints to only allow the installation of one EIP (of the four available parks). There are two aspects to be accounted for in each solution: the economic objective function and the pollutant concentration at the final disposal (environmental issue). Therefore, the best economic

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

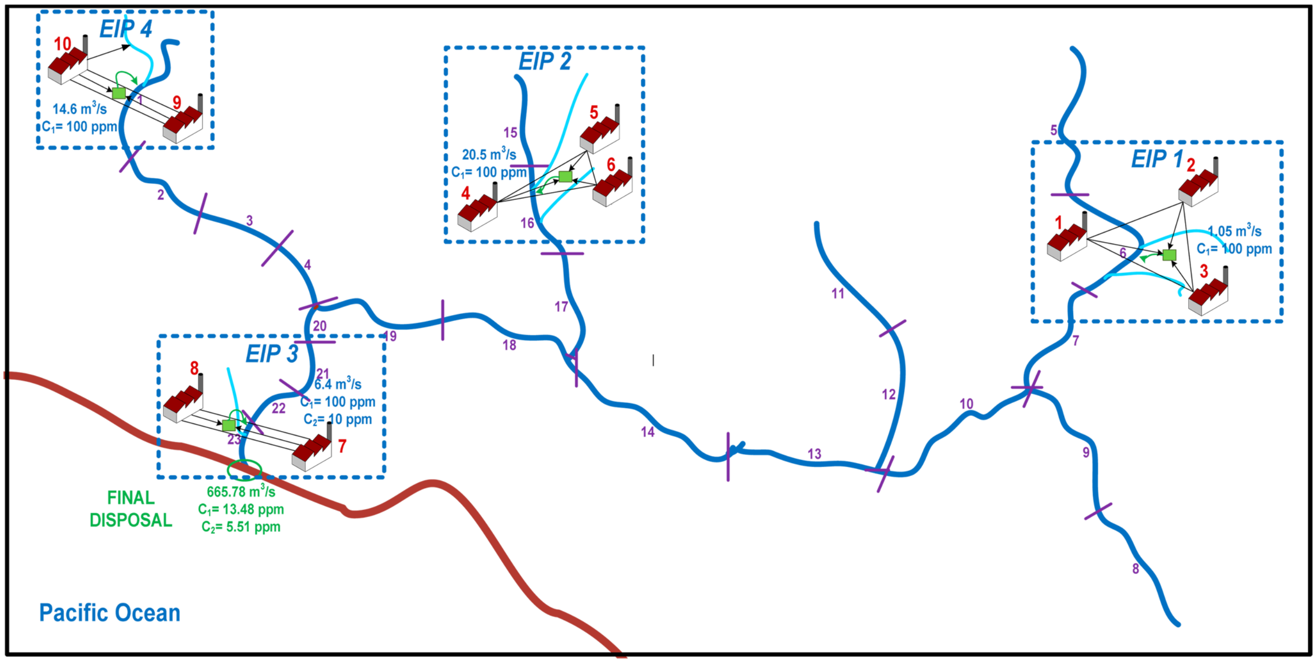


Figure 8. Industrial parks reconfigured into eco-industrial parks for the Balsas watershed.

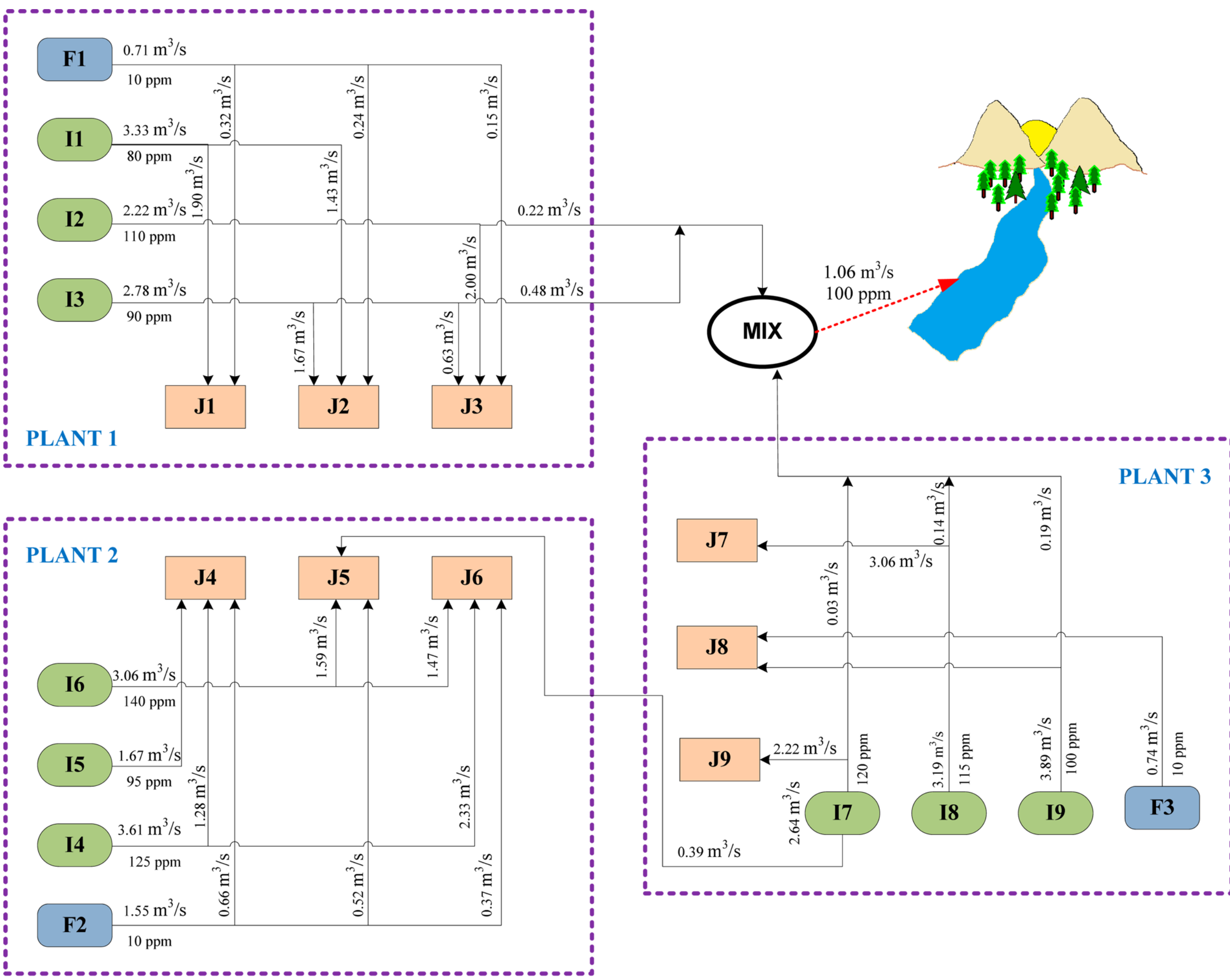


Figure 9. Optimal configuration for the eco-industrial park (EIP) 1.

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

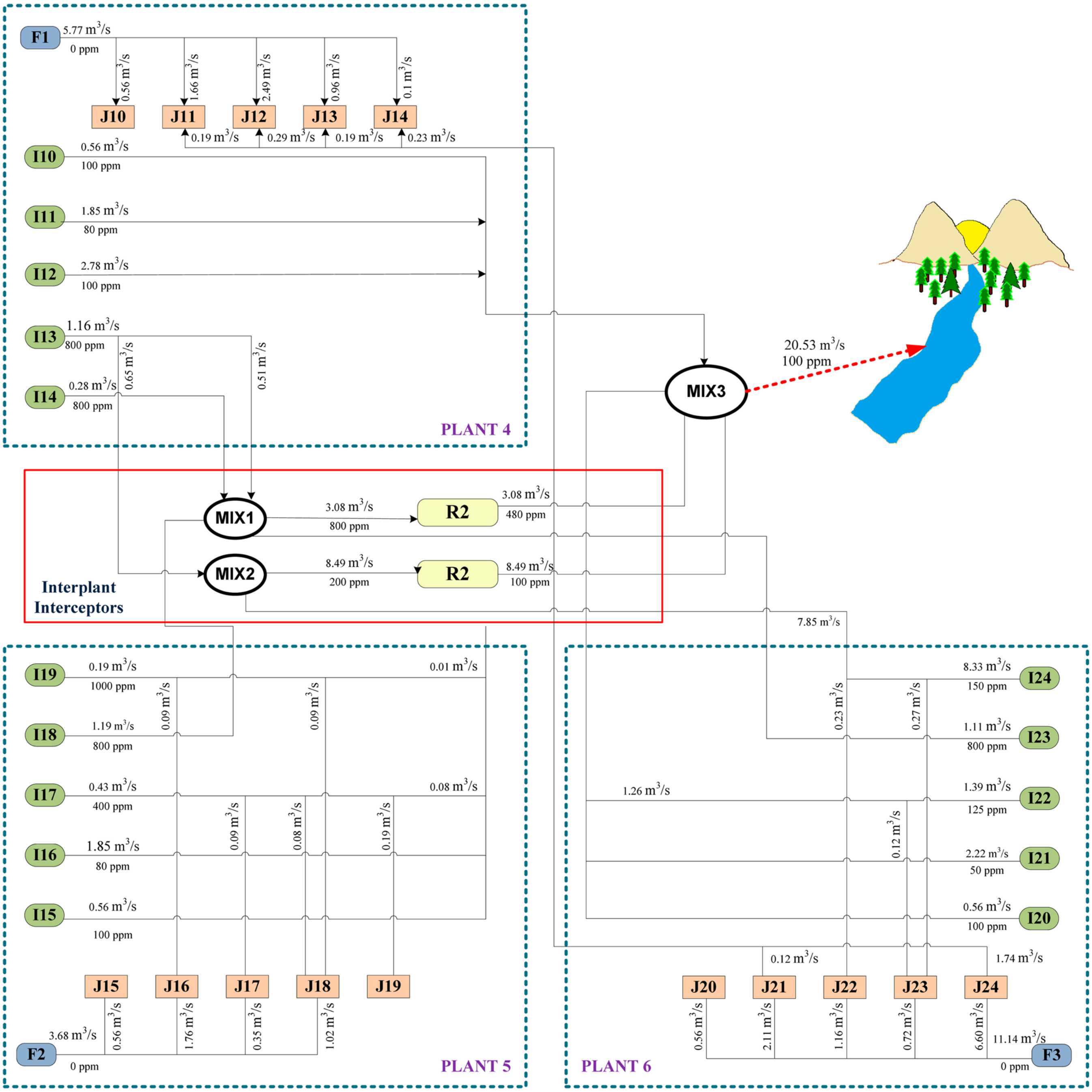


Figure 10. Optimal configuration for the eco-industrial park (EIP) 2.

solution in this section is obtained when Park 1 is modified yielding a *TAC* of $\$106.6 \times 10^3$ /y and the pollutants 1 and 2 have concentrations at the final disposal of 25.68 and 5.87 ppm, respectively. In this solution, it can be obtained a reduction of 2.9% for pollutant 1 and 3.8% for pollutant 2. Otherwise, when the environmental concern is prioritized, the selected industrial park for modification is Park 3, which achieves concentrations for the pollutants 1 and 2 of 17.78 and 5.48 ppm, respectively. In other words, it can reduce 32.78% of the pollutant 1 discharged to the Pacific Ocean and 10.16% of the pollutant 2; but the cost to reconfigure the Park 3 is $\$1,141.6 \times 10^3$/y (see Figure 5).

Case 2. This case involves the possibility to introduce up to two EIPs with the purpose of getting the lowest cost. The solution selects Parks 1 and 3 to be reconfigured and yields a *TAC* of $\$1,248.3 \times 10^3$/y, whereas the condition for the discharge to the final disposal is a concentration for pollutants 1 and 2 of 16.68 and 5.22 ppm, respectively (see Figure 6). If we consider in this case the minimization of the concentration at the final disposal for pollutant 1, the concentration for pollutants 1 and 2 are 16.06 and 5.74 ppm, respectively, involving a *TAC* of $\$2,788.8 \times 10^3$/y (representing a decrement in the concentration of pollutant 1 of 3.17% but with an increase in the *TAC* of 124%).

Case 3. This case involves the selection of up to three EIPs to be installed in Balsas watershed. The best economic solution considers the retrofitting of Parks 1, 2, and 3 and yields a *TAC* of $\$2,895.4 \times 10^3$/y with 14.93 and 5.48 ppm of pollutants 1

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

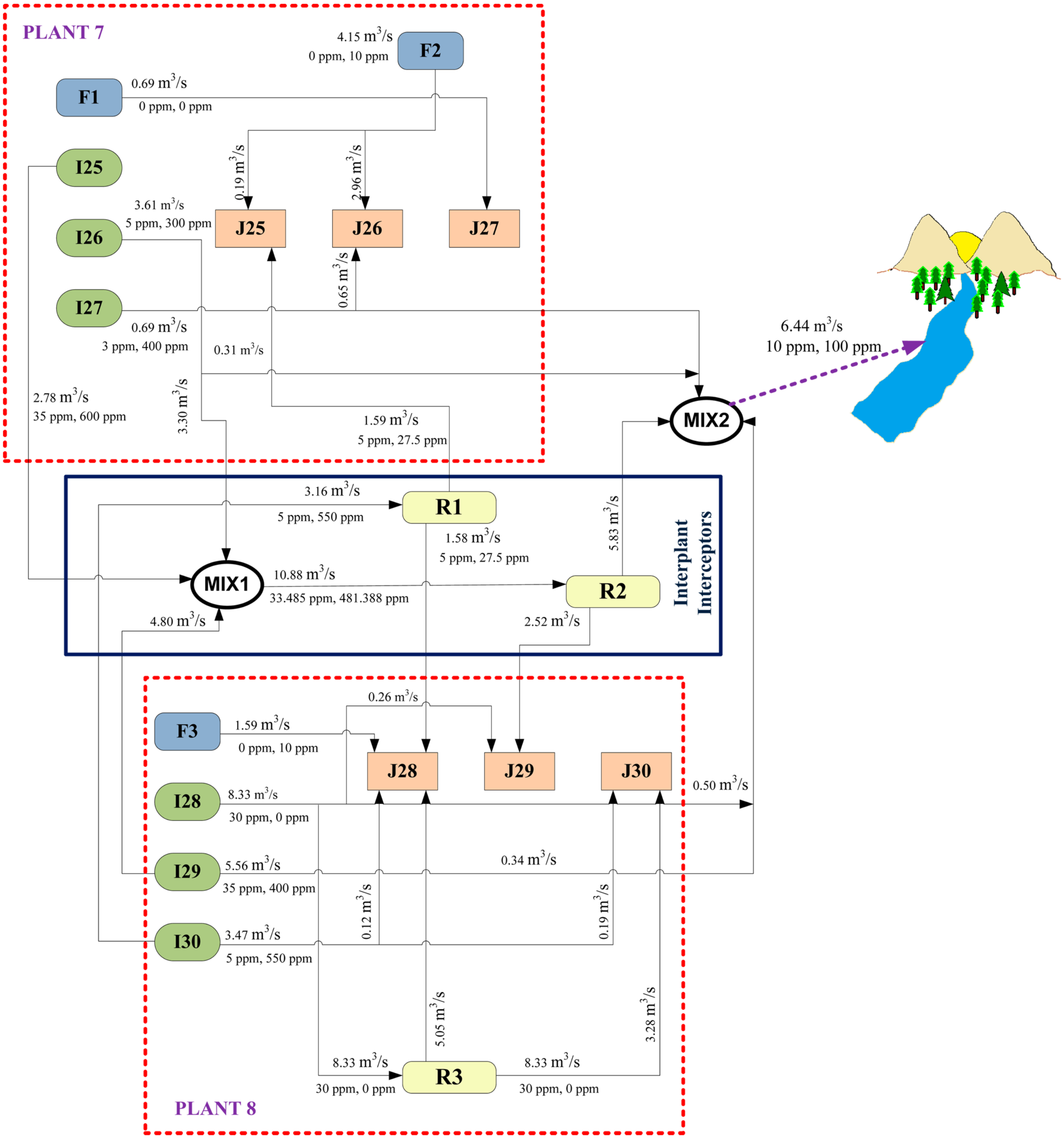


Figure 11. Optimal configuration for the eco-industrial park (EIP) 3.

and 2 discharged to the ocean, respectively (see Figure 7). Considering as optimization objective function the minimization of the concentration of pollutant 1 discharged to the ocean, the solution involves the reconfiguration of parks 2, 3, and 4; this combination has a *TAC* of \$5,873.8 × 10^3/y and discharges 14.65 ppm of pollutant 1 and 5.76 ppm of pollutant 2 to the final disposal. Furthermore, for the case when the optimal solution involves the minimization of the concentration of pollutant 2 discharged to the ocean, it is possible to get a concentration for pollutant 2 discharged to the ocean of 5.24 ppm (i.e., 4.38% lower than the best economic solution); however, the concentration of pollutant 1 has a value of 15.24 ppm and the *TAC* increases to \$4,333.4 × 10^3/y, this solution is obtained when the parks 1, 3, and 4 are reconfigured as eco-industrial parks.

Case 4. Finally, in Case 4 there is no constraint on the number of EIPs to be installed. The optimal economic solution is presented in Figure 8, whereas Figures 9−12 show the configuration for the EIPs found in Figure 8. This solution shows the wastewater stream and its concentration for each park once the reconfiguration is carried out. Comparing Figures 4 and 8, there are significant reductions in the flowrates discharged to the watershed and the fulfillment of the environmental regulations, which produces relevant environmental benefits, specifically the concentration for pollutant 1 discharged to the ocean is 13.48 ppm; pollutant 2 has a concentration of 5.51 ppm (in the original case, the

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

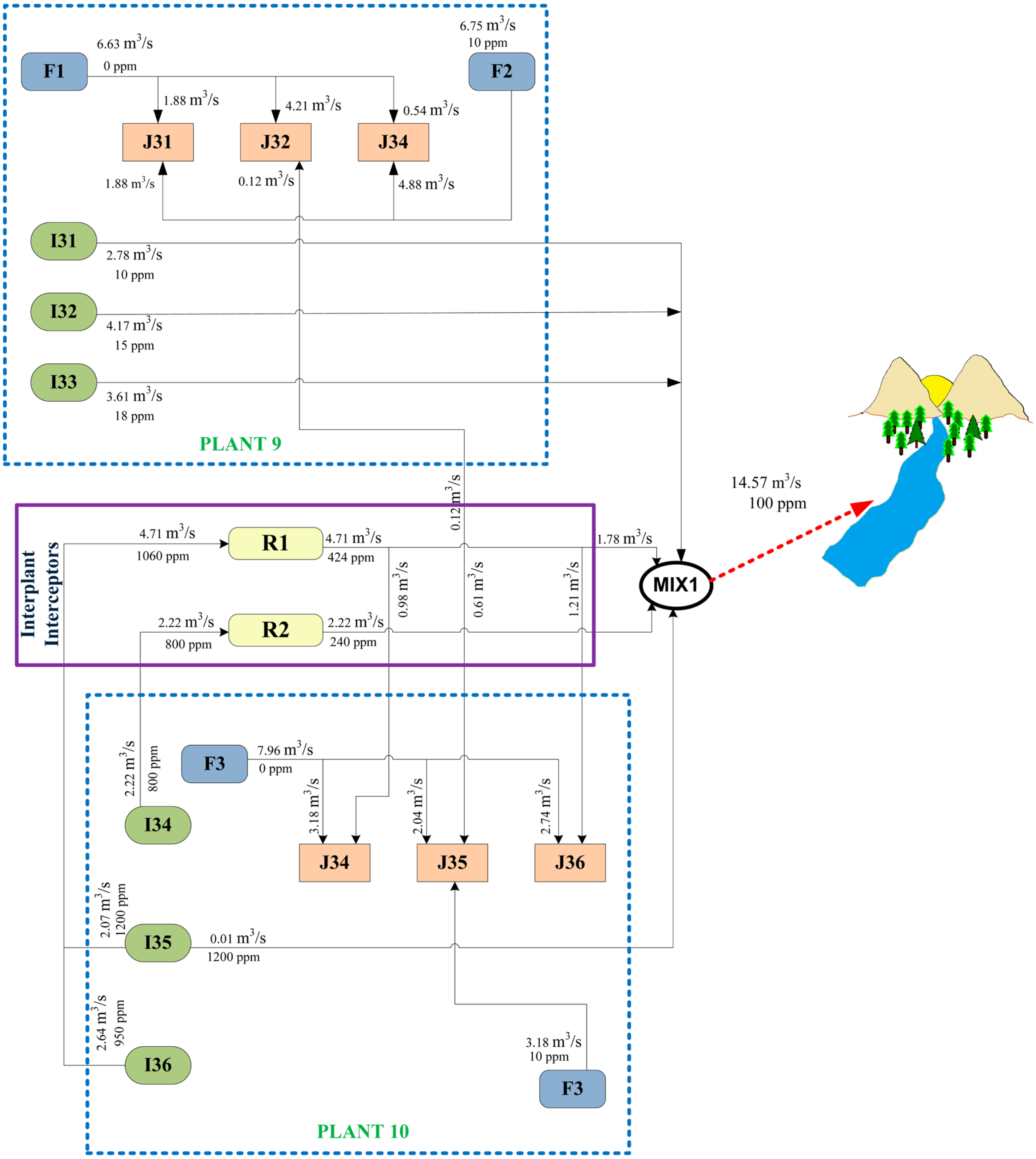


Figure 12. Optimal configuration for eco-industrial park (EIP) 4.

concentrations for pollutants 1 and 2 are 26.45 and 6.10 ppm, respectively). In this case, if the minimization of the concentration of pollutant 1 is considered, it is possible to reduce the pollutant 1 49% with respect to the initial conditions (remember that pollutant 1 is more dangerous than pollutant 2), whereas pollutant 2 can be diminished 9.67%; however, the *TAC* generated by the transformation of the four industrial parks is \$5,980.5 $\times$ 10^3/y, which represents a reduction of 65.43% with respect to the original process (\$17,298.0 $\times$ 10^3/y). For this reason, the implementation of the proposed methodology does not only include environmental benefits but it also improves the economic aspects.

Finally, this problem involves 2481 continuous variables, 1049 binary variables and 2537 constraints; the CPU time varied depending on the Pareto point, but a mean time of 9.7 s was consumed in the used computer.

■ CONCLUSIONS

This work has presented an optimization methodology for the introduction of multiple EIPs and integrating them with the surrounding watersheds. The objectives seek to minimize the environmental impact over the surrounding watershed at the minimum cost. The proposed model determines the set of industrial facilities that must be selected to be part of an EIP and provides the optimal location, sizing, and task of each EIP. The optimization approach also accounts for the interaction of the industrial effluents with other discharges and uses (agricultural, domestic, as well as several natural phenomena)

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

in the surrounding watershed. The spatial representation of the watershed includes the impact of the natural phenomena on the flows and concentrations of the pollutants.

A case study from Mexico has been presented to show the applicability of the proposed optimization formulation. Several industries located around the Balsas watershed have been considered to propose the installation of a set of EIPs in order to improve the sustainability of this watershed. The results show that it is possible to improve the water quality of the watershed at relatively low cost while satisfying the water demands.

AUTHOR INFORMATION

Corresponding Author

*J. M. Ponce-Ortega. E-mail: jmponce@umich.mx. Tel.: +52 443 3223500 ext. 1277. Fax: +52 443 3273584.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Authors acknowledge the financial support obtained from CONACyT.

NOMENCLATURE

$A_{r,t}$ cultivated area associated to the tributary *t* in the reach *r*, ha
C set for compounds $\{c \mid c = 1,...,Nc\}$
$CD_{c,r}$ concentration of the component *c* for direct discharges to the reach *r*, ppm
$CD_{c,r,t}$ concentration of the component *c* for agricultural discharges in the tributary *t* of the reach *r*, ppm
$CEP_{c,p}$ concentration of the component *c* for the discharge from the eco-industrial park *p* after the reconfiguration, ppm
$CH_{c,r}$ concentration of the component *c* for total discharges to the reach *r*, ppm
$CI_{c,r,t}$ concentration of the component *c* for industrial discharges in the tributary *t* of the reach *r*, ppm
$CIP_{c,p}$ concentration of the component *c* for the discharge of the industrial park *p* before the reconfiguration, ppm
$ci^{in}_{c,int,p}$ inlet concentration of the component *c* for the interceptor *int* in the park *p*, ppm
$ci^{out}_{c,int,p}$ outlet concentration of the compound *c* for the interceptor *int* in the park *p*, ppm
$cim_{c,int,p}$ removed load for the compound *c* in the interceptor *int* for the park *p*, g/s
$CL_{c,r}$ concentration of the component *c* for total losses in the reach *r*, ppm
$CL_{c,r,t}$ concentration of the component *c* for total losses in the tributary *t* of the reach *r*, ppm
$CP_{c,r}$ concentration of the component *c* for the precipitation discharged to the reach *r*, ppm
$CP_{c,r,t}$ concentration of the component *c* for precipitation discharges in the tributary *t* of the reach *r*, ppm
cpp parameter for capital cost for cross-plant piping
$CQ_{c,r}$ concentration of the component *c* in the reach *r*, ppm
$cs_{c,i,p}$ concentration of the component *c* for the source *i* in the park *p*, ppm
$CS^{treated}_{l,r,t}$ concentration of the component *c* for residual treated wastewater discharged to the tributary *t* of the reach *r*, ppm
$CS^{untreated}_{c,r,t}$ concentration of the component *c* for residual wastewater discharged without treatment to the tributary *t* of the reach *r*, ppm
$CT_{c,r,t}$ concentration of the component *c* for flowrate discharged from tributary *t* to the reach *r*, ppm
$CU_{c,r}$ concentration of the component *c* for water used from the reach *r*, ppm
$CU_{c,r,t}$ concentration of the component *c* for water used in the tributary *t* of the reach *r*, ppm
$cu_{c,j,p}$ concentration of the component *c* for the sink *j* in the park *p*, ppm
$CUM_{c,int}$ unit cost for the mass removed of the pollutant *c* in the interceptor *int*, US$/Kg
CU Unit cost of the pipe, US$
CU_{int} unit cost for interceptor *int*, US$
CU_w unit cost for fresh water *w*, US$/m^3
$cw_{c,w,p}$ concentration of the component *c* for the fresh source *w* in the park *p*, ppm
D length of pipe segment, m
D_r direct discharges to the reach *r*, m^3/s
$D_{r,t}$ agricultural discharges in the tributary *t* of the reach *r*, m^3/s
Dsh conversion factor to change seconds into hours, 3600 s/h
EP_p discharges coming from the eco-industrial park *p* after the reconfiguration, m^3/s
EOF environmental objective function, ppm
$FT_{r,t}$ discharge from the tributary *t* to the reach *r*, m^3/s
$fie_{int,p}$ flowrate sent from the interceptor *int* to the environment in the park *p*, m^3/s
$FI_{int,p}$ flowrate in the interceptor *int* in the park *p*, m^3/s
$fii_{int,p}$ internal flowrates for the interceptor *int* in the park *p*, m^3/s
$fis_{int,j,p}$ flowrate sent from the interceptor *int* to the sink *j* in the park *p*, m^3/s
$FS_{i,p}$ flowrate of the source *i* in the park *p*, m^3/s
FU_j flowrate entering to the sink *j* in the park *p*, ton/h
$fse_{i,p}$ flowrate of the source *i* discharged to the environment in the park *p*, m^3/s
$fsi_{i,int,p}$ flowrate sent from the source *i* to the interceptors *int* in the park *p*, m^3/s
$fss_{i,j,p}$ flowrate sent directly from the source *i* to the sink *j* in the park *p*, m^3/s
FWC fresh water cost, US$/y
$fws_{w,j,p}$ flowrate of the fresh water *w* sent to the sink *j* in the park *p*, m^3/s
H_r total discharge (i.e., industrial, sanitary) to the reach *r*, m^3/s
H_Y annual working hours, h/y
I set for process sources $\{i \mid i = 1,...,Ni\}$
$I_{r,t}$ industrial stream discharged to the tributary *t* of the reach *r*, m^3/s
INT set for interceptors $\{int \mid int = 1,...,Nint\}$
IP_p discharges coming from the industrial park *p* before the reconfiguration, m^3/s
J set for process sinks $\{j \mid j = 1,...,Nj\}$
K_F factor used to annualize the inversion, y^{-1}
k_c kinetic constant for the degradation for compound *c*
L_r total losses (filtration and evaporation) from the reach *r*, m^3/s

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

$L_{r,t}$ total losses (filtration and evaporation) in the tributary t to the reach r, m^3/s
M lower or upper values respect a specific variable
P set for parks $\{p \mid p = 1,...,Np\}$
P_r precipitation discharged to the reach r, m^3/s
$P_{r,t}$ precipitation discharged in the tributary t of the reach r, m^3/s
PC cross plant pipeline capital cost, US$/y
Q_r flowrate leaving the reach r, m^3/s
$r_{c,r}$ reaction carried out in the reach r for compound c, g/s
$r_{c,r,t}$ reaction carried out in the tributary t of the reach r for compound c, g/s
R set for reaches $\{r \mid r = 1,...,Nr\}$
$RR_{c,int}$ conversion factor for the compound c in the interceptor int, dimensionless
$S_{r,t}^{untreated}$ residual wastewater without treatment discharged to the tributary t of the reach r, m^3/s
$S_{r,t}^{treated}$ residual treated wastewater discharged to the tributary t of the reach r, m^3/s
T set for tributaries $\{t \mid t = 1,...,Nt\}$
TAC total annual cost, US$/y
TC treatment cost, US$/year
U_r water used from reach r, m^3/s
$U_{r,t}$ water used from tributary t that discharges to reach r, m^3/s
V_r volume for reach r, m^3
$V_{r,t}$ volume for tributary t from reach r, m^3
W set for types of fresh water $\{w \mid w = 1,...,Nw\}$

Greek Symbols

$\alpha_{r,t}$ required agricultural flowrate related to the tributary t that discharges to the reach r, m^3/ha s
$\beta_{r,t}$ discharged agricultural flowrate related to the tributary t that discharges to the reach r, m^3/ha s
σ_c reaction order for compound c
ρ density, Kg/m^3
v velocity, m/s

Binary Variables

$x_{i,j,p}^1$ used to determine the existence of pipe from source i to process sink j in the park p
$x_{i,int,p}^2$ used to determine the existence of pipe from source i to interceptor int in the park p
$x_{int,j,p}^3$ used to determine the existence of pipe from interceptor int to process sink j in the park p
$x_{int,p}^4$ used to determine the existence of pipe from interceptor int to environment in the park p
$z_{int,p}^{treat}$ used to determine the existence of the interceptor int in the park p

Subscripts

c compound
i source
j sink
int interceptor
p park
r reach
t tributary
w type of fresh water

Superscripts

in inlet
max upper limit
min lower limit
out outlet

REFERENCES

(1) El-Halwagi, M. M.; Gabriel, F.; Harrell, D. Rigorous graphical targeting for resource conservation via material recycle/reuse networks. *Ind. Eng. Chem. Res.* **2003**, *42*, 4319−4328.
(2) Hortua, A. C.; El-Halwagi, M. Integrated approach for simultaneous mass and property integration for resource conservation. *ACS Sustainable Chem. Eng.* **2013**, *1* (1), 29−38.
(3) Foo, D. C. Y. State-of-the-art review of pinch analysis techniques for water network synthesis. *Ind. Eng. Chem. Res.* **2009**, *48*, 5125−5159.
(4) Noureldin, M. M. B.; El-Halwagi, M. M. Synthesis of C-H-O symbiosis networks. *AIChE J.* **2015**, 1242−1262.
(5) Acobsen, N. B. Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *J. Ind. Ecol.* **2006**, *10*, 239−255.
(6) Lombardi, D. R.; Laybourn, P. Redefining industrial symbiosis. *J. Ind. Ecol.* **2012**, *16*, 28−37.
(7) Chertow, M. R. Industrial symbiosis: Literature and taxonomy. *Annual Rev. Energy Environ.* **2000**, *25*, 313−337.
(8) Ehrenfeld, J.; Gertler, N. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *J. Ind. Ecol.* **1997**, *1*, 67−79.
(9) Lamberta, A. J. D.; Boonsb, F. A. Eco-industrial parks: Stimulating sustainable development in mixed industrial parks. *Technovation* **2002**, *22* (8), 471−484.
(10) Yu, F.; Han, F.; Cui, Z. Evolution of industrial symbiosis in an eco-industrial park in China. *J. Cleaner Prod.* **2015**, *87*, 339−347.
(11) Wang, G.; Feng, X.; Hoonga, C. K. Symbiosis analysis on industrial ecological system. *Chin. J. Chem. Eng.* **2014**, *22* (6), 690−698.
(12) Foo, D. C. Y. Flowrate targeting for threshold problems and plant-wide integration for water network synthesis. *J. Environ. Manage.* **2008**, *88* (2), 253−274.
(13) Bandyopadhyay, S.; Sahu, G. C.; Foo, D. C. Y.; Tan, R. R. Segregated targeting for multiple resource networks using decomposition algorithm. *AIChE J.* **2010**, *56* (5), 1235−1248.
(14) Chew, I. M. L.; Foo, D. C. Y.; Tan, R. R. Flowrate targeting for interplant resource conservation network. Part 2: Unassisted integration scheme. *Ind. Eng. Chem. Res.* **2010**, *49* (14), 6456−6468.
(15) Chew, I. M. L.; Foo, D. C. Y. Automated targeting for interplant water integration. *Chem. Eng. J.* **2009**, *153* (1−3), 23−36.
(16) Chew, I. M. L.; Ng, D. K. S.; Foo, D. C. Y.; Majozi, T.; Gouws, J. Synthesis of direct and indirect interplant water network. *Ind. Eng. Chem. Res.* **2008**, *47*, 9485−9496.
(17) Lovelady, E. M.; El-Halwagi, M. M. Design and integration of eco-industrial parks for managing water resources. *Environ. Prog. Sustainable Energy* **2009**, *28*, 265−272.
(18) Lim, S. R.; Park, J. M. Interfactory and intrafactory water network system to remodel a conventional industrial park to a green eco-industrial park. *Ind. Eng. Chem. Res.* **2010**, *49*, 1351−1358.
(19) Rubio-Castro, E.; Ponce-Ortega, J. M.; Nápoles-Rivera, F.; El-Halwagi, M. M.; Serna-González, M.; Jimenez-Gutiérrez, A. Water integration of eco-industrial parks using a global optimization approach. *AIChE J.* **2010**, *40*, 9945−9960.
(20) Chew, I. M. L.; Thukkaivarrna, S. L.; Tan, R. R.; Foo, D. C. Y. Analysis of inter-plant water integration with direct integration schemes through game theory approach: Pareto optimal solution with interventions. *Clean Technol. Environ. Policy* **2011**, *13* (1), 49−62.
(21) Rubio-Castro, E.; Ponce-Ortega, J. M.; Serna-Gonzalez, M.; Jimenez-Gutierrez, A.; El-Halwagi, M. M. A global optimal formulation for the water integration in eco-industrial parks considering multiple pollutants. *Comput. Chem. Eng.* **2011**, *35*, 1558−1574.
(22) Tan, R. R.; Taskhiri, M. S.; Chiu, A. S. F. MILP model for energy optimization in EIP water networks. *Clean Technol. Environ. Policy* **2011**, *13* (5), 703−712.
(23) Alnouri, S. Y.; Linke, P.; El-Halwagi, M. M. Optimal interplant water networks for industrial zones: Addressing interconnectivity options through pipeline merging. *AIChE J.* **2014**, *60* (8), 2853−2874.

DOI: 10.1021/acssuschemeng.5b00276
ACS Sustainable Chem. Eng. 2015, 3, 1564−1578

(24) Rubio-Castro, E.; Ponce-Ortega, J. M.; Serna-González, M.; El-Halwagi, M. M. Optimal reconfiguration of multi-plant water networks into an eco-industrial park. *Comput. Chem. Eng.* **2012**, *44*, 58−83.

(25) Lovelady, E. M.; El-Halwagi, M. M.; Chew, I. M. I.; Ng, D. K. S.; Foo, D. C. Y.; Tan, R. R. A property-integration approach to the design and integration of eco-industrial parks. In *Design for Energy and the Environment: Proceedings of the 7th International Conference on the Foundations of Computer-Aided Process Design (FOCAPD)*; El-Halwagi, M. M., Linninger, A. A., Eds.; CRC Press/Taylor & Francis: Boca Raton, FL, 2009; pp 559−568.

(26) Rubio-Castro, E.; Ponce-Ortega, J. M.; El-Halwagi, M. M.; Pham, V. Global optimization in property-based interplant water integration. *AIChE J.* **2013**, *59* (3), 813−833.

(27) Liao, Z. W.; Wu, J. T.; Jian, B. B.; Wang, J. D.; Yang, Y. R. Design methodology for flexible multiple plant water networks. *Ind. Eng. Chem. Res.* **2007**, *46*, 4954−4963.

(28) Cheng-Liang, C.; Chung-Yen, L.; Foo, D. C. Y. Synthesis of inter-plant water networks involving batch and continuous processes. *Chem. Eng. Trans.* **2011**, *25*, 587−592.

(29) Montastruc, L.; Boix, M.; Pibouleau, L.; Azzaro-Pantel, C.; Domenech, S. On the flexibility of an eco-industrial park (EIP) for managing industrial water. *J. Cleaner Prod.* **2013**, *43*, 1−11.

(30) Bishnu, S. K.; Linke, P.; Alnouri, S. Y.; El-Halwagi, M. M. Multiperiod planning of optimal industrial city direct water reuse networks. *Ind. Eng. Chem. Res.* **2014**, *53* (21), 8844−8865.

(31) Boix, M.; Montastruc, L.; Pibouleau, L.; Azzaro-Pantel, C.; Domenech, S. Industrial water management by multiobjective optimization: From individual to collective solution through eco-industrial parks. *J. Cleaner Prod.* **2012**, *22*, 85−97.

(32) Aviso, K. B.; Tan, R. R.; Culaba, A. B. Designing eco-industrial water exchange networks using fuzzy mathematical programming. *Clean Technol. Environ. Policy* **2010**, *12* (4), 353−363.

(33) Chen, C. L.; Hung, S. W.; Lee, J. Y. Design of inter-plant water network with central and decentralized water mains. *Comput. Chem. Eng.* **2010**, *34* (9), 1522−1531.

(34) Aviso, K. B.; Tan, R. R.; Culaba, A. B.; Foo, D. C. Y.; Hallale, H. Fuzzy optimization of topologically constrained eco-industrial resource conservation networks with incomplete information. *Eng. Optim.* **2011**, *43* (3), 257−279.

(35) Tan, R. R.; Aviso, K. B.; Cruz, J. B., Jr.; Culaba, A. B. A note on an extended fuzzy bi-level optimization approach for water exchange in eco-industrial parks with hub topology. *Process Saf. Environ. Prot.* **2011**, *89* (2), 106−111.

(36) Tashkhiri, M. S.; Tan, R. R.; Chiu, A. S. F. Emergy-based fuzzy optimization approach for water reuse in an industrial park. *Resour., Conserv. Recycl.* **2011**, *55* (7), 730−737.

(37) Lovelady, E. M.; El-Halwagi, M. M.; Krishnagopalan, G. A. An integrated approach to the optimization of water usage and discharge in pulp and paper plants. *Int. J. Environ. Pollut.* **2007**, *29* (1−3), 274−307.

(38) Noureldin, M. M. B.; El-Halwagi, M. M. Synthesis of C-H-O symbiosis networks. *AIChE J.* **2015**, *61* (4), 1242−1262.

(39) Boix, M.; Montastruc, L.; Azzaro-Pantel, C.; Domenech, S. Optimization methods applied to the design of eco-industrial parks: A literature review. *J. Cleaner Prod.* **2015**, *87* (1), 303−317.

(40) El-Baz, A. A.; Ewida, K. T.; Shouman, M. A.; El-Halwagi, M. M. Material flow analysis and integration of watersheds and drain systems II: Integration and solution strategies with application to ammonium management in Bahr El-Baqar drain system. *Clean Technol. Environ. Policy* **2005**, *7* (1), 78−86.

(41) Lira-Barragán, L. F.; Ponce-Ortega, J. M.; Serna-González, M.; El-Halwagi, M. M. An MINLP model for the optimal location of the new industrial plant with simultaneous consideration of economic and environmental criteria. *Ind. Eng. Chem. Res.* **2011**, *50* (2), 953−964.

(42) Lira-Barragán, L. F.; Ponce-Ortega, J. M.; Serna-González, M.; El-Halwagi, M. M. Synthesis of water networks considering the sustainability of the surrounding watershed. *Comput. Chem. Eng.* **2011**, *35*, 2837−2852.

(43) Burgara-Montero, O.; Ponce-Ortega, J. M.; Serna-González, M.; El-Halwagi, M. M. Optimal design of distributed treatment system for the effluents discharged to the rivers. *Clean Technol. Environ. Policy* **2012**, *14*, 925−942.

(44) Burgara-Montero, O.; El-Baz, A. A.; Ponce-Ortega, J. M.; El-Halwagi, M. M. Optimal design of a distributed treatment system for increasing dissolved oxygen in watersheds through self-rotating discs. *ACS Sustainable Chem. Eng.* **2013**, *1* (10), 1267−1279.

(45) Burgara-Montero, O.; Ponce-Ortega, J. M.; Serna-González, M.; El-Halwagi, M. M. Incorporation of the seasonal variations in the optimal treatment of industrial effluents discharged to watersheds. *Ind. Eng. Chem. Res.* **2013**, *52* (14), 5145−5160.

(46) Lira-Barragán, L. F.; Ponce-Ortega, J. M.; Nápoles-Rivera, F.; Serna-González, M.; El-Halwagi, M. M. Incorporating property-based water networks and surrounding watersheds in site selection of industrial facilities. *Ind. Eng. Chem. Res.* **2013**, *52* (1), 91−107.

(47) Martinez-Gomez, J.; Burgara-Montero, O.; Ponce-Ortega, J. M.; Nápoles-Rivera, F.; Serna-González, M.; El-Halwagi, M. M. On the environmental, economic and safety optimization of distributed treatment systems for industrial effluents discharged to watersheds. *J. Loss Prev. Process Ind.* **2013**, *26* (5), 908−923.

(48) López-Villarreal, F.; Lira-Barragan, L. F.; Rico-Ramirez, V.; Ponce-Ortega, J. M.; El-Halwagi, M. M. An MFA optimization approach for pollution treading considering the sustainability of the surrounding watershed. *Comput. Chem. Eng.* **2014**, *63*, 140−151.

(49) Lovelady, E. M.; El-Baz, A. A.; El-Monayeri, D.; El-Halwagi, M. M. Reverse problem formulation for integrating process discharges with watersheds and drainage systems. *J. Ind. Ecol.* **2009**, *13*, 914−927.

(50) Haimes, Y. Y. The integration of system identification and system optimization. Ph.D. Dissertation, University of California, Los Angeles, Los Angeles, CA, 1970.

(51) Haimes, Y. Y.; Lasdon, L. S.; Wismer, D. A. On a bicriterion formulation of the problems of integrated system identification and system optimization. *IEEE Transactions on Systems, Man, and Cybernetics* **1971**, *1*, 296−297.

(52) Bixby, R. E. ; Fenelon, M.; Gu, Z.,; Rothberg, E.; Wunderling, R. MIP: Theory and practice—closing the gap. In *System Modelling and Optimization: Methods, Theory and Applications*; Powell, M. J. D., Scholtes, S., Eds.; Springer: New York, 2000; pp 19−50.

(53) Diwekar, U. M. *Introduction to Applied Optimization*; Kluwer Academic Press: Norwell, MA, 2003.

(54) Brooke, A.; Kendrick, D.; Meeruas, A.; Raman, R. *GAMS-Language guide*; GAMS Development Corp.: Washington, DC, 2015.

(55) CONAGUA. *Water Atlas in Mexico 2013*; Mexican National Water Commission: Mexico City, Mexico, 2013.