

# Synthesis of Distributed Biorefining Networks for the Value-Added Processing of Water Hyacinth

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**ABSTRACT:** Water hyacinth causes severe ecological problems in the infested water bodies. Several strategies have been proposed to eliminate this plant. Nevertheless, most of them have not been economically attractive. This paper proposes a general superstructure and a mathematical programming model for the sustainable elimination of water hyacinth through a distributed biorefining network. The proposed model optimizes the selection of the products, the siting and sizing for the processing facilities, and the selection of the markets, while accounting for technical and economic constraints. A case study for the central part of Mexico, where water hyacinth is a serious problem, is used to show the applicability of the proposed holistic approach. The results show that an optimally synthesized distributed biorefining network is capable of sustainable and economic elimination of water hyacinth from contaminated water bodies while generating value. Additionally, the results shown through Pareto curves allow the identification of a set of optimal solutions featuring trade-offs between economic and environmental objectives.

**KEYWORDS:** Water hyacinth, Biorefinery, Distributed systems, Sustainable design, Supply chain, Optimization



## INTRODUCTION

Water hyacinth (*Eichhornia crassipes*) is a key cause of concern in several water bodies (e.g., lakes, rivers, canals) around the world.<sup>1</sup> This plant grows rapidly and can completely cover water bodies, causing difficulty of navigation and depletion of nutrients and dissolved oxygen that are essential for aquatic life. These effects have negative impact on the environment, human health, and economic development.<sup>2,3</sup> To avoid the ecological problems associated with water hyacinth, several strategies have been proposed to control its growth. There are two main approaches for water hyacinth control in water bodies: one is chemical control and the other is mechanical control. Chemical control affects drastically the sustainability of the water systems because it uses herbicides and other toxic chemicals that have negative impacts in aquatic life. In addition, chemical processes for water hyacinth control are inefficient when there is substantial rain. On the other hand, the mechanical process is actually the most widely used method for water hyacinth elimination; however, the major drawback of this approach is that it consumes a lot of energy and, therefore, is economically inefficient. There are two other methods that alter directly the ecosystem. One of them is management of the habitat, which involves the change of the conditions in a given water body; however, the modifications on such conditions can cause adverse effects on others species of plants and animals. The second method is biological control,

which introduces another species into the ecosystem that must be able to consume the water hyacinth but also can affect drastically the aquatic life in the water body. It should be noted that, in many cases, water hyacinth quickly reappears due to its rapid growth.

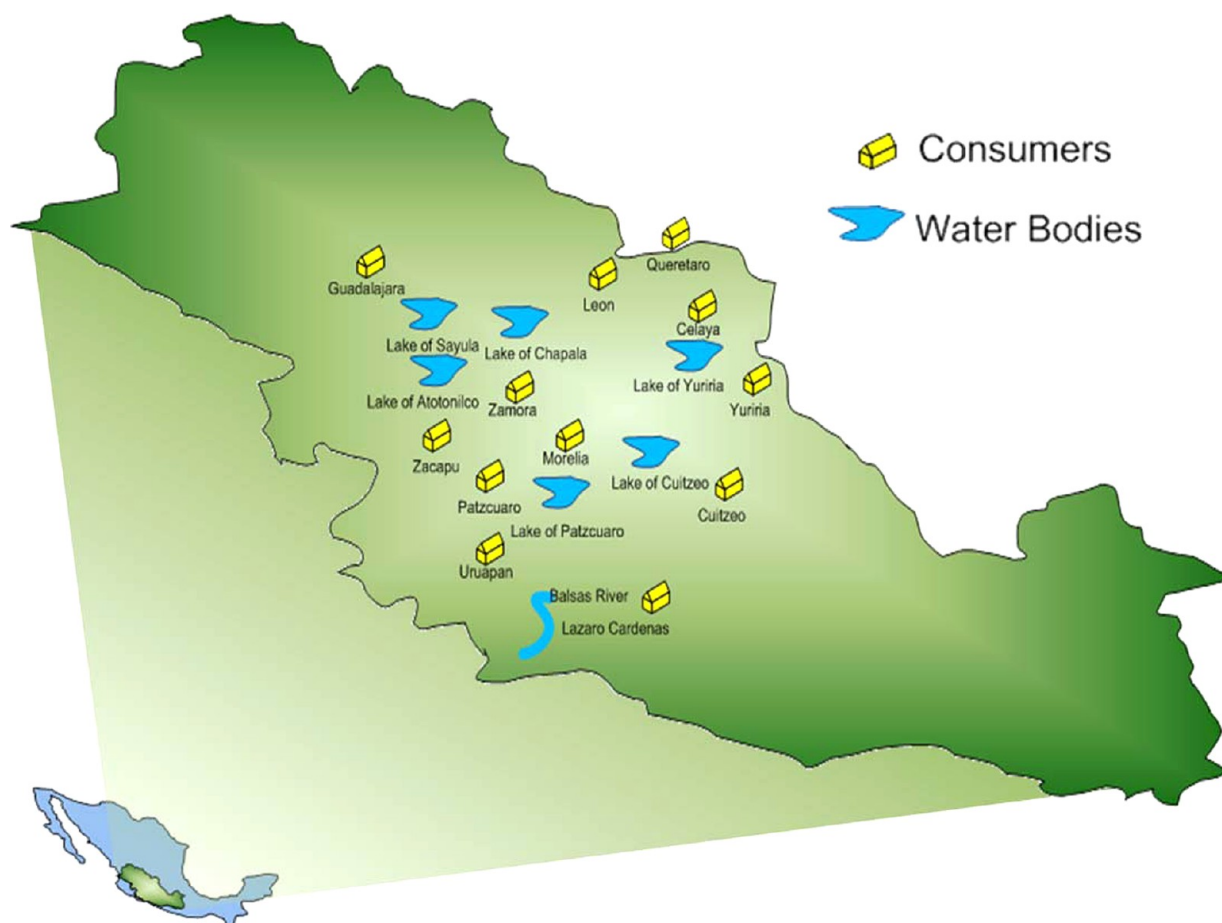
Recently, several uses for the water hyacinth have been reported, including its use for wastewater treatment<sup>4–6</sup> and as feedstock for biofuels production. For instance, several techniques have been proposed for the production of bioethanol using water hyacinth as feedstock through fermentation,<sup>7–19</sup> a set of compounds (methanol, ethanol, acetic acid, caproic acid, butyric acid, valeric acid, and heptanoic acid, among others) through the MixAlco process,<sup>20–22</sup> and biogas and fertilizers through digestion.<sup>23–27</sup> Water hyacinth can also be used as a biomass feedstock for combustion to provide heat in industrial facilities.<sup>28,29</sup> However, these works are stand-alone studies that have not taken into account system interactions (e.g., effects of economies of scale on processing costs) nor supply chain optimization.

Several studies have focused on supply chain optimization for biorefineries, particularly when agricultural sources are used as feedstock. The optimization of the supply chain has been

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**Figure 1.** Schematic representation for the distribution of sources and sinks of the addressed problem.

presented as an MILP (Mixed Integer Linear Programming) problem considering several objectives.<sup>30</sup> Some methodologies for obtaining optimal supply chains of biorefineries are based on a steady state operation.<sup>31–42</sup> Other research efforts have included the dynamic behavior.<sup>35,42–44</sup> Furthermore, recently some works on this topic have included environmental criteria for optimal selection of biorefinery configuration, raw materials, products, and processing paths,<sup>45–52</sup> as well as optimal site selection involving transportation costs.<sup>53–57</sup> Because bioresources are not constant in time, some methodologies have been developed to determine optimal supply chains under uncertainty.<sup>58,59</sup>

To make the processing of water hyacinth economically attractive and sustainable, economies of scale must be considered along with distributed configurations for the supply chain because of its sources (i.e., water bodies that require to be remediated), processing technologies, produced products, and consumers of the final products that are distributed in different places (Figure 1). Consequently, it is crucial to develop an optimization model for distributed biorefineries processing water hyacinth that allows answering the following questions:

- What products should be produced?
- What technologies should be used?
- Where should the processing facilities be located? What should be the sizes of these processing facilities?
- What are the optimal size and location for the central processing facilities?
- What markets can be satisfied with the produced goods?
- What are the associated transportation costs?

- To what extent should the available water hyacinth be eliminated?
- What to do with the produced clean water?
- What is the tax credit (if any) required to make water hyacinth elimination economically attractive?

Hence, the solution of such a model will provide the optimal configuration of the supply chain network that minimizes the total net cost considering simultaneously the remediation of water bodies. Notice that the model formulation must involve economic and environmental criteria. Therefore, this paper proposes a multi-objective mathematical programming model based on a superstructure of a distributed biorefinery system for the sustainable elimination of the water hyacinth from water bodies in a macroscopic system while accounting for economies of scale and production of biofuels, chemical products, and clean water satisfying technical and economic constraints. The proposed formulation considers two types of processing plants (central and secondary processing plants). The secondary processing plants are distributed facilities near to secondary water bodies infested with water hyacinth located in places far from industrialized zones with limited or small processing capacity; whereas the central processing facilities are big industrial facilities located in industrialized places. The unit processing cost in the secondary processing plants is greater than the unit processing cost in the central processing facilities; however, the advantage of the secondary processing facilities is that the overall transportation costs can be reduced when they are implemented because they contribute to a significant decrease in

the transport requirements of the raw material (water hyacinth), which represents the largest volume of material to be transported in the network. Therefore, in the proposed approach, the optimization model must select the optimal placement of central and secondary processing facilities as well as the associated capacity and distribution of products and raw materials accounting simultaneously for the harvesting, processing, and transportation costs. Hence, the proposed optimization model allows choosing the following issues:

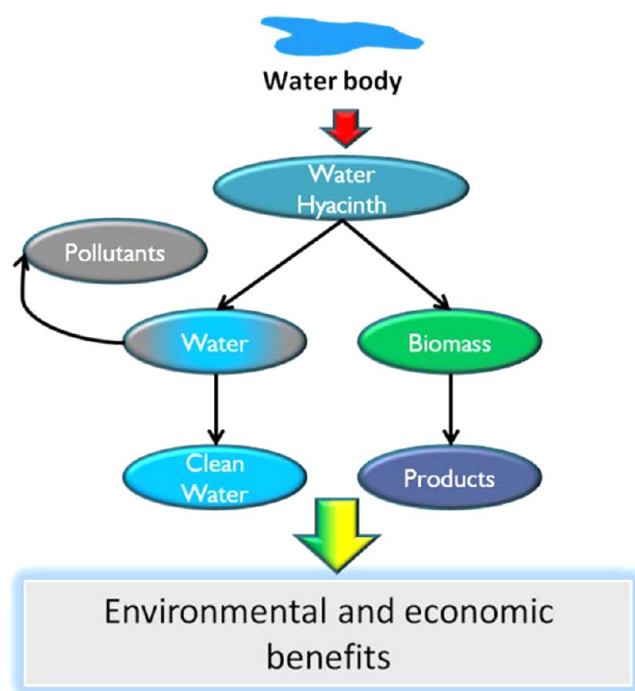
- Optimal products
- Optimal technologies
- Size and location of processing facilities
- Size and location of central processing facilities
- Satisfied demands for each market for the considered products
- All distribution and transportation costs associated with the supply chain
- Extent of elimination of available water hyacinth for each water body under consideration
- Consumers of the produced clean water
- Tax credit required to make this strategy economically attractive

This paper is organized as follows: Outline of the Model Formulation section presents the definition of the addressed problem. Model Formulation section shows the proposed mathematical programming model. Results section presents the applicability of the proposed model to a case study, and finally, the conclusions of the paper are presented in the Conclusions section.

### ■ OUTLINE OF THE MODEL FORMULATION

The water hyacinth can be considered as a raw material to produce a set of products because it includes biomass in its structure; in addition, this plant has a lot of water. In this regard, the water hyacinth is a source of clean water and dry biomass that can be obtained when this plant is processed. The removed water has some pollutants, so it has to be treated to eliminate them and yield clean water. Therefore, as shown in Figure 2, the processing of water hyacinth contributes to clean the water bodies and, at the same time, generates biomass and clean water that are valuable.

The proposed model is based on the superstructure presented in Figure 3, which also considers the representation shown in Figure 4, where there are several places (rivers and lakes) distributed over a given region (shown in Figure 1) that have huge amounts of water hyacinth. In the optimization formulation, a superstructure must be constructed to include the possible places to locate the secondary and central processing facilities, the possible water bodies to be treated, and the possible consumers. The water bodies to be treated are the places infested by water hyacinth. The central processing facilities can be located in the places where there are huge amounts of available water hyacinth and are close to industrialized zones; whereas the secondary processing facilities can be located near to water bodies infested by the water hyacinth and far from industrialized zones. Usually, the secondary processing facilities are smaller than the central processing facilities, and the unit processing costs for the central processing plants are lower than those for secondary processing plants. Consumers are selected considering the demands for the products that can be produced by the system. The produced clean water can be sent to the near consumers by pipelines; whereas the chemical



**Figure 2.** Representation of the potential uses of water hyacinth obtained from the water bodies.

products and biofuels can be sent by truck, train, or pipeline (if they are liquids) to the consumers. To efficiently solve this problem, this paper proposes to use the water hyacinth as a biomass source to produce biofuels and others products, which can be used to satisfy the energetic requirements and specific demands of products generated for the places of a given region.

Therefore, the addressed problem in this paper can be defined as follows: given are a set of water bodies ( $s$ ) with specified amounts of water hyacinth; also, given are several markets for the products manufactured with known demands ( $k$ ). The problem then consists of determining the location for the processing facilities ( $i$ ) and their sizes, the technologies used ( $j$ ), the requirements of water hyacinth in the different places ( $m$ ), and the distribution of the products ( $p$ ). The objective is to find the optimal distributed biorefinery system that simultaneously minimizes the overall net cost (or maximizing the net profit), while maximizing the percentage of the eliminated water hyacinth in order to control the water hyacinth growth in different water bodies.

### ■ MODEL FORMULATION

Prior to the present model formulation, the following indexes used are defined:  $s$  represents the water bodies that are sources of water hyacinth,  $i$  is the processing facility,  $j$  corresponds to biomass processing technologies available,  $p$  corresponds to the bioproducts,  $k$  is used to represent the markets for the bioproducts,  $n$  is used to define the technologies used to treat the recovered water,  $c$  is used to define the pollutants present in the recovered water, and  $m$  represents the water consumers. This way, the proposed model will combine the supply chain and water networks optimization models for the optimal design of a water hyacinth-based biorefinery in a distributed macroscopic system. Then, the proposed model is stated as follows.

**Mass Balance for Harvesting of Water Hyacinth.** There are two main methods to control the water hyacinth: chemical

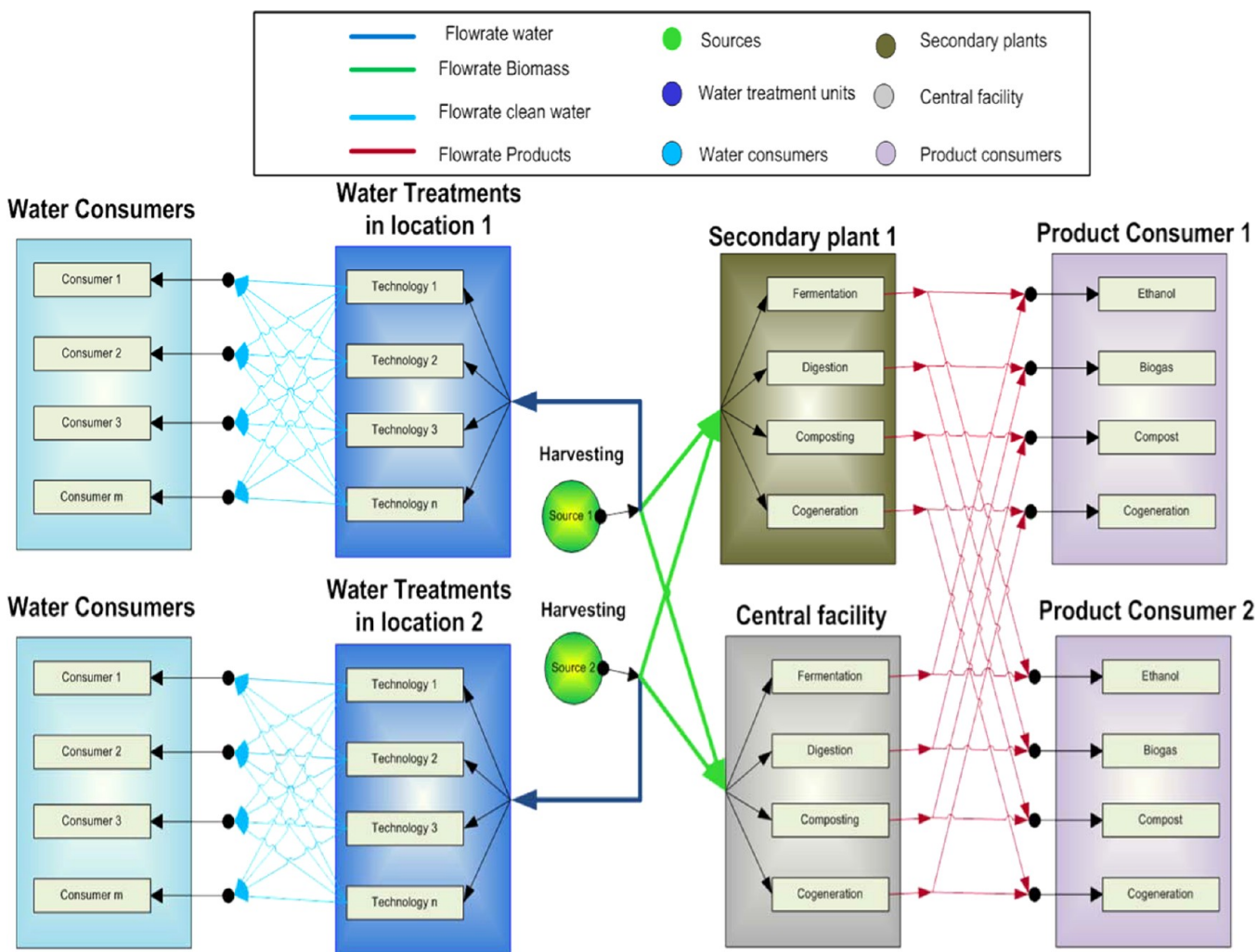


Figure 3. Superstructure for the distributed supply chain based on water hyacinth.

control and mechanical control. Some of the advantages of mechanical control are (a) removal of superfluous nutrients, (b) immediate control without significant damage to the ecosystem, and (c) suitability for open flowing as well as closed water systems. However, mechanical control has an associated high energy consumption due mainly to the power requirement for harvesting. So, one of the most important factors for mechanical control of the water hyacinth is the large cost for harvesting, which is location dependent.

The water hyacinth used at source  $s$  ( $Fwh_s$ ) can be harvested and processed to extract biomass ( $Fb_s$ ) and water ( $Fw_s$ ). The harvesting technology can extract the biomass from the water hyacinth with a given efficiency ( $Zwh_s$ ) as follows:

$$Fwh_s \cdot Zwh_s = Fb_s, s \in S \quad (1)$$

In the same way, the harvesting technology can extract the water content in the water hyacinth with a given efficiency ( $Zw_s$ ) as follows:

$$Fwh_s \cdot Zw_s = Fw_s, s \in S \quad (2)$$

**Availability for Harvested Water Hyacinth.** Harvested water hyacinth must be lower or equal than the maximum available water hyacinth ( $Fwh_s^{\max}$ ) at source  $s$ .

$$Fwh_s \leq Fwh_s^{\max}, s \in S \quad (3)$$

In this paper, the mechanical method is used for harvesting the water hyacinth. As was mentioned above, this method is widely used due to its advantages, although it is too expensive and time consuming.<sup>24</sup> There are several machines for harvesting water hyacinth, for example, a conveyor-chopper, single conveyor, and modified clamshell bucket. These machines have a maximum limit of harvesting and an efficiency to obtain the water hyacinth. Several data for the water hyacinth harvesting process have been reported.<sup>24</sup>

**Mass Balance for Splitters before the Processing Plants.** The dry-biomass extracted from water hyacinth in each location  $s$  ( $Fb_s$ ) can be segregated and directed to the processing facility located in place  $i$  ( $fb_{s,i}^{\text{hub}}$ ) and to the central facility ( $fb_s^{\text{cen}}$ ) to treat it and to obtain final products:

$$Fb_s = \sum_{i \in I} fb_{s,i}^{\text{hub}} + fb_s^{\text{cen}}, s \in S \quad (4)$$

**Balances for Mixers before the Processing Facilities.** The total biomass flow rate inlet to the processing facility  $i$  and sent to the different bioconversion technologies  $j$  ( $fb_{i,j}^{\text{hub}}$ ) is equal to the sum of the biomass distributed from the different harvesting places  $s$  ( $fb_{s,i}^{\text{hub}}$ ) as follows:

$$\sum_{s \in S} fb_{s,i}^{\text{hub}} = \sum_{j \in J} fb_{i,j}^{\text{hub}} \forall i \in I \quad (5)$$



Figure 4. Representation for the distributed supply chain based on water hyacinth.

**Balances for Technologies Used in the Processing Facilities.** In each processing facility, there are several technologies available that can be used to transform the biomass to final products. For example, biomass from the water hyacinth can be fermented to produce bioethanol; this process has been modeled previously,<sup>5–8</sup> and the technical performance and associated costs have been determined. This way, the technologies available for the fermentation of the water hyacinth are characterized with known conversion factors ( $\alpha_{j,p}^{\text{hub}}$ ) that represent the mass of product (i.e.,  $p$  = bioethanol) produced for a given amount of biomass from water hyacinth. The general approach for the fermentation of water hyacinth to produce ethanol has been reported<sup>19</sup> and is shown in Figure 5.

The MixAlco process<sup>20–22,64</sup> is an interesting technology that can be used to produce a mixture of mixed alcohols through fermentation, thermal conversion, and hydrogenation from biomass (Figure 6). This technology has been accurately modeled and optimized to determine its conversion efficiency<sup>20,60</sup> (i.e., the amount of mixed alcohols obtained from a given amount of biomass,  $\alpha_{j,p}^{\text{hub}}$ ).

Anaerobic digestion is a biological process by which organic matter is degraded in the absence of oxygen producing biogas.<sup>24</sup> The biogas produced can be used to generate energy or electricity. This has been an interesting option to produce energy given the rising cost of fossil fuels. An advantage is that the water hyacinth can be easily degraded because it has a high content of fermentable matter that can be transformed in biogas. Digestion of this plant can solve the problems caused by its excessive growth in the water bodies. However, this treatment has some special

technical requirements, which are difficult to implement in rural areas. The general process is shown in Figure 7.

On the other hand, the water hyacinth can be treated to produce compost by aerobic decomposition. The compost is an interesting product where agriculture is a significant economic activity. It is important to note that, in this case, the high moisture content of the water hyacinth is an advantage because the preparation of 1 tonne of compost needs about 2700 L of water<sup>24</sup> that can be obtained from the water hyacinth.

Another option to obtain a useful product from water hyacinth is deoxy liquefaction.<sup>61</sup> Deoxy liquefaction is a process where biomass can be converted into liquid fuels indirectly through gasification to syngas followed by catalytic conversion and direct liquefaction. In this process, most of the oxygen in biomass is released in the form of CO and CO<sub>2</sub>. There is about 2.9% oxygen contained in the oil. This process is classified as a hydrothermal process. This is an alternative to increase the energy content in the biomass.

Direct burning is another option to use the water hyacinth; however, this plant has a moisture content of about 90%, and when its moisture is reduced, the energy density is close to 15.23 MJ kg<sup>-1</sup>. This option can be used in small scale at places near water bodies to produce energy.

Therefore, the optimization approach must select the type of technology used ( $j$ ) in each processing facility ( $i$ ) to produce the different products ( $p$ ). This is modeled through the following relationships:

$$fb_{i,j}^{\text{hub}} \cdot \alpha_{j,p}^{\text{hub}} = \text{wprod}_{i,j,p}^{\text{hub}}, \forall i \in I, j \in J, p \in P \quad (6)$$

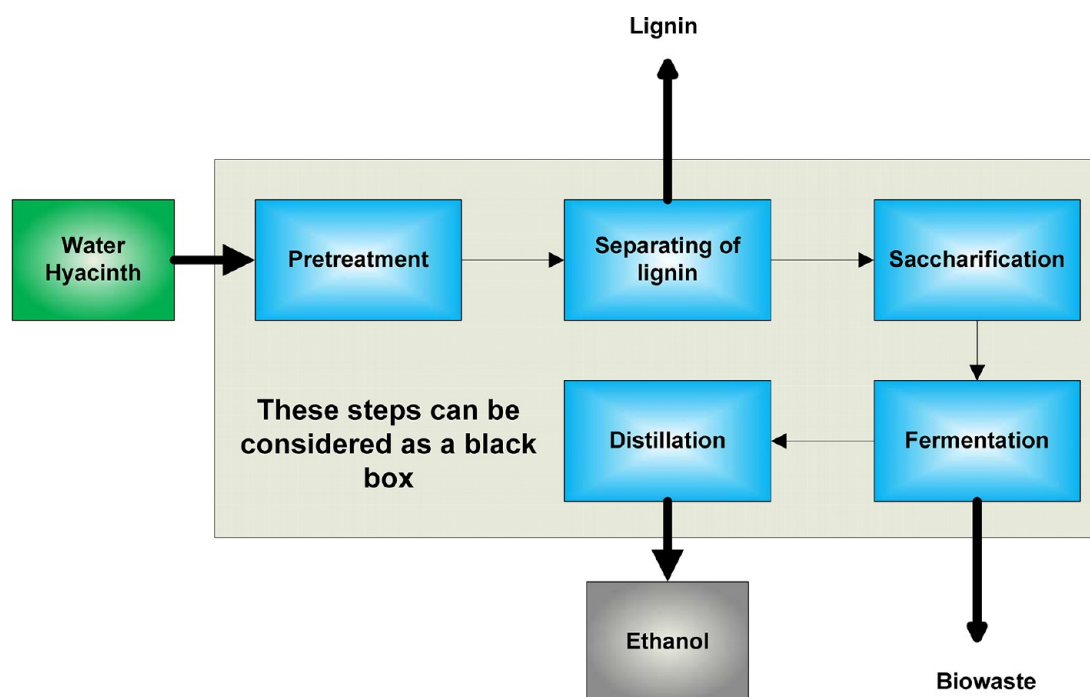


Figure 5. General approach to produce ethanol from water hyacinth.

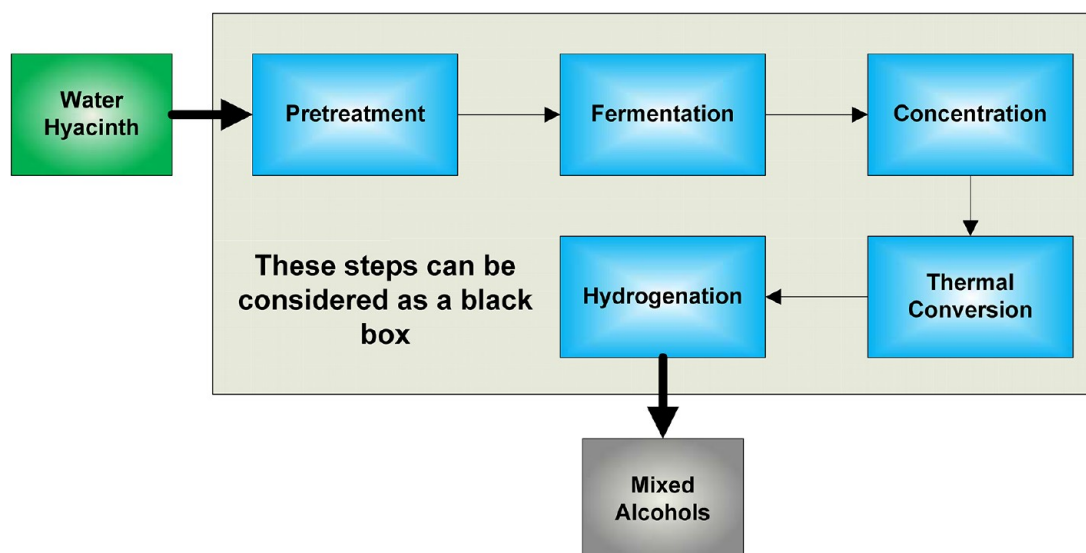


Figure 6. MixAlco process to yield bioethanol from water hyacinth.

**Balances for Mixers before the Central Processing Facilities.** The total biomass flow rate inlet to the central processing facilities and sent to the different bioconversion technologies ( $fb_s^{\text{cen}}$ ) is equal to the sum of the biomass distributed from the different harvesting places  $s$  ( $wb_j^{\text{cen}}$ ) as follows:

$$\sum_{s \in S} fb_s^{\text{cen}} = \sum_{j \in J} wb_j^{\text{cen}} \quad (7)$$

**Balances for Technologies of Central Processing Facilities.** In central processing facilities, there are several bioconversion technologies  $j$  available for transforming the biomass ( $wb_j^{\text{cen}}$ ) and to produce different products ( $wprod_{j,p}^{\text{cen}}$ ) with a given efficiency ( $\alpha_{j,p}^{\text{cen}}$ ) that can be optimized previously. The advantage of the central facility is to account for the economies of scale and

to reduce the capital and operational costs associated to big units. This is modeled as follows:

$$wb_j^{\text{cen}} \cdot \alpha_{j,p}^{\text{cen}} = wprod_{j,p}^{\text{cen}}, \forall j \in J, p \in P \quad (8)$$

**Balances for Splitters after Each Processing Facility.** The products  $p$  obtained in the processing facility  $i$  ( $wprod_{i,j,p}^{\text{hub}}$ ) using different technologies  $j$  are segregated and directed to the consumers located in different places  $k$  ( $gprod_{i,j,p,k}^{\text{hub}}$ ):

$$wprod_{i,j,p}^{\text{hub}} = \sum_{k \in K} gprod_{i,j,p,k}^{\text{hub}}, \forall i \in I, j \in J, p \in P \quad (9)$$

Notice that the outlet flow rates in this equation are optimization variables, and therefore, it is not required to include explicitly split fractions. The previous explanation also applies to all the splitters modeled in the optimization formulation.

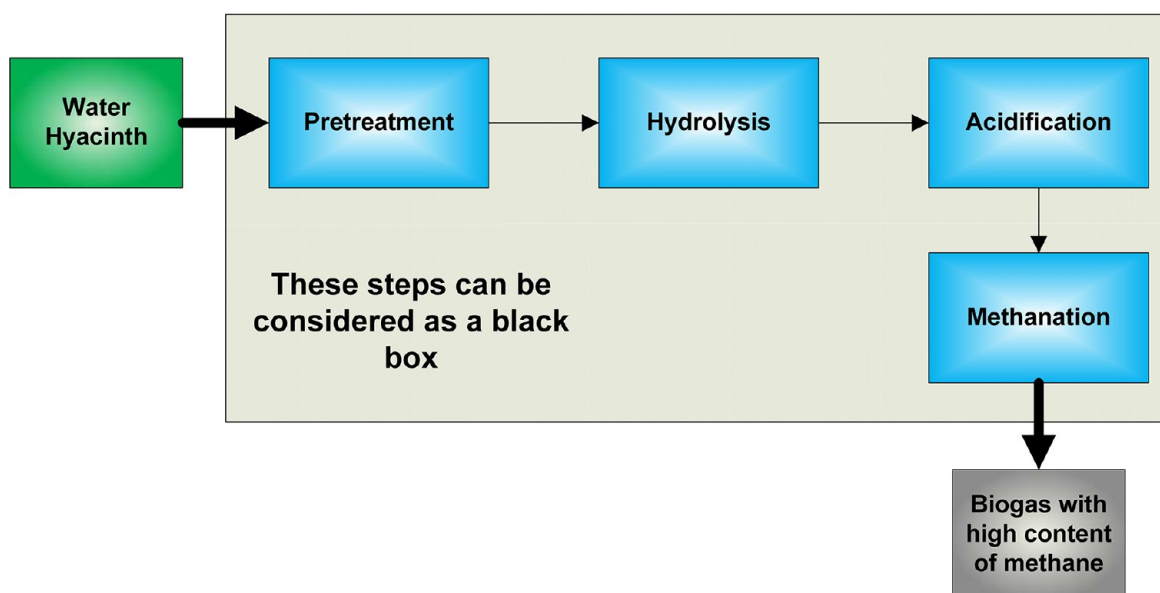


Figure 7. General description to produce biogas through anaerobic digestion from water hyacinth.

**Balances for Splitters after the Central Processing Facilities.** The products  $p$  obtained in the central processing facilities ( $w_{j,p}^{\text{cen}}$ ) using different technologies  $j$  are segregated and directed to the consumers located in different places  $k$  ( $g_{j,p,k}^{\text{cen}}$ ):

$$w_{j,p}^{\text{cen}} = \sum_{k \in K} g_{j,p,k}^{\text{cen}} \quad \forall j \in J, p \in P \quad (10)$$

**Balances for Markets.** The product  $p$  inlet to the market in place  $k$  ( $G_{p,k}^{\text{con}}$ ) is equal to the products sent from all preprocessing plants ( $g_{i,j,p,k}^{\text{hub}}$ ) and the central processing facilities ( $g_{j,p,k}^{\text{cen}}$ ):

$$\sum_{i \in I} \sum_{j \in J} g_{i,j,p,k}^{\text{hub}} + \sum_{j \in J} g_{j,p,k}^{\text{cen}} = G_{p,k}^{\text{con}}, \quad \forall p \in P, k \in K \quad (11)$$

**Demands for Consumers.** The flow rate for each product  $p$  inlet to the market  $k$  ( $G_{p,k}^{\text{con}}$ ) must be lower than the maximum demand in each location ( $G_{p,k}^{\text{con,max}}$ ):

$$G_{p,k}^{\text{con}} \leq G_{p,k}^{\text{con,max}}, \quad \forall p \in P, k \in K \quad (12)$$

**Balances for Water Treatment in Each Source.** The water extracted from the water hyacinth in each source ( $F_{w_s}$ ) is sent to a set of treatment technologies  $n$  ( $f_{wt_{s,n}}$ ) to eliminate given pollutants to make it suitable for specific uses:

$$F_{w_s} = \sum_{n \in N} f_{wt_{s,n}}, \quad \forall s \in S \quad (13)$$

**Water Treatment Technology in Each Source.** There are several treatment technologies  $n$  available to eliminate the pollutants  $c$  for the water extracted from the water hyacinth with given efficiencies  $\gamma_{n,c}$  relating the inlet composition to the water treatment technologies  $Z_{i,c}^{\text{in}}$  with the outlet composition  $Z_{i,n,c}^{\text{out}}$  as follows:

$$Z_{s,n,c}^{\text{out}} = Z_{s,c}^{\text{in}} \cdot (1 - \gamma_{n,c}), \quad \forall s \in S, n \in N, c \in C \quad (14)$$

**Mass Balance for Splitters after Water Treatment.** Water extracted from the water hyacinth from source  $s$  and

treated with technology  $n$  can be sent to the water consumer  $m$  ( $h_{w_{s,n,m}}$ ), and this is modeled as follows:

$$f_{w_{T_{s,n}}} = \sum_{m \in M} h_{w_{s,n,m}}, \quad \forall s \in S, n \in N \quad (15)$$

**Mass Balance for Mixers before Each Water Consumer.** The total water flow rate directed to the water consumer  $m$  ( $H_{w_{s,m}}$ ) is equal to the sum of the water flow rate from any treatment unit  $n$  ( $h_{w_{s,n,m}}$ ):

$$\sum_{n \in N} h_{w_{s,n,m}} = H_{w_{s,m}}, \quad \forall s \in S, m \in M \quad (16)$$

**Component Balance for Mixers before Each Water Consumer.** The following balances are required to determine the components present in the water directed to the consumers ( $Z_{w_{s,m,c}}^{\text{con}}$ ):

$$\sum_{n \in N} (h_{w_{s,n,m}} \cdot Z_{w_{s,n,c}}^{\text{out}}) = H_{w_{s,m}} \cdot Z_{w_{s,m,c}}^{\text{con}}, \quad \forall s \in S, m \in M, c \in C \quad (17)$$

It is important to note that eq 17 is a nonlinear relationship because it has a bilinear term, which is formed by the product of the composition of pollutant in the discharge of the water treatment units ( $Z_{w_{s,n,c}}^{\text{con}}$ ) and the total water flow rate directed to the water consumers ( $H_{w_{s,m}}$ ). This is the only one nonlinear relationship in the model.

**Demand for Water Consumers.** Each water consumer  $m$  has a specific maximum water demand ( $H_{w_{s,m}}^{\text{max}}$ ). This constraint is written as follows:

$$H_{w_{s,m}} \leq H_{w_{s,m}}^{\text{max}}, \quad \forall s \in S, m \in M \quad (18)$$

**Constraints for Water Quality for Each Consumer.** There are specific constraints for the concentration of some pollutants  $c$  in each water consumer depending on the use; therefore, the maximum water concentration ( $Z_{w_{s,m,c}}^{\text{con,max}}$ ) for each consumer is stated as follows:

$$Z_{w_{s,m,c}}^{\text{con}} \leq Z_{w_{s,m,c}}^{\text{con,max}}, \quad \forall s \in S, m \in M, c \in C \quad (19)$$

**Operational Cost for Processing Facilities.** The operational cost for the processing facilities ( $\text{CostHub}_{ij}^{\text{op}}$ ) depends on the treated flow rate of biomass from the water hyacinth ( $f_{ij}^{\text{hub}}$ ) and the associated unit cost ( $\beta_j^{\text{hubop}}$ ) for each source  $i$  and processing technology  $j$ :

$$\text{costHub}_{ij}^{\text{op}} = f_{ij}^{\text{hub}} \cdot \beta_j^{\text{hubop}}, \forall i \in I, j \in J \quad (20)$$

**Capital Cost for Processing Facilities.** The capital costs for the processing facilities ( $\text{CostHub}_{ij}^{\text{cap}}$ ) are determined considering nonlinear functions with fixed ( $A_{ij}^{\text{hub}}$ ) and variable terms ( $B_{ij}^{\text{hub}} \cdot (f_{ij}^{\text{hub}})^{\sigma}$ ), where  $\sigma$  is usually between 0.6 and 0.9 to account for the economies of scale. In this work, the second nonconvex term is replaced by a set of linear segments as follows:

$$\text{costHub}_{ij}^{\text{cap}} = A_{ij}^{\text{hub}} + B_{ij}^{\text{hub}}, \forall i \in I, j \in J \quad (21)$$

The term ( $B_{ij}^{\text{hub}}$ ) is modeled through the following disjunction:

$$\forall q \begin{cases} Y_{ij,q}^{\text{hub}} \\ f_{ij,q}^{\text{hub}^{\min}} \leq f_{ij}^{\text{hub}} \leq f_{ij,q}^{\text{hub}^{\max}} \\ A_{ij}^{\text{hub}} = a_{ij,q}^{\text{hub}} \\ B_{ij}^{\text{hub}} = b_{ij,q}^{\text{hub}} \cdot f_{ij}^{\text{hub}} \end{cases}, i \in I, j \in J$$

Previous disjunction is reformulated as follows. First, only one linear segment can be selected:

$$\sum_{q \in Q} y_{ij,q}^{\text{hub}} = 1, \forall i \in I, j \in J \quad (22)$$

**Table 1. Available Biomass from Water Hyacinth for Each Water Body**

water body	wet biomass production (tonne/ha year)	infested area (ha)	annual wet biomass production (tonnes/year)	reference for infested area
Chapala	1530	4500	6,887,903	62
Patzcuaro	1530	3037	4,648,569	63
Cuitzeo	1530	9628	14,737,052	64
Yuriria	1530	5820	8,908,355	65–69
Sayula	1530	4548	6,961,374	65–69
Atotonilco	1530	1508	2,308,213	65–69
Balsas	1530	1,719,220	2,631,516,762	65–69

**Table 2. Demands for Each Product at Each Place**<sup>70,71</sup>

product consumer	ethanol (tonnes/year)	biogas (tonnes/year)	acetic acid (tonnes/year)	compost (tonnes/year)	HCF (tonnes/year)	energy (GJ/year)
Morelia	40,512	706	797	799	465	20,382
Lazaro Cardenas	9933	173	195	20	114	4998
Guadalajara	212,523	3705	4179	419	2441	106,923
Queretaro	44,548	777	876	88	512	22,413
Leon	79,798	1391	1569	157	917	40,147
Patzcuaro	4877	85	96	96	56	2454
Celaya	78,071	1361	1535	154	897	39,279
Zamora	31,014	541	610	61	356	15,604
Uruapan	52,554	916	1034	104	604	26,441
Yuriria	11,796	206	232	23	135	5935
Cuitzeo	4704	82	93	9	54	2367
Zacapu	12,241	213	241	24	141	6159

Then, each continuous variable is disaggregated as follows:

$$f_{ij}^{\text{hub}} = \sum_{q \in Q} df_{ij,q}^{\text{hub}}, \forall i \in I, j \in J \quad (23)$$

$$A_{ij}^{\text{hub}} = \sum_{q \in Q} dA_{ij,q}^{\text{hub}}, \forall i \in I, j \in J \quad (24)$$

$$B_{ij}^{\text{hub}} = \sum_{q \in Q} dB_{ij,q}^{\text{hub}}, \forall i \in I, j \in J \quad (25)$$

Then, the relationships are stated in terms of the disaggregated variables as follows:

$$f_{ij,q}^{\text{hub}^{\min}} \cdot y_{ij,q}^{\text{hub}} \leq df_{ij,q}^{\text{hub}} \leq f_{ij,q}^{\text{hub}^{\max}} \cdot y_{ij,q}^{\text{hub}}, \forall i \in I, j \in J, q \in Q \quad (26)$$

$$dA_{ij,q}^{\text{hub}} = a_{ij,q}^{\text{hub}} \cdot y_{ij,q}^{\text{hub}}, \forall i \in I, j \in J, q \in Q \quad (27)$$

$$dB_{ij,q}^{\text{hub}} = b_{ij,q}^{\text{hub}} \cdot df_{ij,q}^{\text{hub}}, \forall i \in I, j \in J, q \in Q \quad (28)$$

In the previous disjunction, for a given treated flow rate ( $f_{ij,q}^{\text{hub}}$ ), relationship 26 is used to activate the corresponding binary variable; then, just one binary variable ( $y_{ij,q}^{\text{hub}}$ ) can take a value of one because of relationship 22. Next, the disaggregated variables are calculated through eqs 27 and 28. Notice that only the disaggregated variables for the active segment  $q$  are able to take values greater than zero, and these

**Table 3. Water Demand for Each Water Consumer and Quality Required**<sup>72,73</sup>

water consumer	water demand (hm <sup>3</sup> /year)	use	maximum concentration pollutant (mass fraction)
Morelia	141	public	$5.00 \times 10^{-07}$
Lazaro Cardenas	23	industrial	$1.00 \times 10^{-06}$
Guadalajara	496	industrial	$1.00 \times 10^{-06}$
Queretaro	104	industrial	$1.00 \times 10^{-06}$
Leon	186	industrial	$1.00 \times 10^{-06}$
Patzcuaro	17	public	$5.00 \times 10^{-07}$
Celaya	91	industrial	$1.00 \times 10^{-06}$
Zamora	36	public	$5.00 \times 10^{-07}$
Uruapan	61	public	$5.00 \times 10^{-07}$
Yuriria	14	public	$5.00 \times 10^{-07}$
Cuitzeo	5	public	$5.00 \times 10^{-07}$
Zacapu	14	industrial	$1.00 \times 10^{-06}$



are assigned to the original continuous variables through eqs 23–25. It is noteworthy that the advantage of using disjunctive formulations is the easy representation and reformulation of complicated logical relationships; the disjunctive formulation does not affect the solution strategy because the corresponding algebraic reformulation is the one that is solved.

**Operational Cost for Central Processing Facilities.** The operational cost for central processing facilities ( $\text{CostCen}_j^{\text{op}}$ ) depends on the treated flow rate of biomass from the water hyacinth ( $\text{wb}_j^{\text{cen}}$ ) and the unit cost associated ( $\beta_j^{\text{cenop}}$ ) for each processing technology  $j$ :

$$\text{costCen}_j^{\text{op}} = \text{wb}_j^{\text{cen}} \cdot \beta_j^{\text{cenop}}, \forall j \in J \quad (29)$$

**Capital Cost for Central Processing Facilities.** The capital costs for central processing facilities ( $\text{CostCen}_j^{\text{cap}}$ ) are determined considering the fixed ( $A_j^{\text{cen}}$ ) and variable parts in the same way than for preprocessing facilities as follows:

$$\text{costCen}_j^{\text{cap}} = A_j^{\text{cen}} + Bf_j^{\text{cen}}, \forall j \in J \quad (30)$$

**Table 4. Efficiency To Remove the Pollutant for Each Technology Considered**

technology to eliminate Cr(VI)	efficiency	reference
ion exchange resins	0.99	74
ion exchange Mexican clinoptilolite	0.2	75
electroplating HA 216	0.5	76

**Table 5. Efficiencies for Processing Technologies**

product	technology	conversion factor	units	reference
ethanol	acid hydrolysis and fermentation, 10% sulfuric Acid	0.19	g/dry g	6, 7
ethanol	acid hydrolysis and fermentation, 1% sulfuric Acid	0.35	g/dry g	7
biogas	anaerobic digestion	291	mL/dry g	23
compost	composting	0.7	g/dry g	24
acetic acid	MixAlco process	0.3	g/dry g	20
high caloric fuel	deoxy liquefaction	0.05	g/dry g	61
energy	cogeneration	15.23	kJ/dry g	61

**Table 6. Transportation Costs for Biomass from Water Hyacinth Sources to Processing Plants<sup>a</sup>**

water Body	Chapala		Patzcuaro		Cuitzeo		Yuriria		Sayula		Atotonilco		Balsas	
	distance (km)	transp \$US/tonne	distance (km)	transp \$US/tonne	distance (km)	transp \$US/tonne	distance (km)	transp \$US/tonne	distance (km)	transp \$US/tonne	distance (km)	transp \$US/tonne	distance (km)	transp \$US/tonne
processing plant														
Morelia	284	22.44	59	4.66	34	2.69	64	5.06	394	31.13	297	23.46	250	19.75
Lazaro Cardenas	555	43.85	263	20.78	341	26.94	378	29.86	427	33.73	476	37.60	67	5.29
Leon	253	19.99	259	20.46	178	14.06	145	11.46	329	25.99	329	25.99	456	36.02
Queretaro	359	28.36	244	19.28	161	12.72	139	10.98	456	36.02	358	28.28	439	34.68
Guadalajara	48	3.79	282	22.28	275	21.73	306	24.17	111	8.77	111	8.77	434	34.29
Celaya	299	23.62	194	15.33	109	8.61	67	5.29	415	32.79	317	25.04	389	30.73
Zamora	152	12.01	132	10.43	159	12.56	188	14.85	203	16.04	143	11.30	270	21.33
Uruapan	261	20.62	57	4.50	141	11.14	172	13.59	304	24.02	244	19.28	168	13.27
Yuriria	301	23.78	117	9.24	30	2.37	1	0.08	408	32.23	315	24.89	314	24.81
Cuitzeo	272	21.49	88	6.95	1	0.08	30	2.37	379	29.94	284	22.44	283	22.36
Zacapu	214	16.91	65	5.14	99	7.82	130	10.27	321	25.36	228	18.01	259	20.46

<sup>a</sup>Based on a constant transportation cost of \$US 0.079/ (tonne km) to transport biomass for highway.

The term ( $Bf_j^{\text{cen}}$ ) is modeled through the following disjunction:

$$\forall \left[ \begin{array}{c} Y_{j,q}^{\text{cen}} \\ \text{wb}_{j,q}^{\text{cen min}} \leq \text{wb}_j^{\text{cen}} \leq \text{wb}_{j,q}^{\text{cen max}} \\ A_j^{\text{cen}} = a_{j,q}^{\text{cen}} \\ Bf_j^{\text{cen}} = b_{j,q}^{\text{cen}} \cdot \text{wb}_j^{\text{cen}} \end{array} \right], j \in J$$

The previous disjunction is reformulated as follows:

$$\sum_{q \in Q} y_{j,q}^{\text{cen}} = 1, \forall j \in J \quad (31)$$

$$\text{wb}_j^{\text{cen}} = \sum_{q \in Q} \text{dw}_{j,q}^{\text{cen}}, \forall j \in J \quad (32)$$

$$A_j^{\text{cen}} = \sum_{q \in Q} \text{d}A_{j,q}^{\text{cen}}, \forall j \in J \quad (33)$$

$$Bf_j^{\text{cen}} = \sum_{q \in Q} \text{d}B_{j,q}^{\text{cen}}, \forall j \in J \quad (34)$$

$$\text{wb}_{j,q}^{\text{cen min}} \cdot y_{j,q}^{\text{cen}} \leq \text{dw}_{j,q}^{\text{cen}} \leq \text{wb}_{j,q}^{\text{cen max}} \cdot y_{j,q}^{\text{cen}}, \forall j \in J, q \in Q \quad (35)$$

$$\text{d}A_{j,q}^{\text{cen}} = a_{j,q}^{\text{cen}} \cdot y_{j,q}^{\text{cen}}, \forall j \in J, q \in Q \quad (36)$$

$$\text{d}B_{j,q}^{\text{cen}} = b_{j,q}^{\text{cen}} \cdot \text{dw}_{j,q}^{\text{cen}}, \forall j \in J, q \in Q \quad (37)$$

The explanation for previous relationships is similar to the one corresponding to the distributed processing facilities.

**Operational Cost for Water Treatment Units.** The operational cost for the water treatment units ( $\text{CostWT}_{s,n}^{\text{op}}$ ) depends on the water flow rate treated ( $\text{fwt}_{s,n}$ ) and the unit cost associated ( $\beta_{s,n}^{\text{wtop}}$ ) for each treatment unit  $n$ :

$$\text{costWT}_{s,n}^{\text{op}} = \text{fwt}_{s,n} \cdot \beta_{s,n}^{\text{wtop}}, \forall s \in S, n \in N \quad (38)$$

**Capital Cost for Water Treatment Units.** Capital costs for water treatment units ( $\text{CostWT}_{s,n}^{\text{cap}}$ ) are determined considering the fixed ( $A_{s,n}^{\text{WT}}$ ) and variable parts in the same way than for distributed processing facilities as follows:

$$\text{costWT}_{s,n}^{\text{cap}} = A_{s,n}^{\text{WT}} + Bf_{s,n}^{\text{WT}}, \forall s \in S, n \in N \quad (39)$$

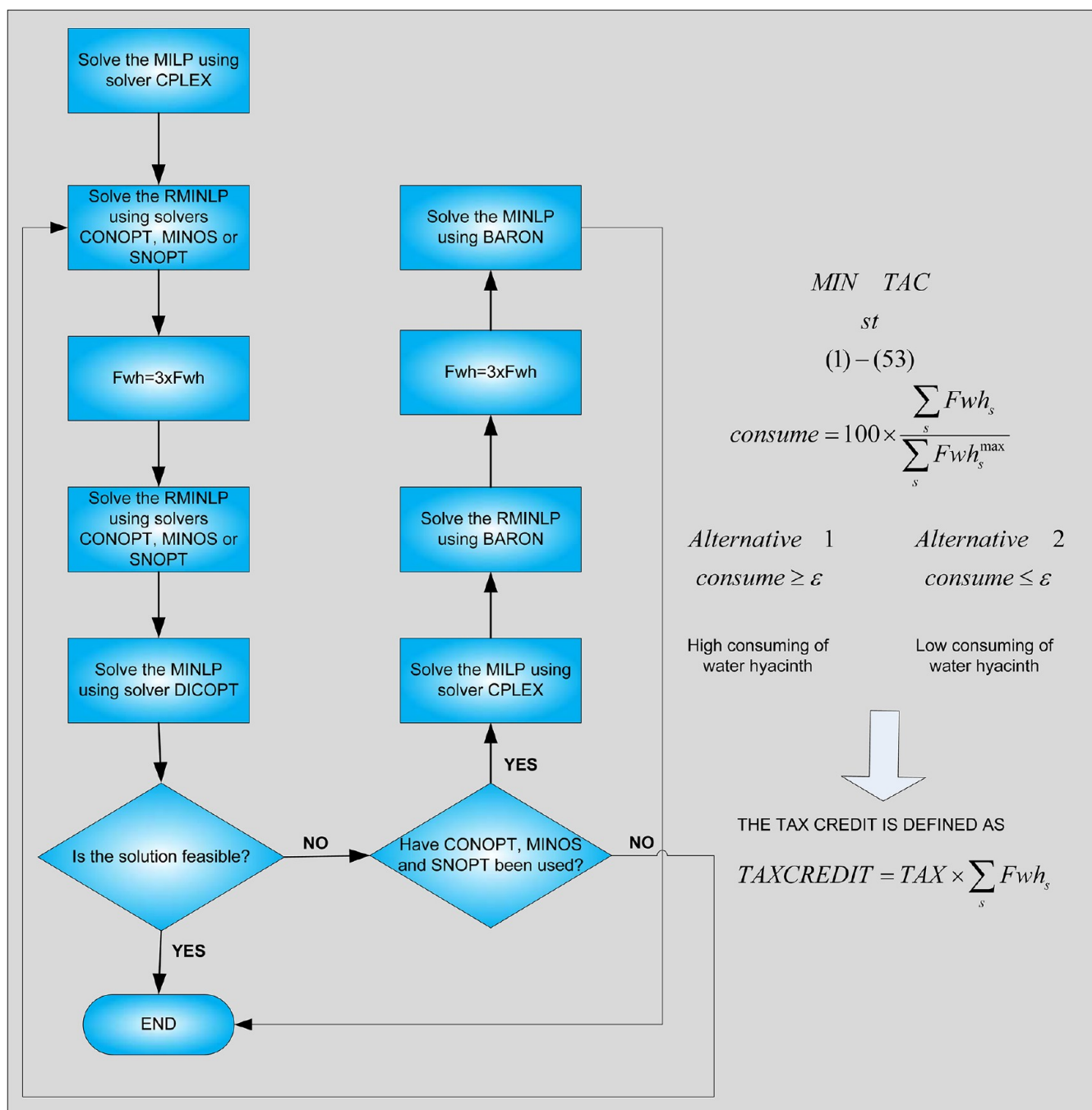


Figure 8. Solution procedure of the addressed problem.

The term ( $Bf_{i,n}^{WT}$ ) is modeled through the following disjunction:

$$\bigvee_q \left[ \begin{array}{l} Y_{s,n,q}^{WT} \\ fwt_{s,n,q}^{min} \leq fwt_{s,n} \leq fwt_{s,n,q}^{max} \\ A_{s,n}^{WT} = a_{s,n,q}^{WT} \\ Bf_{s,n}^{WT} = b_{s,n,q}^{WT} \cdot fwt_{s,n} \end{array} \right], \forall s \in S, n \in N, q \in Q$$

The previous disjunction is reformulated to obtain:

$$\sum_{q \in Q} y_{s,n,q}^{wt} = 1, \forall s \in S, n \in N \quad (40)$$

$$fwt_{s,n} = \sum_{q \in Q} dfwt_{s,n,q}, \forall s \in S, n \in N \quad (41)$$

$$A_{s,n}^{wt} = \sum_{q \in Q} dA_{s,n,q}^{wt}, \forall s \in S, n \in N \quad (42)$$

$$Bf_{s,n}^{wt} = \sum_{q \in Q} dBf_{s,n,q}^{wt}, \forall s \in S, n \in N \quad (43)$$

$$\begin{aligned} fwt_{s,n,q}^{min} \cdot y_{s,n,q}^{wt} &\leq dfwt_{s,n,q} \\ &\leq fwt_{s,n,q}^{max} \cdot y_{s,n,q}^{wt}, \forall s \in S, n \in N, q \in Q \end{aligned} \quad (44)$$

$$dA_{s,n,q}^{\text{wt}} = a_{s,n,q}^{\text{wt}} \cdot \gamma_{s,n,q}^{\text{wt}}, \forall s \in S, n \in N, q \in Q \quad (45)$$

$$dB_{s,n,q}^{\text{wt}} = b_{s,n,q}^{\text{wt}} \cdot \text{dwt}_{s,n,q}, \forall s \in S, n \in N, q \in Q \quad (46)$$

The explanation for previous relationships is similar to the one corresponding to the distributed processing facilities.

**Harvesting Cost.** The water hyacinth harvesting cost (CostHarvesting) is determined on the basis of the amount harvested ( $Fwh_s$ ) and the associated unit harvesting cost ( $\beta_s^{\text{Harvesting}}$ ) for each location  $s$  as follows:

$$\text{costHarvesting} = \sum_{s \in S} Fwh_s \cdot \beta_s^{\text{Harvesting}} \quad (47)$$

Notice that the unit harvesting costs depend on the place because the difficulty associated to this operation is different for each location. It should be noted that an important factor included in the harvesting costs is the energy required.

**Water Transportation Cost.** The water transportation cost consists of the transportation of untreated and treated water considering the unit costs  $\beta_{s,n}^{\text{Transp}}$  and  $\beta_{s,n,m}^{\text{Transp}}$ , respectively:

$$\begin{aligned} \text{costTransWater} = & \sum_{s \in S} \sum_{n \in N} f_{s,n} \cdot \beta_{s,n}^{\text{Transp}} \\ & + \sum_{s \in S} \sum_{n \in N} \sum_{m \in M} h_{s,n,m} \cdot \beta_{s,n,m}^{\text{Transp}} \end{aligned} \quad (48)$$

**Biomass Transportation Cost.** The biomass transportation cost (CostTransBM) includes the biomass transportation cost from the source to the processing facilities ( $\beta_{s,i}^{\text{hubTransp}}$ ) and to the central processing facilities ( $\beta_{s,i}^{\text{bcenTransp}}$ ):

$$\begin{aligned} \text{costTransBM} = & \sum_{s \in S} \sum_{i \in I} f_{s,i}^{\text{hub}} \cdot \beta_{s,i}^{\text{hubTransp}} \\ & + \sum_{s \in S} f_{s,i}^{\text{cen}} \cdot \beta_{s,i}^{\text{bcenTransp}} \end{aligned} \quad (49)$$

**Products Transportation Cost.** The transportation cost for the products includes the one corresponding for the transportation of products from the processing facilities ( $\beta_{i,j,p,k}^{\text{hubTransp}}$ ) and from the central processing facilities ( $\beta_{j,p,k}^{\text{cenTransp}}$ ):

$$\begin{aligned} \text{costTransProd} = & \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{k \in K} g_{i,j,p,k}^{\text{hub}} \cdot \beta_{i,j,p,k}^{\text{hubTransp}} \\ & + \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{k \in K} g_{i,j,p,k}^{\text{cen}} \cdot \beta_{j,p,k}^{\text{cenTransp}} \end{aligned} \quad (50)$$

**Total Operational Cost.** The total operational cost (CostOperational) is given by the sum of the associated costs to the operation of the distributed processing facilities (CostHub $_{ij}^{\text{op}}$ ), central processing facilities (CostCen $_{j}^{\text{op}}$ ) and water treatment units (CostWT $_{s,n}^{\text{op}}$ ):

$$\begin{aligned} \text{costOperational} = & \sum_{i \in I} \sum_{j \in J} \text{costHub}_{i,j}^{\text{op}} + \sum_{j \in J} \text{costCen}_{j}^{\text{op}} \\ & + \sum_{s \in S} \sum_{n \in N} \text{costWT}_{s,n}^{\text{op}} \end{aligned} \quad (51)$$

**Total Capital Cost.** The total capital cost (CostCapital) includes the associated costs for the distributed processing facilities (CostHub $_{ij}^{\text{cap}}$ ), central processing facilities (CostCen $_{j}^{\text{cap}}$ ), and water treatment units (CostWT $_{s,n}^{\text{cap}}$ ):

$$\begin{aligned} \text{costCapital} = & \sum_{i \in I} \sum_{j \in J} \text{costHub}_{i,j}^{\text{cap}} + \sum_{j \in J} \text{costCen}_{j}^{\text{cap}} \\ & + \sum_{s \in S} \sum_{n \in N} \text{costWT}_{s,n}^{\text{cap}} \end{aligned} \quad (52)$$

**Total Sales.** The total sales (sales prod) correspond to the sales of the products and water as follows:

$$\text{SalesProd} = \sum_{p \in P} \sum_{k \in K} G_{p,k}^{\text{con}} \beta_p^{\text{prod}} + \sum_{s \in S} \sum_{m \in M} H_{w_s,m} \beta_m^{\text{wat}} \quad (53)$$

In previous relationship,  $\beta_p^{\text{prod}}$  and  $\beta_m^{\text{wat}}$  are the unit prices for the products  $p$  and water  $m$ , respectively.

**Total Net Annual Cost (Negative of Total Net Profit).** The total net annual cost for the overall system (TAC) (which is equal to the negative of the total net annual profit) includes the water hyacinth harvesting cost (CostHarvesting) plus the transportation cost associated to the water (CostTransWater), biomass (CostTransBM) and products (CostTransProd), plus the operational (CostOperational) and capital costs (CostCapital), minus the total sales (SalesProd) and the tax credit (TAXCredit). Therefore, the total net annual cost is stated as follows:

$$\begin{aligned} \text{TAC} = & \text{costHarvesting} + \text{costTransWater} + \text{costTransBM} \\ & + \text{costTransProd} + \text{costOperational} \\ & + K_F \cdot \text{costCapital} - \text{SalesProd} - \text{TAXCredit} \end{aligned} \quad (54)$$

**Percentage of Eliminated Water Hyacinth.** In this study, the environmental objective function is to maximize the percentage of eliminated water hyacinth. This function is environmentally representative because it indicates how much water hyacinth is eliminated from water bodies. The percentage of eliminated water hyacinth is defined as follows:

$$\text{consume} = 100 \frac{\sum_s Fwh_s}{\sum_s Fwh_s^{\text{max}}} \quad (55)$$

## REMARKS

- The optimization problem consists of minimizing the TAC (given by eq 54) and maximizing the percentage of eliminated water hyacinth (given by eq 55) subject to relationships 1–53. To solve this multi-objective optimization model, the constraint method has been implemented; this way, to generate a set of Pareto solutions that trade-off these two objectives, the problem for minimizing the TAC subject to relationships 1–53 and subject to one of the following constraints  $\text{consume} \geq \varepsilon$  or  $\text{consume} \leq \varepsilon$  must be solved for several values of  $\varepsilon$ . The first constraint allows generating a Pareto curve for high elimination of water hyacinth, while the second one is to obtain a Pareto curve for low elimination of water hyacinth.
- The model considers simultaneously the supply chain for the bioproducts obtained from the water hyacinth, the

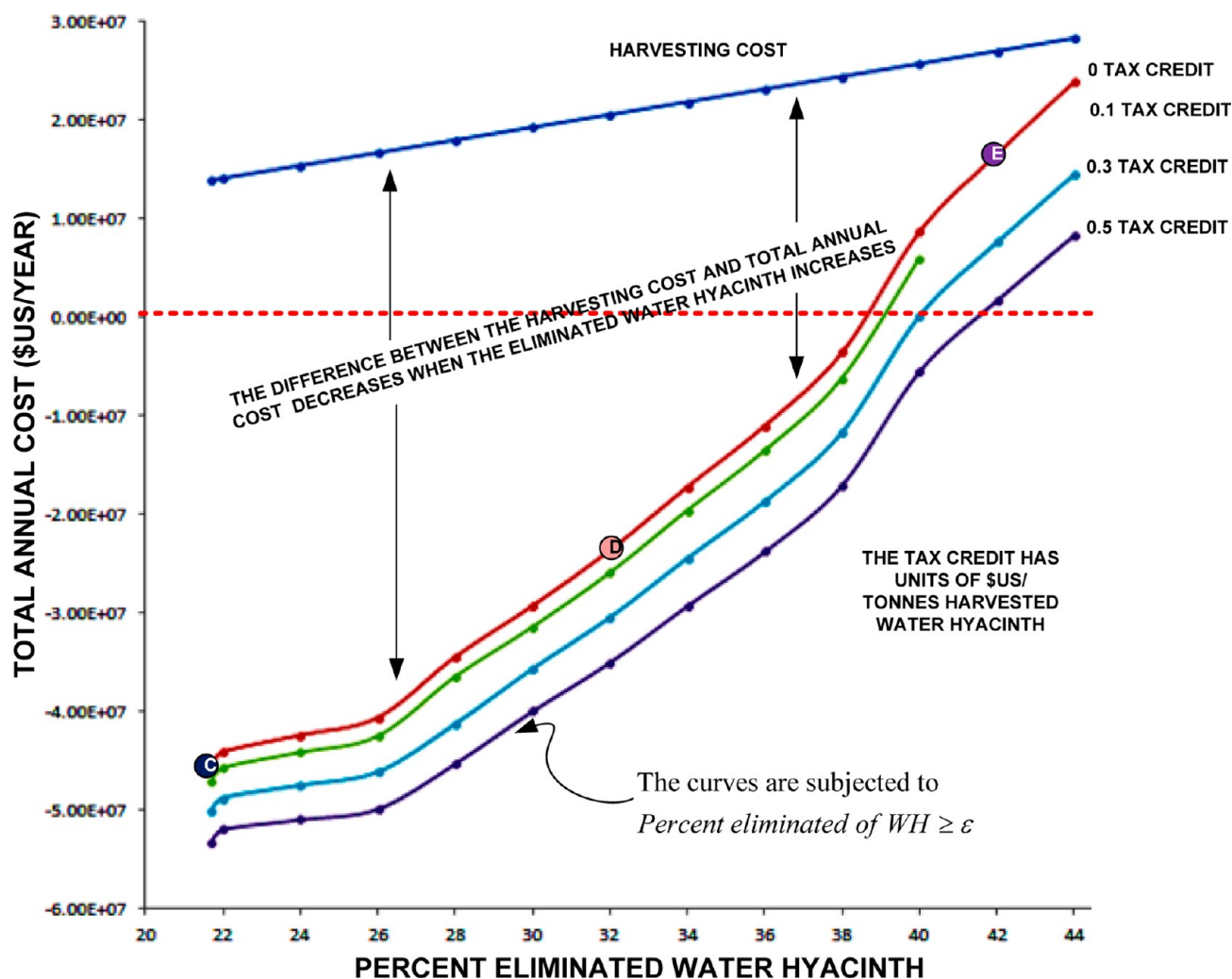


Figure 9. Pareto curves for alternative 1 (TAC versus percentage of eliminated water hyacinth).

- remediation of the water bodies, and the recycle and reuse of the recovered water.
- The optimization model simultaneously optimizes the selection of bioconversion technologies for the water hyacinth and the water treatment; it also takes into account the optimization of the size and location for the distributed processing and central processing facilities to account for the economies of scale. In addition, the model considers which products should be selected (bioproducts and type of water) and the optimal distribution for the products in the different markets.
  - This optimization model could be very useful to solve an environmental problem (controlling water hyacinth in water bodies) and, at the same time, to obtain economic benefits due to revenues from sale of products (bioproducts and water).
  - For modeling, the splitters only mass balances are required, which state that the flow of the inlet stream is equal to the flows of the outlet streams. It is noteworthy that the flows of the outlet streams are optimization variables (this is, the outlet flow rates are determined by the optimization process), and therefore, it is not required to include a split fraction because it is implicit in the optimization process.

- If the number of potential places to install central and distributed processing facilities is big enough, the associated number of binary variables can be increased significantly. In this case, also the CPU time required to solve the problem increases exponentially. If this CPU time is huge enough, a prescreening approach can be implemented to eliminate potential places that may not be promissory (i.e., water bodies with small amount of water hyacinth, places far from the consumers, etc.).

## RESULTS

To show the applicability of the proposed methodology, a case study from Mexico is used. This case is considered because the central part of Mexico has a lot of water bodies highly infested with water hyacinth; therefore, the sustainability of these systems is in risk. Several approaches have been proposed, and some of them have been implemented to solve this problem (including several chemical and physical treatments) without good results (some of them are very expensive, others have severe adverse adjacent impacts, and others are not efficient to eliminate the water hyacinth). To apply the proposed methodology in such a region, first the potential harvesting sites are identified as the water bodies seriously infested with water

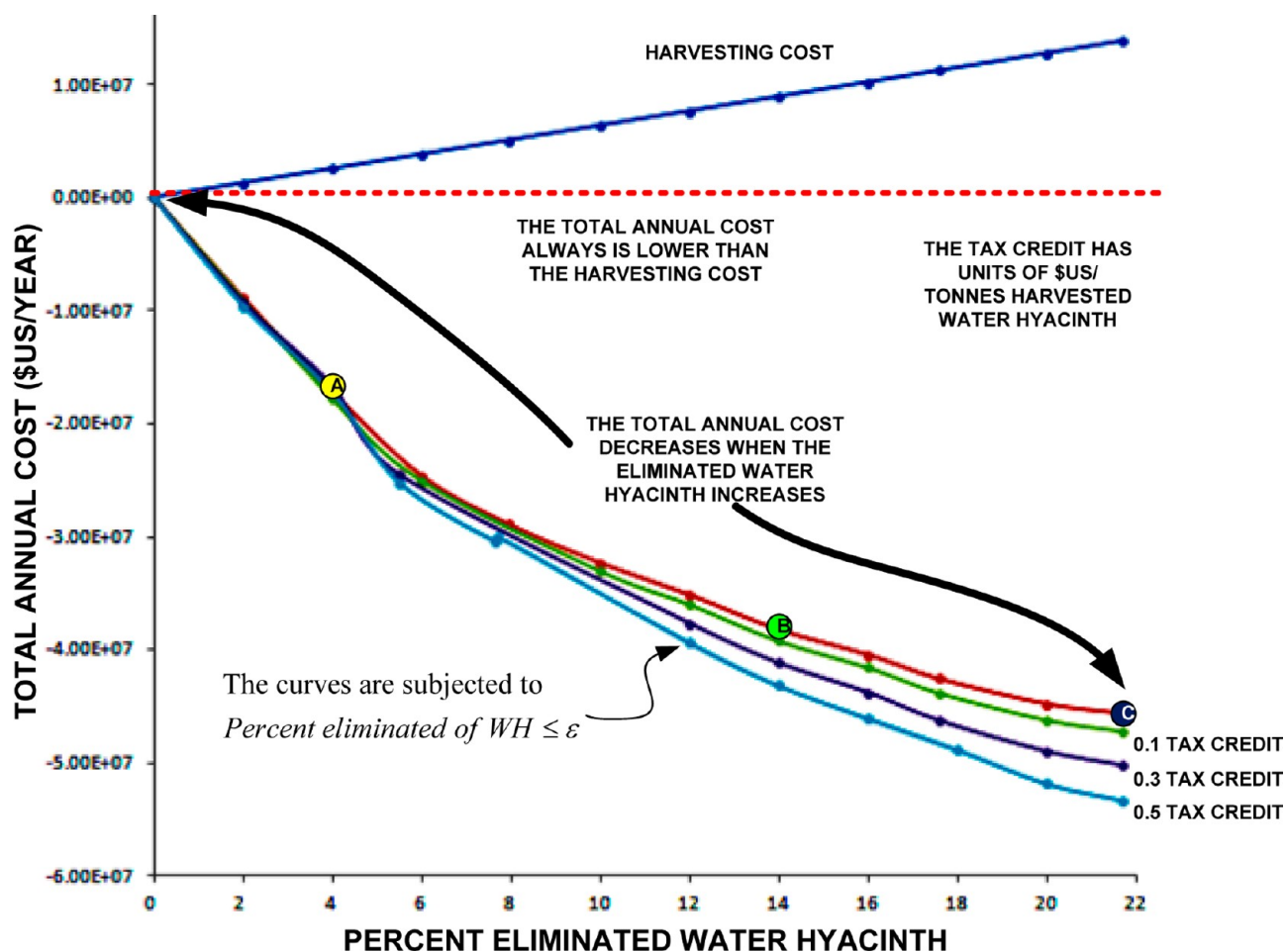


Figure 10. Pareto curves for alternative 2 (TAC versus % eliminated water hyacinth).

hyacinth. Thus, the Lake of Chapala is one of the harvesting sites proposed because it is the most important lake of Mexico and is infested with water hyacinth, too. This lake is very close to Guadalajara, the second largest city of Mexico. Another site is the Balsas River, which is one of the greatest rivers in the central part of Mexico. This river supplies cooling water to the most important thermo-electric plant in the state of Michoacan in Mexico. In addition, the Lakes of Patzcuaro and Cuitzeo are proposed as harvesting sites. These lakes are close to the cities of Patzcuaro and Morelia, respectively; the Lake of Patzcuaro has an endemic species of fish named white fish, and tourism and fishing are the most important activities in this region. Also, the lake of Yuriria is an important lake of the state of Guanajuato and is infested with water hyacinth. In this regard, these harvesting sites are very important water bodies in the considered system. Furthermore, the refinery candidates correspond to the main cities around such water bodies because the objective of a distributed system is to decrease the costs (mainly transportation costs), and hence, the transportation distances must be short. Besides, the demand zones are located in cities around the water bodies because these locations have a given demand of biofuels, water, and chemicals, among others products. Figure 1 shows the water bodies polluted with water hyacinth, and Table 1 presents the available biomass of water hyacinth for each place considered in this example. In addition, Figure 1 shows the places that demand some bioproducts (in this case, the bioproducts considered are ethanol, mixed alcohols, biogas, fertilizers, and biomass for heating), and Table 2

presents the demand at each place for such products. Table 3 gives the water demand for each place with the quality constraints for the pollutants considered. The treatment technologies available for obtaining water from water hyacinth are given in Table 4, which also shows the removal efficiency for each technology (in this case only Cr(VI) is considered as the only pollutant in water; however, the study can be extended to include additional pollutants). Table 5 presents the efficiency to obtain the products for the different technologies considered. On the other hand, the biomass is transported in truck by highways (because transportation by truck is the most widely used in this zone of Mexico); the unit biomass transportation costs are shown in Table 6. The water transportation is by pipelines, and the water transportation cost is about \$US 1.63/m<sup>3</sup> transported water for a distance from 500 m.

Using these data, the model formulation was coded in GAMS, and this consists of 210 binary variables, 8054 continuous variables, and 2958 constraints. The problem was solved using a computer with an i7 processor at 2.2 GHz with 6 GB of RAM. Notice that the MINLP (Mixed Integer NonLinear Programming) problem has to be solved several times to determine the Pareto curve TAC versus percentage of eliminated water hyacinth. Therefore, good initial guesses must be required to properly solve the MINLP problem. Also, notice that there is a bilinear term in eq 17, which introduces non-convexities into the model of the problem. Therefore, it is necessary to propose a solution strategy to generate good

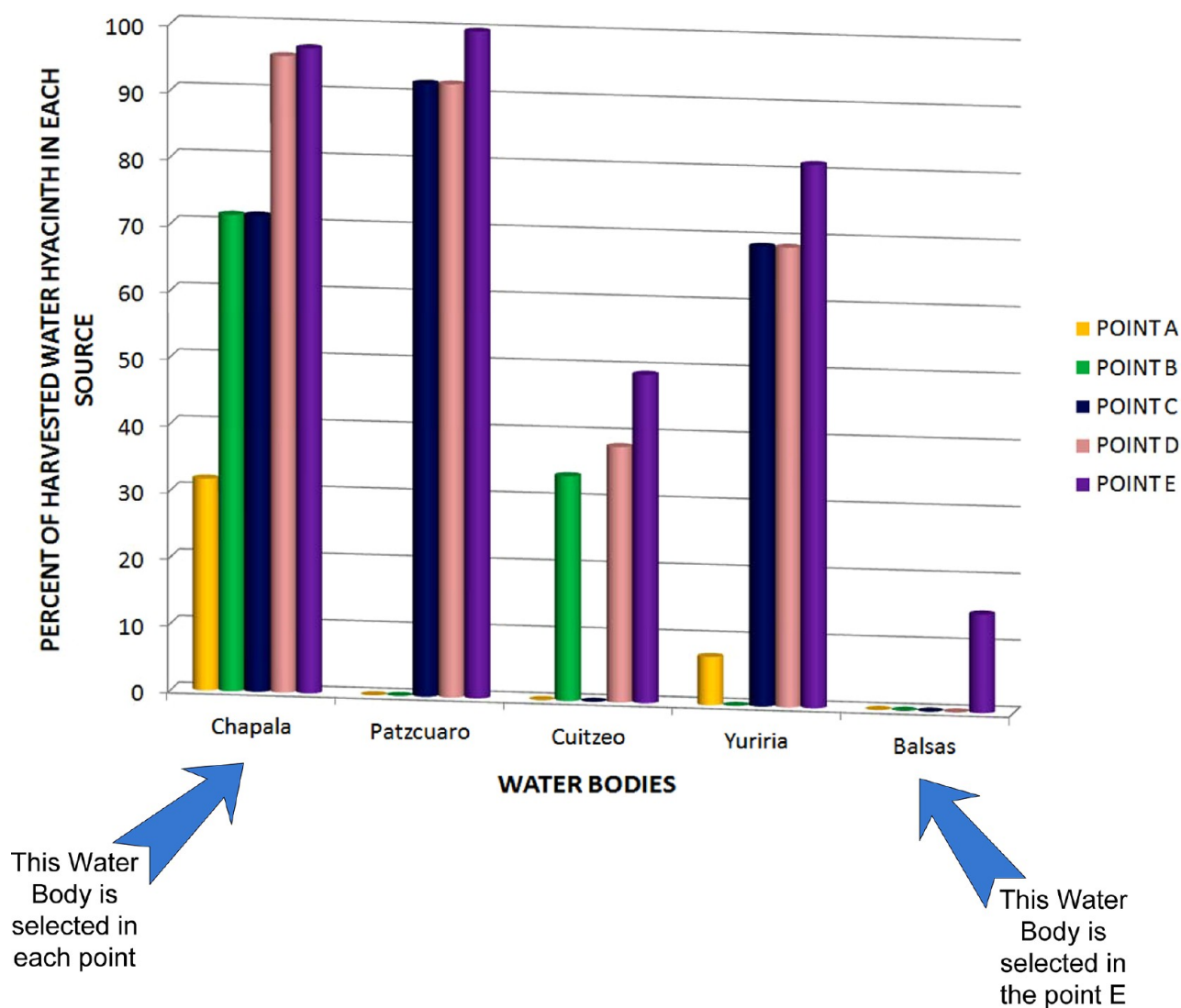
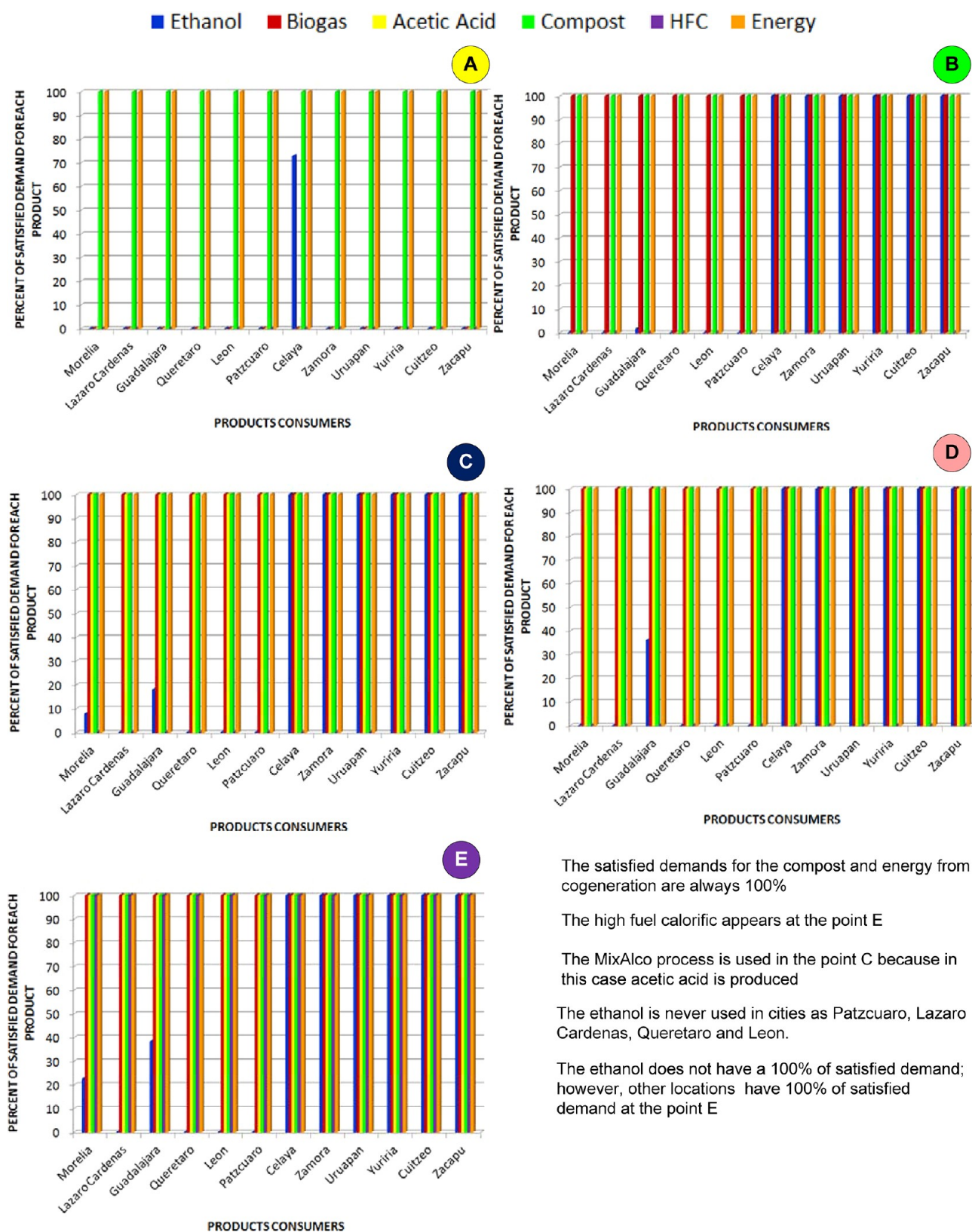


Figure 11. Representation of eliminated water hyacinth at each source and overall.

initial values because the quality of the solution for the full MINLP problem depends on the starting point of the optimization. If the starting point was bad, the conventional MINLP solvers (e.g., DICOPT, BARON, and SBB) could fail to provide a feasible solution or converge to a local optimum far from the optimal global. To generate an effective initialization of variables, the following strategy is proposed. First, a simplified MILP (Mixed Integer Linear Programming) problem is formulated and solved to obtain good initial guesses for the binary variables. This problem does not include eq 17, which is the only expression in the model that contains nonlinear terms. Then, an analysis to determine the best values for the percentage of eliminated water hyacinth was carried out to obtain initial guesses for the continuous variables. In this analysis, values for the eliminated water hyacinth between 0.5 and 4 times of the solution provided by the RMINLP (Relaxed Mixed Integer NonLinear Programming) problem (RMINLP corresponds to the case when the binary variables are transformed into continuous variables) were tested. This sensitivity analysis showed that the best value to provide good initial guesses corresponds to 3. Using the initial guesses so obtained for integer and continuous

variables, the original MINLP problem is solved without complications.

The suggested solution strategy to solve this problem was implemented in the modeling language GAMS. First, the MILP problem is solved using the solver CPLEX. The solution of the MILP problem provides the values of the integer variables that are used to solve the RMINLP problem using any one of the solvers CONOPT, MINOS, or SNOPT. After that, the amount of eliminated water hyacinth is specified as 3 times the eliminated water hyacinth corresponding to the RMINLP solution in order to solve the MINLP with DICOPT. If the previous strategy produces an infeasible solution, then it is necessary to use the solver CPLEX for solving the MILP problem and the solver BARON for solving the RMINLP problem and the original MINLP problem. The problem was solved for different levels of the constraints to get the Pareto curve; each point of the Pareto curve consumes from 1.39 to 4.73 s when the solver CONOPT, MINOS, or SNOPT are used to solve the RMINLP problem, from 0.172 to 0.218 s when the solver CPLEX is used to solve the MILP problem, from 2.76 to 3.12 s when the solver DICOPT is used to solve the MINLP problem and, finally, from 548.28 to 1203 s when the solver BARON is used to solve the RMINLP as



**Figure 12.** Distribution of the satisfied demands of products at different consumer sites for the points indicated in Figures 9 and 10.

well as the MINLP problems. The general solution procedure is presented in Figure 8.

In addition, the problem was solved for several tax credits, which is a subvention for eliminating water hyacinth from the sources. In this case, four tax credits were considered

The satisfied demands for the compost and energy from cogeneration are always 100%

The high fuel calorific appears at the point E

The MixAlco process is used in the point C because in this case acetic acid is produced

The ethanol is never used in cities as Patzcuaro, Lazaro Cardenas, Queretaro and Leon.

The ethanol does not have a 100% of satisfied demand; however, other locations have 100% of satisfied demand at the point E

(0, 0.1, 0.3, and 0.5 \$US/tonne eliminated water hyacinth). For each tax credit, a Pareto curve was obtained, all of which are shown in Figures 9 and 10.

It is important to note that the harvesting cost for the stand-alone operation that only eliminates the water hyacinth is

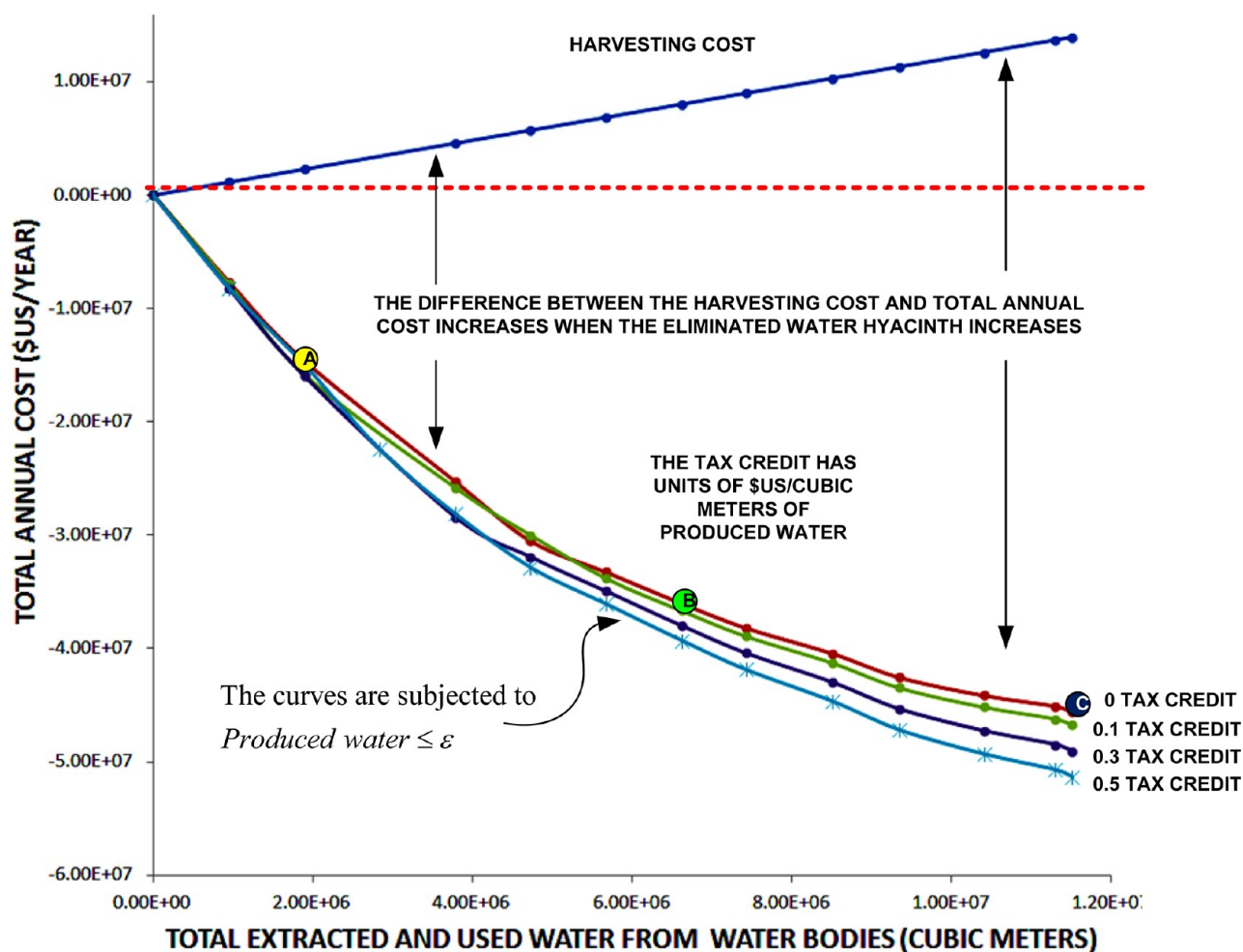


Figure 13. Pareto curves for the TAC versus produced water (Alternative 1).

always greater than the TAC for the integrated process because in this case the plant is not used to obtain various products. On the other hand, when the water hyacinth is considered as raw material to obtain a set of products, it is possible to generate solutions attractive economically (which means that the harvesting cost is lower than the sales for the products manufactured).

As shown in Figure 9 for alternative 1, the TAC increases when the eliminated water hyacinth increases. It leads to a decrease in the difference between the harvesting cost and the total annual cost, while the eliminated water hyacinth increases. The part of the Pareto curves for negative TAC represents attractive solutions (i.e., the net profit is positive because this is equal to  $-TAC$ ).

On the other hand, in Figure 10, the Pareto curves are opposites because the TAC begins at a value of zero and decreases while the harvesting cost increases. The maximum amount of eliminated water hyacinth is about 22%, and this point is represented with the letter C, for a tax credit of zero. Point C in Figure 10 is the same solution represented as point C in Figure 9. As observed, point C represents an inflection point in the curve for the TAC. The difference between Figure 9 and Figure 10 is that Figure 9 is based on alternative 1 to solve the problem (high elimination of water hyacinth), whereas Figure 10 represents the case when the elimination of water hyacinth is low.

A set of points were selected to observe the change of the TAC with respect to the harvesting cost; for example, in point A, the harvesting cost is \$US 2,564,582 and the TAC is \$US  $-1.72 \times 10^7$ , then the difference between the TAC and the harvesting cost is about 700% of the harvesting cost. This is explained by the large sales revenues from the different products produced. On the other hand, in point C, the percentage of this difference is about 400%. Finally, in point E, the difference between the harvesting cost and the sale of products represents about 40% of the harvesting cost.

Another analysis can be done when each point is shown on the basis of the percentage eliminated of water hyacinth from each water body. Because the total percentage can be high, however, it can be low at a specific water body.

Figure 11 shows the individual consumption of water hyacinth at each source. The main water body for the case study is the Lake of Chapala, so it is selected to consider the specific elimination of water hyacinth with different percentages. For example, point A represents an elimination of 30% of the water hyacinth in this lake, whereas in point C, almost 100% of the water hyacinth is eliminated from this water body. On the other hand, the second water body most important for this system is the Balsas river because it has a large amount of this plant; however, this river is located close to the west coast and far from other water bodies and cities; therefore, the elimination of water hyacinth from the



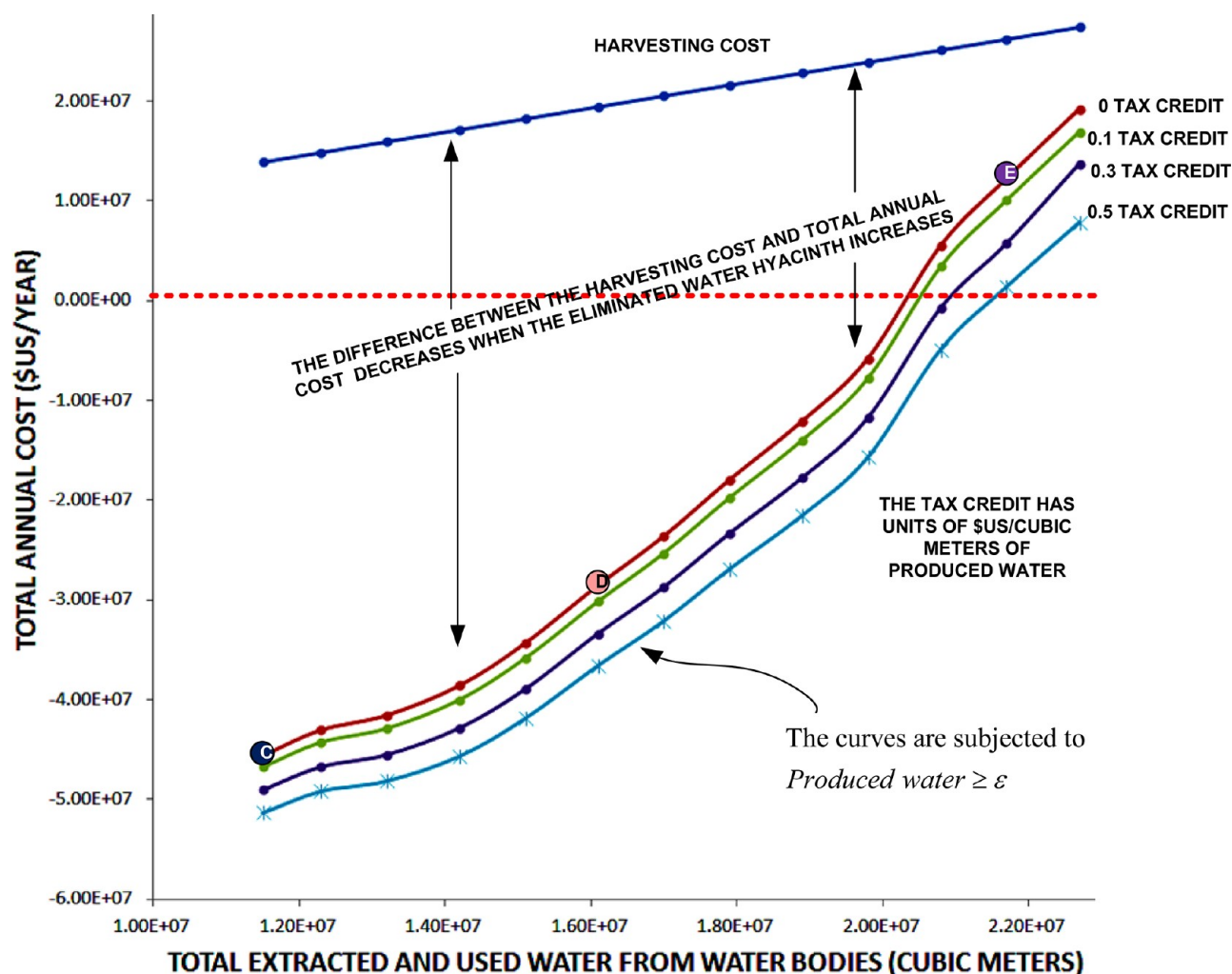


Figure 14. Pareto curves for the TAC versus the produced water (Alternative 2).

Balsas river is selected only in point E. Notice in Figure 9 that this point represents a high consumption of water hyacinth, but it also has a greater TAC respect to the other solutions. In addition, in the addressed problem the water bodies corresponding to the lakes of Patzcuaro, Cuitzeo, and Yuriria are important because they are the closest ones to the main cities and are related to significant economic activities.

Figure 12 shows the distribution for the satisfied demands of products at the different consumer places for the points indicated in Figures 9 and 10, which show that compost and energy are the main products because in all points their demands are fully satisfied. Ethanol does not appear in cities like Patzcuaro, Lazaro Cardenas, Queretaro, and Leon. Notice that the maximum demand satisfied for ethanol is at point E; also, High Fuel Caloric appears in this point. Furthermore, the MixAlco process is used in point C to produce acetic acid.

On the other hand, an analysis was done to identify the impact of the produced clean water on the minimization of total annual cost including several tax credits and two alternatives for produced water. The first option is when a low production of water is required, and the second option is for a high production of clean water. The behavior is similar to the analysis corresponding to the harvested water hyacinth. The

harvesting cost is always greater than the total annual cost, which means that for this case always there is a positive net profit (or that the TAC is negative). There is an inflection point between these two options, which is represented as point C in Figures 13 and 14.

Notice in Figure 13 that the TAC decreases when the tax credit increases; this effect is more significant in this second option because in this case the Pareto curves have always positive net profits. Notice in Figure 13 (option 1) the Pareto curves for the point when the TAC of zero corresponds to an amount of produced water of zero.

At this point, from the previous analysis, the following important questions appear: Where is the water hyacinth for the production of clean water coming from? Where should the clean water produced be distributed? This way, Figure 15 shows the distribution of the water bodies for the different points on the Pareto curves of Figures 13 and 14. Figure 15 also shows the distribution of the extracted clean water from the different water bodies to the water consumers.

It is important to note that the produced water in a specific water body should be used by the closest water consumer because in these cases the water transportation cost is lower. Also, the number of selected water bodies increases when the amount of produced clean water is maximized.

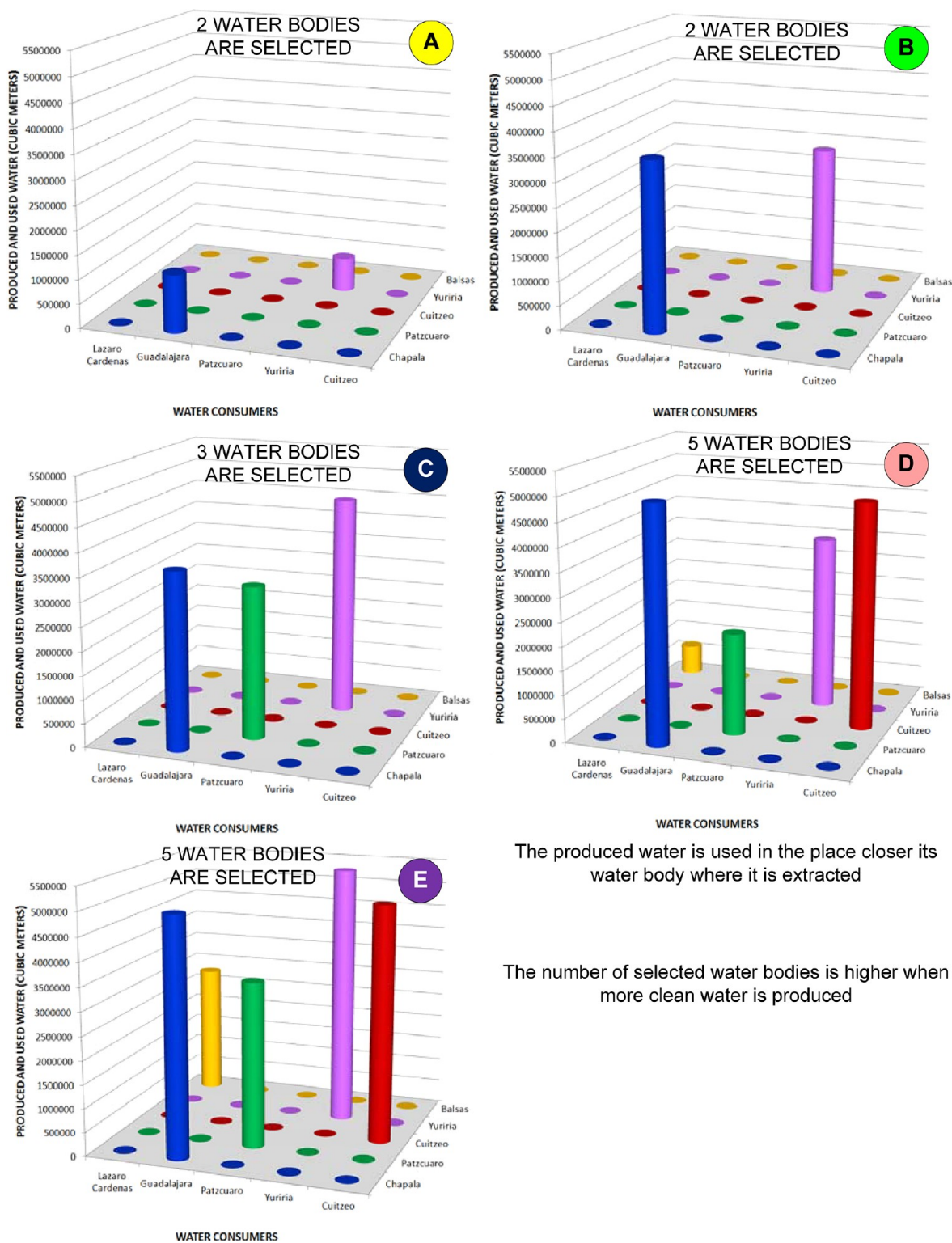


Figure 15. Distribution of water bodies and water consumers selected for the different points in the Pareto curves of Figures 13 and 14.

## CONCLUSIONS

This paper has presented a new formulation for the cleaning of water bodies of water hyacinth and the value-added processing through a distributed biorefinery system that produces several bioproducts (including biofuels and specialty chemicals) and clean water. The optimization model is formulated as a multi-objective optimization problem that simultaneously considers minimization of the total annual cost and maximization of the

amount eliminated of water hyacinth from the water bodies (or maximization for the production of clean water), while satisfying technical and environmental constraints. The results are shown through Pareto curves to represent the trade-offs between the contradicting objectives and to allow determining the solution that best satisfies the specific requirements.

The proposed approach impacts on the sustainability of the system in three dimensions: economic, social, and environmental.

The economic criterion consists of maximization of profit due to the processing of the eliminated water hyacinth. The environmental dimension is based on cleaning of water bodies infested with water hyacinth. The social dimension consists of providing benefits to the population such as appropriate conditions to allow several human activities on water bodies and the possibility to create several jobs in the harvesting sites.

The application of the proposed methodology to a case study of one of the most important hydrologic regions in Mexico shows that it is useful to generate solutions to clean water bodies, obtain clean water, and produce several biofuels and specialty chemicals obtaining positive net profits. Therefore, the proposed methodology shows that distributed biorefinery systems can be an economical and sustainable option to eliminate the water hyacinth from water bodies.

Finally, the proposed model is general and can be applied to any case of interest with the proper input data. In addition, the proposed model can be extended to consider other plants that can be considered as pollutants in water bodies.

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### Notes

The authors declare no competing financial interest.

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## NOMENCLATURE

### Parameters

$a_{s,n,q}^{WT}$	Unit fixed capital costs for water treatment units accounting for limits given
$a_{i,j,q}^{hub}$	Unit fixed capital costs for processing facilities accounting for limits given
$a_{j,q}^{cen}$	Unit fixed capital costs for central processing facilities accounting for limits given
$b_{s,n,q}^{WT}$	Unit variable capital costs for water treatment units accounting for limits given
$b_{i,j,q}^{hub}$	Unit variable capital costs for processing facilities accounting for limits given
$b_{j,q}^{cen}$	Unit variable capital costs for central processing facilities accounting for limits given
$B_{ij}^{hub}$	Unit variable cost for distributed processing facilities $j$
$f b_{i,j,q}^{hub\min}$ $f b_{i,j,q}^{hub\max}$	Maximum and minimum limits for the amount of processed biomass in processing facilities
$f w t_{s,n,q}^{\min}$ $f w t_{s,n,q}^{\max}$	Maximum and minimum limits for amount of processed biomass in water treatment units
$F w h_s^{\max}$	Amount of water hyacinth available in place of source
$G_{p,k}^{con\max}$	Maximum amount of product $p$ to market $k$
$H_{w,m}^{\max}$	Maximum water demand in market $m$
$w b_{j,q}^{cen\min}$ $w b_{j,q}^{cen\max}$	Maximum and minimum limits for amount of processed biomass in central processing facilities
$Z w_s$	Efficiency to extract water from water hyacinth in source $s$
$Z w_{s,c}^{in}$	Inlet composition of pollutant to water treatment technologies

$Z w_{s,n,c}^{out}$	Outlet composition of pollutant to water treatment technologies
$Z w_{s,m,c}^{con\max}$	Maximum composition of pollutant in discharged water to markets
$Z w h_s$	Efficiency to extract biomass from water hyacinth in source $s$
$\alpha_{j,p}^{hub}$	Efficiency factor in processing facility for technology $j$ for conversion of dry biomass to produce $p$
$\alpha_{j,p}^{cen}$	Efficiency factor in central processing facility for technology $j$ for conversion of dry biomass to product $p$
$\beta_j^{cenop}$	Unit operational cost associated to route $j$ and central processing facility
$\beta_{s,n}^{wtop}$	Unit operational cost associated to source $i$ and water treatment units
$\beta_j^{hubop}$	Unit operational cost associated to technology $j$ in processing facility
$\beta_s^{Harvesting}$	Unit harvesting costs for each location $s$
$\beta b c n_s^{Transp}$	Unit transportation cost of biomass from source $s$ to central processing facility
$\beta b h u b_{s,i}^{Transp}$	Unit transportation cost for biomass from source $s$ to processing facility $i$
$\beta c e n p r o d_{j,p,k}^{Transp}$	Unit transportation cost for products from centralizer to markets
$\beta h i b p r o d_{i,j,p,k}^{Transp}$	Unit transportation cost for products from processing facilities to markets
$\beta w t_{s,n}^{Transp}$	Untreated water unit cost
$\beta w t_{s,n,m}^{Transp}$	Treated water unit cost
$\sigma$	Exponent to consider economies of scale
$\gamma_{n,c}$	Efficiency to eliminate pollutant $c$ from extracted water from water hyacinth

### Variables

$A_{ij}^{hub}$	Fixed capital cost for processing facilities
$A_j^{cen}$	Fixed cost for capital cost of central processing facilities
$A_{s,n}^{WT}$	Fixed cost of capital cost of water treatment units
$B_{ij}^{hub}$	Term used to linearize capital costs for processing facilities
$B_j^{cen}$	Term used to linearize capital costs for central processing facilities
$B_{j,n}^{WT}$	Term used to linearize capital costs for water treatment units
$C o s t H u b_{ij}^{op}$	Operational cost for processing facilities
$C o s t H u b_{ij}^{cap}$	Capital cost for processing facilities
$C o s t c e n_j^{op}$	Operational cost for the central processing facilities
$C o s t c e n_j^{cap}$	Capital cost for the central processing facilities
$C o s t W T_{s,n}^{op}$	Operational cost for the water treatment units
$C o s t W T_{s,n}^{cap}$	Capital cost for the water treatment units
$C o s t C a p i t a l$	Total capital cost
$C o s t H a r v e s t i n g$	Water hyacinth harvesting cost
$C o s t O p e r a t i o n a l$	Total operational cost
$C o s t T r a n s B M$	Biomass transportation cost

CostTransProd  
Products transportation cost

CostTransWater  
Water transportation cost

$dA_{ij,q}^{\text{hub}}$   
Disaggregated variable used for fixed part of capital costs in processing facilities

$dA_{j,q}^{\text{cen}}$   
Disaggregated variable used for fixed part of capital costs in central processing facilities

$dA_{s,n,q}^{\text{wt}}$   
Disaggregated variable for fixed capital costs for water treatment units

$dB_{ij,q}^{\text{hub}}$   
Disaggregated variable used for variable part of capital costs in processing facilities

$dB_{j,q}^{\text{cen}}$   
Disaggregated variable used for variable part of capital costs in centralizers

$dB_{s,n,q}^{\text{wt}}$   
Disaggregated variable for variable capital costs for water treatment units

$dB_{ij,q}^{\text{hub}}$   
Disaggregated variable used for processed biomass

$df_{wt,s,n,q}$   
Disaggregated variable for biomass processed in water treatment units

$dw_{j,q}^{\text{cen}}$   
Disaggregated variable used for processed biomass in the central processing facilities

$Fb_s$   
Amount of extracted biomass

$fb_{s,i}^{\text{hub}}$   
Amount of dry extracted biomass in location  $s$  that is directed to processing facility located in place  $i$

$fb_s^{\text{cen}}$   
Amount of dry extracted biomass in location  $s$  that is directed to central facility

$fb_{ij}^{\text{hub}}$   
Amount of dry biomass in processing facility  $i$  that is processed with technology  $j$

$fw_s$   
Amount of extracted water

$fwh_s$   
Amount of water hyacinth used in place of source  $s$

$fwt_{s,n}$   
Amount of treated water by technology  $n$

$gprod_{ij,p,k}^{\text{hub}}$   
Amount of product segregated and directed to the market  $k$  from processing facility  $i$

$gprod_{j,p,k}^{\text{cen}}$   
Amount of product segregated and directed to the market  $k$  from central facility

$G_{p,k}^{\text{con}}$   
Product  $p$  inlet to the market  $k$

$hw_{s,n,m}$   
Amount of water from the place  $s$  treated by technology  $n$  sent to the water consumer  $m$

$H_{W,s,m}$   
Total water flow rate directed to the water consumer  $m$

NetProfit  
Total net profit for overall system

SalesProd

Total sales correspond to sales for products

$wb_j^{\text{cen}}$   
Amount of distributed biomass to the technology  $j$  in the central processing facilities

$wprod_{ij,p}^{\text{hub}}$   
Amount of produced product  $p$  from biomass of the processing facility  $i$  by technology  $j$

$wprod_{i,p}^{\text{cen}}$   
Amount of produced product  $p$  from biomass of central processing facility by route  $j$

$Zw_{s,m,c}^{\text{con}}$   
Composition of pollutant in discharged water to consumers

### Binary Variables

$y_{ij,q}^{\text{hub}}$  Binary variable used for the capital cost

$y_{j,q}^{\text{cen}}$  Binary variable used for capital cost in central processing facility

$y_{s,n,q}^{\text{wt}}$  Binary variable used in capital cost in water treatment units

$Y_{ij,q}^{\text{hub}}$  Boolean variable used in capital costs

$Y_{j,q}^{\text{cen}}$  Boolean variable in capital costs for central processing facility

$Y_{s,n,q}^{\text{WT}}$  Boolean variable in capital costs for water treatment units

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