Multiobjective Optimization for Designing and Operating More Sustainable Water Management Systems for a City in Mexico

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This article proposes a multiobjective optimization model for the design of a macroscopic water system of a Mexican city that solves simultaneously the planning and scheduling of water storage and distribution tasks. The model, which considers rainwater harvesting and reclaimed water reusing as alternative water sources, maximizes the revenues from water sales and minimizes simultaneously the water consumption and land use. A case study based on the city of Morelia in Mexico was solved. It was found that the use of alternative water sources (such as harvested rainwater) along with an appropriate planning and scheduling of storage and distribution tasks have the potential to reduce the pressure over natural reservoirs significantly. Our approach considers simultaneously economic and environmental concerns, thereby contributing to the implementation of more sustainable alternatives in urban water distribution. © 2015 American Institute of Chemical Engineers *AIChE J*, 61: 2428–2446, 2015

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Introduction

Recently, research on how to improve water management worldwide has significantly increased due to water scarcity problems arising in several regions of the world. As a result, several approaches for water saving and conservation through water recycling, reusing and regeneration have been reported. An important case is the industrial sector, where several sources of water can be recycled to reduce fresh water consumption (thereby reducing as well the amount of wastewater discharged into the environment). In this context, Gouws et al.[1] presented a review for industrial water minimization involving batch processes. Jeżowski[2] presented another review regarding industrial water networks using graphical and mathematical programming techniques. Besides Verdaguer et al.[3] presented a combinatorial optimization procedure with multiple constraints to treat industrial effluents. More recently, Ibrić et al.[4] implemented a study for industrial water networks for different complexities, ranging from simple water networks up to combined water, wastewater treatment and heat exchanger networks.

Other studies have focused on developing methodologies for the optimal use of water considering the effect of the wastewater discharged from the industries. In this context, Boix et al.[5] proposed a multiobjective optimization strategy formulated as a mixed-integer linear programming (MILP) problem for designing an industrial water network that minimizes the amount of fresh water, regenerated water, and number of network connections in ecoindustrial parks. Alnouri et al.[6] presented an optimization approach for designing interplant water networks involving pipeline design. Furthermore, Burgara-Montero et al.[7] proposed a mathematical programming approach to take into account the effect of the industrial wastewater discharges over the surrounding environment during the synthesis of industrial water networks, and then Burgara-Montero et al.[8] incorporated seasonal variations in this model. Furthermore, Lira-Barragán et al.[9] reported an approach to determine the environmental impact for the industrial wastewater discharges, while Lira-Barragán et al.[10,11] incorporated constraints based on properties and included different options for wastewater treatment. In addition, Martinez-Gomez et al.[12] incorporated safety issues to the industrial wastewater discharges during the synthesis of industrial water networks. Furthermore,

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Wang et al.[13] developed a multiple objective optimization approach for the management of agricultural and soil resources. In the same way, Raul et al.[14] proposed a simulation model to mitigate the irrigation water deficit in a rice crop system, considering groundwater as a supplement source without compromising the resource. The important economic and environmental benefits observed with the use of industrial water networks have motivated the development of similar approaches for synthesizing water networks at the macroscopic level. For example, some approaches have focused on the use of alternative water sources such as reclaimed water and harvested rainwater. Along these lines, Li et al.[15] evaluated the domestic water demand in Ireland, which might be satisfied with harvested rainwater and reclaimed gray water. Domènech and Saurí[16] implemented a comparative study of the use of rainwater in single and multifamily buildings; they found that a relatively small storage tank could be enough to satisfy the toilet flushing demand. Domènech et al.[17] studied the use of harvested rainwater in developing countries. Liu et al.[18] presented a MILP model for the optimal management of water resources in the Greek islands of Syros and Paros-Antiparos. Booker et al.[19] discussed the modeling advances on water management policies in the last 25 years.[20–22] Howari and Ghrefat[23] developed a methodology for the environmental assessment of the quality of water, soil, and air in Jordan. They pointed out the detrimental impact of human activities on these three important aspects, and in the case of water, they stressed out the importance of using alternative water sources. These included reclaimed wastewater, harvested rainwater, importation of water across boundaries, and desalination of brackish and seawater as effective manners to overcome water scarcity. Atilhan et al.[24] applied a system integration approach for the water management in Qatar. Nápoles-Rivera et al.[25] presented a mathematical programming model for the optimal allocation of water in a macroscopic system considering rainwater harvesting and water reclamation as options to minimize the natural resources depletion, while Nápoles-Rivera et al.[26] incorporated in the model uncertain aspects and Rojas-Torres et al.[27] included future projected water demands. Zhang et al.[28] proposed a multiobjective optimization model for a sustainable design and implementation of wastewater reuse in China that considers wastewater reuse supplies and demands, economic performance, and pollutant reductions. Newman et al.[29] reported a multiobjective algorithm for planning and designing water infrastructures taking into account integrated urban water management principles applied to a rural greenfield.

It should be noted that previous methodologies for the implementation of water networks accounting for rainwater harvesting and reclaimed wastewater in a macroscopic system have focused on optimizing a single objective function. Hence, to the best of our knowledge, in this context, the simultaneous optimization of multiple objectives, such as economic and environmental, has not been addressed so far in the literature. Considering environmental aspects along with economic ones is of paramount importance, since it allows identifying win-win scenarios in which both objectives are simultaneously improved. Furthermore, there are different environmental impacts whose optimization should be considered separately. Therefore, to overcome previous limitations, this article proposes a multiobjective optimization model for the design of macroscopic water systems. The proposed model solves the planning and scheduling of the water storage and distribution tasks simultaneously for a Mexican city, considering natural and alternative water sources (harvested rainwater, reclaimed, and purchased water). The proposed model takes into account simultaneously economic (through the maximization of the overall profit) and environmental (through the minimization of the fresh water consumption and the minimization of the land use) objectives.

Problem Statement

The problem addressed in this article can be defined as follows. Given is a macroscopic system with the following elements:

- sources of water, such as damns, springs, and deep wells (natural sources);
- users, such as industrial, agricultural, and domestic;
- alternative water sources such as harvested rainwater, reclaimed water, and water purchased from another places as potential options to deal with resource scarcity.

The natural sources can be recharged by direct precipitation, by runoff water and by natural tributaries, which are used to satisfy the demands of the users in the city. Water from natural sources is treated in central facilities (i.e., mains) and distributed to final users. The industrial and domestic wastewater is treated in centralized treatment facilities. Reclaimed water can be reused to meet the agricultural demands or might be discharged to the environment. The purchased water from different places is distributed directly to the final users, as it is assumed that this water has the required quality. It is important to mention that the water purchased from external suppliers will be required only if the natural sources in a given location are not enough to satisfy the water demand. Furthermore, this is a common practice in some countries where one municipality with water scarcity buys fresh water from a different municipality to satisfy its water demands. Finally, as an alternative source to meet the needs of the users, harvested rainwater can be stored in different devices (storage tanks and artificial ponds), which can be installed as required.

The problem we aim to solve consists of finding the optimal planning and scheduling for the management of the resources that satisfies the demands in a macroscopic system while maximizing the economic profit and minimizing the environmental impact. For attaining the latter objective, it is necessary to maintain minimum consumption levels of natural resources and minimize at the same time the impact caused to the environment due to land use (for storage devices) and fresh water consumption. The economic objective, conversely, is the maximization of the revenues from the sales of water minus the capital and operational costs of distribution and storage.

Mathematical Model

The proposed model is based on the superstructure shown in Figure 1. It is a multiobjective and multiperiod optimization formulation. The model considers explicitly the population growth rate and the associated increase in water demand, the value of the money over time, and the change in the precipitation patterns due to climate change, which is predicted based on historical data. The model determines as well the optimal location and installation time of storage tanks and artificial ponds.

The model uses the following indexes: k denotes natural sources, m the tributaries that recharge the natural sources,

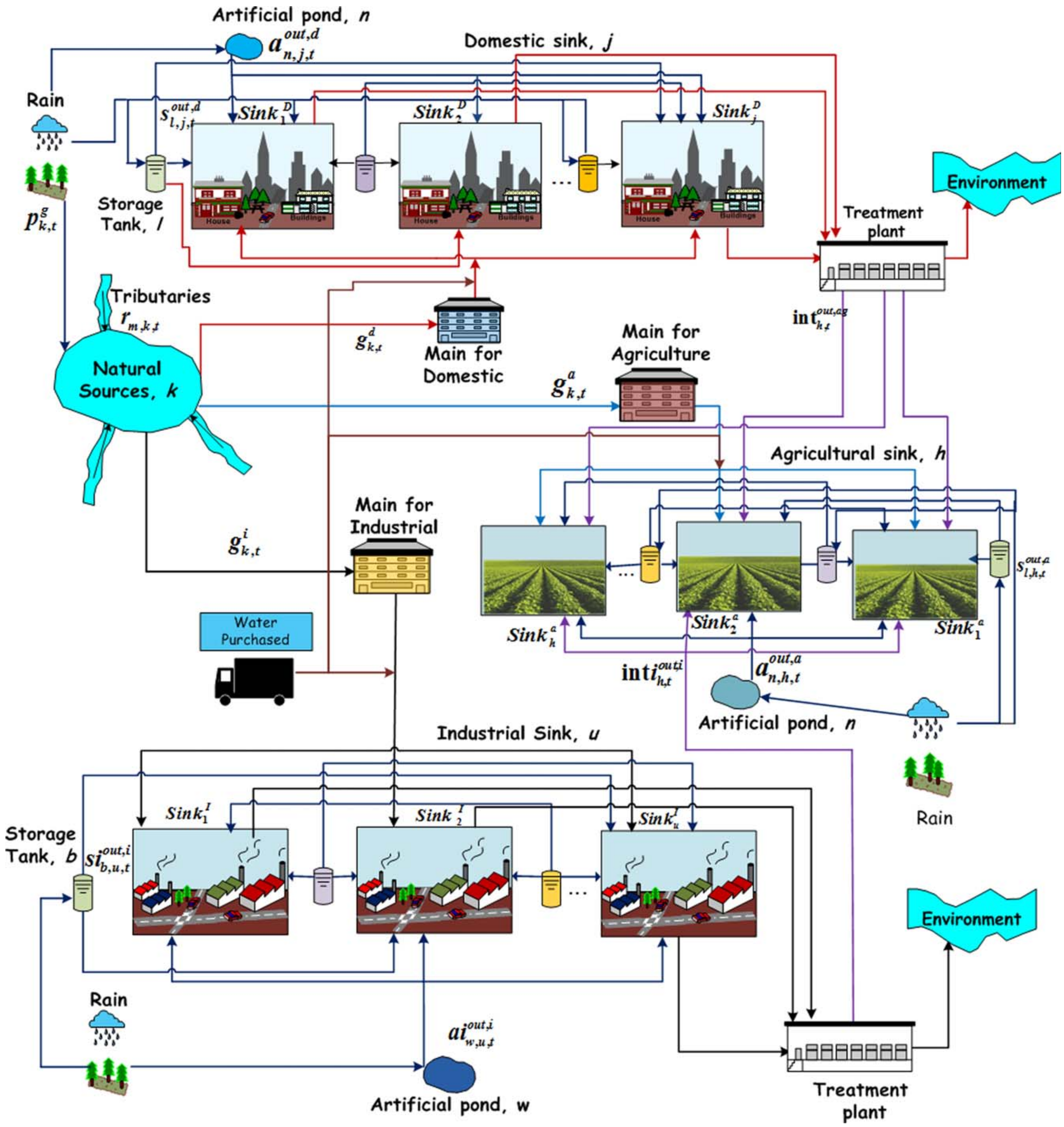

Figure 1. Superstructure for water distribution at macroscopic level.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

and t is the time period. Besides l and n represent the possible location for storage tanks and artificial ponds, respectively, for domestic and agricultural sinks; b and w represent the possible location for storage tanks and artificial ponds as well as for industrial sinks. Finally, j represents domestic sinks, h agricultural sinks, and u industrial sinks. The model defines a set of mass balances in the mixing and splitting points of the network. In addition, it includes a set of equations required to select the location and time of installation of the storage devices (in case they are installed).

Mass balance for natural water sources

The water accumulation in natural water sources is determined from the initial water inventory in natural source k ($G_{k,t-1}$) and the inlets and outlets over the time period. In Eq. 1, the terms $r_{m,k,t}$ are the inlets from all the tributaries that contribute to stream k, whereas $p^g_{k,t}$ are the inlets from direct precipitation and runoff water collection. The outlets are the water sent to the different mains: domestic ($g^{\text{d}}_{k,t}$), agricultural ($g^{\text{a}}_{k,t}$), and industrial ($g^{\text{i}}_{k,t}$). In practice, these facilities could be in the same location, but for modeling purposes, they are considered as different facilities in which different levels of treatment are given to the natural sources depending on the final use of the processed water

$$G_{k,t}-G_{k,t-1}=\sum_{m\in M} r_{m,k,t}+p^g_{k,t}-g^{\text{d}}_{k,t}-g^{\text{a}}_{k,t} -g^{\text{i}}_{k,t}-v^g_{k,t}-\text{Drop}^g_{k,t}\ , \quad \forall k\in K, \forall t\in T \tag{1}$$

The term $p^g_{k,t}$ can be calculated as the sum of the runoff water collected plus the direct precipitation as follows

$$p^g_{k,t} = \mathrm{ROWV}_{k,t} + \mathrm{DPWV}_{k,t}\,, \quad k \in K, t \in T \tag{2}$$

The runoff water ($\mathrm{ROWV}_{k,t}$) is a function of the runoff coefficient, the total annual precipitation, and the collection area

$$\mathrm{ROWV}_{k,t} = P_t \cdot A^{\mathrm{ROW}}_k \cdot \mathrm{Ce}, \quad k \in K, \ t \in T \tag{3}$$

where Ce can be obtained (with indirect methods) from the annual precipitation and the parameter K, which takes into account the type and use of land[30]

$$\mathrm{Ce} = \frac{Ka(P^{\mathrm{Total}} - 250)}{2000}, \quad Ka \le 0.15 \tag{4}$$

$$\mathrm{Ce} = \frac{Ka\left(P^{\mathrm{Total}} - 250\right)}{2000} + \frac{Ka - 0.15}{1.5}, \quad Ka > 0.15 \tag{5}$$

The direct precipitation can be calculated as a function of the collecting area and the monthly precipitation

$$\mathrm{DPWV}_{k,t} = P_t \cdot A^{\mathrm{DPW}}_k, \quad k \in K, t \in T \tag{6}$$

The terms $v^g_{k,t}$ and $\mathrm{Drop}^g_{k,t}$ represent the water losses (due to evaporation, filtration, and losses in the distribution process, which are here considered to be a 20% of the collected water) and the excess water (i.e., amount of water that exceeds the maximum capacity of source k), which physically means an over-flooding

$$v^g_{k,t} = 0.2\left[\sum_{m \in M} r_{m,k,t} + p^g_{k,t}\right], \quad k \in K, t \in T \tag{7}$$

In order to avoid overexploitation of the natural sources, a set of constraints that impose conditions on the water use is included. Hence, the maximum water extraction from any source cannot exceed 20% of the available water in a single period, while the minimum acceptable level in any source cannot drop below 35% of the maximum capacity

$$g^{\mathrm{d}}_{k,t} + g^{\mathrm{a}}_{k,t} + g^{\mathrm{i}}_{k,t} + v^g_{k,t} \le 0.2 G_{k,t-1}\,, \quad \forall k \in K, \forall t \in T \tag{8}$$

$$G_{k,t} \ge 0.35 G^{\max}_k, \quad \forall k \in K, \forall t \in T \tag{9}$$

It is noteworthy that the overall mass balance for the aquifer is not explicitly stated. This is because it is assumed that underground sources (deep wells) take water from the city aquifer, so the balance for these sources (as represented by Eq. 1) include all the inlets and outlets to these sources and thus to the aquifer. In this work, for modeling purposes, the deep wells were clustered in groups. However, from a practical point of view, it would be better to model the wells individually, considering information such as whether they take water from the superficial aquifer or the deep aquifer, their current water level, and so forth. This makes possible to define an explicit mass balance for the aquifer rather than for the cluster. This balance provides a good estimate of the deficit or surplus water in the aquifer. Furthermore, the water used in agricultural activities is not fully consumed by the crops, and it might eventually reach the city aquifer as runoff water. This assumption might be valid under the following considerations: (1) moderate or low agricultural activity (which leads to low water consumption when compared with the rest of the users, which is the case of Morelia); (2) efficient irrigation techniques, such as drip irrigation; and (3) the weather conditions are such that the water not consumed is evaporated. Therefore, the runoff water that effectively reaches the aquifer is negligible.

Mass balance for precipitation in artificial water devices

The capacity for rainwater harvesting for artificial devices depends on the precipitation level in a specific location and season of the year, the available collection area, and the runoff coefficient as follows

$$P = f(\mathrm{Area},\ Ce,\ \mathrm{Precipitation}) \tag{10}$$

The precipitation data can be easily retrieved from meteorological stations. Several authors have reported data of runoff coefficients for roofs, which range from 0.7 to 0.95 depending on the roof building material.[31] The collection area is defined as the available roof area nearby to the storage device. Four different types of storage devices are considered. The first two correspond to storage devices used for domestic and agricultural users (storage tanks and artificial ponds)

$$P^{\mathrm{s}}_{l,t} = P_t \cdot A^{\mathrm{s}}_l \cdot \mathrm{Ce}^{\mathrm{s}}, \quad l \in L, t \in T \tag{11}$$

$$P^{\mathrm{a}}_{n,t} = P_t \cdot A^{\mathrm{a}}_n \cdot \mathrm{Ce}^{\mathrm{a}}, \quad n \in N, t \in T \tag{12}$$

where $P^{\mathrm{s}}_{l,t}$ is the total available water for storage tank l over time period t. $P^{\mathrm{a}}_{n,t}$ is the total available water for artificial pond n over time period t. A^{s}_l and A^{a}_n are the collecting areas available for each type of storage.

The second set of storage devices (storage tanks and artificial ponds) is used for industrial applications. $P^{\mathrm{si}}_{b,t}$ is the total available water for industrial storage tank b over time period t and $P^{\mathrm{ai}}_{w,t}$ is the total available water for artificial pond w over time period t

$$P^{\mathrm{si}}_{b,t} = P_t \cdot A^{\mathrm{si}}_b \cdot \mathrm{Ce}^{\mathrm{si}}, \quad b \in B, t \in T \tag{13}$$

$$P^{\mathrm{ai}}_{w,t} = P_t \cdot A^{\mathrm{ai}}_w \cdot \mathrm{Ce}^{\mathrm{ai}}, \quad w \in W, t \in T \tag{14}$$

where A^{si}_b and A^{ai}_w are the collection areas available for each type of storage.

Once the availability of harvested rainwater has been calculated, the effective collected rainwater is evaluated as follows

$$P^{\mathrm{s}}_{l,t} = s^{\mathrm{in}}_{l,t} + v^{\mathrm{s}}_{l,t}, \quad l \in L, t \in T \tag{15}$$

$$P^{\mathrm{a}}_{n,t} = a^{\mathrm{in}}_{n,t} + v^{\mathrm{a}}_{n,t}, \quad n \in N, t \in T \tag{16}$$

$$P^{\mathrm{si}}_{b,t} = \mathrm{si}^{\mathrm{in}}_{b,t} + v^{\mathrm{si}}_{b,t}, \quad b \in B, t \in T \tag{17}$$

$$P^{\mathrm{ai}}_{w,t} = \mathrm{ai}^{\mathrm{in}}_{w,t} + v^{\mathrm{ai}}_{w,t}, \quad w \in W, t \in T \tag{18}$$

As stated in the previous equations, the total available rainfall for each time period (t) can be sent to storage tanks ($s^{\mathrm{in}}_{l,t}$) or artificial ponds ($a^{\mathrm{in}}_{n,t}$) for domestic and agricultural users. Similarly, for industrial users, the available harvested rainwater can be stored in tanks ($\mathrm{si}^{\mathrm{in}}_{b,t}$) or artificial ponds ($\mathrm{ai}^{\mathrm{in}}_{w,t}$). If there is no storage capacity; then, the excess water can be discarded. The last term in Eqs. 15−18 takes into account this possibility and is used to avoid overflowing in the storage devices. It should be noticed that there is a set of devices for domestic and agricultural users and a different set for industrial users. This allows to account for the fact that the quality of the water required in an industrial process is significantly different than the one required for agricultural or domestic uses, and so are the corresponding treatment costs. Hence, the quality of the water at the exit of the devices meets these requirements. This assumption considers as well the differences in costs of the devices and the incentives for the tax credits associated to recycling industrial wastewater.

Mass balance in storage tanks

The mass balances for the storage tanks states that the accumulation over the time period t ($S_{l,t}$) is equal to the amount of water stored in the previous time ($S_{l,t-1}$) plus the inlet and minus the summation of the outlets. In this case, the only inlet to the storage tanks corresponds to harvested rainwater ($s_{l,t}^{\mathrm{in}}$), whereas the outlets are the water sent to domestic ($s_{l,j,t}^{\mathrm{out,d}}$) and agricultural ($s_{l,h,t}^{\mathrm{out,a}}$) users. The existence and capacity of these tanks are both determined as part of the optimization process

$$S_{l,t}-S_{l,t-1}=s_{l,t}^{\mathrm{in}}-\sum_{j\in J}s_{l,j,t}^{\mathrm{out,d}}-\sum_{h\in H}s_{l,h,t}^{\mathrm{out,a}}\,,\quad \forall l\in L,\,\forall t\in T \tag{19}$$

In the same way, the balance for storage tanks in industrial facilities is as follows

$$\mathrm{SI}_{b,t}-\mathrm{SI}_{b,t-1}=\mathrm{si}_{b,t}^{\mathrm{in}}-\sum_{u\in U}\mathrm{si}_{b,u,t}^{\mathrm{out,i}}\,,\quad \forall b\in B,\,\forall t\in T \tag{20}$$

Storage devices close to sinks can be used to reduce piping and pumping costs (pp cost). In the previous equation, $\mathrm{SI}_{b,t}$ represents the accumulation over the time period t, $\mathrm{SI}_{b,t-1}$ is the accumulation over the previous time period $t-1$, $\mathrm{si}_{b,t}^{\mathrm{in}}$ is the stored precipitation over the time period t, and $\mathrm{si}_{b,u,t}^{\mathrm{out,i}}$ is the water sent to industrial sinks.

Mass balance in artificial ponds

The mass balances for artificial ponds are equivalent to those applied to storage tanks. For domestic and agricultural users, the balance is the following

$$A_{n,t}-A_{n,t-1}=a_{n,t}^{\mathrm{in}}-\sum_{j\in J}a_{n,j,t}^{\mathrm{out,d}}-\sum_{h\in H}a_{n,h,t}^{\mathrm{out,a}}\,,\quad \forall n\in N,\ \forall t\in T \tag{21}$$

where $A_{n,t}$ is the water stored over the time period t, $A_{n,t-1}$ is the water stored over the previous time period $(t-1)$, $a_{n,t}^{\mathrm{in}}$ is the harvested rainwater, $a_{n,j,t}^{\mathrm{out,d}}$ is the water consumed by domestic users, and $a_{n,h,t}^{\mathrm{out,a}}$ is the water consumed by agricultural users.

For industrial users, the balance is stated as follows

$$\mathrm{AI}_{w,t}-\mathrm{AI}_{w,t-1}=\mathrm{ai}_{w,t}^{\mathrm{in}}-\sum_{u\in U}\mathrm{ai}_{w,u,t}^{\mathrm{out,i}}\,,\quad \forall w\in W,\,\forall\, t\in T \tag{22}$$

where $\mathrm{AI}_{w,t}$ is the water stored over the time period t, $\mathrm{AI}_{w,t-1}$ is the water stored over the previous time period, $\mathrm{ai}_{w,t}^{\mathrm{in}}$ is the collected rainwater and $\mathrm{ai}_{w,u,t}^{\mathrm{out,i}}$ is the consumed water.

Mass balance in mains

Natural water sources are sent to different mains to receive an appropriate treatment depending on their final use. In the main for domestic users, the sum of the natural water sources ($g_{k,t}^{\mathrm{d}}$) sent to it is equal to the sum of the water sent from the domestic main to the domestic sinks ($f_{j,t}$)

$$\sum_{k}g_{k,t}^{\mathrm{d}}=\sum_{j\in J}f_{j,t}\,,\quad t\in T \tag{23}$$

Similarly, the agricultural mains receive water from natural sources ($g_{k,t}^{\mathrm{a}}$) and distribute it to agricultural users ($r_{h,t}$) as follows

$$\sum_{k\in K}g_{k,t}^{\mathrm{a}}=\sum_{h\in H}r_{h,t}\,,\quad t\in T \tag{24}$$

where $r_{h,t}$ is the flow rate sent from the agricultural main to agricultural sinks h over the time period t.

Finally, the water received in the industrial main ($g_{k,t}^{\mathrm{i}}$) is distributed to the different industrial sinks ($q_{u,t}$)

$$\sum_{k\in K}g_{k,t}^{\mathrm{i}}=\sum_{u\in U}q_{u,t}\,,\quad t\in T \tag{25}$$

where $q_{u,t}$ is the flow rate sent from the industrial main to the industrial sink u over the time period t.

Balance for domestic sinks and domestic treatment plants

The domestic demands ($D_{j,t}^{\mathrm{ds}}$) can be met using water from the domestic main, water from the storage tanks or water from the artificial ponds. The demand in each sink is a function of the population and season of the year (the demand increases during the hottest months of the year and reduces during the coldest months). The balance for domestic sinks is the following

$$D_{j,t}^{\mathrm{ds}}=f_{j,t}+\sum_{l\in L}s_{l,j,t}^{\mathrm{out,d}}+\sum_{n\in N}a_{n,j,t}^{\mathrm{out,d}}+\mathrm{fpch}_{j,t},\quad j\in j,\ t\in T \tag{26}$$

where $\mathrm{fpch}_{j,t}$ is the water purchased (when needed) to meet the demand. The outlet flow from domestic sinks is divided in two terms, the first one ($\mathrm{cw}_{j,t}^{\mathrm{d}}$) accounts for the water consumed and/or lost in the domestic sinks, and the second one ($\mathrm{int}_{j,t}^{\mathrm{in}}$) represents the wastewater generated in domestics sinks. This water can be sent to a treatment plant, where it can be regenerated and used in agricultural sinks ($\mathrm{int}_{t}^{\mathrm{out}}$) or sent to final disposal ($\mathrm{cw}_{t}^{\mathrm{tp}}$). The water sent to final disposal is not suitable for any use on its current form and only satisfies minimum environmental constraints. If it is desired to fully reuse this water, further treatment would be required to adequate it to satisfy the requirements of its final use

$$D_{j,t}^{\mathrm{ds}}=\mathrm{cw}_{j,t}^{\mathrm{d}}+\mathrm{int}_{j,t}^{\mathrm{in}}\,,\quad j\in j,\,t\in T \tag{27}$$

$$\sum_{j}\mathrm{int}_{j,t}^{\mathrm{in}}=\mathrm{int}_{t}^{\mathrm{out}}+\mathrm{cw}_{t}^{\mathrm{tp}}\,,\quad t\in T \tag{28}$$

The treated water can be sent to any agricultural sink as follows

$$\mathrm{int}_{t}^{\mathrm{out}}=\sum_{h}\mathrm{int}_{h,t}^{\mathrm{out,ag}},\quad t\in T \tag{29}$$

Balance in agricultural sinks

For agricultural users, the demands ($D_{h,t}^{\mathrm{as}}$) can be met with streams from the agricultural main ($r_{h,t}$), storage tanks ($s_{l,h,t}^{\mathrm{out,a}}$), artificial ponds ($a_{n,h,t}^{\mathrm{out,a}}$), purchased water ($\mathrm{rpch}_{h,t}$), reclaimed water from domestic treatment plants ($\mathrm{int}_{h,t}^{\mathrm{out,ag}}$), and reclaimed water from industrial treatment plants ($\mathrm{int}_{h,t}^{\mathrm{out,i}}$) as follows

$$D_{h,t}^{\mathrm{as}}=r_{h,t}+\sum_{l\in L}s_{l,h,t}^{\mathrm{out,a}}+\sum_{n\in N}a_{n,h,t}^{\mathrm{out,a}}+\mathrm{rpch}_{h,t}+\mathrm{int}_{h,t}^{\mathrm{out,ag}}+\mathrm{inti}_{h,t}^{\mathrm{out,i}},\quad h\in H,t\in T \tag{30}$$

It is assumed that the entire flow received in the agricultural sinks is consumed in the production process. This assumption holds for moderate or low agricultural activity (which leads to low water consumption compared with the rest of the users), for the case when irrigation techniques are efficient (such as drip irrigation), and when the weather conditions are such that the water not consumed is evaporated (so the runoff water that effectively reaches the aquifer is negligible).

Balance in industrial sinks and industrial treatment plants

The industrial demands ($D^{\text{di}}_{u,t}$) are met with water from industrial mains ($q_{u,t}$), water from storage tanks ($\text{si}^{\text{out,i}}_{b,u,t}$), water from artificial ponds ($\text{ai}^{\text{out,i}}_{w,u,t}$), and purchased water ($\text{qpch}_{u,t}$) as follows

$$D^{\text{di}}_{u,t} = q_{u,t} + \sum_{b\in B} \text{si}^{\text{out,i}}_{b,u,t} + \sum_{w\in W} \text{ai}^{\text{out,i}}_{w,u,t} + \text{qpch}_{u,t}, \qquad u \in U,\ t \in T \tag{31}$$

The outlet water from industrial users is divided into two terms, the first one, ($\text{cw}^{\text{di}}_{u,t}$) is the water consumed and/or lost in the production process, and the second one, ($\text{int}i^{\text{in}}_{u,t}$) represents the water that exists as wastewater. This water can be sent to the industrial treatment plant, and either regenerated for use in agriculture or disposed to the environment

$$D^{\text{di}}_{u,t} = \text{cw}^{\text{di}}_{u,t} + \text{int}i^{\text{in}}_{u,t}, \quad \forall u \in U, \forall t \in T \tag{32}$$

$$\sum_{u} \text{int}i^{\text{in}}_{u,t} = \text{int}i^{\text{out}}_{t} + \text{cwi}^{\text{tpi}}_{t}, \quad t \in T \tag{33}$$

The treated water can be sent to any agricultural sink as follows

$$\text{int}i^{\text{out,i}}_{t} = \sum_{h} \text{int}i^{\text{out,i}}_{h,t}, \quad t \in T \tag{34}$$

Equations for installing storage tanks or artificial ponds for different users

The following set of equations limits the maximum capacities of the different storage devices. Here, $S^{\max}_{l}$ and $A^{\max}_{n}$ are the maximum capacity for the storage tanks and artificial ponds for domestic and agricultural purposes, respectively. $\text{SI}^{\max}_{b}$ and $\text{AI}^{\max}_{w}$ are the maximum capacity for storage tanks and artificial ponds for industrial facilities, respectively

$$S^{\max}_{l} \geq S_{l,t}, \quad l \in L,\ t \in T \tag{35}$$

$$A^{\max}_{n} \geq A_{n,t}, \quad n \in N,\ t \in T \tag{36}$$

$$S^{\max}_{l} \geq s^{\text{in}}_{l,t}, \quad l \in L,\ t \in T \tag{37}$$

$$A^{\max}_{n} \geq a^{\text{in}}_{n,t}, \quad n \in N,\ t \in T \tag{38}$$

$$\text{SI}^{\max}_{b} \geq \text{SI}_{b,t}, \quad b \in B,\ t \in T \tag{39}$$

$$AI^{\max}_{w} \geq A_{w,t}, \quad w \in W,\ t \in T \tag{40}$$

$$\text{SI}^{\max}_{b} \geq \text{si}^{\text{in}}_{b,t}, \quad b \in B,\ t \in T \tag{41}$$

$$\text{AI}^{\max}_{w} \geq \text{ai}^{\text{in}}_{w,t}, \quad w \in W,\ t \in T \tag{42}$$

These equations enforce that the accumulation in a storage device and the water entering such device during a single time period should not exceed its maximum capacity. The existence of storage tanks is modeled as follows: if a tank is needed at any time period, then the binary variable, $z^{s}_{l,t}$ is equal to one and the storage tank is installed in location l at time period t (for domestic and agricultural storage). In the opposite case, the binary variable is zero, the tank is not installed, and the associate installation cost would be zero. The same reasoning is used for the artificial ponds of domestic and agricultural users ($z^{\text{a}}_{n,t}$), for industrial storage tanks ($z^{\text{si}}_{b,t}$), and for industrial artificial ponds ($z^{\text{ai}}_{w,t}$).

The storage devices have a maximum capacity of storage (for agricultural and domestic users is $\delta^{\text{s,max}}_{l}$; while for artificial ponds the limit is $\delta^{\text{a,max}}_{n}$). Finally, in the case of industrial users, the limits are $\delta^{\text{si,max}}_{b}$ and $\delta^{\text{ai,max}}_{w}$ for storage tanks and artificial ponds, respectively.

In this article, the cost functions are related to the location of the storage tanks and artificial ponds. In the cost equations presented next, A and B are constants used to determine the fixed and variable costs of storage tanks, and C and D are the constants associated to the fixed cost and variable cost of artificial ponds. $\text{Cost}^{\text{s}}_{l}$ and $\text{Cost}^{\text{si}}_{b,t}$ are the costs of storage tanks for domestic and agricultural users, and for industrial users, respectively. $\text{Cost}^{\text{a}}_{n,t}$ and $\text{Cost}^{\text{ai}}_{w,t}$ are the costs for artificial ponds for domestic and agricultural users, and for industrial users, respectively. α is a positive exponent lower than 1, which takes into account the economies of scale. Additionally, the factor K_{F} is used to annualize the investment for each of the storages. It considers the inflation effect on investment costs and the value of money through the time. VP is the net present value, which represents the total value of the investment for storage installation and assesses the value of money over time of each storage facility. We next describe in more detail the costing and capacity equations that apply to tanks and ponds.

For domestic and agricultural storage tanks

$$\sum_{t} z^{\text{s}}_{l,t} \leq 1, \quad \forall l \in L \tag{43}$$

$$S_{l,t'} \leq \delta^{\text{s,max}}_{l} \sum_{t=1}^{t=t'} z^{s}_{l,t}, \quad \forall l \in L, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{44}$$

$$s^{\text{in}}_{l,t'} \leq \delta^{\text{s,max}}_{l} \sum_{t=1}^{t=t'} z^{\text{s}}_{l,t}, \quad \forall l \in L, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{45}$$

$$\text{Cost}^{\text{s}}_{l} = \left(\sum_{t} K_{\text{F}_{l,t}}\, \text{VP}_{l,t}\, z^{\text{s}}_{l,t} \right) \cdot A + \left(\sum_{t} K_{\text{F}_{l,t}} \text{VP}_{l,t} \cdot \text{Zag}^{\text{s}}_{l,t} \right)^{\alpha} \cdot B, \quad \forall l \in L \tag{46}$$

Equation 46 determines the installation cost for storage devices for domestic and agricultural use. $K_{\text{F}_{l,t}}$ is the annualized investment factor that takes into account the effect of inflation on investment costs and the value of the money through the time depending on the period in which the unit is installed. This value, which is considered when the installation of the storage device is necessary in a given location (l) and time period (t), is defined as $K_{\text{F}_{l,t}} = 1/(1+i)^{t}$. Conversely, $\text{VP}_{l,t}$ is the factor to adjust to the present value the annualized capital cost, and $\text{Zag}^{\text{s}}_{l,t}$ is an additional variable used to linearize the cost functions, which has not been considered in previous models,[26,27] via the following reformulation

$$\text{Zag}^{\text{s}}_{l,t} \leq S^{\max}_{l} + \text{ML}_{l,t} \cdot \left(1 - z^{\text{s}}_{l,t}\right), \quad \forall l \in L, \forall t \in T \tag{47}$$

$$\text{Zag}^{\text{s}}_{l,t} \geq S^{\max}_{l} - \text{ML}_{l,t} \cdot \left(1 - z^{\text{s}}_{l,t}\right), \quad \forall l \in L, \forall t \in T \tag{48}$$

$$\text{Zag}^{\text{s}}_{l,t} \leq \text{ML}_{l,t} \cdot \left(z^{\text{s}}_{l,t}\right), \quad \forall l \in L, \forall t \in T \tag{49}$$

where $\text{ML}_{l,t}$ is a very large value that acts as an upper bound on the volume of the installed tanks. Thus, when variable $z^{\text{s}}_{l,t}$

takes the value of 1 (the installation of the storage tank is required), variable $\mathrm{Zag}^{\mathrm{s}}_{l,t}$ takes the value of the maximum volume of storage $S^{\max}_{l}$ and it allows calculating the cost of installation of the storage tank.

For domestic and agricultural artificial ponds

$$\sum_{t} z^{\mathrm{a}}_{n,t} \leq 1, \quad \forall n \in N \tag{50}$$

$$A_{n,t'} \leq \delta^{\mathrm{a,max}}_{n} \sum_{t=1}^{t=t'} z^{\mathrm{a}}_{n,t}, \quad \forall n \in N, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{51}$$

$$a^{\mathrm{in}}_{n,t'} \leq \delta^{\mathrm{a,max}}_{n} \sum_{t=1}^{t=t'} z^{\mathrm{a}}_{n,t}, \quad \forall n \in N, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{52}$$

$$\mathrm{Cost}^{\mathrm{a}}_{n} = \left(\sum_{t} K_{\mathrm{F}_{n,t}} \mathrm{VP}_{n,t} z^{\mathrm{a}}_{n,t} \right) \cdot C + \left(\sum_{t} K_{\mathrm{F}_{n,t}} \mathrm{VP}_{n,t} \cdot \mathrm{Zag}^{\mathrm{a}}_{n,t} \right)^{\alpha} \cdot D, \quad \forall n \in N \tag{53}$$

Similarly to storage tanks, $\mathrm{Zag}^{\mathrm{a}}_{n,t}$ is an additional variable that allows for the use of linear cost functions via the following reformulation

$$\mathrm{Zag}^{\mathrm{a}}_{n,t} \leq A^{\max}_{n} + \mathrm{MN}_{n,t} \cdot \left(1 - z^{\mathrm{a}}_{n,t}\right), \quad \forall n \in N, \forall t \in T \tag{54}$$

$$\mathrm{Zag}^{\mathrm{a}}_{n,t} \geq A^{\max}_{n} - \mathrm{MN}_{n,t} \cdot \left(1 - z^{\mathrm{a}}_{n,t}\right), \quad \forall n \in N, \forall t \in T \tag{55}$$

$$\mathrm{Zag}^{\mathrm{a}}_{n,t} \leq \mathrm{MN}_{n,t} \cdot \left(z^{\mathrm{a}}_{n,t}\right), \quad \forall n \in N, \forall t \in T \tag{56}$$

where $\mathrm{MN}_{n,t}$ is an upper bound on the volume of artificial ponds.

For industrial storage tanks, the formulation is the following

$$\sum_{t} z^{\mathrm{si}}_{b,t} \leq 1, \quad \forall b \in B \tag{57}$$

$$\mathrm{SI}_{b,t'} \leq \delta^{\mathrm{si,max}}_{b} \sum_{t=1}^{t=t'} z^{\mathrm{si}}_{b,t}, \quad \forall b \in B, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{58}$$

$$\mathrm{si}^{\mathrm{in}}_{b,t'} \leq \delta^{\mathrm{si,max}}_{b} \sum_{t=1}^{t=t'} z^{\mathrm{si}}_{b,t}, \quad \forall b \in B, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{59}$$

$$\mathrm{Cost}^{\mathrm{si}}_{b} = \left(\sum_{t} K_{\mathrm{F}_{b,t}} \mathrm{VP}_{b,t} z^{\mathrm{si}}_{b,t} \right) \cdot A + \left(\sum_{t} K_{\mathrm{F}_{b,t}} \cdot \mathrm{VP}_{b,t} \mathrm{Zag}^{\mathrm{si}}_{b,t} \right)^{\alpha} \cdot B, \quad \forall b \in B \tag{60}$$

In the same way, $\mathrm{Zag}^{\mathrm{si}}_{b,t}$ is an additional variable used in linear cost functions based on the following reformulation

$$\mathrm{Zag}^{\mathrm{si}}_{b,t} \leq \mathrm{SI}^{\max}_{b} + \mathrm{MB}_{b,t} \cdot \left(1 - z^{\mathrm{si}}_{b,t}\right), \quad \forall b \in B, \forall t \in T \tag{61}$$

$$\mathrm{Zag}^{\mathrm{si}}_{b,t} \geq \mathrm{SI}^{\max}_{b} - \mathrm{MB}_{b,t} \cdot \left(1 - z^{\mathrm{si}}_{b,t}\right), \quad \forall b \in B, \forall t \in T \tag{62}$$

$$\mathrm{Zag}^{\mathrm{si}}_{b,t} \leq \mathrm{MB}_{b,t} \cdot \left(z^{\mathrm{si}}_{b,t}\right), \quad \forall b \in B, \forall t \in T \tag{63}$$

where $\mathrm{MB}_{b,t}$ is an upper bound on the volume of installing tanks for industrial users.

For industrial artificial ponds, the formulation is as follows

$$\sum_{t} z^{\mathrm{ai}}_{w,t} \leq 1, \quad \forall w \in W \tag{64}$$

$$\mathrm{AI}_{w,t'} \leq \delta^{\mathrm{ai,max}}_{w} \sum_{t=1}^{t=t'} z^{\mathrm{ai}}_{w,t}, \quad \forall w \in W, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{65}$$

$$\mathrm{ai}^{\mathrm{in}}_{w,t'} \leq \delta^{\mathrm{ai,max}}_{w} \sum_{t=1}^{t=t'} z^{\mathrm{ai}}_{w,t}, \quad \forall w \in W, \forall t \in T, \forall t' \in T', \forall t' \leq t \tag{66}$$

$$\begin{aligned} \mathrm{Cost}^{\mathrm{ai}}_{w} = &\left(\sum_{t} K_{\mathrm{F}_{w,t}} \mathrm{VP}_{w,t} \cdot z^{\mathrm{ai}}_{w,t} \right) \cdot \\ &C + \left(\sum_{t} K_{\mathrm{F}_{w,t}} \mathrm{VP}_{w,t} \cdot \mathrm{Zag}^{\mathrm{ai}}_{w,t} \right)^{\alpha} \cdot D, \quad \forall w \in W \end{aligned} \tag{67}$$

where $\mathrm{Zag}^{\mathrm{ai}}_{w,t}$ is an additional variable used in the linear cost functions based on the following reformulation

$$\mathrm{Zag}^{\mathrm{wi}}_{w,t} \leq \mathrm{AI}^{\max}_{w} + \mathrm{MW}_{w,t} \cdot \left(1 - z^{\mathrm{ai}}_{w,t}\right), \quad \forall w \in W, \forall t \in T \tag{68}$$

$$\mathrm{Zag}^{\mathrm{ai}}_{w,t} \geq \mathrm{AI}^{\max}_{w} - \mathrm{MW}_{w,t} \cdot \left(1 - z^{\mathrm{ai}}_{w,t}\right), \quad \forall w \in W, \forall t \in T \tag{69}$$

$$\mathrm{Zag}^{\mathrm{ai}}_{w,t} \leq \mathrm{MW}_{w,t} \cdot \left(z^{\mathrm{ai}}_{w,t}\right), \quad \forall w \in W, \forall t \in T \tag{70}$$

where $\mathrm{MW}_{w,t}$ is an upper bound on the volume for industrial artificial ponds.

The installation of storage devices has an impact on land use. Variable ARS_{l} denotes the surface occupied by the storage tank for domestic use and agriculture. Similarly, for industrial tanks, the occupied land is ARSI_{b}, while for artificial ponds, it is ARL_{n} (domestic and agricultural users) and ARI_{w} for industrial users. The occupied area of storage devices is determined as follows.

For storage tanks for domestic and agricultural use

$$S^{\max}_{l} = \mathrm{ARS}_{l} \cdot \mathrm{ATS}_{l}, \quad \forall l \in L \tag{71}$$

For industrial tanks

$$\mathrm{SI}^{\max}_{b} = \mathrm{ARSI}_{b} \cdot \mathrm{ATSI}_{b}, \quad \forall b \in B \tag{72}$$

where ATS_{l} (domestic and agricultural users) and ATSI_{b} (industrial) denote the height of the tank.

In the case of artificial ponds, it is also considered the area for rainwater harvesting, because it impacts significantly on the environment. The total area of collection used for domestic and agricultural artificial ponds is denoted by APA_{n} and for industrial artificial ponds by API_{w}. These variables are calculated from the available areas for rainwater harvesting for agriculture and industrial use, denoted by A^{a}_{n} and A^{ai}_{w}, respectively. Note that the collected rainwater is, therefore, a function of these areas, as stated in the precipitation balance. The storage tanks require also an area for harvesting, but it is assumed that the rooftops can be used for this purpose, and thus, this area is not considered in the land use equation. Variables ATN_{n} (domestic and agricultural users) and ATNI_{w} (industrial) denote the height of artificial ponds.

The land used for artificial domestic and agricultural ponds is determined as follows

$$A^{\max}_{n} = \mathrm{ARL}_{n} \cdot \mathrm{ATN}_{n}, \quad \forall n \in N \tag{73}$$

$$\mathrm{APA}_{n} = \sum_{t} z^{\mathrm{a}}_{n,t} \cdot A^{\mathrm{a}}_{n}, \quad \forall n \in N \tag{74}$$

In the same way, for industrial artificial ponds, the following equations apply

$$\mathrm{AI}_w^{\max} = \mathrm{ARI}_w \cdot \mathrm{ATNI}_w, \quad \forall w \in W \tag{75}$$

$$\mathrm{API}_w = \sum_t z_{w,t}^{\mathrm{ai}} \cdot A_w^{\mathrm{ai}}, \quad \forall w \in W \tag{76}$$

Definition of the objective functions

The objective function of the model includes three criteria. The first one is to maximize the net profit from the sales of water used in the city. The second one is to minimize water consumption from natural sources. The third one is to minimize land use (associated with the storage devices). The calculation of each objective is described in detail below.

Economic objective

The proposed economic objective function considers water sales for domestic, agricultural, and industrial purposes (water sales), minus the cost associated to the treatment (treatment cost) and distribution of water (pp cost) as well as the cost associated to the installation and operation of artificial tanks (storage cost). This is stated as follows

$$\text{Profit} = \text{water sales} - \text{treatment cost} - \text{storage cost} - \text{pp cost} \tag{77}$$

The sale price of water depends only on the final use, but not on its source. The revenue can be calculated as follows

$$\begin{aligned}
\text{water sales} = & \left(\sum_k \sum_t g_{k,t}^{\mathrm{d}} + \sum_l \sum_j \sum_t s_{l,j,t}^{\mathrm{out,d}} + \sum_n \sum_j \sum_t a_{n,j,t}^{\mathrm{out,d}}\right)\mathrm{DSC} \\
& + \left(\sum_k \sum_t g_{k,t}^{\mathrm{a}} + \sum_l \sum_h \sum_t s_{l,h,t}^{\mathrm{out,a}} + \sum_n \sum_h \sum_t a_{n,h,t}^{\mathrm{out,a}} + \sum_h \sum_t \mathrm{int}_{h,t}^{\mathrm{out,ag}}\right)\mathrm{ASC} \\
& + \left(\sum_k \sum_t g_{k,t}^{\mathrm{i}} + \sum_b \sum_u \sum_t \mathrm{si}_{b,u,t}^{\mathrm{out,i}} + \sum_w \sum_u \sum_t \mathrm{ai}_{w,u,t}^{\mathrm{out,i}} + \sum_h \sum_t \mathrm{inti}_{h,t}^{\mathrm{out,i}}\right)\mathrm{ISC} \\
& + \left(\sum_j \sum_t \mathrm{fpch}_{j,t} + \sum_h \sum_t \mathrm{rpch}_{h,t} + \sum_u \sum_t \mathrm{qpch}_{u,t}\right)\mathrm{PSC}
\end{aligned} \tag{78}$$

where DSC is the price of water for domestic use, ASC is the price of water for agricultural purposes, ISC is the price of water for industrial users, and PSC is the price for water purchased from external suppliers.

Note that different costs are assumed because each source has its own water quality and each user requires different water specifications. Thus, depending on the source and use, the treatment cost is calculated as follows

$$\begin{aligned}
\text{treatment cost} = & \\
& \left(\sum_k \sum_t g_{k,t}^{\mathrm{d}}\mathrm{CTND} + \sum_k \sum_t g_{k,t}^{\mathrm{a}}\mathrm{CTNA} + \sum_k \sum_t g_{k,t}^{\mathrm{i}}\mathrm{CTNI}\right) \\
& + \left(\sum_l \sum_j \sum_t s_{l,j,t}^{\mathrm{out,d}} + \sum_n \sum_j \sum_t a_{n,j,t}^{\mathrm{out,d}}\right)\mathrm{CTAD} \\
& + \left(\sum_l \sum_h \sum_t s_{l,h,t}^{\mathrm{out,a}} + \sum_n \sum_h \sum_t a_{n,h,t}^{\mathrm{out,a}}\right)\mathrm{CTAA} \\
& + \left(\sum_b \sum_u \sum_t \mathrm{si}_{b,u,t}^{\mathrm{out,i}} + \sum_w \sum_u \sum_t \mathrm{ai}_{w,u,t}^{\mathrm{out,i}}\right)\mathrm{CTAI} \\
& + \left(\sum_h \sum_t \mathrm{int}_{h,t}^{\mathrm{out,ag}} \sum_h \sum_t \mathrm{int}\, i_{h,t}^{\mathrm{out,i}}\right)\mathrm{CTPA} \\
& + \left(\sum_j \sum_t \mathrm{fpch}_{j,t}\mathrm{CTFP} + \sum_h \sum_t \mathrm{rpch}_{h,t}\mathrm{CTRP} + \sum_u \sum_t \mathrm{qpch}_{u,t}\mathrm{CTQP}\right) \\
& + \left(\sum_t \mathrm{Cw}_t^{\mathrm{tp}} + \sum_t \mathrm{Cw}_t^{\mathrm{tpi}}\right)\mathrm{CTPE}
\end{aligned} \tag{79}$$

where CTND is the treatment cost for natural streams for domestic use, CTNA is the treatment cost for natural streams for agricultural use, CTNI is the treatment cost of natural streams for industrial use, and CTAD and CTAA are the treatment costs of rainwater for domestic and agricultural purposes, respectively. CTAI is the cost of treating rainwater for industrial use, CTP is the treatment cost for the regeneration of wastewater for agricultural use and CTPE is the cost of wastewater treatment. The water purchased has a different cost depending on the user. Therefore, CTFP, CTRP, and CTQP are costs for domestic, agricultural, and industrial uses, respectively.

The storage cost is obtained from the summation of the annualized cost of artificial reservoirs for both domestic and agricultural ($\mathrm{Cost}_l^{\mathrm{s}}$ and $\mathrm{Cost}_n^{\mathrm{a}}$ for tanks and ponds, respectively) as well as for industrial use ($\mathrm{Cost}_b^{\mathrm{si}}$ and $\mathrm{Cost}_w^{\mathrm{ai}}$ for tanks and artificial ponds, respectively)

$$\text{storage cost} = \sum_l \mathrm{Cost}_l^{\mathrm{s}} + \sum_n \mathrm{Cost}_n^{\mathrm{a}} + \sum_b \mathrm{Cost}_b^{\mathrm{si}} + \sum_w \mathrm{Cost}_w^{\mathrm{ai}} \tag{80}$$

The pp cost associated to the transportation of water from one location to another is obtained from the following information: PCSTD is the unit transportation cost from storage tank l to domestic sink j, PCASD is the unit pumping cost from artificial pond n to domestic sink j, PCSTA is the unit cost of pipeline and pumping from storage tank l to agricultural sink h, PCASA is the unit cost of piping and pumping from an artificial pond n to agricultural sink h, PCSTI is the unit cost of piping and pumping from industrial storage tank b to industrial sink u, PCASI is the unit cost of piping and pumping from industrial artificial pond w to industrial sink u, PCND, PCNA, and PCNI are the unit costs of piping and pumping from natural sources k to domestic, agricultural, and industrial mains, respectively. The cost of piping and pumping purchased water for different users is PFP (domestic), PRP (agricultural), and PQP (industrial). Finally, PCTW (domestic) and PCTI (industrial) are the unit costs of piping and pumping from treatment plants to agricultural sinks h. Thus, the total cost of piping and pumping is determined as follows

$$\begin{aligned}
\text{pp cost} = & \sum_l \sum_j \sum_t s_{l,j,t}^{\mathrm{out,d}}\mathrm{PCSTD} + \sum_n \sum_j \sum_t a_{n,j,t}^{\mathrm{out,d}}\mathrm{PCASD} \\
& + \sum_l \sum_h \sum_t s_{l,h,t}^{\mathrm{out,a}}\mathrm{PCSTA} + \sum_n \sum_h \sum_t a_{n,h,t}^{\mathrm{out,a}}\mathrm{PCASA} \\
& + \sum_b \sum_u \sum_t \mathrm{si}_{b,u,t}^{\mathrm{out,i}}\mathrm{PCSTI} + \sum_w \sum_u \sum_t \mathrm{ai}_{w,u,t}^{\mathrm{out,i}}\mathrm{PCASI} \\
& + \sum_k \sum_t g_{k,t}^{\mathrm{d}}\mathrm{PCND} + \sum_k \sum_t g_{k,t}^{\mathrm{a}}\mathrm{PCNA} + \sum_k \sum_t g_{k,t}^{\mathrm{i}}\mathrm{PCNI} \\
& + \sum_h \sum_t \mathrm{int}_{h,t}^{\mathrm{out,ag}}\mathrm{PCTW} + \sum_j \sum_t \mathrm{fpch}_{j,t}\mathrm{PFP} \\
& + \sum_h \sum_t \mathrm{rpch}_{h,t}\mathrm{PRP} + \sum_u \sum_t \mathrm{qpch}_{u,t}\mathrm{PQP} \\
& + \sum_h \sum_t \mathrm{int}\, i_{h,t}^{\mathrm{out,i}}\mathrm{PCTI}
\end{aligned} \tag{81}$$

Objective for water consumption

One of the objective functions of the study is the minimization of the consumption of natural sources of water, which is described by the following equation

$$\text{water consumption} = \sum_k \sum_t g^{d}_{k,t} + \sum_k \sum_t g^{a}_{k,t} + \sum_k \sum_t g^{i}_{k,t} + \sum_j \sum_t \text{fpch}_{j,t} + \sum_h \sum_t \text{rpch}_{h,t} + \sum_u \sum_t \text{qpch}_{u,t} \quad (82)$$

It should be noticed that the water consumption accounts for all fresh resources including the water purchased from other places.

Objective for land use

The land use, which must be minimized, is determined as follows

$$\text{land use} = \sum_l \text{ARS}_l + \sum_b \text{ARSI}_b + \sum_n \text{ARL}_n + \sum_w \text{ARI}_w + \sum_n \text{APA}_n + \sum_w \text{API}_w \quad (83)$$

Finally, the model can be expressed in compact form as follows (for each individual objective that must be minimized)

$$\begin{aligned} &\max_{x,y} \{\text{profit}(x,y)\} \\ (\text{M1}) \quad &\text{s.t} \quad \text{Eqs. 1 to 81} \end{aligned} \quad (84)$$

$$\begin{aligned} &\min_{x,y} \{\text{water consumption}(x,y)\} \\ (\text{M2}) \quad &\text{s.t} \quad \text{Eqs. 1 to 81} \end{aligned} \quad (85)$$

$$\begin{aligned} &\min_{x,y} \{\text{land use}(x,y)\} \\ (\text{M3}) \quad &\text{s.t} \quad \text{Eqs. 1 to 81} \end{aligned} \quad (86)$$

The model can be solved by standard methods for multi-objective optimization, where x in Eqs. 84–86, represents continuous variables that denote operating conditions and design variables, while y represents binary variables that model the existence of artificial storage devices. Without loss of generality, in this article we will apply the epsilon constraint method[32] to obtain the Pareto solutions of the problem.

Case Study

This section presents a case study to illustrate the applicability of the proposed model. The city of Morelia (Michoacán, Mexico) was selected as a case study for storage and distribution of water. Morelia is the capital of the state of Michoacán. It is the city with the highest unit water cost in Mexico and has a serious overexploitation problem of its natural resources that has led to an annual deficit of 2.46 m of the city aquifer according to Avila-Oliveira and Garduño-Monroy.[33] The city has a population of 729,279 habitants,[34] and according to data from the National Council of Water-Mexico, currently the annual consumption in Morelia city is 137,521,771.4 m^3/year (338.75 L per capita per day approximately).[35] Conversely, the agricultural activity in Morelia requires 21,348,208.28 m^3/year. Finally, the industrial activities consume 26,005,188.32 m^3/year.

The main natural sources in the city are 105 deep wells, four springs, and the Cointzio dam. For modeling purposes, the deep wells are clustered in 10 groups (according to their location) and the springs in one group, whereas the Cointzio dam is considered as one source. Hence, 12 natural sources are considered. The Cointzio dam has a maximum capacity[36] of 84.3×10^6 m^3, the springs have a combined capacity of 49×10^6 m^3, and finally the deep wells are connected to the Morelia-Querendaro aquifer, and the total capacity for each group is 8×10^6 m^3. The demands in the city traditionally are satisfied extracting water from deep wells, 43.93%, springs (33.41%), and the Cointzio dam (22.66%).[33] Specific constraints are imposed to prevent the use of more than 20% of the current capacity in a single time period, and also to avoid reducing the level of the source below 35% of its maximum capacity. The tariff of water in the city of Morelia is, on average, US$1.4/$m^3$ according to the publication of the official newspaper of the constitutional government of the state of Michoacán.[37] It is assumed that the wastewater generated in domestic and industrial sinks is partially treated to be reused in agricultural sinks, while the rest is disposed to the environment. This surplus wastewater could be reincorporated to the cycle when adequate infrastructure is available to regenerate it for different purposes. In general, the environmental regulations are less stringent (at least in Mexico) than the constraints for uses in agricultural, domestic, or industrial activities. Hence, surplus wastewater appears as a lost in the fresh water balance. In the case study, this surplus wastewater is discharged far from the city (because of the environmental regulation), so it is effectively lost from the aquifer of Morelia. It is noteworthy that this is a common practice around the word.

According to the National Council of Population-Mexico,[38] the average urban population growth rate for the period 2015–2030 will be around 0.27% per year, and along with the population growth, the demands will also increase. Conversely, according to data of the National Meteorological Service, the annual precipitation has decreased over the last years and this tendency is expected to hold.[39] This information was used to make the projection of the water demand and precipitation availability during the period 2015–2020.

The problem consists of finding the optimal distribution of water that satisfies the domestic, agricultural, and industrial demands in the period 2015–2020 for Morelia in terms of the three objectives: maximization of profit, minimization of water consumption, and minimization of land use. For the sake of simplicity, the city is divided in five areas: Center (CE), North-East (NE), North-West (NW), South-East (SE), and South-West (SW), which are shown in Figure 2 (taken and adapted from INEGI[34,40]). Each section contains a given number of Basic Geo Statistic Area (BGSAs) defined as a group of 293 blocks. The information for defining the BGSAs was taken from INEGI,[40] which considers the population in each section of the city. The calculations consider as well the location of the main industrial and agricultural users. It is considered that there are 20 tanks available for domestic service and agricultural activity, and 20 for industrial service. In the same way, six artificial ponds can be installed for domestic and agricultural users, and six artificial ponds for industrial users.

The monthly precipitation in Morelia in the period 1951–2010, according to the Meteorological National System,[41] was taken as reference for the time span of the project. The rainfall is expected to decrease by 6% by 2030. The precipitation data of the period analyzed (2015–2020) are shown in Table S1 (available in the Supporting Information).

To calculate the runoff coefficient in Morelia, Ka is assumed to be equal to 0.263, a value based on the ground type and distribution in the city.[42] For the first year, this runoff coefficient is calculated as follows:

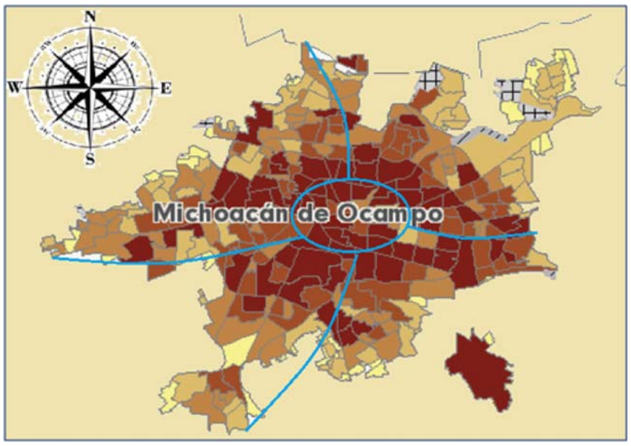

Figure 2. Morelia City simplified geographic division (adapted from INEGI[34,40]).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$$Ce=\frac{0.263(768.9-250)}{2000}+\frac{0.263-0.15}{1.5}=0.1435$$

For the remaining years, the procedure is the same and only the annual precipitation changes.

The maximum capacity for the storage tanks is 50,000 m^3 and for the artificial ponds is 600,000 m^3, independently of the type user. The constant parameters used in the cost functions for the storage devices A, B, C, and D (see Eqs. 46, 53, 61, and 68) take values of A = 28,080 ($), B = 4.9134 ($), C = 151,968 ($/m^3), and D = 4.9895 ($/m^3), respectively.

The pp cost for water sent from a storage tank to any sector or from an artificial pond to any sector are shown in Tables S2–S5 (available in the Supporting Information). The pp cost for industrial and domestic users are the same but differs from those used for agricultural users.

Results

The proposed model was coded in the software GAMS.[43] It features 34,371 constrains, 3120 discrete variables, and 44,571 continuous variables. Note that the model is an MILP (the cost functions for the installation of storages are linearized and the exponential factor is assumed to be equal to 1). The MILP was solved with the solver CPLEX on a computer with an Intel Core i5 Processor at 2.40 GHz with 4 GB of RAM. The solution time of each model instance is around 120 s.

First, the model is optimized according to each of the three objectives (economic, consumed fresh water, and used land) independently. Tables 1 and 2 summarize the results obtained in each case. Later on, the model was optimized for every pair of objectives. Hence, rather than solving the original model in the space of three objectives, we report the solutions obtained by optimizing each pair of single indicators. This is indeed an approximation made for simplicity. Note, however, that the inherent trade-offs between objectives can be studied by the inspection of the bicriteria Pareto fronts.

Table 1. Profit, Water Consumption, and Land Use in Solutions A, B, and C

Objective	Solution A: maximizing profit	Solution B: minimizing water consumption	Solution C: minimizing land use
Profit ($)	2.60×10^8	-4.74×10^9	-5.32×10^9
Water consumption (m^3)	6.21×10^8	5.07×10^8	7.20×10^8
Occupied land use (m^2)	5.87×10^6	5.89×10^6	0

Solution A: Maximum profit

Solution A corresponds to the maximization of the profit. The maximum profit solution yields a profit of $259,860,000, the fresh water consumed is 621,270,000 m^3 and the land use is 5,874,700 m^2. As seen in Table 1, the consumed fresh water is 18% of the total required. Meanwhile, the occupied land increases 99% with respect to the minimum obtained.

The maximum profit solution is schematically represented in Figure 3, which provides the configuration at the end of the time horizon (when all the investments have already been made). Notice that the model decides to install 15 storage tanks for domestic use, five of which are installed in the first year, five in the second year, three in the third year, and two in the fifth year. The water contained in storage tanks for domestic use is 7.7 × 10^6 m^3. Besides, six artificial ponds are installed: two in the first year, two in the second year, and two in the third year. They provide a total water of 5.99 × 10^6 m^3 that is sent from artificial ponds to domestic users. Similarly, 20 storage tanks are installed for industrial use, six in the first year, five in the second year, four in the third year, and five in the fourth year. The water sent from the storage tanks to industrial use is 9.17 × 10^6 m^3. Furthermore, two artificial ponds are installed in the first year, two in the second year, and two in the third year, with a total amount of water for industrial use of 4.76 × 10^6 m^3. It should be noted that this configuration makes no use of either treated water or external water.

Solution B: Minimum fresh water consumption

Solution B corresponds to the minimization of the fresh water consumption. The model identifies a solution with a

Table 2. Results Obtained of Profit, Water Consumption, and Land Use in Solutions: D, E, F, and G in the Time Span of Project

	Solution D: minimizing land use with a limit on water consumption		Solution E: maximizing profit with a limit on land use		Solution F: maximizing profit with a limit on water consumption		
Objective	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Solution G: GOAL method
Profit ($)	-3.42×10^9	-2.21×10^9	2.40×10^8	2.60×10^8	2.60×10^8	2.27×10^8	2.27×10^8
Water consumption (m^3)	6.17×10^8	5.08×10^8	7.20×10^8	6.16×10^8	6.60×10^8	5.08×10^8	5.07×10^8
Occupied land (m^2)	0	5.89×10^6	0	5.89×10^6	5.89×10^6	5.89×10^6	5.89×10^6

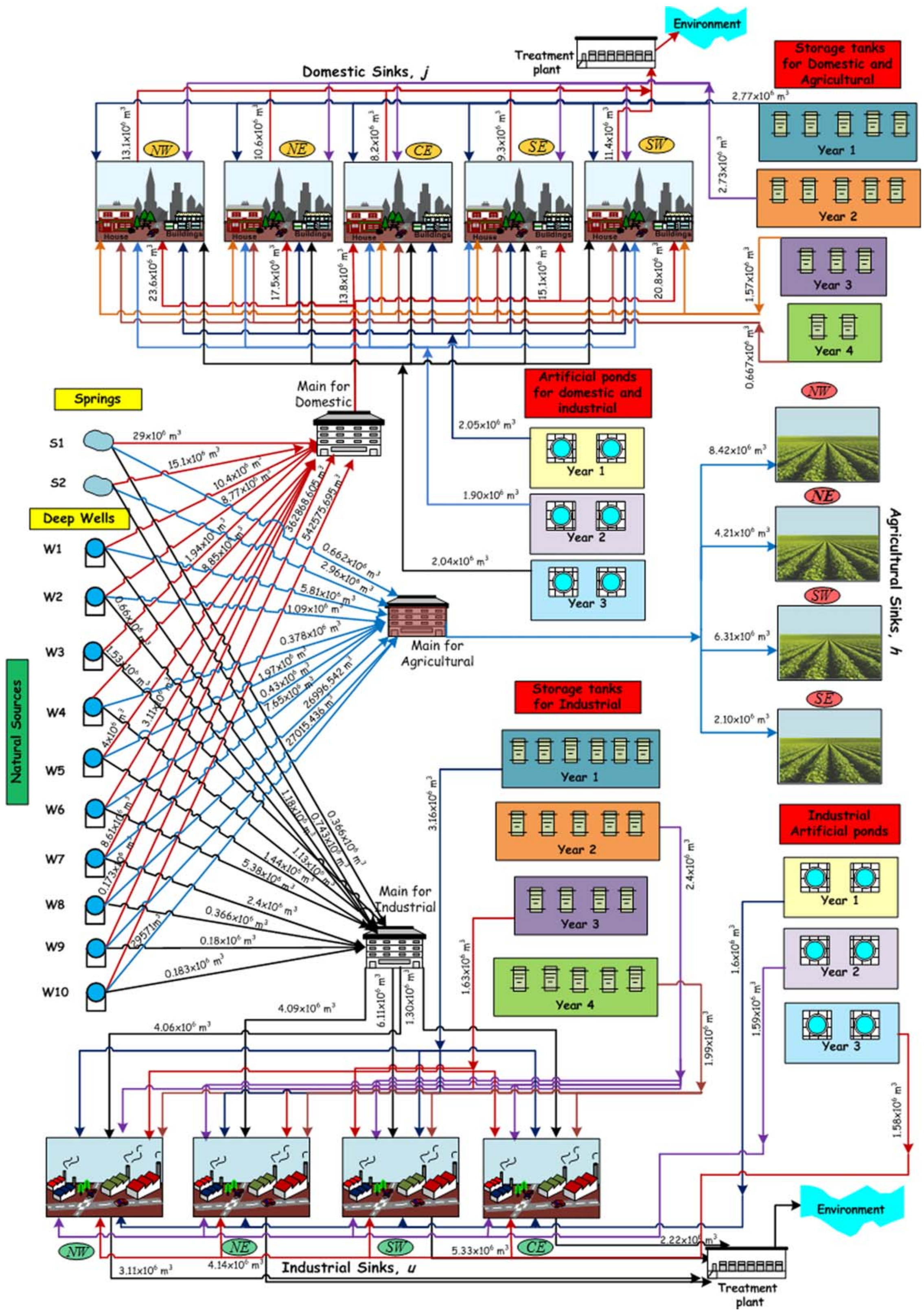

Figure 3. Configuration for maximum profit—Solution A.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

total fresh water consumption of 507,180,000 m^3, a profit of $-$\$4,735,000,000, and a land use of 5,892,700 m^2. Table 1 shows that the profit of Solution B increases 12% with respect to that in Solution C, although Solution B has the maximum value of used land. Besides, as shown in Figure 4, the model decides to install 20 storage tanks for domestic use, five in the first year, five in the second year, five in the third year, and five in the fourth year. The water collected in the tanks and sent to domestic use is 9.59×10^6 m^3. Moreover, six artificial ponds are required; two are installed in

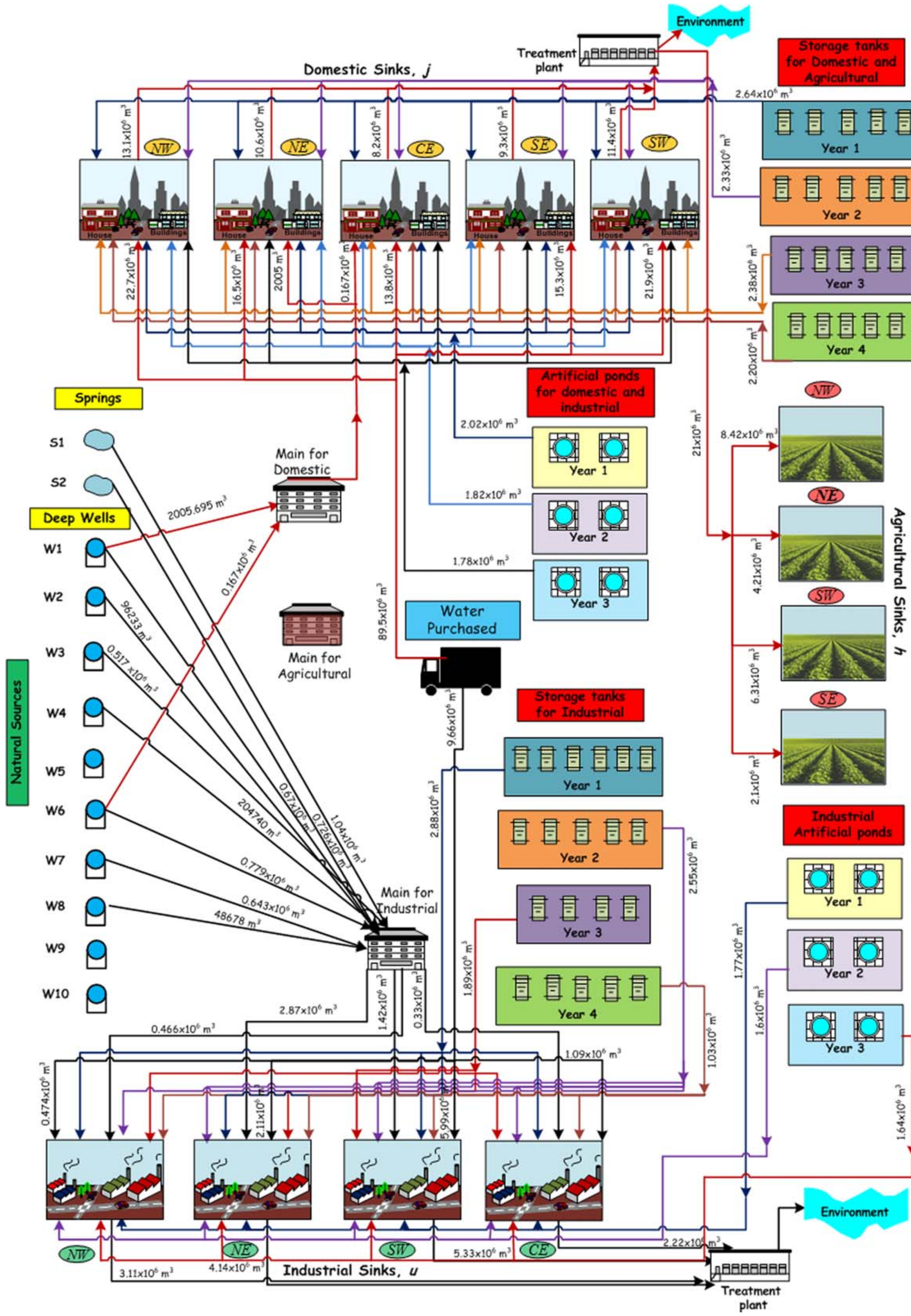

Figure 4. Configuration for minimum consumed fresh water—Solution B.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the first year, two in the second year, and other two in the third year. The total water sent from the artificial ponds to domestic users is 5.62×10^6 m^3. In the same way, 20 storage tanks for industrial use are installed, six in the first year, five in the second year, four in the third year, and five in the fourth year. The water sent from the storage tanks to industrial users is 9.35×10^6 m^3. Two artificial ponds are installed in the first year, two in the second year, and two in the third year, and the total amount of water obtained from artificial ponds and consumed in industrial use is

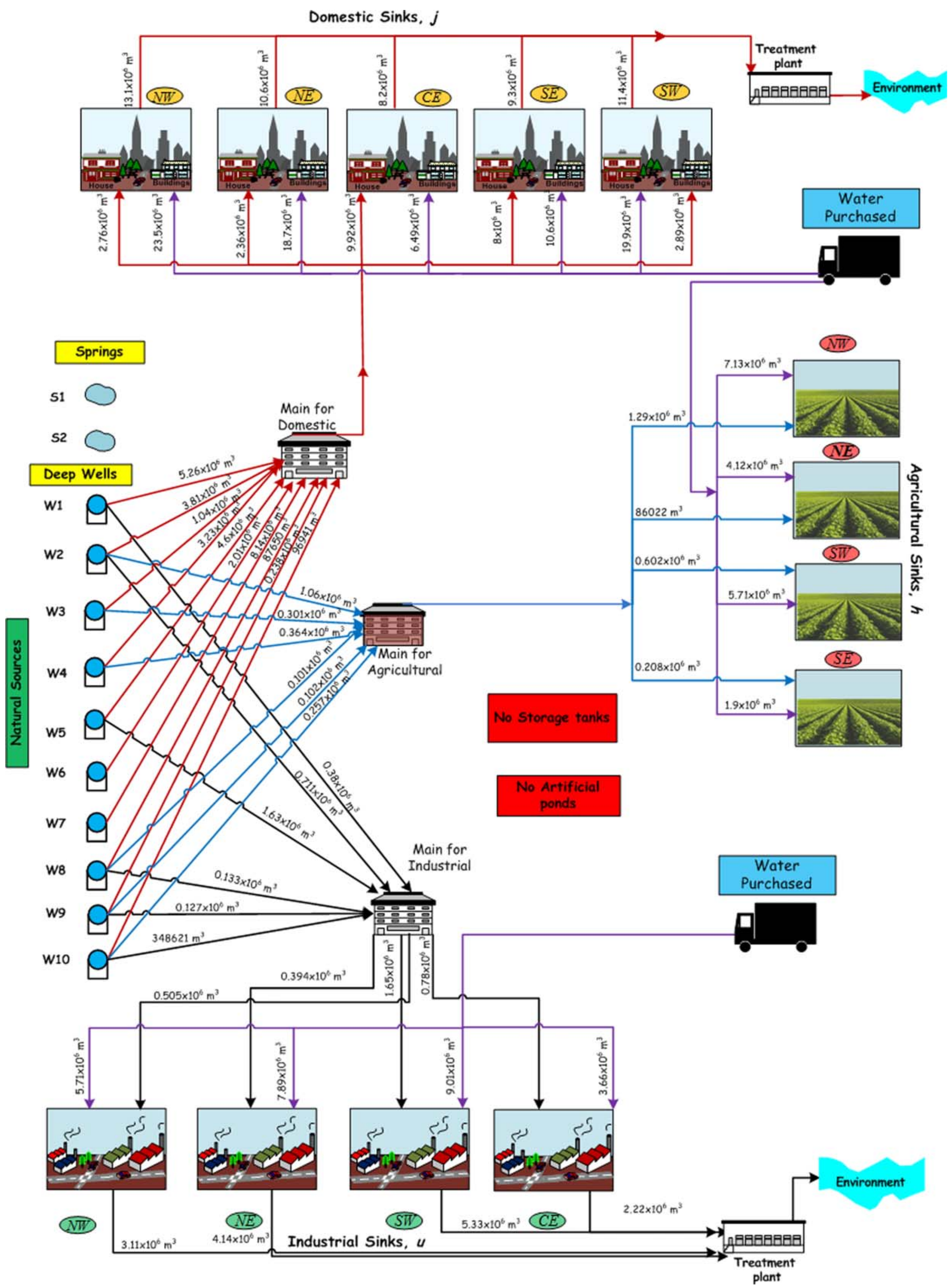

Figure 5. Configuration for minimum land use—Solution C.

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5.01×10^6 m^3. This solution purchases 89.5×10^6 m^3 of water for domestic use and 9.66×10^6 m^3 for industrial use. In addition, the agricultural demand is completely satisfied with reclaimed water, yielding significant savings of fresh water from natural sources.

Solution C: Minimum land use

Solution C corresponds to the minimization of the land use. The minimum land use is 0 m^2, the net profit is −\$5,317,000,000, and the fresh water consumption is 719,690,000 m^3. As shown in Figure 5, the calculated

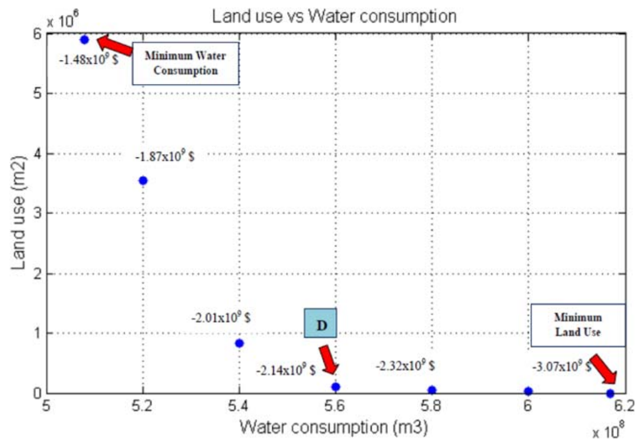

Figure 6. Pareto curve for land use vs. fresh water consumption.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

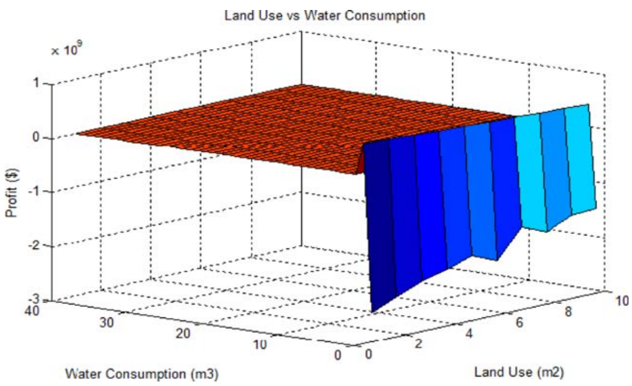

Figure 7. Relationship between three objectives minimizing the fresh water consumption and land use.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

solution does not require the installation of any type of storage device. Furthermore, this solution does not use treated water, instead it purchases fresh water to meet the users' needs. For domestic users, the amount of water purchased is

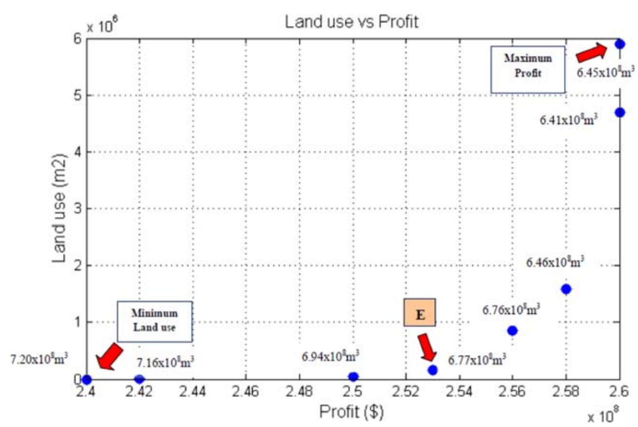

Figure 8. Pareto curve for profit vs. land use.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

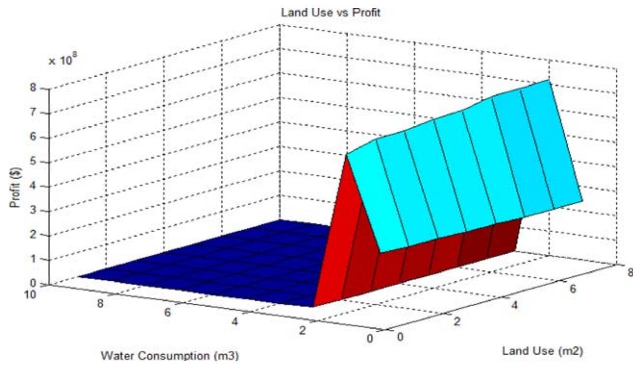

Figure 9. Relationship between three objectives minimizing the land use and maximizing the profit.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

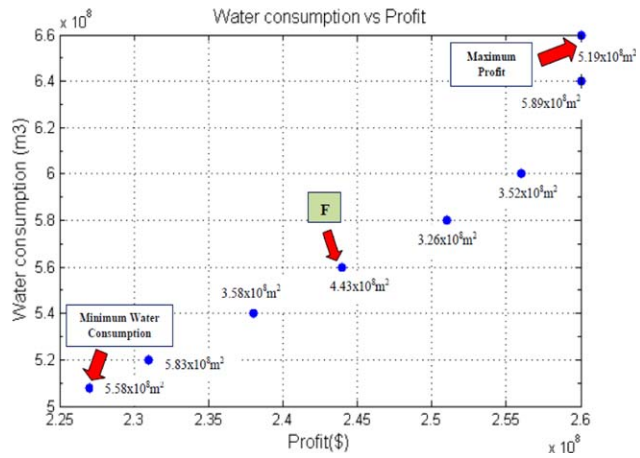

Figure 10. Pareto curve for profit vs. fresh water consumption.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

76.7×10^6 m^3, for agricultural users is 18.9×10^6 m^3, and for industrial users is 26.3×10^6 m^3. This policy has a large negative effect on the profit, with drops to its minimum value as compared to the other extreme solutions. In addition, this solution yields the maximum consumption of fresh

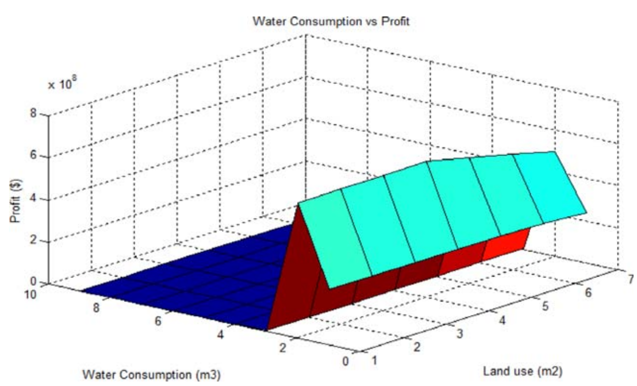

Figure 11. Relationship between three objectives minimizing the fresh water consumption and maximizing the profit.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

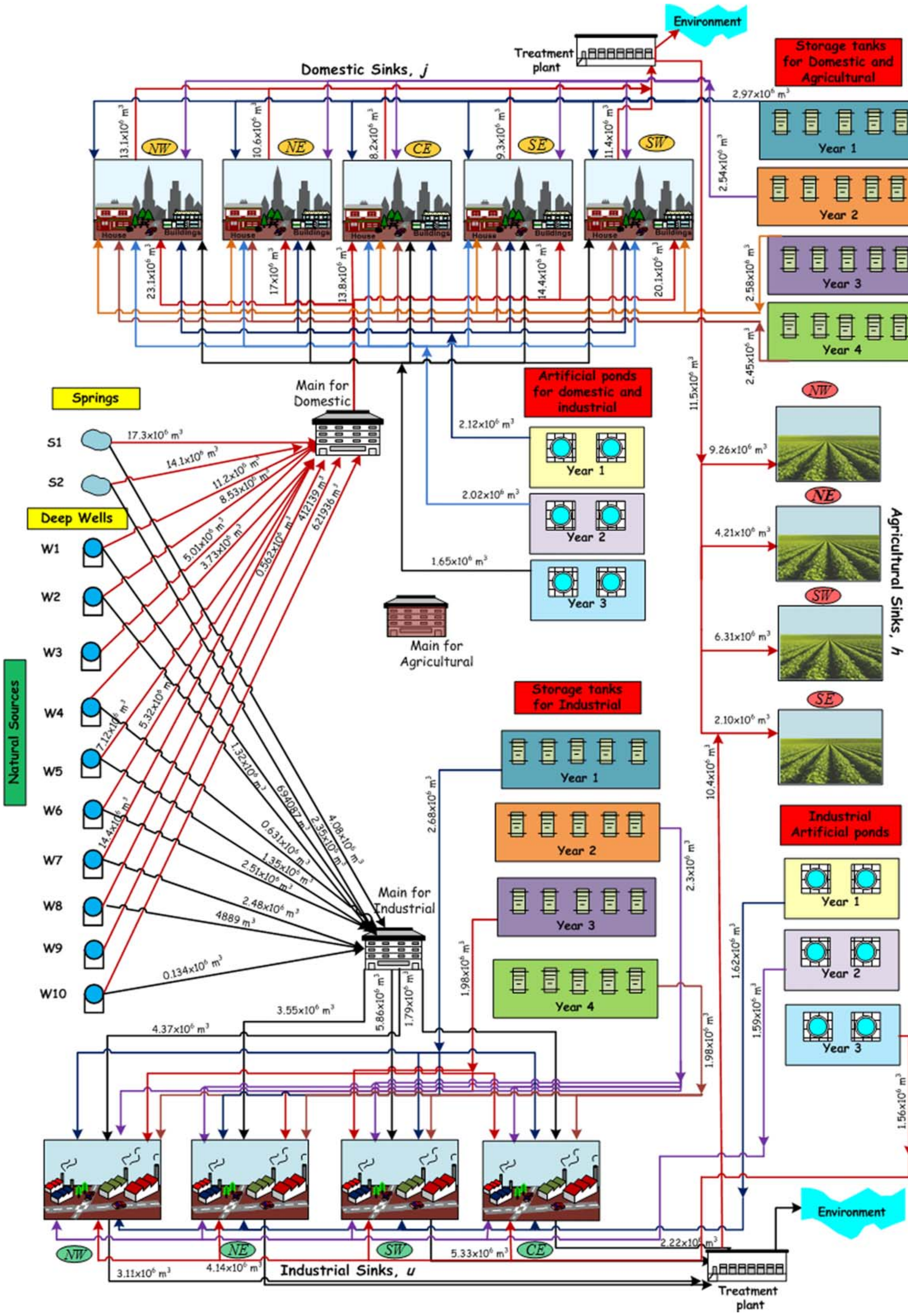

Figure 12. Configuration for Solution G.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

water. After analyzing the extreme solutions separately, we next calculate the biobjective Pareto fronts. These provide insight into the optimal trade-offs between the objectives considered in the analysis.

Pareto front fresh water vs. land use

Figure 6 shows the Pareto curve for the simultaneous minimization of the fresh water consumption and land use. Notice that when land use decreases, fresh water consumption increases, which shows that these objectives are competing with each other. Solution D represents an appealing alternative with a proper balance between the two objectives. Figure 7 shows a 3-D plot that provides insight into the relationships between the three objectives when fresh water consumption and land use are simultaneously minimized.

Table 2 shows the maximum and minimum values attained by each solution in each objective (profit, water consumption, and land use).

The water consumption in Solution D is 5.6×10^8 m^3 and the land use 1×10^5 m^2. This is a solution with a good balance between fresh water consumption and land use. However, its profit is negative ($-\$3.18 \times 10^9$), which constitutes a major shortcoming.

Pareto front land use vs. profit

Figure 8 shows the Pareto curve land use vs. profit. When the profit increases, the land use increases as well. Particularly, the profit is increased by installing storage devices that allow selling more water. Solution E shows a good balance between both objectives. The profit in this solution is $\$2.53 \times 10^8$ and the land use is 1.51×10^5 m^2. It should be noted that the profit in Solution E is close to the maximum profit that can be attained (i.e., $\$2.6 \times 10^8$). In addition, the water consumption is 6.55×10^8 m^3, which represents 9% less than the maximum water consumption. Figure 9 shows a 3-D plot that provides insight into the relationships between the three objectives when the land use and profit are simultaneously optimized.

Pareto front profit vs. fresh water consumption

Figure 10 shows the Pareto curve profit vs. fresh water consumption. Notice that in this figure, the profit increases with the consumption of fresh water, mainly because this case does not require the installation of new devices. Solution F is an intermediate point with a profit of $\$2.44 \times 10^8$ and a water consumption of $5.6 \times 10^8 m^3$. This solution, however, shows a high land use (i.e., 5.89×10^6 m^2). Additionally, Figure 11 shows the three objectives when fresh water consumption and profit are optimized.

Solution G

Finally, using the information obtained in the previous solutions, the optimization model was transformed into a single optimization one. The single objective model seeks to minimize the distance (norm 1) from the utopia point, which is stated as follows

$$\begin{aligned} \text{GOAL} = & (\text{maximum value of profit} - \text{profit}) \\ & + (\text{water consumption} - \text{minimum value of water consumption}) \\ & + (\text{land use} - \text{minimum value of land use}) \end{aligned} \tag{87}$$

This solution is referred to as GOAL solution, and corresponds to Solution G. Due to the difference in scale of the objectives, the GOAL solution might prefer the objective with the major scale. To circumvent this limitation, a normalization of the GOAL objective is proposed as follows

$$\begin{aligned} \text{GOAL} = & \frac{(\text{maximum value of profit} - \text{profit})}{\text{maximum value of Profit}} \\ & + \frac{(\text{water consumption} - \text{minimum value of water consumption})}{\text{minimum value of water consumption}} \\ & + \frac{(\text{land use} - \text{minimum value of land use})}{\text{minimum value of land use}} \end{aligned} \tag{88}$$

Figure 12 shows the resulting configuration associated with Solution G. The net profit is $\$2.27 \times 10^8$, the fresh water consumption is 5.07×10^8 m^3, and the land use is 5.89×10^6 m^2. As seen, there is a considerable saving of fresh water because the agricultural demand is completely satisfied with reclaimed water from treatment plants (reusing a total reclaimed water of 21.9×10^6 m^3). Moreover, 20 storage tanks for domestic use are installed. A total of 10.5×10^6 m^3 of water is used to meet domestic demands. Six artificial ponds are installed that provide 5.79×10^6 m^3 of water that are used for domestic users. This leads to significant savings in fresh water consumption, which leads in turn to lower impacts to the environment. Similarly, 20 storage tanks for industrial users are installed, with a total water consumption of 9.18×10^6 m^3. Furthermore, 6 artificial ponds provide 4.76×10^6 m^3 for industrial demands. This configuration saves a significant amount of water, which lowers the impact to the environment. Hence, the impact due to the installation of artificial water reservoirs compensates for the savings in fresh water consumption from natural sources.

Conclusions

This article has presented a multiobjective optimization method for synthesizing water networks at the macroscopic level. Our approach accounts for rainwater harvesting and reclaimed wastewater reusing as main means for satisfying water demands of different sectors such as industrial, domestic, and agriculture. The proposed model determines the optimal storage and distribution of collected water by maximizing the overall profit and minimizing the fresh water consumption and land use simultaneously. The model is a multiobjective MILP that was solved by optimizing pairs of objectives separately. To this end, we used the epsilon constraint method.

The proposed model was applied to a case study based on the city of Morelia in Mexico. Numerical results show that the installation of storage devices reduces the consumption of fresh water from natural sources. This is achieved using storage tanks, which supply up to 18% of water demand of the city. In addition, water reclamation can effectively complement the use of harvested rainwater, providing enough water for agricultural activities in the city even during drought seasons. The treated water that is reused in the agricultural users can fully satisfy this demand, which represents 13% of the total demand of the city. Although the purchase of water has been an option in this study, it is likely that in the future such option will seldom be available due to large external prices and availability of resources. The final goal of our tool is to promote the adoption of more sustainable alternative for water management in cities.

Notation

Parameters

A_n^{a} = collection area in location n for artificial ponds a
A_w^{ai} = collection area in location w for industrial artificial ponds ai
A_n^{max} = maximum capacity of artificial ponds A in location n
A_l^{s} = collection area in location l for storage tank s
A_b^{si} = collection area in location b for industrial storage tanks si
A_k^{ROW} = area of collection for runoff water for natural sources k
A_k^{DPW} = area of collection for direct precipitation for natural sources k
AI_w^{max} = maximum capacity of industrial artificial ponds AI in location w
ASC = cost of water for agricultural use
ATN_n = depth of artificial ponds in location n
$ATNI_w$ = depth of artificial ponds in location w
ATS_l = height of storage tanks in location l
$ATSI_b$ = height of storage tanks industrial in location b
Ce^{a} = runoff coefficient for artificial ponds a
Ce^{ai} = runoff coefficient for industrial artificial ponds ai
Ce^{s} = runoff coefficient for storage tanks s
Ce^{si} = runoff coefficient for industrial storage tanks si
CTAA = treatment cost for rainwater for agricultural used
CTAI = treatment cost for rainwater for industrial used
CTFP = treatment cost for water purchased with domestic used
CTND = treatment cost for natural sources with domestic used
CTNA = treatment cost for natural sources with agricultural used
CTNI = treatment cost for natural sources with industrial used
CTAD = treatment cost for rainwater for domestic used
CTP = treatment cost for regeneration of waste water for agricultural used
CTPE = treatment cost for regeneration of waste water for final disposal
CTRP = treatment cost for water purchased with agricultural used
CTQP = treatment cost for water purchased with industrial used
$D_{h,t}^{as}$ = agricultural users h demands in time t
$D_{u,t}^{di}$ = industrial users u demands in time t
$D_{j,t}^{ds}$ = domestic users j demands in time t
$DPWV_{k,t}$ = water collected from direct precipitation in natural sources k in time t
DSC = water sale cost for domestic use
ISC = cost of water for industrial use
Ka = parameter that is function of type and land
$K_{F\,l,t}$ = factor to take into account the annualized investment for storage tanks in location l in time t
$K_{F\,n,t}$ = factor to take into account the annualized investment for artificial ponds in location n in time t
$K_{F\,b,t}$ = factor to take into account the annualized investment for storage industrial tanks in location b in time t
$K_{F\,w,t}$ = factor to take into account the annualized the investment index for artificial industrial ponds in location w in time t
$ML_{l,t}$ = factor related to volume for storage tanks in location l in time t
$MN_{n,t}$ = factor related to volume for artificial ponds in location n in time t
$MB_{b,t}$ = factor related to volume for industrial storage tanks in location b in time t
$MW_{w,t}$ = factor related to volume for artificial industrial ponds in location w in time t
P_t = precipitation over time period t
P^{total} = annual precipitation
PCSTD = unit cost of transport from storage tank l to domestic sink j
PCASD = unit cost of pumping from artificial pond n to domestic sink j
PCSTA = unit cost of pipeline and pumping from storage tank in location l to agricultural sink h
PCASA = unit cost of piping and pumping from an artificial pond in location n to agricultural sink h
PCSTI = unit cost of piping and pumping from industrial storage tank in location b to industrial sink u
PCASI = unit cost of piping and pumping from industrial artificial pond in location w to industrial sink u
PCND = unit costs of piping and pumping from natural sources k to domestic main
PCNA = unit costs of piping and pumping from natural sources k to agricultural main
PCNI = unit costs of piping and pumping from natural sources k to industrial main
PCTW = unit costs of piping and pumping from treatment plant to agricultural sinks h
PCTI = unit costs of piping and pumping from industrial treatment plant to agricultural sinks h
PFP = unit costs of piping and pumping from place of water purchase to domestic users j
PQP = unit costs of piping and pumping from place of water purchase to industrial users u
PRP = unit costs of piping and pumping from place of water purchase to agricultural users h
PSC = water sale cost for water purchased sent to users
$p_{k,t}^{g}$ = water collected from direct precipitation and runoff water in sources k at time t
$r_{m,k,t}$ = segregated flow rate from the tributaries m to natural sources k over time period t
$ROWV k,t$ = runoff water collection in natural sources k over time period t
S_l^{max} = maximum capacity of storage tanks S in location l
SI_b^{max} = maximum capacity of industrial storage tanks SI in location b
$VP_{l,t}$ = factor to consider the value of investment for storage tank in location l in time period t
$VP_{n,t}$ = factor to consider the value of investment for artificial ponds in location n in time period t
$VP_{b,t}$ = factor to consider the value of investment for industrial storage tanks in location b in time period t
$VP_{w,t}$ = factor to consider the value of investment for artificial industrial ponds in location w in time period t

Binary variables

$z_{n,t}^{a}$ = binary variable to select the installation of artificial ponds a in location n at time t
$z_{w,t}^{ai}$ = binary variable to select the installation of artificial industrial ponds ai in location w in time t
$z_{l,t}^{s}$ = binary variable for installing storage tanks s in location l at time t
$z_{b,t}^{si}$ = binary variable to select the installation of industrial storage tanks si in location b in time t

Variables

$A_{n,t}$ = existing water in artificial ponds A in location n in time t
$A_{n,t-1}$ = existing water in artificial ponds A in location n in previous time period $t-1$
$a_{n,t}^{in}$ = water obtained from rainfall sent to artificial ponds a in location n in time t
$a_{n,j,t}^{out,d}$ = segregated flow rate from artificial ponds a in location n sent to domestic users j in time t
$a_{n,h,t}^{out,a}$ = segregated flow rate from artificial ponds a in location n sent to agricultural users h in time t
$AI_{w,t}$ = existing water in industrial artificial ponds AI in location w in time t
$AI_{w,t-1}$ = existing water in artificial ponds AI in location w in time previous $t-1$
$ai_{w,t}^{in}$ = water obtained from rainfall sent to artificial industrial ponds ai in location w in time t
$ai_{w,u,t}^{out,i}$ = segregated flow rate from industrial artificial ponds ai in location w sent to industrial users u in time t
$APAn$ = total area occupied by artificial ponds in location n
$APIw$ = total area occupied by artificial industrial ponds in location w
$ARIn$ = area occupied by the artificial ponds in location n
$ARIw$ = area occupied by the artificial industrial ponds in location w
$ARSl$ = area occupied by the storage tanks in location l
$ARSIb$ = area occupied by the industrial storage tanks in location b
Ce = runoff coefficient
$Cost_n^{a}$ = cost of artificial pond a in location n
$Cost_w^{ai}$ = cost of industrial artificial pond ai in location w
$Cost_l^{s}$ = cost of storage tank s in location l
$Cost_b^{si}$ = cost of industrial storage tank si in location b
$cw_{j,t}^{d}$ = water consumed and losses in domestic sinks j in time t
$cw_{u,t}^{di}$ = water consumed and losses in industrial sink u in time t
cw_t^{tp} = water reclaimed in domestic treatment plant and sent to final disposal in time t
cwi_t^{tpi} = water reclaimed in industrial treatment plant and sent to final disposal in time t
$Drop_{k,t}^{g}$ = water that exceeds the maximum capacity of natural sources k in time t

$f_{j,t}$ = segregated flow rate sent from the domestic main to the domestic users j in time t

$\mathrm{fpch}_{j,t}$ = segregated flow rate of water purchased sent to domestic users j in time t

$G_{k,t}$ = existing water in natural sources k in time t

$G_{k,t-1}$ = existing water in natural sources k in time previous $t-1$

$g^{\mathrm{a}}_{k,t}$ = segregated flow rate from the natural sources k to main agricultural a in time t

$g^{\mathrm{d}}_{k,t}$ = segregated flow rate from the natural sources k to main domestic d in time t

$g^{\mathrm{i}}_{k,t}$ = segregated flow rate from the natural sources k to main industrial i in time t

$\mathrm{int}^{\mathrm{in}}_{j,t}$ = wastewater produced in domestic sinks j in time t

$\mathrm{int}i^{\mathrm{in}}_{u,t}$ = wastewater sent to industrial treatment plant in time t

int^{out}_{t} = wastewater sent to treatment plant in time t

$\mathrm{int}^{\mathrm{out,ag}}_{h,t}$ = water reclaimed and sent to agricultural sinks h in time t

$\mathrm{int}i^{\mathrm{out,i}}_{h,t}$ = water reclaimed in industrial treatment plant and sent to agricultural sinks h in time t

$P^{\mathrm{a}}_{n,t}$ = available precipitation in location n for artificial ponds a in time t

$P^{\mathrm{ai}}_{w,t}$ = available precipitation in location w for industrial artificial ponds ai in time t

$P^{\mathrm{s}}_{l,t}$ = available precipitation in location l for storage tanks s in time t

$P^{\mathrm{si}}_{b,t}$ = available precipitation in location b for industrial storage tanks si in time t

$q_{u,t}$ = segregated flow rate sent from the industrial main to the industrial users u in time t

$\mathrm{qpch}_{u,t}$ = segregated flow rate of water purchased sent to industrial users u in time t

$r_{h,t}$ = segregated flow rate sent from the agricultural main to the agricultural users h in time t

$\mathrm{rpch}_{h,t}$ = segregated flow rate of water purchased sent to agricultural users h in time t

$S_{l,t}$ = existing water in storage tanks s in location l in time t

$S_{l,t-1}$ = existing water in storage tanks s in location l in time previous t-1

$s^{\mathrm{in}}_{l,t}$ = water obtained from rainfall sent to storage tanks s in location l in time t

$\mathrm{si}^{\mathrm{in}}_{b,t}$ = water obtained from rainfall sent to industrial storage tanks si in location b in time t

$s^{\mathrm{out,a}}_{l,h,t}$ = segregated flow rate from storage tanks s in location l sent to agricultural users h in time t

$s^{\mathrm{out,d}}_{l,j,t}$ = segregated flow rate from storage tanks s in location l sent to domestic users j in time t

$\mathrm{SI}_{b,t}$ = existing water in industrial storage tanks SI in location b in time t

$\mathrm{SI}_{b,t-1}$ = existing water in industrial storage tanks SI in location b in time previous $t-1$

$\mathrm{si}^{\mathrm{out,i}}_{b,u,t}$ = segregated flow rate from industrial storage tanks si in location b sent to industrial users u in time t

$v^{\mathrm{a}}_{n,t}$ = water losses in artificial ponds a in time t

$v^{\mathrm{ai}}_{w,t}$ = water losses in artificial industrial ponds ai in time t

$v^{g}_{k,t}$ = water losses in natural sources k in time t

$v^{\mathrm{s}}_{l,t}$ = water losses in storage tanks s in time t

$v^{\mathrm{si}}_{b,t}$ = water losses in industrial storage tanks si in time t

$\mathrm{Zag}^{\mathrm{s}}_{l,t}$ = variable for installing storage tanks in location l in time t

$\mathrm{Zag}^{\mathrm{a}}_{n,t}$ = variable for installing artificial ponds in location n in time t

$\mathrm{Zag}^{\mathrm{si}}_{b,t}$ = variable for installing industrial storage tanks in location b in time t

$\mathrm{Zag}^{\mathrm{ai}}_{w,t}$ = variable for installing artificial industrial ponds in location w in time t

Greek letters

α = exponent to take into account the economies of scale

$\delta^{\mathrm{a,max}}_{n}$ = maximum flow sent to artificial ponds a in location n at time t

$\delta^{\mathrm{ai,max}}_{w}$ = maximum flow sent to industrial artificial ponds ai in location w at time t

$\delta^{\mathrm{s,max}}_{l}$ = maximum flow sent to storage tanks s in location l in time t

$\delta^{\mathrm{si,max}}_{b}$ = maximum flow sent to industrial storage tanks si in location b in time t

Sets

B = set for location of industrial storage tanks $(b|b=1,\ldots,B)$

H = set for agricultural sinks $(h|h=1,\ldots,H)$

J = set for domestic sinks $(j|j=1,\ldots,J)$

K = set for natural sources $(k|k=1,\ldots,K)$

L = set for location of storage tanks $(l|l=1,\ldots,L)$

M = set for tributaries $(m|m=1,\ldots,M)$

N = set for location of artificial ponds $(n|n=1,\ldots,N)$

T = set for time period $(t|t=1,\ldots,T)$

U = set industrial sinks $(u|u=1,\ldots,U)$

W = set for location of industrial artificial ponds $(w|w=1,\ldots,W)$

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