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Optimal Design of a Distributed Treatment System for Increasing Dissolved Oxygen in Watersheds through Self-Rotating Discs

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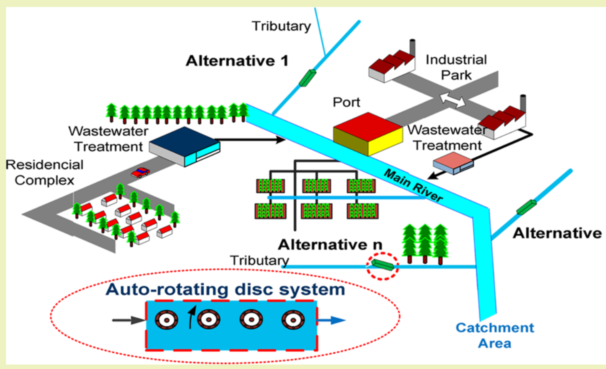
ABSTRACT: Dissolved oxygen in water bodies is a property of major importance for sustaining aquatic life in watersheds. Because of the increasing pollution discharges in watersheds around the world, there has been a consistent reduction in the levels of dissolved oxygen. Self-rotating discs "SRD" are low-cost devices that can increase the level of dissolved oxygen in watersheds. The design of SRD systems involves the determination of the number of rows of discs, spacing between discs, and flow rate to be treated. In this paper, a general optimization framework is presented to determine the optimal design of a distributed treatment system to increase the dissolved oxygen in the watersheds based on self-rotating devices. A material flow analysis model is coupled with the performance functions of the SRD. The optimization model is aimed at selecting the tributaries that require treatment, determining the flow rate to be treated, and designing the number and spacing of the SRD. The methodology is applied to a case study corresponding to the Bahr El-Baqar watershed in Egypt. The results are displayed through Pareto optimal solutions that trade off the economic and environmental objectives.



KEYWORDS: *Dissolved oxygen in watersheds, Distributed treatment system, Material flow analysis, Optimization, MINLP, Self-rotating discs*

INTRODUCTION

Water is a vital resource for agriculture, transportation, manufacturing, and several human activities. Despite its great importance, water is one of the worst managed resources around the world.[1] Rivers and receiving water bodies are impacted by different polluted discharges. In agricultural areas, the generated effluents contain fertilizers with high concentrations of nitrogen and phosphorus that increase the nutrients of the system and cause excessive growth of biomass (e.g., algae) that can lead to eutrophication.[2−5] Oxygen is produced and consumed in water bodies. Oxygen production is associated with the photosynthesis process, and its consumption depends on the decomposition reactions of organic matter and other chemical reactions related to the decomposition of inorganic compounds. The continuous discharge of effluents with high contents of organic matter and nutrients leads to enhanced demand for oxygen that can compromise the sustainability of aquatic lives that depend on oxygen for growth and production of metabolites.[6−9] Furthermore, oxygen is essential in self-purification in the biodegradation of contaminants in water bodies and in the maintenance of good water quality conditions. The increase in dissolved oxygen is an important issue, and there are conventional methods that are typically used for enhancing dissolved oxygen through mechanical aeration surfaces or by dilution of contaminants. Nonetheless, these methods may require substantial economic, human, energy, and material resources. For instance, the energy cost associated with the aeration process represents more than 50% of the overall cost of the system.[10,11]

One of the promising approaches for enhancing dissolved oxygen is the use of self-rotating discs "SRD" or self-rotating biological contactors "SRBC" (Figure 1).[12] These devices require low capital investment and involve almost no operating cost. Additionally, they require low maintenance and need no external energy to be operated because they exploit the natural mechanical energy (free energy) of rivers/channels to produce turbulence through the self-rotating process that increases dissolved oxygen.

Watersheds are complex ecological systems that are influenced by several phenomena that result from the dynamic interactions of the activities taking place around them. Several water quality models have been used to evaluate the performance of watersheds. In this context, Cooper[13] employed the Streeper−Phelps model to assess the dynamic of dissolved oxygen in rivers/channels contaminated with nitrogenous compounds. The Streeper−Phelps model predicts the amount of dissolved oxygen

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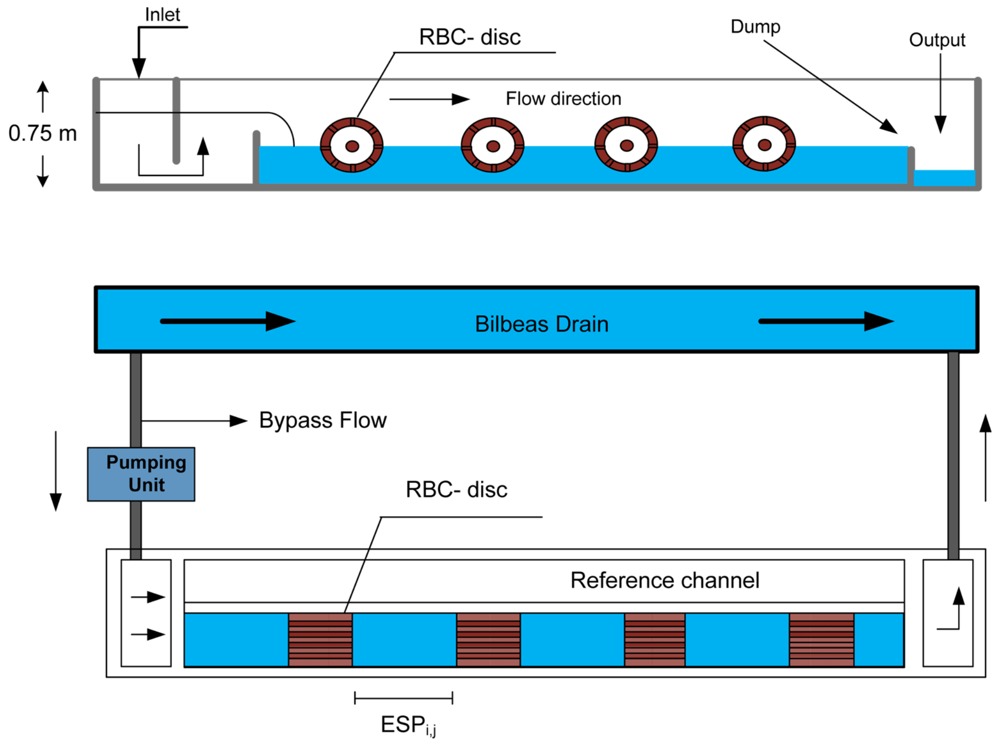

Figure 1. Schematic representation of SRD.

in a given location considering the degradation of organic matter and the addition of oxygen by aeration. Drolc and Koncan[14] used the water quality QUAL2E model for assessing the impact of wastewater discharges on the dissolved oxygen concentration in the river Sava near Ljubljana in Serbia. There are other water quality models to track the chemical species in watersheds. This way, the material flow analysis technique (MFA) has been used to assess the causes of pollution in a region considering all relevant activities such as water supplies, physical phenomena, and chemical and biochemical processes that affect the functioning of the watersheds. Baccini and Bruner[15] developed a MFA model to analyze ecosystems with human activities that exchange mass and energy with their surroundings. Moreover, Lampert and Bruner[16] proposed a MFA model for tracking major nutrients in the Danube River. Drolc and Zagorc-Koncan[17] applied the MFA model in the river Krka in Slovenia. El-Baz et al.[18,19] presented a MFA model for tracking nitrogen species (ammonium ions) in the Bahr El-Baqar drain located in Egypt, and Lovelady et al.[20] reformulated a MFA model to determine the maximum allowable discharges to ensure the sustainability of a watershed. Similarly, Lira-Barragán et al.[21,22] implemented a MFA model to determine the optimal location of new industrial facilities considering the sustainability of the watershed. Then, Lira-Barragán et al.[23] extended this model to consider properties rather than restrictions based on the composition, which is more suitable for systems constituted with multiple contaminants. Recently, Burgara-Montero et al.[24] reported a methodology for implementing a distributed treatment system for industrial effluents discharged to a watershed and minimizing the concentration of pollutants in the receiving water bodies based on a MFA formulation. However, all previous approaches have not considered the optimal design of self-rotating devices for improving the dissolved oxygen integrated into a distributed treatment for the watershed.

This paper presents a mathematical programming model for optimally determining the location of a SRD system, selecting the tributaries that must be treated, identifying the number of discs to be installed, and specifying the spacing between the disks to achieve a certain level of dissolved oxygen in the catchment areas at the end of the main river/channel of the watershed. The efficiency for increasing the dissolved oxygen is associated with the treated flow rate, number of discs that are installed, and spacing between them. To model the SRD system, a mathematical model is proposed based on experimental data where the design variables are the treated flow rate, location to install the system, number of rows of self-rotating discs, and spacing between rows. The proposed model considers the minimization of the total annual costs to obtain a desired water quality. The proposed methodology is also used to show the trade-offs between the considered objectives and to allow the decision maker to choose the optimal solution.

■ PROBLEM STATEMENT

Figure 2 shows a watershed that receives a continuous intake of effluents that depletes the dissolved oxygen. The presence of large amounts of organic matter is indicative of the low levels of dissolved oxygen and the threat to aquatic life. The objective is to develop a systematic procedure to find the optimal configuration of a SRD system that can be placed in the watershed to increase the dissolved oxygen to reach a desired level in the final catchment area. To track the dissolved oxygen across the watershed, the system is characterized mathematically by a MFA model. The MFA model takes into account relevant aspects such as inputs, outputs, and chemical and biochemical reactions and interactions with the surroundings. The optimization model will identify the tributaries that need to be treated to increase the dissolved oxygen concentration and the efficiency required for the SRD system to meet the oxygen restrictions imposed on the watershed.

The objective function is to minimize the total annual cost (TAC) and maximize the water quality as expressed by dissolved oxygen. This is a multi-objective optimization problem. The capital and operating costs depend on the number of SRD, treated flow

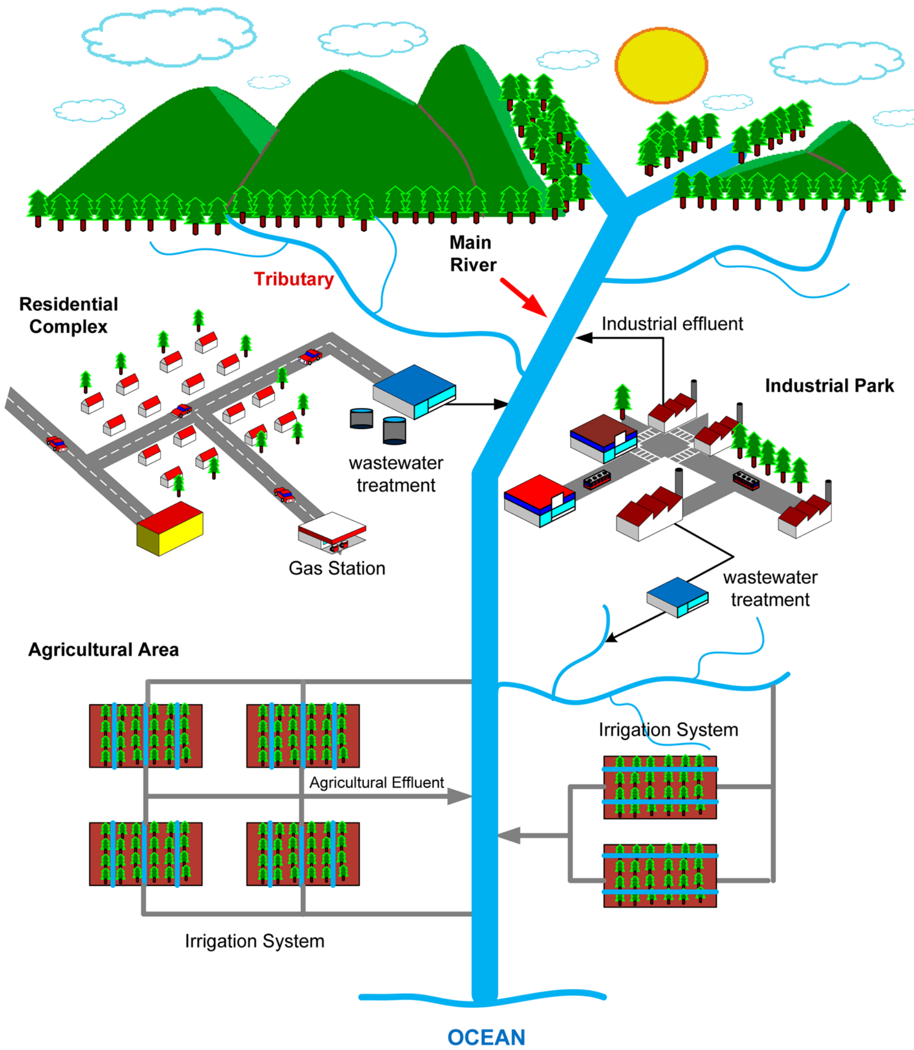

Figure 2. Schematic representation of a typical watershed.

rate, spacing between the discs, and dissolved oxygen concentration at the inlet flow rate. Additionally, this paper identifies the required efficiencies to increase the dissolved oxygen based on the flow rate, number of discs, and spacing between the discs.

■ THEORETICAL DEVELOPMENT AND MATHEMATICAL FORMULATION

In this paper, the proposed model is developed to couple a MFA with the performance of SRD systems that in turn is correlated to the treated flow rate, number of SRD installed, and spacing between discs. The MFA model evaluates all inputs and outputs on the main river/channel and secondary rivers/channels (tributaries), uses and discharges caused by agricultural activities, and treated and untreated wastewater discharges from industrial and domestic sectors. Furthermore, it takes into account natural phenomena such as rainfall, evaporation, and filtration; these phenomena significantly alter the composition of the dissolved oxygen in the macroscopic system. For adequate tracking of the average composition of the dissolved oxygen, the river/channel must be divided into sections called reaches, where the mean concentration can be considered constant (these sections are shown in Figure 3). The flow rate and dissolved oxygen concentration are different in each section of the river/channel. The tributaries that flow into the main river/channel receive also discharges of different sectors (agriculture, industry, and domestic). The flow rate ($EFLU_{i,j}$) and the concentration of dissolved oxygen ($DOEFLU_{i,j}$) of the tributaries modify the concentration of the dissolved oxygen in the river/channel sections where they are downloaded. Furthermore, the model involves the chemical and biochemical reactions that take place in the tributaries to account for the production and consumption of dissolved oxygen. Therefore, it is important to consider these terms to track the dissolved oxygen through the watershed. Before presenting the model formulation, the following sets are defined: I represents the number of reaches and J represents the number of tributaries; whereas i and j are scripts used to represent reaches and tributaries, respectively.

The formulation for describing the proposed model for increasing the dissolved oxygen in the watersheds is given as follows.

Overall Mass Balance for Each Reach.

$$Q_i = Q_{i-1} + INDR_i + P_i + D_i + \sum_{j=1}^{N_{EFLU,j}} EFLU_{i,j} - L_i - U_i, \ \forall \ i \in I \qquad (1)$$

Equation 1 indicates that the flow rate at the outlet of each reach (Q_i) is equal to the inlet flow rate of the previous reach (Q_{i-1}), plus the industrial effluent discharged to reach ($INDR_i$),

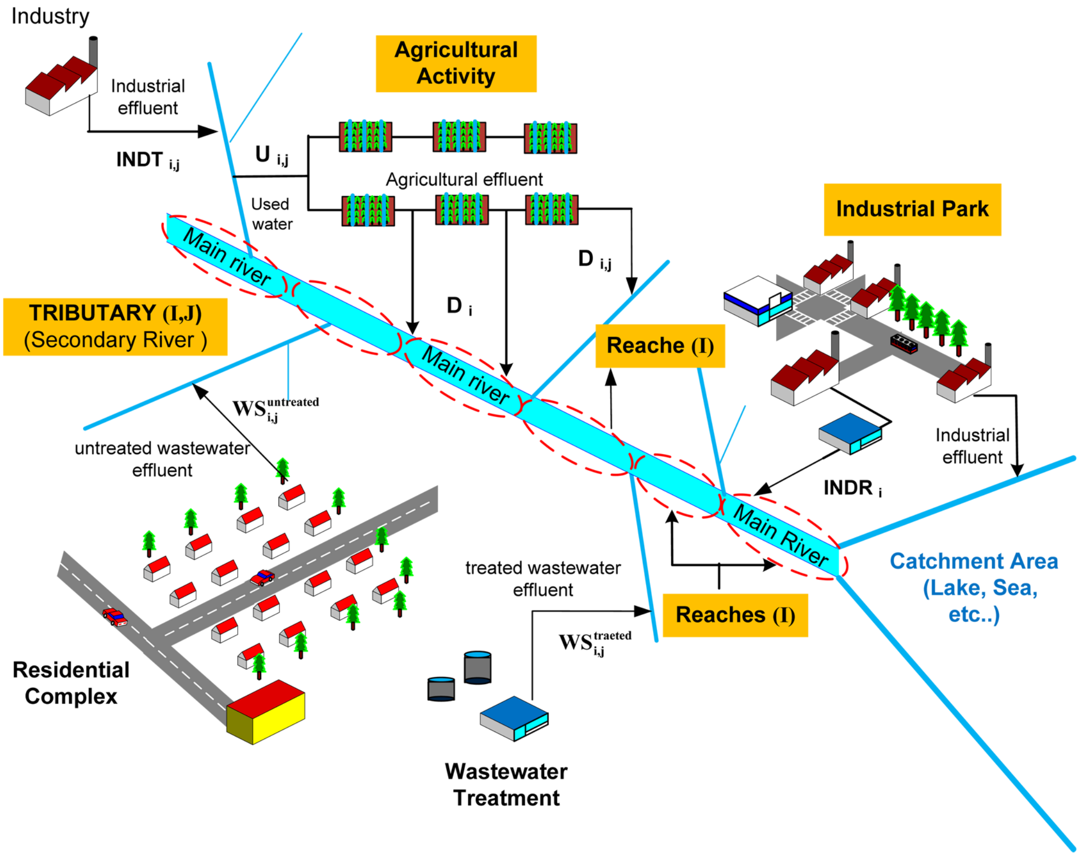

Figure 3. Representation of the proposed MFA model.

plus the direct discharges (D_i), the precipitation discharged to that reach(P_i), and the secondary river/channels discharging to the reach $\sum_{j=1}^{N_{EFL,i}} EFLU_{i,j}$, minus the outputs of the reach considering the natural phenomena of filtration and evaporation (L_i) and the use of water (U_i). For the reach i, the direct discharges (D_i) and uses (U_i) include several terms that are grouped into these parameters; these parameters are determined from reported information. The precipitation in reach i (P_i) is information that can be obtained from statistical meteorological reports in the specific place considered.

Balance for Dissolved Oxygen for Each Reach. Equation 2 represents the amount of dissolved oxygen (DO) that exists in each reach ($Q_i \times DOQ_i$), which is equal to the amount of dissolved oxygen entering the previous section of the river/channel ($Q_{i-1} \times DOQ_{i-1}$), plus the DO amount in the rainfall ($P_i \times DOP_i$), DO amount of direct discharges ($D_i \times DOD_i$), DO involved in the industrial effluents ($INDR_i \times DOINDR_i$), and DO in the tributaries discharging to that reach ($\sum_{j=1}^{N_{EFL,i}} EFLU_{i,j} \times DOEFLUat_{i,j}$), minus the DO lost in the flow rate by filtration and evaporation ($L_i \times DOL_i$) and by the use ($U_i \times DOU_i$), and the DO that disappears due to the degradation of organic matter (this is expressed as $\int_{V=0}^{V_i} r_i dV_i$).

$$Q_i \times DOQ_i = Q_{i-1} \times DOQ_{i-1} + P_i \times DOP_i + D_i \times DOD_i + INDR_i \times DOINDR_i + \sum_{j=1}^{N_{EFL,i}} EFLU_{i,j} \times DOEFLUat_{i,j} - L_i \times DOL_i - U_i \times DOU_i - \int_{V_i}^{V=0} r_i dV_i, \quad \forall\, i \in I \tag{2}$$

Overall Mass Balance for Tributaries.

$$EFLU_{i,j} = WS_{i,j}^{\text{untreated}} + WS_{i,j}^{\text{treated}} + INDT_{i,j} + P_{i,j} + D_{i,j} - L_{i,j} - U_{i,j}, \quad \forall\, i \in I,\ j \in J \tag{3}$$

The flow rate of the effluent ($EFLU_{i,j}$) that is discharged into the main river/channel is equal to the sum of all downloads received by the tributary such as treated wastewater ($WS_{i,j}^{\text{treated}}$), untreated wastewater ($WS_{i,j}^{\text{untreated}}$), industrial effluents ($INDT_{i,j}$), rainfall ($P_{i,j}$), agricultural discharges ($D_{i,j}$), lost caused by the natural phenomena of evaporation and seepage ($L_{i,j}$), and water used in the tributaries ($U_{i,j}$).

Balance for Dissolved Oxygen for Tributaries. The DO exiting a given tributary ($EFLU_{i,j} \times DOEFLU_{i,j}$) is given by the DO of the treated ($WS_{i,j}^{\text{treated}} \times DOWS_{i,j}^{\text{treated}}$) and untreated discharges ($WS_{i,j}^{\text{untreated}} \times DOWS_{i,j}^{\text{untreated}}$), plus the DO of the industrial discharges ($INDT_{i,j} \times DOINDT_{i,j}$), DO of precipitation ($P_{i,j} \times DOP_{i,j}$), DO of direct discharges ($D_{i,j} \times DOD_{i,j}$), minus the DO by evaporation and filtration ($L_{i,j} \times DOL_{i,j}$), and minus the DO of used water ($U_{i,j} \times DOU_{i,j}$) and the natural degradation ($\int_{V=0}^{V_{i,j}} r_{i,j} dV_{i,j}$).

$$EFLU_{i,j} \times DOEFLU_{i,j} = WS_{i,j}^{\text{untreated}} \times DOWS_{i,j}^{\text{untreated}} + WS_{i,j}^{\text{treated}} \times DOWS_{i,j}^{\text{treated}} + INDT_{i,j} \times DOINDT_{i,j} + P_{i,j} \times DOP_{i,j} + D_{i,j} \times DOD_{i,j} - L_{i,j} \times DOL_{i,j} - U_{i,j} \times DOU_{i,j} - \int_{V_{i,j}}^{V=0} r_{i,j} dV_{i,j}, \quad \forall\, i \in I,\ \forall\, j \in J \tag{4}$$

Agricultural discharges ($D_{i,j}$) and uses ($U_{i,j}$) are proportional to the existing agricultural areas around the watershed; these are calculated as follows.

$$D_{i,j} = \lambda_{i,j} \times A_{i,j}, \ \forall\, i \in I,\ j \in J \tag{5}$$

$$U_{i,j} = \beta_{i,j} \times A_{i,j}, \ \forall\, i \in I,\ j \in J \tag{6}$$

where $\lambda_{i,j}$ is the flow rate per unit area m^3/acre seg, and the parameter $\beta_{i,j}$ is the flow rate of water for the affluent j used for irrigation. This flow rate of water is given per unit area (m^3/acre seg) and $A_{i,j}$ is the area covering the tributary j in acres. The parameters $\lambda_{i,j}$ and $\beta_{i,j}$ can be determined experimentally or they can be taken from reported information.

Design of Distributed Treatment System. The SRD system used to increase the *DO* in the watersheds can be located in any tributary that flows into the main river/channel (Figure 4). This way, there are several possibilities to locate the SRD. Therefore, the optimization model must select the best places to locate these systems, flow rate directed to these devises, number of required discs, spacing between discs, and consequently, associated efficiency to improve the *DO* at the minimum total cost. To design the distributed treatment system of SRD, the following disjunction is used for each tributary j that flows into each reach i:

$$\begin{bmatrix} Y_{i,j} \\ (\alpha_{i,j}) \times DOEFLU_{i,j} = DOEFLUat_{i,j} \\ \alpha_{i,j} = C_1 \times EFLU_{i,j} + C_2 \times ND_{i,j} \times ESP_{i,j} \\ \quad + C_3 \times ND_{i,j} + C_4 \times ESP_{i,j} + C_5 \\ \alpha_{i,j}^{\min} \le \alpha_{i,j} \le \alpha_{i,j}^{\max} \\ ND_{i,j}^{\min} \le ND_{i,j} \le ND_{i,j}^{\max} \\ ESP_{i,j}^{\min} \le ESP_{i,j} \le ESP_{i,j}^{\max} \\ CapCost_{i,j} = FCost + VC_{EFLU} \times EFLU_{i,j}^{\delta e} \\ \quad + VC_{ND} \times ND_{i,j}^{\xi e} + VC_{ESP} \\ \quad \times ESP_{i,j}^{\varepsilon e} \\ OpCost_{i,j} = Cu_{EFE}^{op} \times EFLU_{i,j} + Cu_{ND}^{op} \times ND_{i,j} \\ \quad + Cu_{ESP}^{op} \times ESP_{i,j} \end{bmatrix} \vee \begin{bmatrix} \neg Y_{i,j} \\ DOEFLUat_{i,j} = DOEFLU_{i,j} \\ \alpha_{i,j} = 0 \\ ND_{i,j} = 0 \\ ESP_{i,j} = 0 \\ CapCost_{i,j} = 0 \\ OpCost_{i,j} = 0 \end{bmatrix}, \ \forall\, i \in I, \ \forall\, j \in J$$

In a previous disjunction, $DOEFLU_{i,j}$ is the dissolved oxygen in the affluent j that is discharged to the reach i; $DOEFLUat_{i,j}$ is the dissolved oxygen once the flow rate passes through the autorotating discs; $\alpha_{i,j}$ is the efficiency to increase the dissolved oxygen that depends on the treated effluent ($EFLU_{i,j}$), space between discs ($ESP_{i,j}$), and number of discs ($ND_{i,j}$). The Boolean variable $Y_{i,j}$ is associated with the existence of the SRD system. If true, the design equations for the discs system apply. If false ($\neg Y_{i,j}$), the discs system does not exist. Therefore, the dissolved oxygen concentration at the outlet is equal to the concentration of dissolved oxygen in the inlet affluent. *FC* is the unit fixed cost, and VC_{EFLU} is the unit variable cost for the flow rate treated. VC_{ND} is the unit variable cost for the number of SRD, and VC_{ESP} is the unit variable cost for the spacing between discs. Cu_{EFLU}^{op} is the unit operational cost to treat the flow rate of the tributary, Cu_{ND}^{op} is the unit operational cost for the number of SRD, and Cu_{ESP}^{op} is the unit operational cost for the spacing between discs. δe, ξe, and εe are the exponents for the capital costs for the treated flow rate, number of SRD, and spacing between discs, respectively. In addition, $CapCost_{i,j}$ and $OpCost_{i,j}$ are the capital and operating costs for the SRD system used to treat tributary j that discharges to the reach i.

To reformulate a disjunction as a set of algebraic equations, several techniques can be used, including the convex hull and the big M (for background examples, the reader is referred to the reformulations of Raman and Grossmann[25] and Ponce-Ortega et al.[26]). Usually, the convex hull is a good option to reformulate disjunctions that include linear terms because the big M requires additional parameters; however, for the case considered in this paper, the convex hull yields a lot of new disaggregated variables as well as several new constraints, which complicate the solution approach because the CPU time increases significantly. This way, in the present paper, a new reformulation is proposed that requires a lower number of variables and relationships that can be solved easily and in a short CPU time. In the reformulation, the Boolean variables are transformed into binary variables. Therefore, when a Boolean variable is true, the associated binary variable is equal to one; whereas when the Boolean variables are false, the associated binary variables are zero. Then, the above disjunction is reformulated as follows.

First, the continuous variable $DOEFLUat_{i,j}$ is disaggregated as follows

$$DOEFLUat_{i,j} = DOEFLUat_{i,j}^{d1} + DOEFLUat_{i,j}^{d2}, \ \forall\, i \in I, \ j \in J \tag{7}$$

Then, the equations in each disjunction are set in terms of the disaggregated variables.

$$\alpha_{i,j} \times DOEFLU_{i,j} \times y_{i,j} = DOEFLUat_{i,j}^{d1}, \ \forall\, i \in I,\ j \in J \tag{8}$$

$$DOEFLUat_{i,j}^{d2} = DOEFLU_{i,j} \times (1 - y_{i,j}), \ \forall\, i \in I,\ j \in J \tag{9}$$

$$\alpha_{i,j} = C_1 \times EFLU_{i,j} \times y_{i,j} + C_2 \times ND_{i,j} \times ESP_{i,j} + C_3 \times ND_{i,j} + C_4 \times ESP_{i,j} + C_5 \times y_{i,j}, \ \forall\, i \in I, \ j \in J \tag{10}$$

Equation 10 mathematically represents the relationship between the dependent variable (efficiency, $\alpha_{i,j}$, which is defined as the amount *DO* increased in the tributary j discharged to the reach i respect to the original *DO* in such stream) with the independent variables (treated effluent $EFLU_{i,j}$,

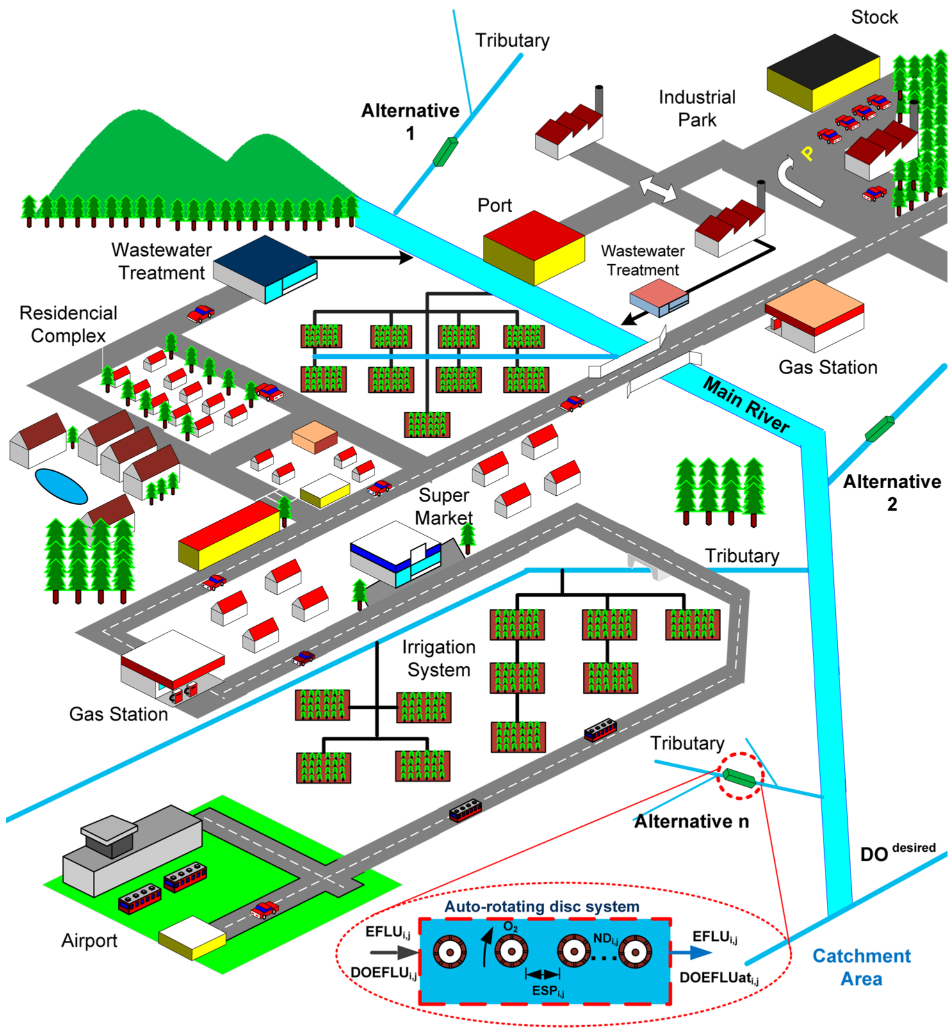

Figure 4. Superstructure for the distributed treatment system.

number of rows between discs $ND_{i,j}$, spacing between rows $ESP_{i,j}$). The correlation for the efficiency to increase the dissolved oxygen through SRD was obtained from a multivariable regression from a series of experiments, where the flow rate, number of discs, and spacing between discs were manipulated.[27,28] The obtained equation is nonlinear due to a bilinear term; this relationship has a correlation factor R^2 of 0.9, which is good enough for preliminary design purposes. When it is required to increase this correlation factor, quadratic relationships can be considered, which increases the correlation factor to 0.99, but the optimization process complicates significantly.

Equation 11 represents the capital cost generated for the installation of the SRD system as a function of the independent variables considered.

$$CapCost_{i,j} = FCost \times y_{i,j} + VC_{EFLU} \times EFLU_{i,j}^{\delta e} \times y_{i,j} + VC_{ND} \times ND_{i,j}^{\xi e} + VC_{ESP} \times ESP_{i,j}^{\varepsilon e}, \ \forall\, i \in I,\ j \in J \quad (11)$$

Equation 12 represents the operating cost as a function of the independent variables as follows.

$$OpCost_{i,j} = Cu_{EFLU}^{op} \times EFLU_{i,j} \times y_{i,j} + Cu_{ND}^{op} \times ND_{i,j} + Cu_{ESP}^{op} \times ESP_{i,j}, \ \forall\, i \in I,\ j \in J \quad (12)$$

Upper limits for the disaggregated variables are stated as follows.

$$DOEFLUat_{i,j}^{d1} \le DOEFLU_{i,j}^{\max} \times (y_{i,j}), \ \forall\, i \in I,\ j \in J \quad (13)$$

$$DOEFLUat_{i,j}^{d2} \le DOEFLU_{i,j}^{\max} \times (1 - y_{i,j}), \ \forall\, i \in I,\ j \in J \quad (14)$$

There are also limits for continuous variables as follows.

$$\alpha_{i,j}^{\min} \times y_{i,j} \le \alpha_{i,j} \le \alpha_{i,j}^{\max} \times y_{i,j}, \ \forall\, i \in I,\ j \in J \quad (15)$$

$$ND_{i,j}^{\min} \times y_{i,j} \le ND_{i,j} \le ND_{i,j}^{\max} \times y_{i,j}, \ \forall\, i \in I,\ j \in J \quad (16)$$

$$ESP_{i,j}^{\min} \times y_{i,j} \le ESP_{i,j} \le ESP_{i,j}^{\max} \times y_{i,j}, \ \forall\, i \in I,\ j \in J \quad (17)$$

Objective Function. The model is formulated as a mult-objective optimization problem that minimizes the total annual cost and maximizes the concentration of dissolved oxygen in the catchment area as follows.

$$OF = \{\min TAC;\ \max DO^{\text{desired}}\} \quad (18)$$

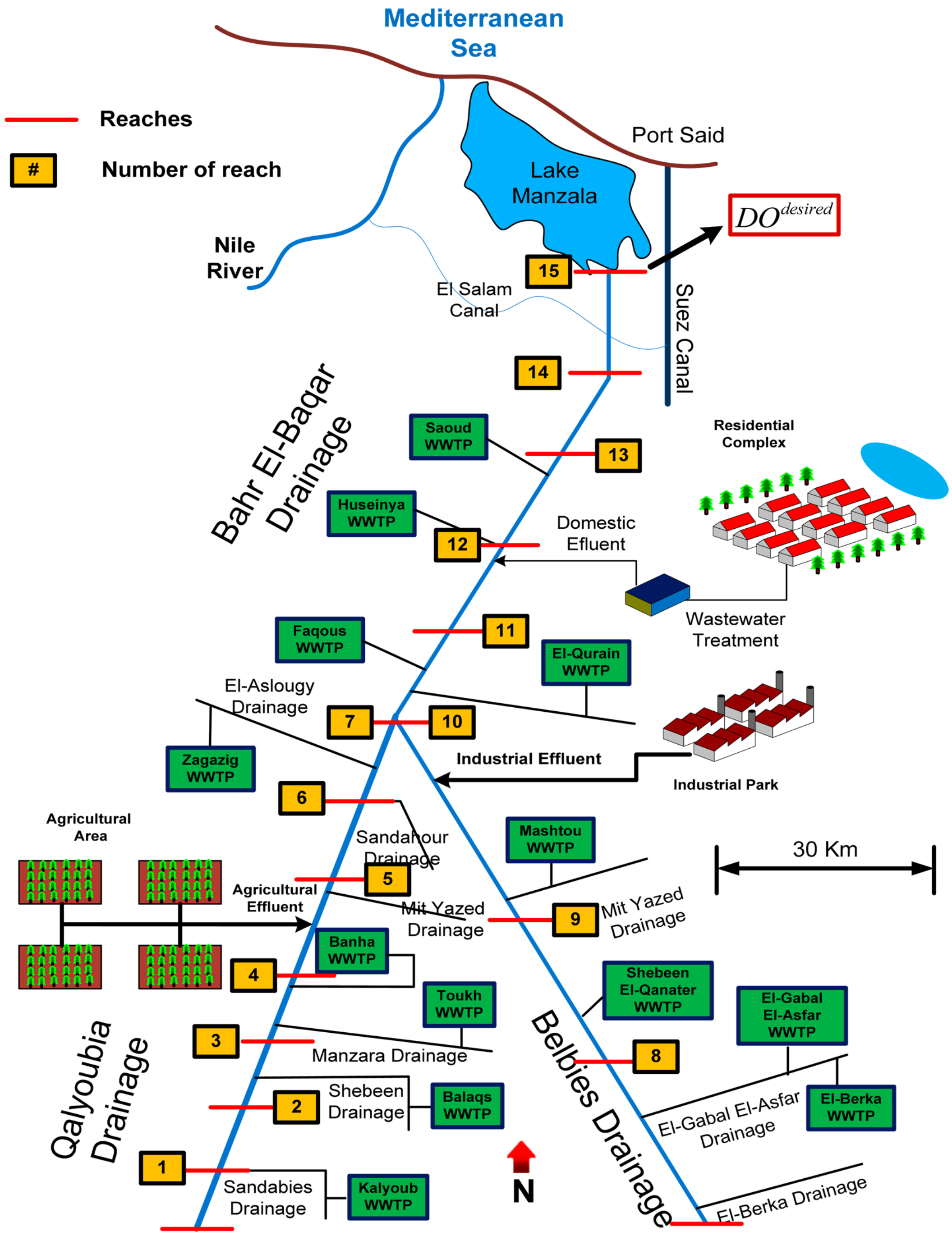

Figure 5. Bahr El-Baqar drain.[18].

Table 1. Dissolved Oxygen "*DO*" Standards[33]

DO standards (ppm)	characterization
9–10	very healthy for all aquatic life
5–6	minimum level for healthy fish
2–4	fish are stressed
1–2	fish died

These two objectives are proportional. This means that when the dissolved oxygen concentration increases that the total annual cost increases; on the other hand, when the concentration of dissolved oxygen decreases, the total annual cost also decreases. This is because an increased dissolved oxygen content in the macroscopic system is necessary to install SRD with the highest efficiency and the highest costs in the tributaries along the main river/channel and thus satisfy the constraint imposed on the catchment area.

The total annual cost is the sum of the capital cost for the SRD system required to increase the dissolved oxygen in any tributary and the operating cost associated to the function of the system. Therefore, the total annual cost is expressed as follows.

$$TAC = K_F \times \left(\sum_{i\in I}\sum_{j\in J} CapCost_{i,j}\right) + H_Y \times \sum_{i\in I}\sum_{j\in J} OpCost_{i,j} \tag{19}$$

In previous equation, *TAC* is the total annual cost ($/year). K_F is a factor used to annualize the capital costs (year^{-1}), and H_Y is the number of hours of operation per year (hours/year).

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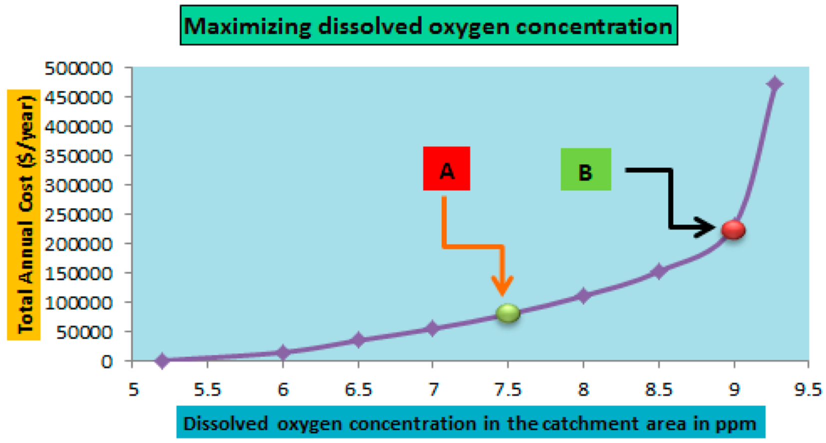

Figure 6. Pareto solutions for the case study.

Table 2. Optimal Configuration for Distributed Treatment System for Dissolved Oxygen Concentration of 7.5 ppm (Scenario A)

tributary	spacing (m)	number of discs	flow rate (m^3/s)	efficiency
1.1	4	2	1.247	2.666
2.1	4	20	6.19	3.000
3.2	4	2	0.099	2.584
7.3	4	5	1.732	2.749
12.1	3.2	2	0.725	2.655
14.2	4	2	2.021	2.631
15.1	4	2	2.035	2.630
15.2	4	2	2.473	2.611

Table 3. Optimal Configuration for Distributed Treatment System for Dissolved Oxygen Concentration of 9 ppm (Scenario B)

tributary	spacing (m)	number of discs	flow rate (m^3/s)	efficiency
1.1	4	20	1.247	3.296
1.2	4	2	0.439	2.702
1.5	4	2	0.387	2.705
2.1	4	20	6.19	3.073
2.2	4	2	0.192	2.713
2.3	4	2	0.243	2.711
3.2	4	20	3.073	3.214
3.4	0.45	2	0.116	2.546
4.3	4	4	0.774	2.757
4.4	4	2	0.151	2.715
5.1	4	2	0.344	2.707
6.1	4	2	0.213	2.712
6.3	4	2	0.589	2.695
6.4	4	20	2.657	3.232
7.1	4	3	0.479	2.700
7.3	4	20	1.732	3.274
9.2	4	2	0.214	2.712
10.2	2	4	0.688	2.691
11.2	4	2	0.165	2.715
11.3	4	20	1.705	3.275
12.1	4	20	0.725	3.319
12.3	4	2	0.258	2.710
13.1	4	20	0.731	3.319
13.2	4	2	0.434	2.702
14.1	4	20	0.731	3.319
14.2	4	20	2.021	3.261
15.1	4	20	2.035	3.26
15.2	4	18	2.473	3.241

To solve this multi-objective optimization problem, the constraint method (e.g., Diwekar[29]) is used in this work to determine the set of Pareto solutions. In this method, the strategy consists in transforming the multi-objective optimization problem into a series of problems with a single target by choosing only one of the objectives as the objective to be minimized (in this case, the *TAC*) and defining the other one as a constraint (in this case, the dissolved oxygen $DO^{desired}$ at the final disposal). This strategy allows identifying the minimum cost required for a given concentration of *DO* at the final disposal. At the same time, this methodology allows to identify the additional investment required to satisfy stricter environmental constraints, which is very useful to take governmental decisions associated with these problems.

RESULTS AND DISCUSSION

A case study is used to show the application of the proposed model. The case study is solved as a MINLP problem with the solver SBB together with the solvers CONOPT and CPLEX included in the software GAMS.[30] There are other solvers available in GAMS for solving MINLP problems (i.e., DICOPT and BARON), but DICOPT usually performs better for models that have a significant and difficult combinatorial part. However, BARON is a global optimization solver that requires good limits for the involved variables, and it consumes a huge CPU time. SBB works well for models that have fewer discrete variables but more difficult nonlinearities (and probably for nonconvex model) like the proposed model. This case corresponds to the Bahr El-Baqar drainage located in Egypt. The number of SRD systems to be placed on the tributaries and the configuration of each system (number of discs, spacing, and treated flow rate) depend on the desired dissolved oxygen concentration in the catchment area that is the Lake Manzala located at the northeastern Nile Delta and the Mediterranean Sea. Water polluted by agriculture, industrial and domestic sewage is transported by the Bahr El-Baqar drainage system (Figure 5) that flows into the southern part of Lake Manzala. This intake of contaminated water in the catchment area decreases the ability of self-purification and increases the accumulation of pollutants, damaging human health and economic activities such as fishing, livestock, and farming. Increasing the concentration of dissolved oxygen in the catchment area is a measure for improving the quality of

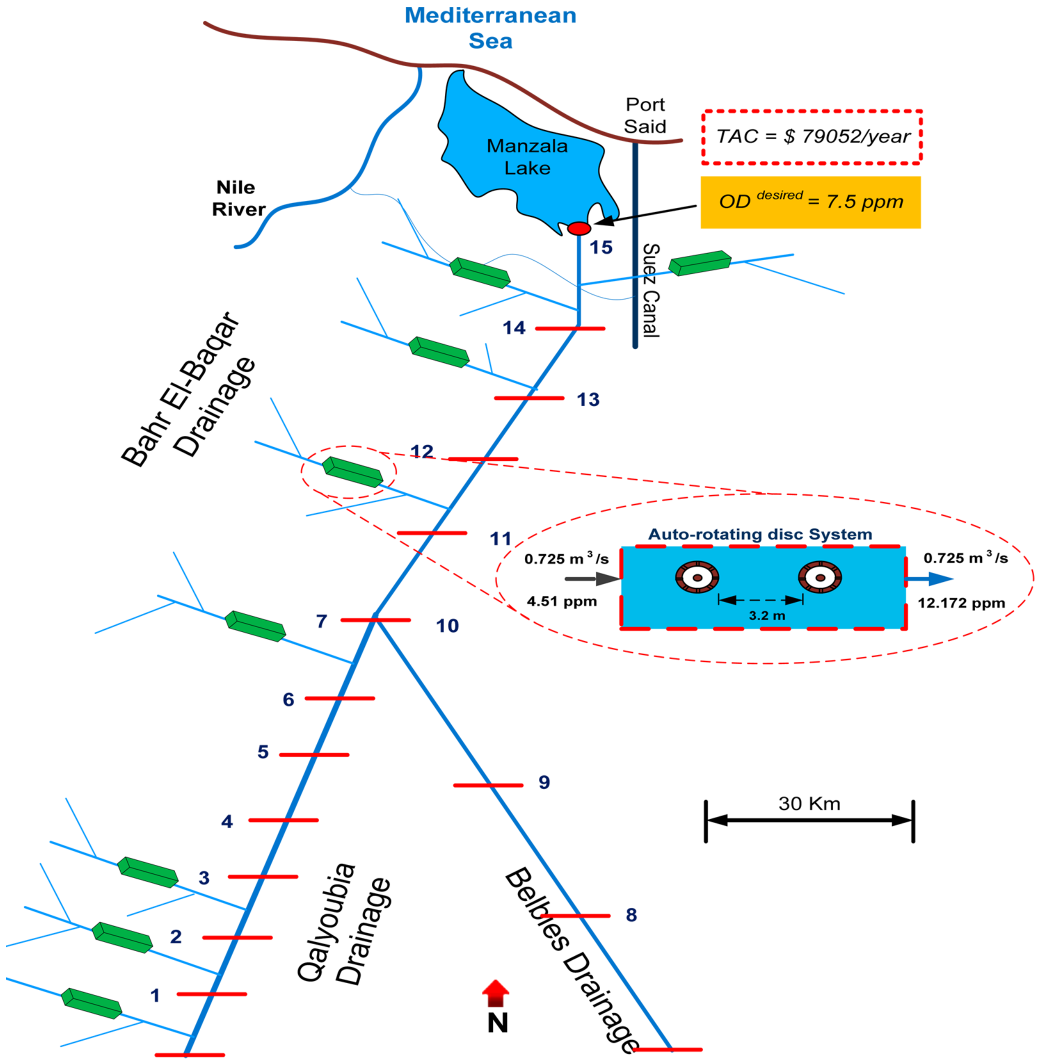

Figure 7. Schematic diagram for the optimal configuration of the distributed treatment system for Scenario A.

water because higher concentrations of dissolved oxygen creates conditions for growing microorganisms for oxidation of organic matter and minimizes stress for the development of species sensitive to lack of oxygen. The characteristics of the Bahr El-Baqar drainage were used as input parameters for the MINLP optimization model described in this paper. The model considers the possibility to include a SRD system in each tributary discharging to the main river/channel. This way, the optimization model must determine the locations to place the SRD systems and the design characteristics. The fixed cost for SRD (*FCost*) is \$400, and the unit variable costs are VC_{EFLU} of \$8000 × 10^{-3}/m^3, VC_{ESP} of \$200 × 10^{-3}/m, and VC_{ND} of \$1000 × 10^{-3}/number of rows. The unit operating costs are Cu^{op}_{EFLU} of \$0.056/m^3, Cu^{op}_{ESP} of \$0.046/h m, and Cu^{op}_{ND} of \$ 0.086/h number of rows.

The reaction for the consumption of dissolved oxygen due to the natural biodegradation process of organic matter follows a first-order kinetic model. The kinetic constant k is 0.9041909 × 10^{-5}/s. In addition, the value for $\lambda_{i,j}$ is 0.000066 m^3/acre seg for all reaches; for reaches 1−6, 8, and 12−15, β = 0.000023 m^3/acre seg; and for reaches 7 and 9−12, β = 0.000011 m^3/acre seg. The operating time is 8000 h/year, and the factor used to annualize the capital costs (K_f) is of 0.33 year^{-1}. The concentrations of the different discharges in the main channel and tributaries are 0 mg/L for precipitation and evaporation, 3.4 mg/L for industrial effluents, 2.5 mg/L for wastewater without treatment and wastewater from agriculture, and 4.2 mg/L for treated water.[31,32]

The dissolved oxygen concentration in Lake Manzala before the installation of the treatment system is 3.5 ppm, which causes the disappearance of organisms and species sensitive to the lack of oxygen. Table 1 shows the characterization of the standards for dissolved oxygen in water bodies (rivers/channels or lakes).

The Pareto curve (Figure 6) shows the solutions obtained for different concentrations of dissolved oxygen imposed in the catchment area. Each point of the curve represents the total annual cost generated for the installation of the SRD system to increase the dissolved oxygen concentration along the river/channel as well as the configuration of the system (treated flow rate, number of discs, and spacing between discs) and thereby satisfying the dissolved oxygen concentration desired in the catchment area. Notice on the right-hand side of Figure 6 that when the oxygen concentration increases so does the total annual cost. This is because more SRD systems are needed to achieve greater concentrations of dissolved oxygen. More SRD systems increase the turbulence in the tributaries where they are installed and thus increase the aeration leading to higher

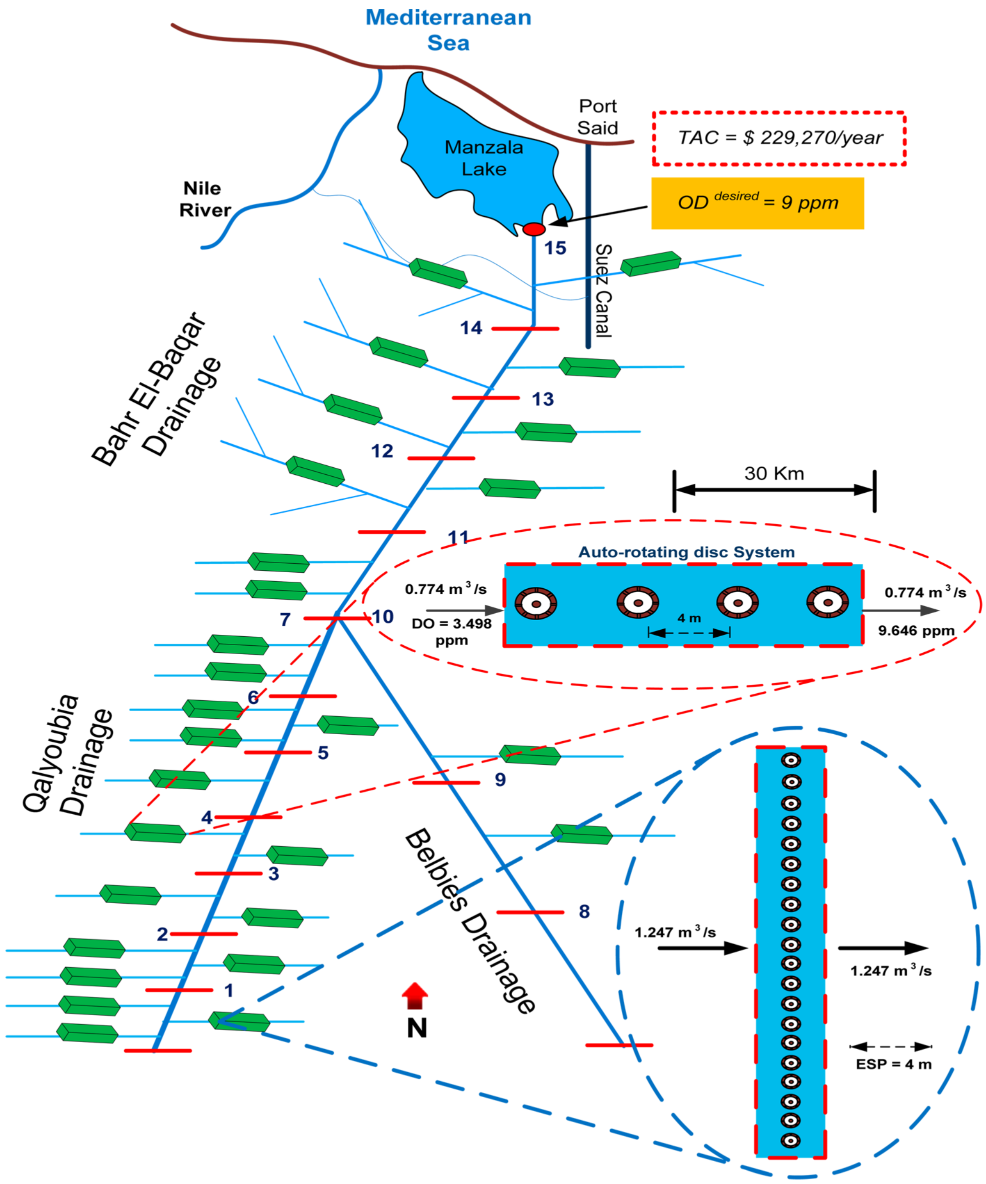

Figure 8. Schematic diagram for the optimal configuration of the distributed treatment system for Scenario B.

levels of dissolved oxygen. On the other hand, on the left-side of Figure 6, the water quality diminishes, and the number of SRD units is lower. Therefore, the total annual cost associated decreases. The decision maker can select the solution that best satisfies the specific requirements based on trading off cost and water quality. On the other hand, the governments can identify the additional investment required for a given concentration in the final disposal. Two scenarios have been selected in which the concentrations for the dissolved oxygen are increased so that the system is able to degrade the contaminants in the tributaries and the catchment area.

First Solution (Scenario A). Solution A of the Pareto set represents the concentration of 7.5 ppm of dissolved oxygen in the catchment area. Table 2 shows the configurations of the distributed treatment system placed on the tributaries along the watershed, including the flow rates, number of discs installed, spacing between discs, and efficiency to meet the dissolved oxygen concentration imposed on the catchment area. The distributed treatment system allows for installation of a SRD system along the watershed; this decreases the treated flow rate. If the traditional centralized systems is implemented, only one SRD would be placed at the end of the system where the total treated flow rate would be greater and so the associated cost. Furthermore, in a centralized system, all the constraints in the different reaches would not be satisfied. Figure 7 shows the optimum solution obtained for the distributed treatment system configuration to satisfy the concentration of 7.5 ppm in the catchment area, wherein each SRD system installed has an associated efficiency to increase the oxygen dissolved in the water stream where they are installed. It was necessary to install eight SRD systems along the watershed, each one with specific configurations. The total annual cost (TAC) for Scenario A is $ 79,052/year.

Second Solution (Scenario B). Point B of the Pareto curve of Figure 6 represents the concentration desired in the catchment area of 9 ppm, and according to Table 1, this represents a very healthy oxygen concentration for all aquatic life. Table 3 shows the optimal configuration of the distributed treatment system to increase the dissolved oxygen in the watershed. Figure 8 shows the schematic diagram of the

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treatment system to indicate the tributaries selected for installing the SRD systems to ensure the desired dissolved oxygen concentration in the catchment area. Notice that when the concentration of dissolved oxygen desired in the catchment area is higher the total annual cost associated increases. This is a consequence of increasing the number of effluents to be treated, which also increases the number of SRD and efficiency of self-rotating disc systems increases (higher number of disks, lower spacing) to increase the dissolved oxygen along the watershed and thus meet the limits for the dissolved oxygen concentration imposed in the catchment area. Furthermore, the proposed approach allows the distributions of the treatment units (optimizing the location and efficiency) to yield the solution with the minimum cost for a given water quality through the watershed and to ensure the sustainability for the final disposal.

CONCLUSIONS

This paper has presented a multi-objective MINLP model for the optimal design of distributed treatment systems to ensure sustainability in watersheds. The environmental objective (increasing the dissolved oxygen in catchment areas) is maximized, and the economic objective (total annual cost) is minimized using the multi-objective constraint method of optimization. The solution alternatives are represented via a superstructure that embeds the various alternatives for selecting the effluents to be treated and the design configurations for the SRD system. The proposed model is based on a disjunctive programming formulation, and the MFA model was used to evaluate all inputs and outputs on the main and secondary rivers/channels (tributaries).

The proposed MINLP model was applied to the Bahr El-Baqar drain (located in Egypt); the optimal results are shown through Pareto curves where several interesting scenarios can be identified. The results show that the proposed model is useful in determining the minimum total cost for the specific requirements of water quality in the catchment area of the river/channel with a distributed processing system with SRD.

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE

INDEXES

i Reach
j Tributary

SETS

I Set for reaches
J Set for tributaries

PARAMETERS

$A_{i,j}$ Tributary area covering j in the reach of river/channel i, acre
C_1 Constant for the efficiency of the SRD for the flow rate, L/m^3
C_2 Constant for the efficiency of the SRD for the number of rows and spacing, 1/number of rows m
C_3 Constant for the efficiency of the SRD for the number of rows, 1/number of rows
C_4 Constant for the efficiency of the SRD for the spacing, 1/m
C_5 Constant for the efficiency of the SRD, dimensionless
Cu_{EFLU}^{op} Unit operational cost for the flow rate of tributary, \$/m^3
Cu_{ND}^{op} Unit operational cost for the number of discs, \$/h number of rows
Cu_{ESP}^{op} Unit operational cost for the spacing between discs, \$/h m
$DOD_{i,j}$ DO concentration in the agricultural effluent discharged to the reach of river/channel i, ppm
$DOINDR_{i,j}$ DO concentration in the industrial effluent j discharged to the reach of river/channel i, ppm
$DOINDT_{i,j}$ DO concentration in the industrial effluent j discharged to the tributary j, ppm
DOL_i DO concentration in the total lost (filtration and evaporation) of the section of river/channel i, ppm
$DOL_{i,j}$ DO concentration in the total lost (filtration and evaporation) of tributary j, ppm
$DOP_{i,j}$ DO concentration in precipitation discharged into the tributary of river/channel reach j and i, ppm
$DO^{desired}$ DO concentration desired at the end of the catchment area, ppm
$DOWS_{i,j}^{untreated}$ DO concentration in the discharge of untreated sewage, ppm
$DOWS_{i,j}^{treated}$ DO concentration in the discharge of treated wastewater, ppm
$DOEFLU_{i,j}$ DO concentration in the tributary, ppm
$DOEFLU_{i,j}^{MAX}$ Upper limit for DO concentration in the tributary after treatment, ppm
D_i Direct discharges in the river/channel reach i, m^3/s
$D_{i,j}$ Direct discharges in the tributary j, m^3/s
$EFLU_{i,j}$ Tributary flow rate j, m^3/s
$ESP_{i,j}^{MAX}$ Upper limit for spacing between discs of the SRD, m
$ESP_{i,j}^{MIN}$ Upper limit for spacing between discs of the SRD, m
$FCost$ Fixed cost for SRD, \$
H_Y Operating time per year, h/year
$INDR_i$ Industrial effluent discharged to the reach, m^3/s
$INDT_{i,j}$ Industrial effluent discharged to the tributary, m^3/s
k Rate constant for degradation of dissolved oxygen in the system, ppm/m^3
K_F Factor used to annualize the capital cost, year^{-1}
$L_{i,j}$ Total lost (filtration and evaporation) in the affluent j, m^3/s
L_i Total lost (filtration and evaporation) in the reach i, m^3/s
$ND_{i,j}^{MAX}$ Upper limit for number of disc of the SRD

$ND_{i,j}^{MIN}$	Lower limit for number of disc of the SRD
P_i	Discharge of precipitation in the reach i, m^3/s
$P_{i,j}$	Discharge of precipitation in the affluent j, m^3/s
r_i	Reaction rate in the reach i.
$r_{i,j}$	Reaction rate in the affluent j.
$U_{i,j}$	Water used from tributary j discharged to reach i, m^3/s
U_i	Water used from reach i, m^3/s
V_i	Volume for reach i, m^3
$V_{i,j}$	Volume for tributary j discharged to reach i, m^3
VC_{EFLU}	Variable unit cost for the SRD associated to the flow rate, $\$/m^3$
VC_{ESP}	Variable unit cost for the SRD associated to the spacing between discs, \$/m
VC_{ND}	Variable unit cost for the SRD associated to the number of rows, \$/number of rows
$WS_{i,j}^{untreated}$	Residual wastewater discharged without treatment to the reach i from tributary j, m^3/s
$WS_{i,j}^{treated}$	Residual treated wastewater discharged to the reach i for tributary j, m^3/s

VARIABLES

$CapCost_{i,j}$	Capital cost, \$
$DOEFLUat_{i,j}$	DO concentration of the tributary after treatment, ppm
$DOEFLUat_{i,j}^{d1}$	DO concentration of the tributary after treatment, disaggregated in the first disjunction, ppm
$DOEFLUat_{i,j}^{d2}$	DO concentration of the tributary after treatment, disaggregated in the second disjunction, ppm
DOQ_i	DO concentration that exists from reach i, ppm
DOQ_{i-1}	DO concentration in the flow inlet to the reach i, ppm
DOU_i	DO concentration in the water used for the section of river/channel i, ppm
$DOU_{i,j}$	DO concentration in the water used in the tributaries j, ppm
$ESP_{i,j}$	Spacing between discs installed in the tributaries, m
$ND_{i,j}$	Number of discs installed in the tributaries
OF	Objective function
$OpCost_{i,j}$	Operational cost, \$/h
Q_i	Flow rate of the output of each reach i, m^3/s
Q_{i-1}	Flow rate of the input of each reach i, m^3/s
TAC	Total annual cost for the distributed SRD system, \$/year
$y_{i,j}$	Binary variable associated with the existence of auto-rotating disc system

GREEK SYMBOLS

$\alpha_{i,j}$	Efficiency factor for increasing the DO in the tributaries j, dimensionless.
$\alpha_{i,j}^{MAX}$	Upper limit for the efficiency of the SRD, dimensionless
$\alpha_{i,j}^{MIN}$	Lower limit for the efficiency of the SRD, dimensionless
$\beta_{i,j}$	Agricultural use of water from tributary i, m^3/acre s
δe	Exponent for the capital cost related to the treated effluent, dimensionless
εe	Exponent for the capital cost related to the spacing between rows, dimensionless
$\lambda_{i,j}$	Agricultural flow rate per area, m^3/acre s
ξe	Exponent for the capital cost related to the number of rows, dimensionless

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