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Designing Water Inter-Plant Networks of Single and Multiple Contaminants through Mathematical Programming

Abeer M. Shoaib [1], Amr A. Atawia [1], Mohamed H. Hassanean [1], Abdelrahman G. Gadallah [2,3] and Ahmed A. Bhran [2,*]

[1] Department of Petroleum Refining and Petrochemical Engineering, Faculty of Petroleum and Mining Engineering, Suez University, Suez P.O. Box 43221, Egypt; a.shoaib@suezuni.edu.eg (A.M.S.); amr.atawia@gmail.com (A.A.A.); mhassanean@yahoo.com (M.H.H.)
[2] Chemical Engineering Department, College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11432, Saudi Arabia; agadallah@imamu.edu.sa
[3] Chemical Engineering Department, National Research Center, Cairo 11241, Egypt
* Correspondence: aabahran@imamu.edu.sa; Tel.: +966-580772698

Abstract: Water is the meaning of life for humans, agricultural and industrial processes; controlling the distribution of water and wastewater between industrial processes is very vital for rationalizing water and preserving the environment. This paper addresses a mathematical approach to optimizing water inter-plant networks. The water network problem is formulated as a nonlinear program (NLP) that is solved by LINGO Software, version 14.0. A generalized two-step mathematical model is designed to be valid for solving networks containing large numbers of sources and sinks. The introduced model is proposed to be used for both single and multiple contaminant problems with up to six contaminants. Two mathematical models are presented to design water inter-plant networks efficiently. Firstly, the introduced model is solved by LINGO, in which the data given are applied; the obtained results are simultaneously sent to a second model (based on Excel Software 2019, v. 16.0), by which the obtained water networks are automatically drawn. The proposed approach has been applied in three case studies; the first case study contains five plants of single contaminants, the second case study contains three plants of single contaminants, and the third case study contains three plants of multiple contaminants. The results showed a noticeable reduction in the percentages of freshwater consumption in the investigated three case studies, which were 38.6, 4.74 and 8.64%, respectively, and the wastewater discharge of the three case studies were decreased by 38.1, 4.61 and 8.65%, respectively.

Keywords: inter-plant water network; nonlinear programming; freshwater consumption; mathematical approach; multiple contaminants

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1. Introduction

The management of water in the inter-plant industrial process has been posed in the last decade since the consumption of global freshwater has increased continuously in industry.

Several processes in fertilizers, refineries and chemical companies use water in cooling systems, the scrubbing of gases, dilution and the adaptation of heat balance in heat exchangers.

Various methodologies have been presented in recent years for minimizing freshwater consumption and reducing the flowrate of wastewater discharge in the design of water inter-plant networks. A stochastic optimization model is proposed by Al-Redhwan et al. to minimize freshwater consumption and to produce a flexible wastewater network; they studied the distribution of wastewater in several processes in oil refinery plants. These processes include the atmospheric crude distillation unit, vacuum distillation unit, and the hydrocracker and kerosene desulfurization unit [1]. A genetic algorithm was presented by Ami et al. to manage the distribution of water in the contaminant sensor network to obtain the optimal system and multi-objective sensor model [2]. A pinch technique was proposed by Chew et al. for the reduction of freshwater and wastewater flowrates: a case study of an iron and steel mill was presented to show the effectiveness of their presented techniques; the processes contained mold cooling, slab cooling, rinsing and fume scrubbing [3]. The production of methanol from molasses was studied by Satyawali et al.: the effluent wastewater which is produced from methanol production included a high strength of pollution and the processes contained several equipment for maintaining temperature, such as cooling towers [4]. Iancu et al. introduced a mathematical model to design a regeneration wastewater network: they presented a case study of a petrochemical plant that contains one water source, six operation units, four contaminants and one regeneration unit to maximize the reuse of wastewater [5]. A case study of a steel plant was presented by Tian et al. to optimize the allocation of water and wastewater between several processes including the power plant, ore dressing, blast furnace, hot air furnace and rinsing residue; the chlorine concentration was presented as the limiting concentration in the design of water–wastewater networks [6]. A systematic methodology is presented by Kim et al. to minimize the cost estimation in the design of wastewater and heat exchange networks in oil refinery processes that contain multiple contaminants; in their work, a mixed integer non-linear programming formulation based on mass and heat balance between the processes is proposed; several processes such as hydrodesulfurization unit and an atmospheric distillation unit were introduced to show the effect of such processes on changing wastewater concentration [7]. An algorithm-based method is proposed by Chew et al. to minimize the flowrate of water resources in the single contaminant system of an inter-plant resource conservation network (IPRCN); they applied their algorithm to three water networks [8]. A different mathematical model is presented by Chen et al. to minimize the consumption of fresh water for the inter-plants; their work is applied to a case study of three plants with multiple contaminant systems [9]. Three wastewater treatment plants were studied by Julien et al. to manage the distribution of microbiological water in the Seine River [10]. An adaptive random search (ARS), which is an optimization approach introduced by Poplewski et al., is applied to several case studies of mixed integer nonlinear problems: a case study of a paper mill was presented with several processes which included pulping (dilution), a paper machine, a cylinder shower and felt showers [11]. An organic production plant was presented by Gopal et al., using treatment units to minimize the concentrations of contaminants and maximize the reuse of wastewater while minimizing the cost of treatment [12]. Yang et al. have proposed mathematical programming approaches that are based on mixed integer nonlinear programming to optimize reuse-recycle wastewater networks using treatment units; several methods, such as reverse osmosis, ion exchange, sedimentation, ultrafiltration and activated sludge, were used to decrease the concentration of contaminants [13]. A simultaneous optimization model was formulated to design a heat-integrated wastewater network based on mixed integer nonlinear programming to minimize the cost of freshwater consumption and the cost of wastewater treatment units [14]. A mixed integer nonlinear program was proposed using regeneration reuse and regeneration recycle in the hollow fiber reverse osmosis membrane to minimize the cost of freshwater and energy consumption; the presented model was applied to a refinery case study which included amine sweeting distillation, hydrotreating and desalting processes and considered the chemical oxygen demand and total dissolved solids to be limiting concentrations [15]. Bozkurt et al. have proposed a mathematical approach based on a framework to solve and optimize a multiple contaminant retrofitting problem; they studied the design of a wastewater treatment plant and the calculation of energy efficiency [16]. A reduction in the total annualized cost and wastewater discharge has been presented by Sueviriyapan et al. using a mixed integer nonlinear program; they applied their technique to a refinery plant and the results showed a decrease in the total annualized cost as well as the wastewater discharge [17]. A two-stage stochastic programming model has been presented to design an optimum water–wastewater network [18]: Naderi et al. studied the effect of hazards on environmental law. Hong et al. developed a strategy of multi-objective optimal control (MOOC) and multi-objective particle swarm optimization (MOPSO) to reduce the consumption of heat and increase the operational efficiency of the wastewater treatment plant [19]. A corn refinery case study was introduced to show the water management techniques presented by Mostafa et al.; several processes were presented to show the flexibility of the presented model, and these processes include gluten separation, starch separation, starch dewatering and glucose evaporation; chemical oxygen demands and total dissolved solids were presented as the limiting concentrations of contaminants in the allocation of freshwater and wastewater between processes [20]. Two techniques of centralized water header are proposed by Fadzil et al. to improve the reuse of wastewater in networks; they presented a case study of a single contaminant system that consists of five plants [21]. Lv et al. presented a step-by-step optimization method in the design of inter-plant water networks; a case study of a single contaminant in southern China was applied to show the applicability of their method [22]. A case study of inter-plant processes between an oil refinery plant and a petrochemical plant was presented by Reinaldo et al. to optimize the distribution of water and wastewater between several processes such as those of the cooling towers, condensers, coolers and boilers [23]. Robles et al. proposed model predictive control (MPC) and particle swarm optimization (PSO) to make a quality control of river basins in the presence of ammonium and nitrites [24]. A concentration potential concept was used by Wang et al. to design an optimal inter-plant water network; a case study of three plants and multiple contaminants was presented to show the effectiveness of their technique [25]. Fard et al. presented a Lagrangian relaxation-based model to make a control of water supply and wastewater collection; they studied the quality of the Azerbaijan province in Iran as a case study to minimize the water supply and wastewater discharge [26]. Mohammad and Chang studied the design of water–wastewater networks in the textile industry; according to the high temperature of the water, up to 60 °C, several contaminants were found in wastewater discharged streams such as chemical oxygen demand [27]. Kumawat et al. proposed a robust formulation in a continuous process to calculate the consumption of freshwater; their technique controlled the flowrates and qualities of the reused and recycled wastewater [28]. Three optimization models are proposed by Grzegorz and Dominic to design a flexible water network while minimizing the total length of the pipeline, the consumption of freshwater and the total annualized costs [29]. A textile industrial cluster was studied to manage the allocation of wastewater flowrate between sources and demands; zero liquid discharge was targeted in the design of a wastewater network that included a single contaminant TDS in several processes like the crystallizer, centrifuge and dilution processes [30]. A maximization of wastewater reuse in the textile dyeing industry was presented by Erkata et al.; several processes needed water in the dying industry such as the singeing, de-sizing, boiling, bleaching and printing processes [31]. A Bayesian optimization approach was proposed by Mariacrocetta et al. to manage the water quality of drainage systems [32]. A scrap tires-into-fuel processing facility was studied by Nessren et al. to design the wastewater network between several processes which include the condenser, decanter, separation, seal-pot and stripping processes; a graphical technique was used to optimize the distribution of wastewater between sinks to sources [33].

Reducing the consumption of freshwater usage and wastewater discharge in water inter-plant networks is a challenge in many plants, such as cement plants, polyethylene plants, oil refineries and fertilizers plants. Managing the distribution of water in inter-plant processes and the large amount of freshwater consumption in different industrial processes, such as those of the condensers, heat exchangers, vacuum systems, cooling and washing processes, refers to the need to minimize the freshwater consumption and wastewater discharge that are leading us to establish the proposed optimization program. Good management of water distribution between plants will consequently result in a considerable reduction in the cost of freshwater as well as wastewater treatment. To date, no generalized model has been introduced to help in designing inter-plant networks aiming to minimize the required freshwater consumption and wastewater discharge including a wide range and number of sources and sinks. In this paper, a generalized model, which is able to deal with up to five inter-plants having up to a hundred sources and a hundred sinks, is introduced. The introduced model could be applied to single contaminant networks as well as multiple contaminants networks. Additionally, the results of running the proposed model are presented simultaneously as a drawn network to facilitate the application of the proposed network construction. The proposed mathematical model is based on equations that are formulated as a nonlinear program with definite constraints and assumptions. After running the mathematical model, the obtained results are shown and sent to a designed Excel software which is able to achieve the water–wastewater inter-plant networks automatically. Three case studies are investigated, and their results are compared with the obtained results in the literature.

2. Methods

In this research, the minimization of freshwater consumption is presented as an objective function in the presence of a single or multi-contaminant system to design water–wastewater inter-plant networks. The present problem could be stated as follows:

- Given a set of sources, reaching up to one hundred sources, where each source (n) has a flowrate (F_{Rn}) in a multi-contaminant reach up to six contaminants (A, B, C, D, E and F), where the concentrations of contaminants in sources are X_{RnA}, X_{RnB}, X_{RnC}, X_{RnD}, X_{RnE} and X_{RnF}, the flowrate of each source has the probability to send to sinks by flowrate $g_{\text{n-i}}$ or send to waste by flowrate G_{n_waste}.
- Given a set of sinks, reaching up to one hundred sinks, where each sink (i) has a flowrate (G_i) with a limiting concentration of contaminants X_{giA}, X_{giB}, X_{giC}, X_{giD}, X_{giE} and X_{giF}, then:
- The freshwater flowrate (F_W) has the probability to feed each sink (i) with a concentration of contaminants X_A, X_B, X_C, X_D, X_E and X_F.
- The total wastewater flowrate is G_{waste} with a concentration of Xw_A, Xw_B, Xw_C, Xw_D, Xw_E and Xw_F.

As shown in Figure 1, the design of the water–wastewater network is illustrated in sequence procedures that started by applying an overall mass balance to each source (n), which has a flowrate (F_{Rn}) that has a probability to distribute to each sink (i) by flowrate $g_{n\text{-}i}$ and to waste by flowrate $G_{n-waste}$, which is shown in Equation (1).

$$F_{Rn} = \sum g_{n-i} + G_{n-Waste} \tag{1}$$

The overall mass balance is applied to each sink (i); the flowrate of each sink (G_i) has the probability to be fed by the freshwater flowrate (F_{wi}) and water flowrate from source to sink (g_{n-i}), as shown in Equation (2).

$$G_i = F_{wi} + \sum g_{n-i} \tag{2}$$

As shown in Equation (3), a component mass balance is applied on each sink having contaminant A: the product of the flowrate of each sink (G_i) by limiting the concentration of contaminant A (X_{giA}) is equal to the sum of the product of the freshwater flowrate (F_{wi}) and the concentration of the freshwater of contaminant A (X_A), and the product of the summation of the water flowrate from source to sink (g_{n-i}) and the concentrations of contaminant A in each source (X_{RnA}).

$$G_i * X_{giA} = F_{wi} * X_A + \sum g_{n-i} * \ X_{RnA} \tag{3}$$

A component mass balance of contaminant B is applied to each sink as shown in Equation (4): the product of (G_i) by the limiting concentration of contaminant B (X_{giB}) is equal to the sum of the product of $F_{w\boldsymbol{i}}$ and the concentration of the freshwater of contaminant B (X_B), and the product of g_{n-i} and the concentrations of contaminant B in each source (X_{RnB}).

$$G_i * X_{giB} = F_{wi} * X_B + \sum g_{n-i} * X_{RnB} \tag{4}$$

By applying a component mass balance of component C to each sink as shown in Equation (5), the result of the product of (G_i) and X_{giC} (the limiting concentration of contaminant C) is equal to the sum of the product of F_{wi} and X_C (the concentration of the freshwater of contaminant C) and the product of g_{n-i} and X_{RnC} (the concentrations of contaminant C in each source).

$$G_i * X_{giC} = F_{wi} * X_C + \sum g_{n-i} * X_{RnC} \tag{5}$$

As shown in Equations (6)–(8), a component mass balance is applied to each sink having contaminants (D, E and F), where X_D, X_E and X_F are the concentrations of contaminants D, E and F of the freshwater flowrate, respectively, and the concentrations of contaminants D, E and F are X_{RnD}, X_{RnE} and X_{RnF}, respectively.

$$G_i * X_{giD} = F_{wi} * X_D + \sum g_{n-i} * X_{RnD} \tag{6}$$

$$G_i * X_{giE} = F_{wi} * X_E + \sum g_{n-i} * X_{RnE} \tag{7}$$

$$G_i * X_{giF} = F_{wi} * X_F + \sum g_{n-i} * X_{RnF} \tag{8}$$

In Equation (9), the overall mass balance is applied to the waste discharge stream; each source has the probability of sending wastewater to waste by a flowrate G_{n_waste}, and the collected wastewater flowrate is G_{waste}.

$$G_{Waste} = \sum G_{n-Waste} \tag{9}$$

Furthermore, a component mass balance is applied to the wastewater discharge of six contaminants (A, B, C, D, E and F), as shown in Equations (10)–(15).

$$G_{Waste} * X_{wA} = \sum G_{n\_waste} * X_{RnA} \tag{10}$$

$$G_{Waste} * X_{wB} = \sum G_{n\_waste} * X_{RnB} \tag{11}$$

$$G_{Waste} * X_{wC} = \sum G_{n\_waste} * X_{RnC} \tag{12}$$

$$G_{Waste} * X_{wD} = \sum G_{n\_waste} * X_{RnD} \tag{13}$$

$$G_{Waste} * X_{wE} = \sum G_{n\_waste} * X_{RnE} \tag{14}$$

$$G_{Waste} * X_{wF} = \sum G_{n\_waste} * X_{RnF} \tag{15}$$

Each sink (i) has the probability of being fed by freshwater flowrate (F_{Wi}); the overall mass balance of the freshwater streams is shown in Equation (16).

$$F_w = \sum F_{wi} \tag{16}$$

LINGO Software, v. 14.0 is used in this work to get the optimum solution. LINGO Software is used to solve linear and nonlinear equations with definite constraints and assumptions; the mathematical approach is based on a nonlinear program (NLP) and the constraints and variables refer to the positive real number or zero values. After running the proposed mathematical model in LINGO Software, the obtained results are sent directly to the Excel software which has the ability to draw the water–wastewater inter-plant network automatically.

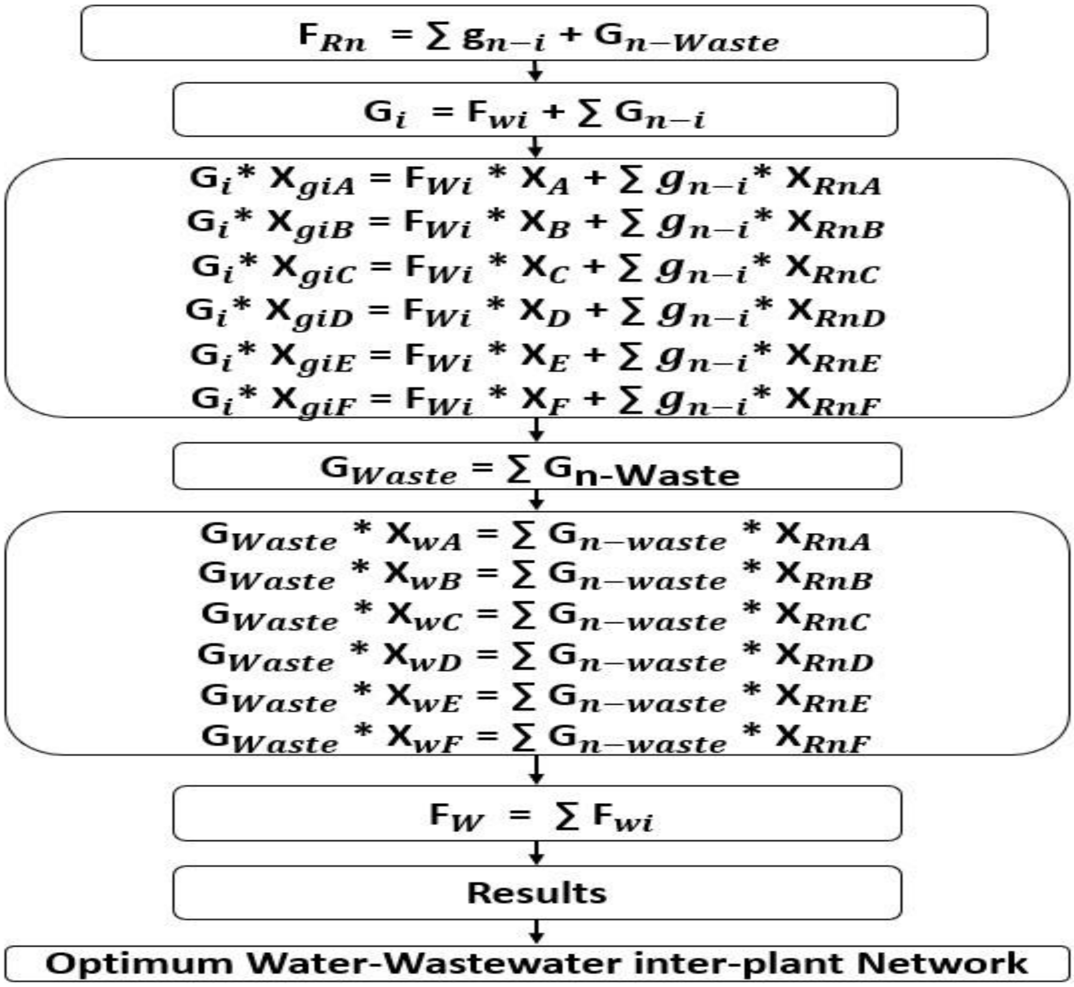

Figure 1. Procedure of optimum design for water–wastewater inter-plant network.

3. Case Studies

The proposed mathematical model was examined by applying it to three case studies that contain single and multi-contaminants to show its effectiveness in designing water–wastewater networks. The presented case studies include a different number of plants in each case study with different contaminants, including total suspended solids (TSS), chemical oxygen demand (COD), hydrocarbon, hydrogen sulfide (H_2S) and total dissolved solids (TDS); these contaminants should be controlled via a mathematical approach to avoid the fouling, cooling efficiency, hardness and corrosion problems in the plants. These case studies are described in the following subsections.

3.1. Case Study 1

Case study 1 contains a single contaminant, which is the total suspended solids (TSS); it was presented by Fadzil et al. [21]. This case study includes five plants; plant A has four sources and four sinks, plant B consists of four sources and four sinks, plant C contains five sources and five sinks, plant D has three sources and two sinks, and plant E contains five sources and five sinks, as shown in Table 1.

Table 1. Limiting flowrates and concentrations of sources and sinks in case study 1.

Plant	Sources and Sinks	Stream Number	Flow Rate (m^3/h)	TSS (ppm)	Plant	Sources and Sinks	Stream Number	Flow Rate (m^3/h)	TSS (ppm)
Plant A	Sources	S1	50	50	Plant B	Sources	S1	20	100
		S2	100	100			S2	100	100
		S3	70	150			S3	40	800
		S4	60	250			S4	10	800
	Sinks	K1	50	20		Sinks	K1	20	0
		K2	100	50			K2	100	50
		K3	80	100			K3	40	50
		K4	70	200			K4	10	400
Plant C	Sources	S1	105	17	Plant E	Sources	S1	40	200
		S2	182.35	44			S2	50	200
		S3	138.7	49			S3	30	400
		S4	92.55	83			S4	60	400
		S5	45.55	115			S5	40	600
	Sinks	K1	182.35	0		Sinks	K1	40	0
		K2	45.55	10			K2	50	100
		K3	138.7	10			K3	30	100
		K4	92.55	10			K4	60	300
		K5	105	87			K5	40	400
Plant D	Sources	S1	150	10	Plant D	Sinks	K1	200	20
		S2	60	50					
		S3	100	85			K2	80	75

3.2. Case Study 2

Case study 2, provided by Lv et al. [22], presents three plants (molasses treatment system (X), yeast production system (Y), and circulating cooling system (Z)) with a single contaminant, which is chemical oxygen demand (COD). Plant X contains five sources and five sinks, plant Y contains five sources and five sinks, while plant Z includes five sources and five sinks. The limiting flowrates and concentrations of contaminants of the sources and sinks are shown in Table 2.

Table 2. The limiting data of sources and sinks in plants X, Y and Z for case study 2.

Plant	Process	Stream Number	Flow Rate (m^3/h)	Limiting Concentration of Contaminant COD (ppm)
Molasses treatment system (X)	Sources	S1	20	100
		S2	66.67	80
		S3	100	100
		S4	41.67	800
		S5	10	800
	Sinks	K1	20	0
		K2	66.67	50
		K3	100	50
		K4	41.67	80
		K5	10	400

Table 2. *Cont.*

Plant	Process	Stream Number	Flow Rate (m^3/h)	Limiting Concentration of Contaminant COD (ppm)
Yeast production system (Y)	Sources	S1	20	100
		S2	66.67	80
		S3	15.63	400
		S4	42.86	800
		S5	6.67	1000
	Sinks	K1	20	0
		K2	66.67	50
		K3	15.63	80
		K4	42.86	100
		K5	6.67	400
Circulating cooling system (Z)	Sources	S1	20	100
		S2	80	50
		S3	50	125
		S4	40	800
		S5	300	150
	Sinks	K1	20	0
		K2	80	25
		K3	50	25
		K4	40	50
		K5	300	100

3.3. Case Study 3

The third case study of the current work was presented by Wang et al. [25]. This case study includes three plants with multiple contaminant systems including the contaminants hydrocarbon, hydrogen sulfide (H_2S) and total dissolved solids (TDS); plant 1 consists of eight sources and eight sinks, plant 2 contains seven sources and seven sinks, while plant 3 consists of three sources and three sinks as shown in Table 3.

Table 3. The limiting flowrates and concentrations of sources and sinks for case study 3.

Plant	Sources and Sinks	Flowrate (m^3/h)	Contaminant A (Hydrocarbon) (ppm)	Contaminant B (H_2S) (ppm)	Contaminant C (TDS) (ppm)
Plant 1	Source 1	30	100	90	50
	Source 2	16	50	70	70
	Source 3	75	150	80	70
	Source 4	21	160	100	90
	Source 5	29	210	200	120
	Source 6	65	80	70	80
	Source 7	61	300	290	170
	Source 8	57	210	170	100

Table 3. *Cont.*

Plant	Sources and Sinks	Flowrate (m^3/h)	Contaminant A (Hydrocarbon) (ppm)	Contaminant B (H_2S) (ppm)	Contaminant C (TDS) (ppm)
Plant 1	Sink 1	30	0	0	0
	Sink 2	16	0	0	0
	Sink 3	75	40	60	20
	Sink 4	21	30	40	70
	Sink 5	29	110	135	60
	Sink 6	65	0	0	0
	Sink 7	61	100	75	20
	Sink 8	57	90	50	34
Plant 2	Source 1	35	110	120	100
	Source 2	40	350	400	210
	Source 3	40	150	180	210
	Source 4	30	210	150	220
	Source 5	30	350	320	310
	Source 6	64	800	1100	1000
	Source 7	50	1500	2100	1800
	Sink 1	35	0	0	0
	Sink 2	40	200	170	150
	Sink 3	40	90	130	100
	Sink 4	30	110	80	150
	Sink 5	30	260	200	180
	Sink 6	64	340	350	400
	Sink 7	50	950	850	900
Plant 3	Source 1	30	900	4500	3000
	Source 2	34	120	12,500	180
	Source 3	56	220	45	9500
	Sink 1	30	150	700	800
	Sink 2	34	20	300	45
	Sink 3	56	120	20	200

4. Results and Discussions

The proposed approach for optimizing water–wastewater inter-plant networks in industrial inter-plants was applied to three case studies (with single and multiple contaminants) and the results are discussed in the following subsections.

4.1. Results and Discussions of Case Study 1

Controlling the limiting concentration of total suspended solids (TSS) in the industrial processes prevented them from causing plugging in the pipelines, cavitation in the pumps, erosion in the unit operation and accumulation which decreases the heat exchange, as shown in Julien et al. [10].

After introducing the data given for case study 1 into the LINGO program, the obtained results of the freshwater consumption flowrate, the flowrates from sources to demands and the flowrates from sources to waste are listed in Table 4 and shown in Figure 2.

Table 4. Freshwater flowrates to sinks, sources flowrates to sinks and to waste for case study 1.

Stream	Flowrate (t/h)	Stream	Flowrate (t/h)	Stream	Flowrate (t/h)	Stream	Flowrate (t/h)
F_w	412.3	$G_{4\text{-waste}}$	53	$G_{10\text{-}13}$	8.5	$G_{14\text{-}1}$	35.3
F_{w5}	20	$G_{5\text{-}3}$	1.9	$G_{10\text{-}14}$	55.8	$G_{14\text{-}11}$	39.1
F_{w9}	182.4	$G_{5\text{-}4}$	0.4	$G_{10\text{-}15}$	12.4	$G_{14\text{-}14}$	75.6
F_{w10}	35.2	$G_{5\text{-}6}$	0.8	$G_{10\text{-}17}$	3.5	$G_{15\text{-}2}$	4
F_{w11}	41	$G_{5\text{-}13}$	3	$G_{10\text{-}18}$	1.8	$G_{15\text{-}6}$	56
F_{w12}	71.5	$G_{5\text{-}15}$	6.7	$G_{10\text{-}19}$	0.7	$G_{16\text{-}4}$	4.2
F_{w14}	22.2	$G_{5\text{-}17}$	1.8	$G_{10\text{-waste}}$	7	$G_{16\text{-}6}$	1.2
F_{w16}	40	$G_{5\text{-}18}$	0.6	$G_{11\text{-}2}$	47.8	$G_{16\text{-}7}$	3.3
$G_{1\text{-}2}$	45	$G_{5\text{-}19}$	0.3	$G_{11\text{-}3}$	29.9	$G_{16\text{-}13}$	8.5
$G_{1\text{-}3}$	0.9	$G_{5\text{-waste}}$	4.5	$G_{11\text{-}4}$	1.5	$G_{16\text{-}15}$	50
$G_{1\text{-}6}$	1.5	$G_{6\text{-}4}$	5.8	$G_{11\text{-}6}$	22.7	$G_{16\text{-}17}$	6.5
$G_{1\text{-}7}$	2	$G_{6\text{-}7}$	1	$G_{11\text{-}7}$	7.1	$G_{16\text{-}18}$	5.9
$G_{1\text{-}17}$	0.4	$G_{6\text{-}18}$	3.3	$G_{11\text{-}13}$	12.3	$G_{16\text{-}19}$	17.8
$G_{1\text{-waste}}$	0.2	$G_{6\text{-}19}$	4.1	$G_{11\text{-}15}$	10.9	$G_{16\text{-}20}$	2.5
$G_{2\text{-}2}$	1.2	$G_{6\text{-}20}$	3	$G_{11\text{-}17}$	3.8	$G_{17\text{-}8}$	0.8
$G_{2\text{-}4}$	7.3	$G_{6\text{-waste}}$	82.8	$G_{11\text{-}18}$	1.9	$G_{17\text{-}19}$	1.1
$G_{2\text{-}13}$	63.6	$G_{7\text{-}8}$	1.9	$G_{11\text{-}19}$	0.9	$G_{17\text{-waste}}$	38.1
$G_{2\text{-}17}$	18	$G_{7\text{-}20}$	7	$G_{12\text{-}4}$	42.3	$G_{18\text{-}4}$	2.3
$G_{2\text{-}18}$	3.6	$G_{7\text{-waste}}$	31.1	$G_{12\text{-}6}$	1.3	$G_{18\text{-}8}$	1.6
$G_{2\text{-waste}}$	6.4	$G_{8\text{-waste}}$	10	$G_{12\text{-}8}$	2	$G_{18\text{-}18}$	2.5
$G_{3\text{-}3}$	5.3	$G_{9\text{-}11}$	58.6	$G_{12\text{-}13}$	8.4	$G_{18\text{-}20}$	14.1
$G_{3\text{-}4}$	4.8	$G_{9\text{-}14}$	46.4	$G_{12\text{-}17}$	6	$G_{18\text{-waste}}$	29.5
$G_{3\text{-}17}$	6.3	$G_{10\text{-}1}$	14.7	$G_{12\text{-}18}$	6.7	$G_{19\text{-waste}}$	30
$G_{3\text{-}18}$	2.7	$G_{10\text{-}2}$	2	$G_{12\text{-}20}$	2.3	$G_{20\text{-}8}$	2.2
$G_{3\text{-}19}$	5.3	$G_{10\text{-}4}$	1.4	$G_{12\text{-waste}}$	23.4	$G_{20\text{-}19}$	27
$G_{3\text{-waste}}$	45.6	$G_{10\text{-}6}$	16.6	$G_{13\text{-}3}$	42	$G_{20\text{-}20}$	8.7
$G_{4\text{-}17}$	1.7	$G_{10\text{-}7}$	26.5	$G_{13\text{-}13}$	0.7	$G_{20\text{-waste}}$	22.1
$G_{4\text{-}19}$	2.7	$G_{10\text{-}10}$	10.4	$G_{13\text{-}17}$	2	$G_{21\text{-}8}$	1.4
$G_{4\text{-}20}$	2.5	$G_{10\text{-}12}$	21	$G_{13\text{-}18}$	0.9	$G_{21\text{-waste}}$	38.6

According to the mass load of sources and sinks, the distribution of water and wastewater flowrates between sources and sinks is achieved. Regarding the obtained results, source 10 feeds thirteen sinks (K1, K2, K4, K6, K7, K10, K12, K13, K14, K15, K17, K18, K19) and waste by flowrates of 14.7, 2, 1.4, 16.6, 26.5, 10.4, 21, 8.5, 55.8, 12.4, 3.5, 1.8, 0.7 and 7 t/h, respectively. However, source 5 feeds seven sinks (K3, K4, K6, K13, K17, K18, K19) and waste by flowrates of 1.9, 0.4, 0.8, 3, 6.7, 1.8, 0.6, 0.3 and 4.5 t/h, respectively.

According to the low mass load of source 11, it does not supply any water to waste and its wastewater feeds ten sinks (K2, K3, K4, K6, K7, K13, K15, K17, K18 and K19) by flowrates of 47.8, 29.9, 1.5, 22.7, 7.1, 12.3, 10.9, 3.8, 1.9 and 0.9 t/h, respectively.

The obtained results show that the total freshwater consumption is 412.3 t/h, which is distributed to sinks K5, K9, K10, K11, K12, K14 and K16 by flowrates of 20, 182.4, 35.2, 41, 71.5, 22.2 and 40 t/h, respectively. However, source 1 supplies K2, K3, K6, K7, K17 and the waste by 45, 0.9, 1.5, 2, 0.4 and 0.2 t/h, respectively.

Regarding source 2, it feeds sinks K2, K4, K13, K17, K18 and waste by 1.2, 7.3, 63.6, 18, 3.6 and 6.4 t/h, respectively. Source 3 feeds five sinks (K3, K4, K17, K18, K19) and waste by flowrates of 5.3, 4.8, 6.3, 2.7, 5.3 and 45.6 t/h, respectively. Source 4 supplies its water to sinks K17, K19, K20 and waste by 1.7, 2.7, 2.5 and 53 t/h flowrates, respectively. Source 6 supplies the waste by 82.8 t/h and it supplies sinks K4, K7, K18, K19 and K20 by 5.8, 1, 3.3, 4.1 and 3 t/h, respectively. Source 7 is supplied to K8, K20 and waste by 1.9, 7 and 31.1 t/h, respectively. Source 8 sends all its water to waste with a flowrate of 10 t/h while source 9 feeds two sinks only (K11 and K14) with flowrates of 58.6 and 46.4 t/h. In addition, source 12 feeds waste by 23.4 t/h and it feeds sinks K4, K6, K8, K13, K17, K18 and K20 by flowrates of 42.3, 1.3, 2, 8.4, 6, 6.7 and 2.3 t/h, respectively.

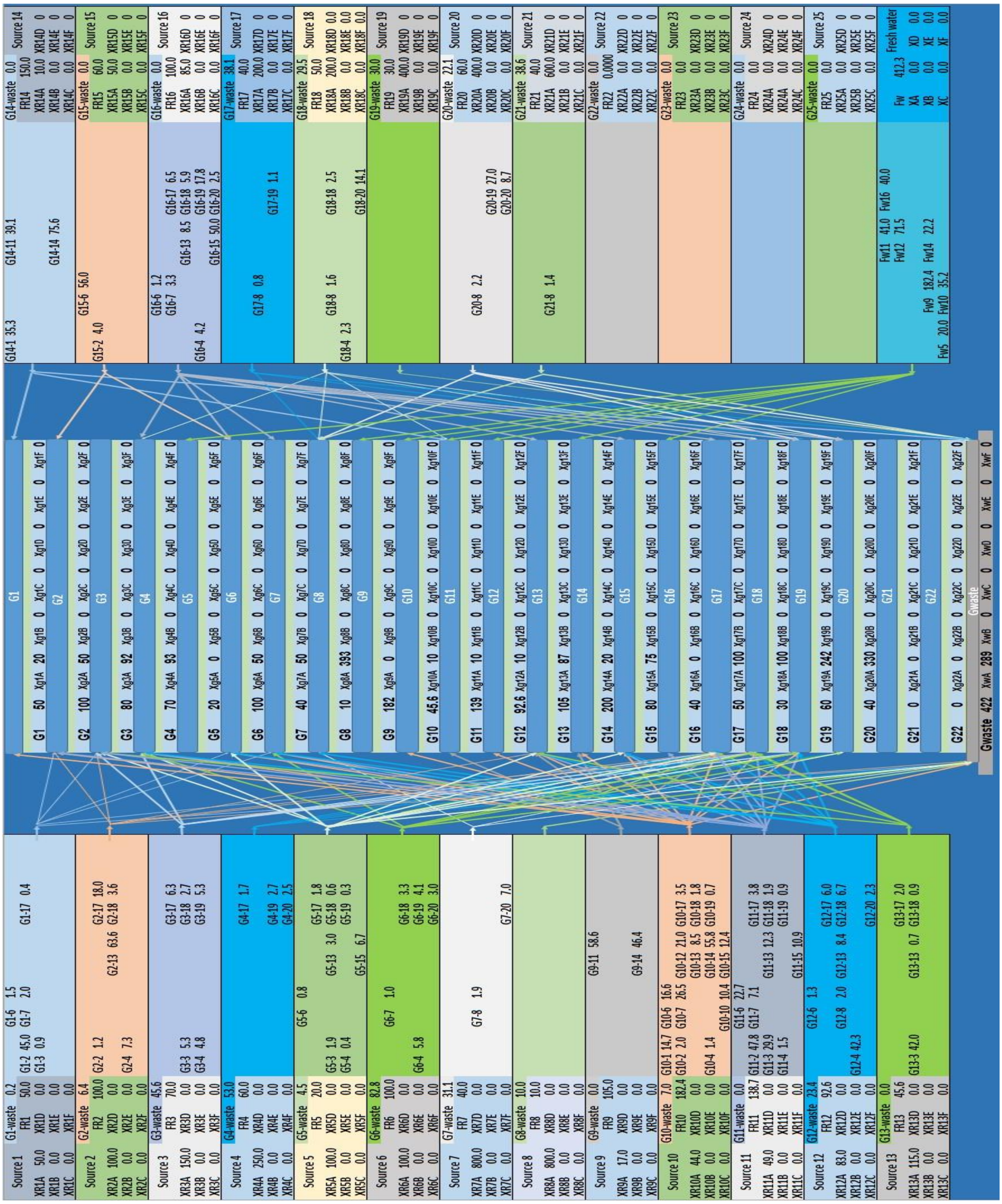

Figure 2. Design of water–wastewater inter-plant network of case study 1.

Source 13 is supplied to sinks K3, K13, K17 and K18 by 42, 0.7, 2 and 0.9 t/h, respectively. At the same time, source 14 feeds sinks K1, K11 and K14 by 35.3, 39.1 and 75.6 t/h flowrates, respectively. Source 15 supplies k2 and k6 by 4 and 56 t/h, respectively. Regarding source 16, it supplies sinks K4, K6, K7, K13, K15, K17, K18, K19 and K20 by 4.2, 1.2, 3.3, 8.5, 50, 6.5, 5.9, 17.8 and 2.5 t/h, respectively. Source 17 feeds sinks K8, K19 and waste by 0.8, 1.1 and 38.1 t/h, respectively. Also, source 18 feeds K4, K8, K18, K20 and waste by 2.3, 1.6, 2.5 and 14.1 t/h, respectively. All discharge water from source 19 is sent to waste by 30 t/h, while source 20 feeds K8, K19, K20 and waste by 2.2, 27, 8.7 and 22.1 t/h. In addition, source 21 feeds only sink 8 by 1.4 t/h and the remainder of its flowrate is supplied to waste by a flowrate of 38.6 t/h. Therefore, the total wastewater flowrate is equal to 422 t/h.

The LINGO results were applied to the introduced Excel program and the drawing of the water–wastewater inter-plant network was achieved automatically.

By comparing the results obtained by the proposed mathematical model with the results of the header design method of the original plants, it is clear that the freshwater consumption decreased from 671.7 to 412.3 t/h by a reduction percentage of 38.6%. Furthermore, the wastewater generated is reduced from 681.7 to 422 t/h by a reduction percentage of 38.1%. These results show the effectiveness of the introduced technique in designing water–wastewater networks by reducing the freshwater consumption as well as by decreasing the wastewater flowrate.

4.2. Results and Discussions of Case Study 2

Increasing the concentration of chemical oxygen demand (COD) leads to an increase in the fouling rate in the heat exchanger, a decrease in the cooling efficiency and blocking in the inner side of the pipelines, as shown in Mariacrocetta et al. [32].

After introducing the flowrates, concentrations of sources and sinks of the two plants to the proposed model, the results are obtained and shown in Table 5 and Figure 3. These results are sent to the prepared Excel software to show the final drawing of the water–wastewater inter-plant network.

Table 5. Freshwater flowrates to sinks, sources flowrates to sinks and to waste for case study 2.

Sinks	F_w (t/h)	Sources Flowrates (t/h)														
		S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**
K1	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K2	44.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22.2
K3	47	20	0	0	0	0	0	25	0	0	0	0	0	8	0	0
K4	11.7	0	0	16.6	0	0	0	0	0	0	0	0	0	13.4	0	0
K5	0	0	0	0	0	2.8	0	0	2.7	0	0	0	0	0	0	4.5
K6	20	0	0	0	0	0	0	0	0	0	0	00	0	0	0	0
K7	25	0	0	0	0	0	0	41.7	0	0	0	0	0	0	0	0
K8	0	0	0	0	0	0	0	0	0	0	0	0	10.9	0	0	4.7
K9	0	0	0	0	0	0	0	0	0	0	0	0	14.3	28.6	0	0
K10	0	0	0	0	0	1.1	0	0	1.8	0	0	0	0	0	0.7	3
K11	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K12	66.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13.3
K13	31.8	0	0	0	0	0	0	0	0	0	0	0	14.8	0	0	3.4
K14	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0
K15	27.7	0	66.7	83.4	0	0	20	0	0	0	0	20	0	0	0	82.1
waste	0	0	0	0	41.7	6.1	0	0	11.1	42.9	6.7	0	0	0	39.3	166.8

The obtained results from the LINGO Software showed that all wastewater of sources S4, S9 and S10 are sent to waste only by flowrates of 41.7, 42.9 and 6.7 t/h, respectively, which referred to the high mass load of sources rather than sinks.

The total consumption of freshwater flowrate is 314.36 t/h and is distributed to sinks K1, K2, K3, K4, K6, K7, K11, K12, K13 and K15 by 20, 44.4, 47, 11.7, 20, 25, 20, 66.7, 31.8 and 27.7 t/h, respectively.

The wastewater flowrate of source 1 is distributed to K3 by 20 t/h, while source 2 feeds K15 by a flowrate of 66.7 t/h. Source 3 distributed its water to K4 and K15 by flowrates of 16.6 and 83.4 t/h, respectively. Source 5 feeds two sinks (K5 and K10) and waste by flowrates 2.8, 1.1 and 6.1 t/h, respectively. Sources S6 and S11 feed only sink 15 by the same flowrates of 20 t/h, while source S7 feeds two sinks, K3 and K7, by 25 and 41.7 t/h, respectively.

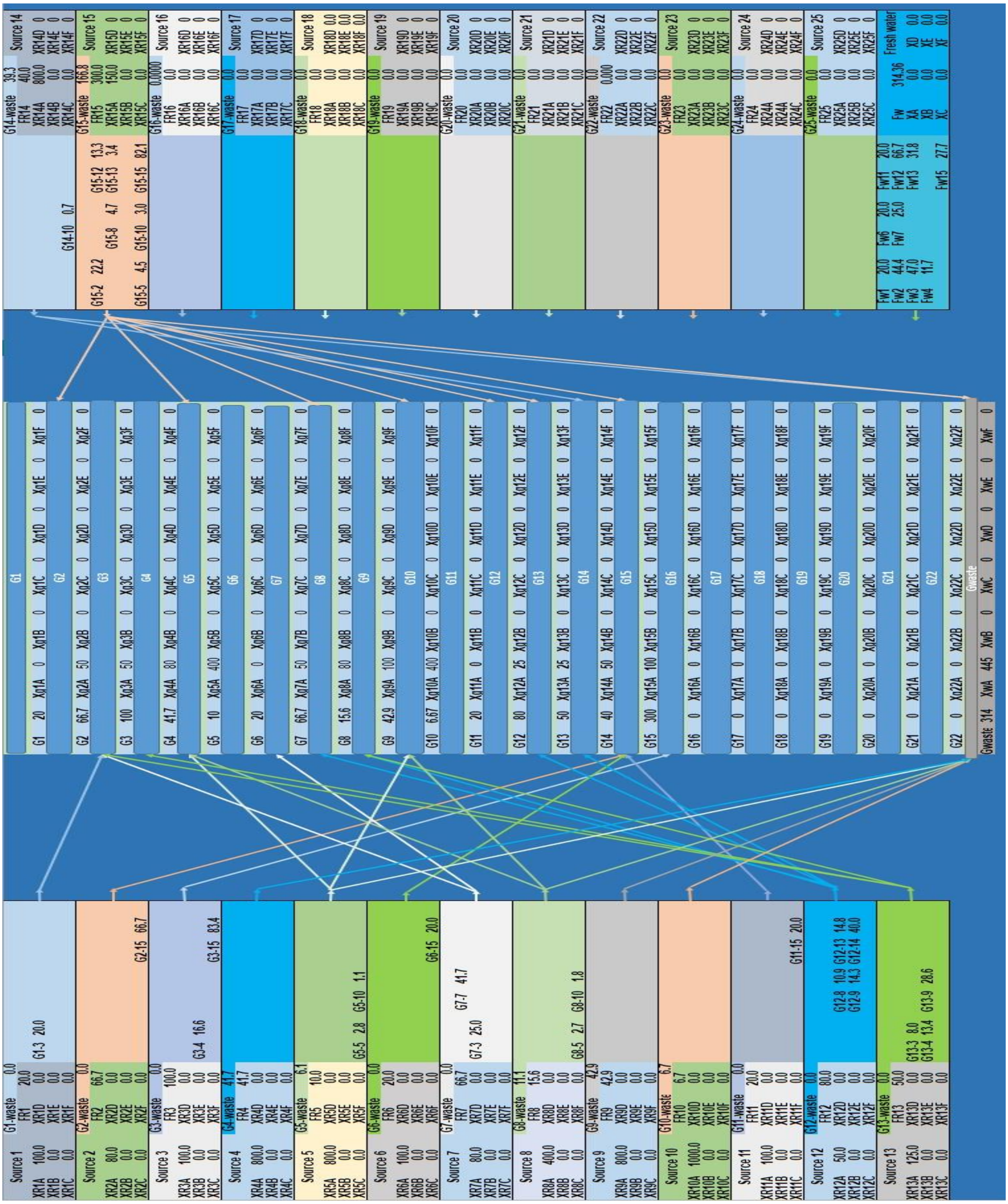

Figure 3. Design of water–wastewater inter-plant network of case study 2.

Source S8 supplied its wastewater to sinks K5, K10 and waste by flowrates of 2.7, 1.8, 11.1 t/h, while source S12 feeds four sinks, K8, K9, K13 and K14, by 10.9, 14.3, 14.8 and 40 t/h, respectively. Source S13 supplied sinks K3, K4 and K9 by 8, 13.4 and 28.6 t/h, respectively.

Source 14 feeds sink 10 and waste by 0.7 and 39.3 t/h, respectively, while source S15 feeds K2, K5, K8, K10, K12, K13, K15 and waste by 22.2, 4.5, 4.7, 3, 13.3, 3.4, 82.1 and 166.8 t/h, respectively.

As shown in Table 6, in the comparison between our technique, which is formulated as a nonlinear program (NLP), and the step-by-step optimization method (Lv et al. [22]), which is formulated as a linear programming model, the consumption of freshwater flowrate decreased from 330 to 314.36 t/h by a reduction percentage of 4.74%, and the wastewater discharge decreased from 329.54 to 314.36 t/h by a reduction percentage of 4.61%. In comparison with the optimization method (Chew et al. [3]) which is formulated by MINLP, the freshwater consumption decreased from 314.96 to 314.36 t/h by a reduction percentage of 0.19% and the wastewater discharge decreased from 538 to 314.6 t/h by a reduction percentage of 41.52%.

Table 6. Comparison between the introduced method and techniques of Chew et al. [3] and Lv et al. [22].

Integration Scheme	The Introduced Method	Optimization Method (Chew et al. [3])	Step-by-Step Optimization Method (Lv et al. [22])
Used Technique	Nonlinear Programming (NLP)	Mixed integer nonlinear programming (MINLP)	Linear Programming (LP)
Freshwater consumption (t/h)	314.36	314.96	330
Wastewater discharge (t/h)	314.36	538	329.54

4.3. Results and Discussions of Case Study 3

The data given in the third case study consist of three plants with multiple contaminants (hydrocarbon, hydrogen sulfide (H_2S) and total dissolved solids (TDS)). The effect of hydrocarbon appears in the increasing of organic matter in the water which increases the fouling rate in the pipelines of the heat exchanger, while the increase in hydrogen sulfide increases the acidity of the water, and consequently the rate of corrosion increases. On the other hand, the higher level of total dissolved solids results in an increase in the formation rate of scales as well as the hardness in the pipelines of plants, as shown in Buabeng et al. [15]. The obtained results of source flow rates to sinks and freshwater flowrates to sinks are shown in Table 7 after introducing these plants' data into the LINGO program. With passing these results to the Excel software, the design of the water–wastewater inter-plant network is achieved automatically, as shown in Figure 4.

Table 7. Freshwater flowrates to sinks, sources flowrates to sinks and to waste for case study 3.

Sources and Fresh Water	Sinks																		Waste
	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	K17	K18	
Fw	30	16	45	12.2	5	65	43.6	29.3	35	0	0	0	0	0	0	0	20.4	40.4	0
S1	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	2.4	0	0	0	0	0	0	0	0	0	0	0	0	13.6	0	0
S3	0	0	0	0	18.1	0	17.4	27.7	0	0	0	6.5	0	0	0	0	0	5.2	0
S4	0	0	0	0	0	0	0	0	0	0	0	4.3	8.8	1.9	6	0	0	0	0
S5	0	0	0	0	00	0	0	0	0	1.3	0	0	0.2	1.9	1.9	0.2	0	0	0
S6	0	0	0	6.4	5.9	0	0	0	0	0	26.7	16.7	0	0	0	0	0	9.4	0
S7	0	0	0	0	0	0	0	0	0	0	0	0	0	42.7	18.3	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	19	0	0	0.2	1.9	8.2	0.2	0	0	27.5
S9	0	0	0	0	0	0	0	0	0	19.4	13.3	2.2	0	0	0	0	0	0	0
S10	0	0	0	0	0	0	0	0	0	0	0	0	0.2	1.9	1.9	0	0	0	36
S11	0	0	0	0	0	0	0	0	0	0	0	0	0.2	1.9	1.9	28.1	0	0	7.8
S12	0	0	0	0	0	0	0	0	0	0	0	0	20.2	7.8	1.9	0	0	0	0
S13	0	0	0	0	0	0	0	0	0	0	0	0	0	1.9	1.9	0	0	0	26.2
S14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.7	0	0	0	62
S15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
S17	0	0	0	0	0	0	0	0	0	0.8	0	0	0.2	0.5	2.5	1.3	0	0	30
S18	0	0	0	0	0	0	0	0	0	0.2	0	0.2	0	1.5	3.8	0.2	0	1.1	49

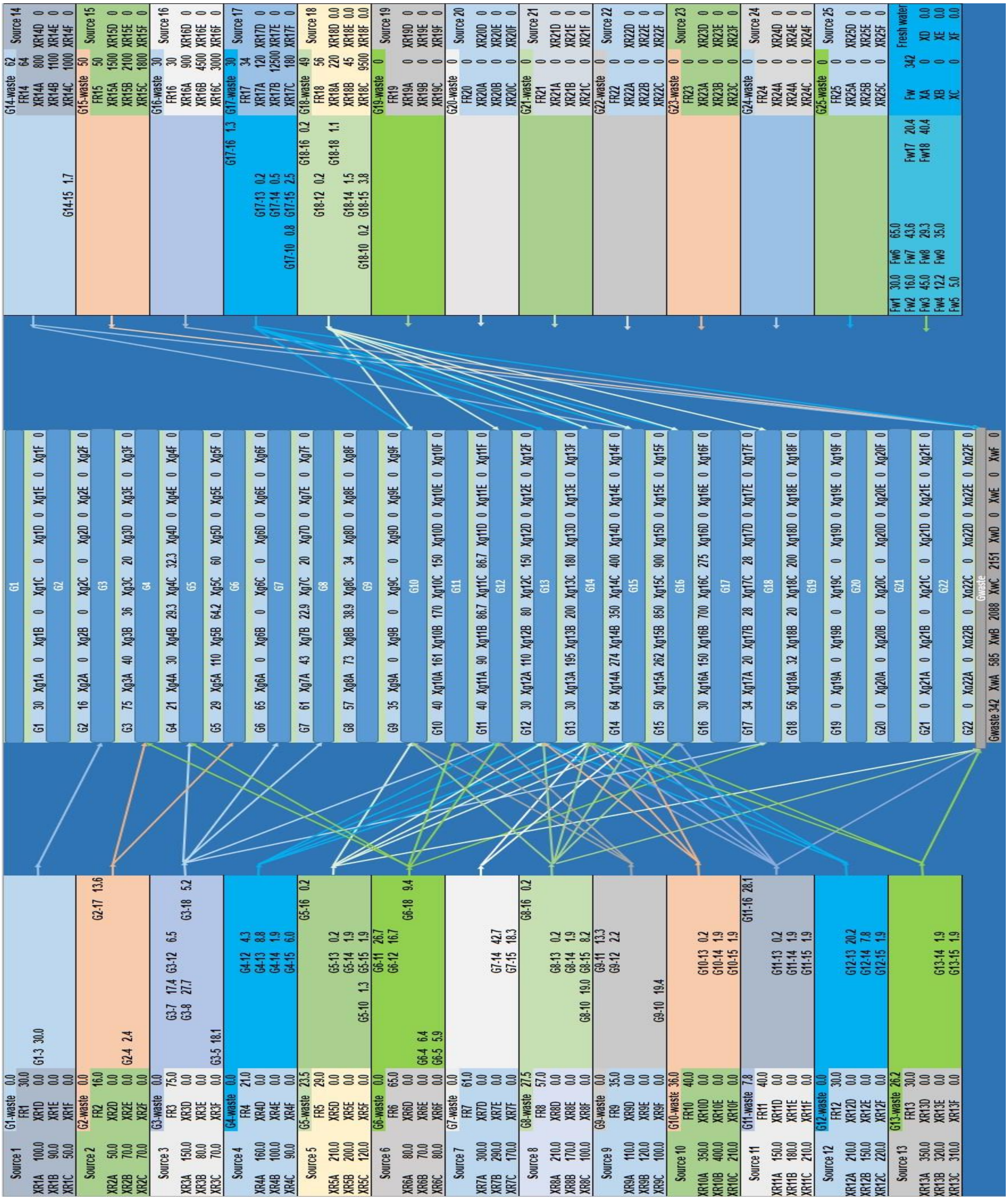

Figure 4. Design of water–wastewater inter-plant network of case study 3.

Regarding the obtained results, there was a decrease in the total consumption of freshwater flowrate from 374.3 t/h to 342 t/h by a reduction percentage 8.64% and the wastewater discharge decreased from 374.3 to 342 t/h by a reduction percentage 8.6%.

The waters of sources S15 and S16 are sent to waste directly because their mass loads are higher than the limiting mass loads of the sinks, but source 1 has a low mass load, so it feeds sink 3 only by 30 t/h.

Source 2 feeds sinks K4 and K17 by 2.4 and 13.6 t/h, respectively, while source S3 feeds K5, K7, K8, K12, and K18 by 18.1, 17.4, 27.7, 6.5 and 5.2 t/h, respectively. Source 4 supplies its wastewater to four sinks, K12, K13, K14 and K15, by flowrates of 4.3, 8.8, 1.9 and 6 t/h, respectively.

Source 5 supplies its wastewater to five sinks, K10, K13, K14, K15, K16, and waste by 1.3, 0.2, 1.9, 1.9 and 0.2 t/h, respectively, while source 6 feeds K4, K5, K11, K12 and K18 by 6.4, 5.9, 26.7, 16.7 and 9.4 t/h, respectively. Source 7 feeds two sinks, K14 and K15, by 42.7 and 18.3 t/h, while source 8 supplies its wastewater to K10, K13, K14, K15, K16 and waste by 19, 0.2, 1.9, 8.2, 0.2 and 27.5 t/h, respectively.

Source 9 feeds K10, K11 and K12 by flowrates of 19.4, 13.3 and 2.2 t/h, respectively, while source 10 supplies its wastewater to K13, K14, K15 and waste by flowrates of 0.2, 1.9, 1.9 and 36 t/h, respectively. Source 11 feeds four sinks K13, K14, K15, K16 and waste by 0.2, 1.9, 1.9, 28.1 and 7.8 t/h, respectively. Source 12 supplies its wastewater to K13, K14 and K15 by 20.2, 7.8 and 1.9 t/h, respectively.

The water of source 13 is sent to K14, K15 and waste at flowrates of 1.9, 1.9 and 26.2 t/h, respectively, while source 14 feeds K15 and waste by 1.7 and 62 t/h, respectively. Source 17 supplies sinks K10, K13, K14, K15, K16 and waste by 0.8, 0.2, 0.5, 2.5, 1.3 and 30 t/h, respectively while source 18 feeds K10, K12, K14, K15, K16, K18 and waste by flowrates of 0.2, 0.2, 1.5, 3.8, 0.2, 1.1 and 49 t/h, respectively.

5. Conclusions

This work is proposed to design water–wastewater inter-plant networks while minimizing the consumption of freshwater used in the plants' processes. A mathematical model is introduced to solve the equations that are formulated as a nonlinear program. Data given of sources and sinks (flowrates and limiting concentration) are introduced to the model and solved by the LINGO software. The obtained results are sent to the Excel software which is responsible for designing and drawing the water–wastewater inter-plant networks automatically. This mathematical approach has the ability to solve for a water system that contains single contaminant or multiple contaminants, with a reach of up to six contaminants. The proposed mathematical approach was applied to three case studies that contain single and multiple contaminants between several plants. The obtained results of the three case studies showed a reduction in the freshwater consumption by percentages of 38.6, 4.74 and 8.64% while the wastewater discharge decreased by percentages of 38.1, 4.61 and 8.6% for case study 1, 2 and 3, respectively. The introduced mathematical model is easy to use and understand because it is required only to enter the flowrates and concentrations of the sources and sinks into the LINGO software and the obtained results will be sent directly to the Excel software which is able to generate and draw the water–wastewater inter-plant network design automatically. This advantage makes this proposed technique beneficial for several industrial plants in the designing of their optimum water inter-plant networks with single and/or multiple contaminants.

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