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Centralised Water Reuse Exchange in Eco-Industrial Park Considering Wastewater Segregation

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Water is a vital resource for sustainable economic and social development. Water over-abstraction is one of the main threats to the environment. Most of the past works considered intra- and inter-plant integrations, in which reused water has been exchanged within a single plant before being transported to the centralised network. Excess wastewater that would be sent to the centralised system likely had the same quality and segregation was not necessary. For this study, only inter-plant and indirect water integration is considered. Water data generated by industries are considered to be directly transported to the centralised network with different wastewater qualities. This paper presents a mathematical programming formulation for centralised water reuse exchange in Eco-Industrial Park (EIP) considering wastewater segregation before centralised treatment with a single contaminant. The mathematical formulations are based on a superstructure that segregates wastewater based on quality before being transported to the centralised utility provider using water header. The main objective is to minimize freshwater consumption in the industry by utilizing regenerated water from the centralised utility provider. The model is coded and solved by using the General Algebraic Modeling System (GAMS) software with non-linear programming (NLP). The model is tested with a case study of three scenarios, each with different numbers of water headers. The results obtained show a significant freshwater saving of 98 % from the inter-plant indirect water integration in Scenario 3, which had the highest number of water headers and regeneration units.

1. Introduction

Global water demand has risen at a rate of about 1 %/y as a result of population growth, economic development, and evolving habits of consumption (United Nations Water, 2018). In 2050, half of the world's 9.7 billion people are expected to live in water-stressed regions. Water shortage affects water use for direct and indirect consumption. Freshwater consumption in the industry has been a threat since the supply of potable water is becoming limited. Water reuse between industries in EIP provides a promising opportunity to reduce freshwater consumption. EIP highlights the cooperation of multiple industries in the same region through the application of the industrial symbiosis principle (Lowe, 2001). As part of an integrated water approach, treated wastewater from industry can provide a reliable alternative water supply. In contrast to other alternative sources such as desalination or groundwater, water reuse requires lower investment costs and energy, as well as reduces greenhouse gas emissions (European Commission, 2019).

Fadzil et al. (2017) presented a Pinch Analysis methodology to target minimum freshwater requirement for total site water integration. Plants were allocated with two centralised water headers of low and high purity. The research only considered direct integration and did not consider centralised treatment before redistributing to the demands. Liu et al. (2017) developed a mathematical model of water network for multi-period cases. Wastewater was not segregated because it was treated using an in-plant regenerator before being transported to the centralised regenerator. Tiu and Cruz (2017) studied the trade-off between economic and environmental objectives as well as the varying economic and environmental goal priorities in water

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integration. The research did not consider wastewater segregation and centralised treatment before redistributing to the demands. The treatment was handled by each participating plant.

Zhang et al. (2018) studied intra- and inter-plant integrations for the steel industry to minimize its total annual cost. The research did not consider wastewater segregation before the centralised treatment. Lv et al. (2018) developed a step-by-step optimization with the concept of intermediate pools of each plant to avoid secondary mixture of wastewater from other plants and to reduce the number of connections between plants. The research did not consider centralised wastewater regeneration. Bi et al. (2019) proposed a two-level optimisation model on the effect of water prices in minimizing overall water consumption by considering the relationship between water supplier and industrial plants and the relationship between plants in EIP. The research did not include wastewater segregation in the water network.

Most of the past research including the papers that were mentioned considered intra- and inter-plant integrations. Past studies considered the exchanged of reused water within a single plant before transporting it to the centralised system. Remaining wastewater that needed to be sent to the centralised system commonly had the same concentration and segregation was not required. In this work, only inter-plant and indirect water integration is considered. Wastewater of various qualities from industries are considered to be fully transported to the centralised system. Direct water reuse exchange within a single plant and between plants are not considered in this paper. In indirect water integration, the role of the centralised utility provider is to manage reused water collection and distribution and ensure the quality of reused water. This concept can provide protection for data confidentiality among plants.

The water data from the industries to the centralised system may vary in terms of flowrate and concentration. Wastewater of high quality cannot be mixed with wastewater of low quality. It may be cost-effective to mix all the effluents, but it is not the best option for joint treatment since different levels of treatment are needed for each type of wastewater (Martin et al., 1996). Mixing wastewater of various qualities will reduce the possibility of reusing wastewater of better quality (Lv et al., 2018). It is very important to classify and segregate the wastewater before the centralised treatment. Regeneration units are considered in this paper to further treat the wastewater in order to reduce the demand on freshwater.

Different industries require water of various levels of purity. Most of the past studies provided only one type of reused water quality from the centralised regeneration unit. The disadvantage is that the one type of reused water quality might not satisfy the requirement of different industries and may result in more freshwater demand. It is very effective to provide various qualities of reused water to fulfil the demands as well as to attract buyers' attention. In this paper, various qualities of reused water are regenerated from the various qualities of wastewater provided by the industries. Wastewater of high quality produces reused water of high quality and vice versa. This paper presents quality-based segregation of wastewater from different industries into several water headers according to its quality in order to classify the wastewater into several grades and regenerates various qualities of reused water. The objective is to target freshwater reduction between industries in EIP by considering wastewater segregation before the centralised treatment. The optimisation model is solved by using a mathematical modelling method and the GAMS software.

2. Problem statement

Given a number of plants having multiple flowrates of water sources and demands with different concentrations of a single contaminant, it is required to develop optimal centralised water exchange by using indirect water integration in which potential sources of wastewater that can be recovered will be collected and segregated before being transported to the centralised system. Segregated wastewaters will be further purified in the regenerator units before redistributed to the demand plants through the water headers. It is desired to determine the quantity and quality of regenerated water that can be supplied to the water demands. It is also desired to determine the minimum quantity of freshwater required by the industry.

3. Methodology

The first step is the identification of data on wastewater sources and water demands for the centralised system. Next is the development of a superstructure network and the formulation of the model. The model is developed to minimize freshwater consumption in the industry by considering indirect water integration. All potential wastewater must go through the centralised system. Direct exchange among plants is not allowed. The wastewater is segregated based on quality and each water header collector transports wastewater of different qualities. Wastewater is transported to the treatment prior to being distributed. Wastewater of different qualities require different treatments. Each water header distributor transports reused water of different qualities to the demands. The model is coded and solved by using the GAMS software (GAMS, 2016). The model is tested with a case study of multiple plants. Figure 1 shows the superstructure network of centralised water system in EIP.

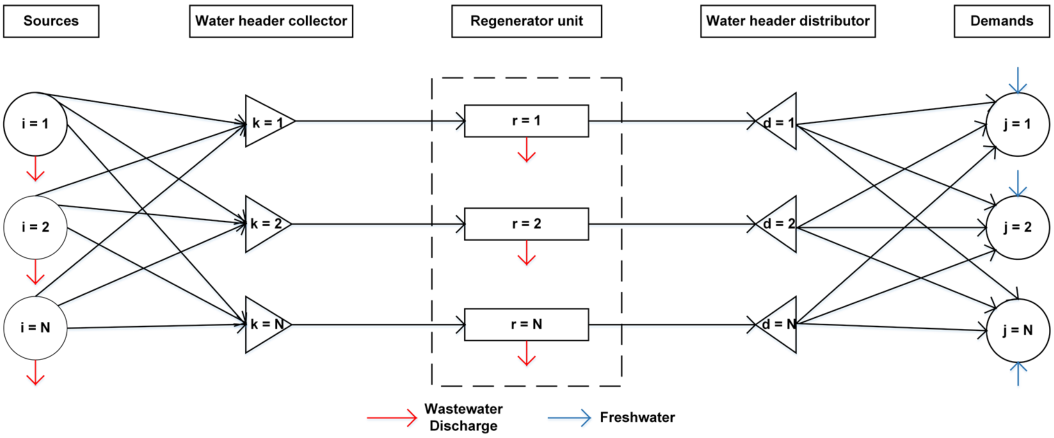

Figure 1: The superstructure network of centralised water system in EIP

3.1 Mathematical models

The objective function is to minimize freshwater consumption among participating plants through the utilization of regenerated water as shown in Eq(1). The subscript i represents water source, j represents water demand, k represents water header collector, d represents water header distributor and r represents regenerator unit. The freshwater flowrate in j is represented by FW_j. The constraints involved are shown in Eq(2) – Eq(23).

$$\text{Min } FW = \sum_j FW_j \tag{1}$$

Mass and component balances for water sources, in which Fi_i is the flowrate of source i, $Fik_{i,k}$ is the flowrate from source i to header collector k, Ci_i is the contaminant concentration in source i and $Cik_{i,k}$ is the contaminant concentration from source i to header collector k.

$$Fi_i = \sum_k Fik_{i,k} \tag{2}$$

$$Fi_i \times Ci_i = \sum_k (Fik_{i,k} \times Cik_{i,k}) \tag{3}$$

Mass and component balances for water header collectors, in which Fk_k is the flowrate in header collector k and Ck_k is the contaminant concentration in header collector k.

$$Fk_k = \sum_i Fik_{i,k} \tag{4}$$

$$Fk_k \times Ck_k = \sum_i (Fik_{i,k} \times Cik_{i,k}) \tag{5}$$

Mass and component balances for regenerator units, in which $Fkr_{k,r}$ is the flowrate from header collector k to regenerator r, $Ckr_{k,r}$ is the contaminant concentration from header collector k to regenerator r, Fr_r is the flowrate in regenerator r and Cr_r is the contaminant concentration in regenerator r.

$$Fkr_{k,r} = Fk_k \tag{6}$$

$$Fkr_{k,r} \times Ckr_{k,r} = Fk_k \times Ck_k \tag{7}$$

$$Fr_r = Fkr_{k,r} \tag{8}$$

$$Fr_r \times Cr_r = Fkr_{k,r} \times Ckr_{k,r} \tag{9}$$

In this work, the regenerator unit with removal ratio is used to calculate the outlet contaminant concentration from the regenerator r, $Cout_r$. RR_r is the removal ratio of regenerator r and $Mreg_r$ is the contaminant mass load removed from regenerator r.

$$Cout_r = Cr_r \times (1\text{-}RR_r) \tag{10}$$

$$Mreg_r = (Cr_r - Cout_r) \times Fr_r \tag{11}$$

Mass and component balances for water header distributors, in which $Frd_{r,d}$ is the flowrate from regenerator r to header distributor d, $Crd_{r,d}$ is the contaminant concentration from regenerator r to header distributor d, Fd_d is the flowrate in header distributor d and Cd_d is the contaminant concentration in header distributor d.

$$Frd_{r,d} = Fr_r \tag{12}$$

$$Frd_{r,d} \times Crd_{r,d} = Fr_r \times Coutr_r \tag{13}$$

$$Fd_d = Frd_{r,d} \tag{14}$$

$$Fd_d \times Cd_d = Frd_{r,d} \times Crd_{r,d} \tag{15}$$

Mass and component balances for water demands, in which $Fdj_{d,j}$ is the flowrate from header distributor d to demand j, $Cdj_{d,j}$ is the contaminant concentration from header distributor d to demand j, Fj_j is the flowrate of demand j, Cj_j is the contaminant concentration in demand j and Cfw_j is the contaminant concentration of freshwater in demand j. Eq(16) ensures that the flowrate to the demand does not exceed the maximum water availability. Eq(17) and Eq(19) ensure the contaminant load for demand does not exceed the maximum limit.

$$\sum_j Fdj_{d,j} \leq Fd_d \tag{16}$$

$$\sum_j (Fdj_{d,j} \times Cdj_{d,j}) \leq Fd_d \times Cd_d \tag{17}$$

$$FW_j + \sum_d Fdj_{d,j} = Fj_j \tag{18}$$

$$(FW_j \times Cfw_j) + \sum_d (Fdj_{d,j} \times Cdj_{d,j}) \leq Fj_j \times Cj_j \tag{19}$$

Eq(20) – Eq(23) ensure that no water will transfer when there is no connection existing. N is a very large non-negative number. $Bik_{i,k}$, $Bkr_{k,r}$, $Brd_{r,d}$ and $Bdj_{d,j}$ are the flow factor parameters to assign the connections.

$$Fik_{i,k} \leq N \times Bik_{i,k} \tag{20}$$

$$Fkr_{k,r} \leq N \times Bkr_{k,r} \tag{21}$$

$$Frd_{r,d} \leq N \times Brd_{r,d} \tag{22}$$

$$Fdj_{d,j} \leq N \times Bdj_{d,j} \tag{23}$$

It is assumed that there is no water loss in the system and only a single contaminant is considered. The NLP model is solved by using GAMS software and CONOPT solver.

4. Case study

For the case study, the water data were adapted from Liu et al. (2016). From the three plants, 9 water sources and 8 water demands were identified as shown in Table 1.

Table 1: The water data for centralised system

Sources				Demands			
Plant	Number	Flowrate (t/h)	Concentration (ppm)	Plant	Number	Flowrate (t/h)	Concentration (ppm)
A	1	20	100	A	1	20	0
	2	58.33	80		2	66.67	50
	3	100	20		3	100	50
B	4	37.14	100	B	4	20	0
	5	51.04	80		5	66.67	50
	6	42.86	200				
C	7	20	100	C	6	20	0
	8	40	50		7	80	25
	9	50	125		8	50	25

In this work, three scenarios with different numbers of water headers and regenerator units were studied. In Scenario 1, one water header and no wastewater segregation were set. In Scenario 2, two water headers and regenerator units with a concentration range of 0 to 50 and 51 to 125 ppm were set. In Scenario 3, three water headers and regenerator units with a concentration range of 0 to 30, 31 to 99 and 100 to 200 ppm were set.

5. Results and discussions

Table 2 shows the results for the case study with different scenarios. The results showed that Scenario 1 with one water header and regeneration unit required the highest flowrate of freshwater compared to the other two scenarios. In addition, Scenario 1 regenerated a larger amount of regenerated water of better quality than that in Liu et al. (2016)'s work. Scenario 2 with two water headers and regeneration units required lower flowrate of freshwater than Scenario 1 and Liu et al. (2016). Scenario 3 with three water headers and regeneration units required the lowest flowrate of freshwater, which was 3.97 t/h with 98 % reduction. In scenario 3, the total regenerated water was 419.37 t/h with three different qualities, which were 0 ppm, 24 ppm and 47 ppm. Figure 2 shows the optimal indirect water integration for Scenario 3.

Table 2: Results for the case study

	Freshwater required (t/h)	Regenerated water (t/h)	Quality of regenerated water (ppm)
Liu et al. (2016)	60	201	38
Scenario 1	60	376.51	24
Scenario 2	50	140	0
		236.51	48
Scenario 3	3.97	100	0
		149.37	24
		170	47

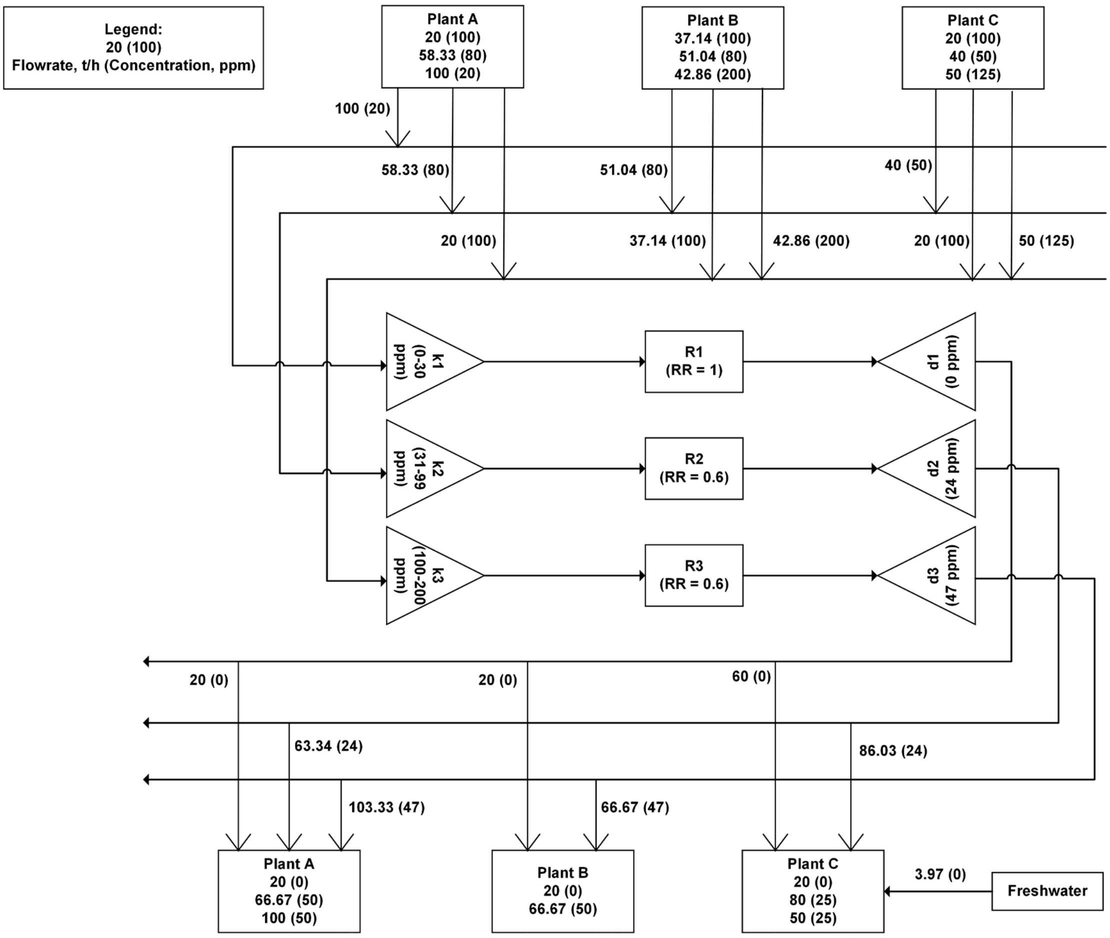

Figure 2: The optimal indirect water integration for Scenario 3

The results indicated that wastewater segregation before centralised treatment can help to save more freshwater by using regenerated water from the centralised utility provider. The increase in the number of water headers can regenerate different qualities of regenerated water to fulfil the requirement of the participating plants and reduce freshwater consumption in the industry. The increase in the number of water headers might increase the total cost of the centralised system such as piping cost, pumping cost, regeneration cost and others. The centralised utility provider can get the profit by selling different qualities of regenerated water. Regenerated water of high quality can be sold at a higher price than regenerated water of low quality. The optimum number of water headers required depends on the requirements of the applications.

6. Conclusion

A new model for a centralised water reuse exchange system between participating plants in EIP that considers wastewater segregation and a single contaminant has been proposed. The mathematical models are based on a superstructure that contains several potential network configurations. By considering only inter-plant and indirect water integration, more wastewater of various qualities can be transported to the centralised water system. The centralised water header collectors were used to segregate wastewater of different qualities before the centralised treatment. By considering wastewater segregation, the centralised treatment has the potential to regenerate various qualities of regenerated water to fulfil the demands and save more freshwater in the industry. The model considered the environmental objective to minimize freshwater consumption in the industry by consuming the regenerated water from the centralised utility provider. From the case study with different scenarios, the results showed that a significant freshwater saving can be obtained from the centralised inter-plant indirect water integration with 98 % freshwater reduction in Scenario 3, which had the highest number of water headers and regeneration units. The suggested methodology can be extended in future studies by considering centralised network costs such as piping cost, regeneration cost and operational cost.

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