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Pricing Mechanism for Centralised Reused Water System with Multiple Water Headers

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Reasonable water pricing is essential for long-term sustainability and financing. The selling prices of reused/regenerated water should enable the generation of revenue that could cover the production costs. In this work, reused/regenerated water prices at different qualities are determined based on the total annualised cost of the centralised system with and without subsidy, quality factor, and profit factor. This paper presents a mathematical programming formulation that aims to maximise the centralised system's profit in the industrial site considering multiple qualities of reused/regenerated water. A case study of numerous scenarios, each with various numbers of water headers and different water prices, is used to test the model. The results obtained show that as the total annualised cost increases, the selling prices of reused/regenerated water increase, the centralised system's profit also increases, and there is a possibility to surpass the freshwater price. For scenarios with subsidy and low total annualised cost, there is an opportunity to increase the centralised system's profit by increasing the profit factor in determining the reused/regenerated water price without exceeding the freshwater price. Based on the case study, Scenario 7 with the highest number of water headers is chosen as it has the highest freshwater reduction, which is 70 %, low total annualised cost, a comparable profit with a profit margin of more than 15 % and the highest profit factor can be applied compared to the other scenarios.

1. Introduction

The reused water is described as wastewater-generated water that has been treated to meet the quality requirements for reuse (EU Water Directors, 2016). Offering the best price for reused water is a strategy for increasing the appeal of potential buyers. It was expected that reused water prices would be lower than freshwater prices to encourage current users of freshwater to convert to reused water. According to USEPA (2012), two techniques are used to develop reused water prices, either the price covers all costs associated with reused water production, allocation, administration and operation, or the price is reduced by cost subsidisation from other sources. Full cost recovery prices comprise the capital and annual costs of the reused water system. Reused water prices are supposed to be lower than potable water prices to encourage existing potable water consumers to switch to reused water. As a result, reused water prices are often subsidised to keep it at or below the level of potable water.

EU Water Directors (2016) stated a few options in considering the price of water reuse. Firstly, there are no charges for the use of treated wastewater, as there are in some cases in Australia. Secondly, the price is determined based on the costs of treatment and distribution to the end-user. Thirdly, treated wastewater is normally less costly than drinking water. Fourthly, the price is determined by the consumers' willingness to pay. Fifthly, the price is determined by market value. Sixthly, prices for both conventional and reused water are the same. Lastly, the price is determined by the cost of recovering environmental and resource costs. According to EU Water Directors (2016), the relationship between conventional water supply and water reuse prices is crucial and must be clearly defined. Setting an overly low price for water reuse may lead to over-use of the water and failing to represent the external cost. EU Water Directors (2016) suggested the increasing block tariff to solve the problem in which as consumption and demand increase, the tariff will increase as well.

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Aviso et al. (2010) presented a fuzzy bi-level optimisation model in the determination of the freshwater and treatment costs associating with water reuse subsidy. The study did not consider reused water price. Tan et al. (2011) proposed a fuzzy bi-level optimisation model in the determination of freshwater, effluent treatment and regenerated water costs. The study did not consider regenerated water price at different quality. Cooley and Phurisamban (2016) adopted a levelised cost approach taking into account all of the capital and operating costs to estimate the cost of alternative water supply. The work did not consider quality and profit factors. Misrol et al. (2020) proposed a model with the combination of domestic and industrial wastewater intending to maximise profit. The study did not clearly state the selling price of water generated from the centralised system. Fadzil et al. (2020) applied the Pinch Analysis method to determine the number of water header. The study assumed the price of water for each header and did not clearly state the pricing mechanism. Misrol et al. (2021) developed a model with the generation of reused water and biogas from wastewater. The study did not clearly state the mechanism of the selling price of water produced.

Although there were a lot of past researches regarding water integration between plants, research regarding the pricing of reused water is still required. Various characteristics of reused water may be required with more than one form of the reused water consumer. If so, it becomes more complex to calculate the user charge for different qualities of reused water. This gap is the subject to be explored in this paper. In this paper, the term 'regenerated water' was used to refer to the treated wastewater for reuse. The main aim is to present a mathematical model that could help the industrial players to identify the best setting price of water at different qualities.

2. Methodology

Figure 1 shows the water integration network of the centralised system between different plants. The subscript i defines water source, j defines water demand, k defines water header collector, r defines regeneration unit, d defines water header distributor, and m defines contaminant. In this mathematical model, the units used are L/h for flowrate, ppm for concentration, kg/h for mass load, and USD/y for total annual costs, total annual revenue, and total annual profit.

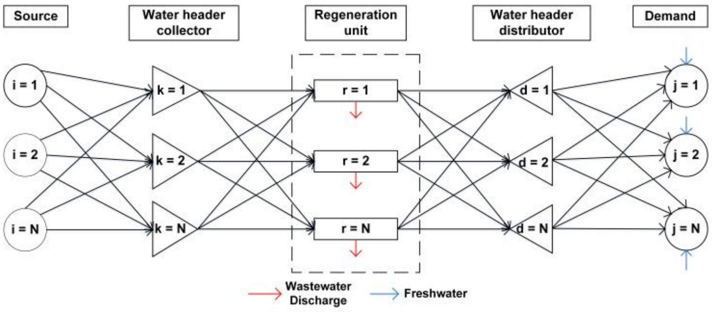


Figure 1: Water integration network of the centralised system

Eq(1a) is the objective function to maximise the centralised system's profit by selling regenerated water. Eq(1b) is the objective function with the addition of subsidy. T^{REV} is the total annual revenue, T^{AC} is the total annualised cost and s is the fraction of subsidy.

$$\text{Max } Profit = T^{REV} - T^{AC} \tag{1a}$$

$$\text{Max } Profit = T^{REV} - [T^{AC} \times (1 - s)] \tag{1b}$$

Eq(2) and Eq(3) are applied for water source. ${F^I}_i$ is the flowrate of source i, ${F^{IK}}_{i,k}$ is the flowrate from source i to header collector k, ${C^I}_{i,m}$ is the contaminant concentration of type m of source i and ${C^{IK}}_{i,k,m}$ is the contaminant concentration of type m from source i to header collector k.

$${F^I}_i = \sum_k {F^{IK}}_{i,k} \quad \forall_i \tag{2}$$

$${F^I}_i \times {C^I}_{i,m} = \sum_k ({F^{IK}}_{i,k} \times {C^{IK}}_{i,k,m}) \; \forall_{i,m} \tag{3}$$

Eq(4) and Eq(5) are applied for water header collector. ${F^K}_k$ is the flowrate in header collector k and ${C^K}_{k,m}$ is the contaminant concentration of type m in header collector k.

$$F^{K}{}_{k} = \sum_i F^{IK}{}_{i,k} \; \forall_{k} \tag{4}$$

$$F^{K}{}_{k} \times C^{K}{}_{k,m} = \sum_i (F^{IK}{}_{i,k} \times C^{IK}{}_{i,k,m}) \; \forall_{k,m} \tag{5}$$

Eq(6) to Eq(11) are applied for regeneration unit. $F^{KR}{}_{k,r}$ is the flowrate from header collector k to regenerator r, $C^{KR}{}_{k,r,m}$ is the contaminant concentration of type m from header collector k to regenerator r, $F^{R}{}_{r}$ is the flowrate in regenerator r, $C^{R}{}_{r,m}$ is the contaminant concentration of type m in regenerator r, $C^{OUTR}{}_{r,m}$ is the outlet contaminant concentration of type m from regenerator r, $RR_{r,m}$ is the removal ratio of contaminant type m in regenerator r, and $M^{R}{}_{r,m}$ is the mass contaminant removed of type m from regenerator r.

$$\sum_r F^{KR}{}_{k,r} = F^{K}{}_{k} \; \forall_{k} \tag{6}$$

$$\sum_r (F^{KR}{}_{k,r} \times C^{KR}{}_{k,r,m}) = F^{K}{}_{k} \times C^{K}{}_{k,m} \; \forall_{k,m} \tag{7}$$

$$F^{R}{}_{r} = \sum_k F^{KR}{}_{k,r} \; \forall_{r} \tag{8}$$

$$F^{R}{}_{r} \times C^{R}{}_{r,m} = \sum_k (F^{KR}{}_{k,r} \times C^{KR}{}_{k,r,m}) \; \forall_{r,m} \tag{9}$$

$$C^{OUTR}{}_{r,m} = C^{R}{}_{r,m} \times (1\text{-}RR_{r,m}) \; \forall_{r,m} \tag{10}$$

$$M^{R}{}_{r,m} = [(C^{R}{}_{r,m} - C^{OUTR}{}_{r,m}) \times F^{R}{}_{r}]/1{,}000{,}000 \; \forall_{r,m} \tag{11}$$

Eq(12) to Eq(15) are applied for water header distributor. $F^{RD}{}_{r,d}$ is the flowrate from regenerator r to header distributor d, $C^{RD}{}_{r,d,m}$ is the contaminant concentration of type m from regenerator r to header distributor d, $F^{D}{}_{d}$ is the flowrate in header distributor d, and $C^{D}{}_{d,m}$ is the contaminant concentration of type m in header distributor d.

$$\sum_d F^{RD}{}_{r,d} = F^{R}{}_{r} \; \forall_{r} \tag{12}$$

$$\sum_d (F^{RD}{}_{r,d} \times C^{RD}{}_{r,d,m}) = F^{R}{}_{r} \times C^{OUTR}{}_{r,m} \; \forall_{r,m} \tag{13}$$

$$F^{D}{}_{d} = \sum_r F^{RD}{}_{r,d} \; \forall_{d} \tag{14}$$

$$F^{D}{}_{d} \times C^{D}{}_{d,m} = \sum_r (F^{RD}{}_{r,d} \times C^{RD}{}_{r,d,m}) \; \forall_{d,m} \tag{15}$$

Eq(16) to Eq(19) are applied for water demand. $F^{DJ}{}_{d,j}$ is the flowrate from header distributor d to demand j, $F^{FW}{}_{j}$ is the freshwater flowrate to demand j, $F^{J}{}_{j}$ is the flowrate of demand j, C^{FW} is the contaminant concentration of freshwater, and $C^{J}{}_{j,m}$ is the contaminant concentration of type m of demand j.

$$\sum_j F^{DJ}{}_{d,j} \le F^{D}{}_{d} \; \forall_{d} \tag{16}$$

$$\sum_j (F^{DJ}{}_{d,j} \times C^{D}{}_{d,m}) \le F^{D}{}_{d} \times C^{D}{}_{d,m} \; \forall_{d,m} \tag{17}$$

$$F^{FW}{}_{j} + \sum_d F^{DJ}{}_{d,j} = F^{J}{}_{j} \; \forall_{j} \tag{18}$$

$$(F^{FW}{}_{j} \times C^{FW}) + \sum_d (F^{DJ}{}_{d,j} \times C^{D}{}_{d,m}) \le F^{J}{}_{j} \times C^{J}{}_{j,m} \; \forall_{j,m} \tag{19}$$

Eq(20) to Eq(24) are applied for the determination of pipes existence. U is a large positive number. $Q^{IK}{}_{i,k}$, $Q^{KR}{}_{k,r}$, $Q^{RD}{}_{r,d}$ are the binary parameters. $V^{DJ}{}_{d,j}$ is the binary variable.

$$F^{IK}{}_{i,k} \le U \times Q^{IK}{}_{i,k} \; \forall_{i,k} \tag{20}$$

$$F^{KR}{}_{k,r} \le U \times Q^{KR}{}_{k,r} \; \forall_{k,r} \tag{21}$$

$$F^{RD}{}_{r,d} \le U \times Q^{RD}{}_{r,d} \; \forall_{r,d} \tag{22}$$

$$F^{DJ}{}_{d,j} \leq U \text{ x } V^{DJ}{}_{d,j} \ \forall_{d,j} \tag{23}$$

$$V^{DJ}{}_{d,j} \leq F^{DJ}{}_{d,j} \ \ \forall_{d,j} \tag{24}$$

Eq(25) is applied to determine the total annual revenue. H^{hour} is the operating hours per year and $P^{RW}{}_{d}$ is the volumetric price of regenerated water.

$$T^{REV} = H^{hour} \text{ x } \textstyle\sum_{d,j}[(F^{DJ}{}_{d,j}/1{,}000) \text{ x } P^{RW}{}_{d}] \tag{25}$$

Eq(26) is applied to determine the total annualised cost. T^{CC} is the total capital cost, A^{F} is the annualised factor and T^{OC} is the total annual operating cost.

$$T^{AC} = (T^{CC} \text{ x } A^{F}) + T^{OC} \tag{26}$$

Eq(27) is applied to determine the total capital cost. T^{CCpipe}, T^{CCpump}, $T^{CCmotor}$, T^{CCreg} are the capital costs of pipe, pump, motor, and regeneration unit.

$$T^{CC} = T^{CCpipe} + T^{CCpump} + T^{CCmotor} + T^{CCreg} \tag{27}$$

Eq(28) is applied to determine the total annual operating cost. T^{OCww} is the annual costs of buying high-quality wastewater. T^{OCpump} and T^{OCreg} are the annual operating costs of pumping and regeneration.

$$T^{OC} = T^{OCww} + T^{OCpump} + T^{OCreg} \tag{28}$$

The details of the cost equations are not shown due to the limited spaces and pages. The MINLP model is solved with a DICOPT solver by using GAMS software (GAMS, 2016). The model is initially run at the baseline freshwater price to get the total annualised cost. The total annualised cost is used to determine the base or minimum regenerated water price as shown in Eq(29). The regenerated water price at different qualities is determined based on the quality factor and profit factor as shown in Eq(30). The quality factor is used to classify the regenerated water price at different quality. The profit factor is used to cover any miscellaneous cost and provide extra profit to the centralised system. The model then is run at the new regenerated water prices.

$$Base\ price = \frac{Total\ annualised\ cost\ (T^{AC})}{Total\ annual\ flow\ of\ regenerated\ water} \tag{29}$$

$$Price = Base\ price\ x\ (1 + quality\ factor + profit\ factor) \tag{30}$$

3. Case study

The water data for the centralised system were modified from Yu et al. (2013) with three plants and two types of contaminants which are total suspended solids (TSS) and chemical oxygen demand (COD) as shown in Table 1. The case study was tested with the different number of water header.

Table 1: The water data for the centralised system

Sources					Demands				
Plant	Number	Flowrate (m^3/h)	Concentration (ppm)		Plant	Number	Flowrate (m^3/h)	Concentration (ppm)	
			TSS	COD				TSS	COD
A	1	10.417	45	80	A	1	10.417	10	40
	2	14.583	70	120		2	41.667	20	50
	3	12.5	100	350		3	6.25	30	65
B	4	20.833	50	75	B	4	33.333	10	40
	5	37.5	65	110		5	83.333	20	50
	6	35.417	100	300		6	8.333	30	65
C	7	12.5	50	80	C	7	16.667	10	40
	8	17.5	60	110		8	54.167	20	50
	9	18.75	110	350		9	4.167	30	65

For one water header in Scenarios 1, 2 and 3, wastewater sources are mixed and produced one quality of regenerated water. For two water headers in Scenarios 4, 5 and 6, wastewater sources are segregated into two classes based on quality and produced two qualities of regenerated water. For three water headers in Scenario 7, wastewater sources are segregated into three classes and produced three qualities of regenerated water.

The quality factor is assumed zero for low-quality water as this quality is assumed to apply the minimum price, 0.1 for medium-quality water, and 0.2 for high-quality water. The profit factor, as well as subsidy fraction, are assumed 0.1 for all scenarios.

4. Results and discussion

Table 2 shows the regenerated water price based on the total annualised cost at different scenarios. Scenarios 1, 2, 4 and 7 achieved the highest freshwater reduction, which was 70 %, whilst Scenario 3 achieved the lowest freshwater reduction, which was 61.3 % because it only produced low-quality regenerated water. The lower total annualised cost was achieved with subsidy which also reflected the lower regenerated water price. The highest price was achieved by Scenario 1 because it had the highest total annualised cost and the price was almost the same as the freshwater price, which was USD 0.75/m^3. The regenerated water prices of the remaining scenarios were still below the freshwater price. Table 3 shows the economic results at different regenerated water prices. The high total annual revenue and total annual profit were achieved by Scenario 1, followed by Scenario 4 and Scenario 5 due to the selling of high-quality regenerated water at a high price. The opposite was achieved by Scenario 3 because low-quality regenerated water was sold at a low price. The profit margin is the same either with or without subsidy because as the total annualised cost increases, resulting in a high regenerated water price, thus, increasing the total annual revenue.

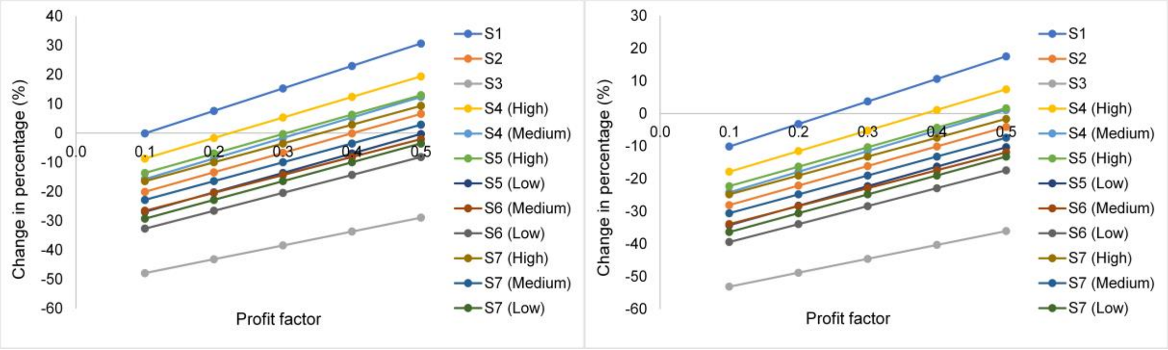
Table 2: The results of regenerated water prices

Scenario	Quality	Freshwater reduction (%)	Flow (m^3/y)	TAC (USD/y)		Price (USD/m^3)	
				Without subsidy	With subsidy	Without subsidy	With subsidy
1	High	70	1,440,000	829,850	746,865	0.749	0.674
2	Medium	70		719,250	647,325	0.599	0.539
3	Low	61.3		511,710	460,539	0.391	0.352
4	High	70		758,410	682,569	0.685	0.616
	Medium					0.632	0.569
5	High	69.6		717,500	645,750	0.648	0.583
	Low					0.548	0.493
6	Medium	65.5		660,930	594,837	0.551	0.496
	Low					0.505	0.454
7	High	70		694,380	624,942	0.627	0.564
	Medium					0.579	0.521
	Low					0.530	0.477

Table 3: The results of economic analysis

Scenario	Total Annual Revenue (USD/y)		Total Annual Profit (USD/y)		Profit margin (%)
	Without subsidy	With subsidy	Without subsidy	With subsidy	
1	1,078,600	970,560	248,750	223,695	23.1
2	862,560	776,160	143,310	128,835	16.6
3	495,330	445,930	-16,380	-14,609	-3.3
4	958,130	861,970	199,720	179,401	20.8
5	879,410	791,180	161,910	145,430	18.4
6	725,400	652,730	64,470	57,893	8.9
7	824,430	741,820	130,050	116,878	15.8

The regenerated water price increased as the profit factor increased. Thus, a further analysis was conducted at each scenario to study the effects of profit factor in determining the regenerated water price, starting with 0.1 and increased up to 0.5 as shown in Figures 2a and 2b. The percentage changes of the regenerated water price from the baseline freshwater price at the increasing profit factor were most likely more than 10 %. The low percentage change indicated that the regenerated water price was close to the freshwater price. However, the regenerated water price must be below the freshwater price. A negative percentage change means that the price does not exceed the freshwater price and vice versa. For without subsidy, Scenario 4 can apply up to 0.2 and Scenarios 2, 5 and 7 can apply up to 0.3 to achieve high profit. For with subsidy, Scenario 1 can apply up to 0.2, Scenario 4 up to 0.3, Scenario 5 up to 0.4, and Scenarios 2 and 7 up to 0.5 to achieve high profit. The higher profit factor could be applied when there was a subsidy and at the same time, the regenerated water prices were still below the freshwater price. Based on the case study, Scenario 7 is chosen as it has a low total annualised cost, a comparable profit and the highest profit factor can be applied.



(a) *(b)*

Figure 2: The percentage changes of regenerated water prices from the baseline freshwater price at different profit factor (a) without subsidy, and (b) with subsidy

5. Conclusions

The high total annualised cost resulting in a high regenerated water price and gave high profit to the centralised system. The disadvantage is that there is a possibility to surpass the freshwater price. The advantage is the prices have not been directly affected by the fluctuation of the freshwater price. However, the prices might surpass the freshwater price if the fluctuation occurred. For scenarios with low total annualised cost, there is an opportunity to have high profit by increasing the profit factor in determining regenerated water price without exceeding the freshwater price. In this case study, Scenario 7 is chosen with 70 % freshwater reduction, low total annualised cost, more than 15 % of profit margin and the highest profit factor can be applied. In future work, the proposed method can consider maintenance costs as well as the effect of different subsidy factor.

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