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Water pinch analysis using multiple contaminants for all wet streams in textile industry

Mariyam Shabbir, Ghulam Hussain*, Mehwish Anis

Institute of Environmental Engineering & Research (IEER), University of Engineering and Technology (UET), Lahore, Pakistan, emails: ghussain@uet.edu.pk (G. Hussain), maryam.shabbir99@gmail.com (M. Shabbir), mehwish@uet.edu.pk (M. Anis)

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A B S T R A C T

Textile sector consumes huge amount of water in water intensive operations including bleaching, dyeing, and finishing. In this study, water pinch analysis (WPA) was applied on a textile industry using multiple contaminant analysis, to minimize the freshwater consumption and wastewater generation. Water design software was used for comprehensive evaluation of direct reuse and regeneration recycle options, for all wet streams of the industry. Three contaminants including total dissolved solids (TDS), total hardness (TH) and chemical oxygen demand (COD) were selected for WPA, contrary to single contaminant approach in the past studies. After applying WPA (direct reuse) one by one for each contaminant, freshwater reduction of 56.5% for TDS, 58.6% for TH and 32.8% for COD was achieved. COD is the most sensitive parameter as it gives minimum freshwater reduction, and hence was selected as a key/limiting contaminant. For regeneration recycle option, selecting moving bed biofilm reactor as regeneration method and COD as limiting contaminant, 69.43% of freshwater reduction was achieved. By application of WPA outcomes, cost reduction of 33% and 50% of the current operating costs could be attained for direct reuse and regeneration recycle options, respectively.

Keywords: Textile industry; Water pinch analysis; Water reuse; Water conservation

1. Introduction

Water shortage is a one of the serious environmental concern nowadays. Water usage is increasing in industries and agriculture because of rapid population growth and economic development. Current global water demand, estimated to be 4,600 km^3/y, is expected to rise by 20%–30% till 2050 [1]. There is a dire need to reduce the water usage due to limited freshwater availability, high cost of supplying freshwater and treating large quantity of wastewater to avoid environmental degradation [2].

The textile industry, as a key contributor to manufacturing firms, is the third biggest consumer of freshwater [3,4]. Typical processes in a textile industry include bleaching, scouring, dyeing, washing, and finishing, which all are water intensive processes. According to estimates, approximately 28.0 million tons of textiles are dyed each year, consuming around 5.0 billion m^3 of freshwater [3].

Many studies have been conducted for water reduction in textile industry applying various water reuse approaches, including process modification [5], decoupling of economic activity and long-term development [6], direct reuse of water [7,8] and optimization of water use by process integration [9]. Technical water management strategy used for water conservation in different industrial sectors is water auditing through water pinch analysis (WPA) [2,10,11]. It is an efficient method for minimization the freshwater consumption and wastewater generation through process integration of water using networks [2].

* Corresponding author.

WPA has been successfully applied in different industrial sectors like sugar industries [2,12,13], oil refineries [10,14–16], brick manufacturing industry [17] and others to come up with water reduction and reuse strategies. It uses either single contaminant approach [14], or multiple (two or three) contaminant approach [18] that depends on mass transfer of the contaminants [10]. Selection of limiting/key contaminant plays an important role in decision making for water reuse, recycle, regeneration and process modification. Key contaminant prevents the reuse potential of water within the processes based on limiting concentration for that process [18]. Precise estimation of water limiting statistics plays a critical role in possible water reduction for a particular system [19].

Various approaches and techniques have been applied to carry out WPA that includes graphical approach [14,20,21], mathematical programming [11,22–24], software based [2,12] and others [15,17,25].

Through application of WPA, significant water reductions can be achieved on industrial level. Xiao and Cai [21] conducted a research on coal industry considering chemical oxygen demand (COD) for the single contaminant approach using graphical method and achieved 21.88% freshwater reduction. Similarly, another research was conducted on brick manufacturing plant by taking total suspended solids (TSS) as limiting contaminant through algebraic technique of WPA and it resulted 15.6% and 56.4% freshwater reduction for direct reuse and water regeneration scheme, respectively [17]. These studies directly targeted one contaminant without considering other contaminants.

On the other hand, Khezri et al. [25] applied WPA on an aluminum anodizing industry. It was based on single contaminant with a new strategy using a variety of pollutants as a contaminant index rather than one contaminant. Another research was conducted for Kaduna Refinery and Petrochemical Company (KRPC). In this study, while using single contaminant approach, multiple wastewater contaminants were used including hardness (H), suspended solid (SS), free hydrocarbons and COD and the viability for water and wastewater minimization through reuse and recovery in the water system was analyzed [14]. Selection of limiting contaminant for single contaminant approach is more feasible by considering multiple contaminants rather than directly targeting one contaminant to check which parameter is the most sensitive for water reuse within all processes.

Graphical approaches are very realistic, yet time consuming for solving single contaminant cases. These are however difficult and often impractical to use for multiple contaminant challenges [10]. To avoid complexity of calculations, different software have been developed based on single contaminant approach. Nowadays, software which are most in use for WPA are Uofk_WPA software [12], RCNet software [2], WaterTarget™ [26] and Water Design software [27]. Water Design software is more user friendly, among others. It uses a single contaminant approach and can optimize up to ten (10) water use operations at a time. It can analyze water reuse, regeneration with and without recycle options for water network recovery. The results of Water Design software closely matches with graphical method [24].

Different researchers have used specific water consuming portion of industries to avoid the complexity of the calculations [18]. A study was conducted on an old textile plant considering only the bleaching department from whole unit for application of WPA [9]. The choice of various processes in a sector plays a vital role in correct implementation of WPA [25]. To have a significant water reduction, maximum water using processes should be considered simultaneously.

In this study, WPA was used employing Water Design software for optimizing the water use in a local textile industry. The study aims to evaluate all the wet process streams quantitatively and qualitatively with the objective to recommend interventions for water conservation through reuse, recycling, and regeneration. Use of Water Design software, use of all wet processes, and selection of multiple contaminants distinguish this study from the previous studies of WPA related to textile industry. The results of WPA on water footprint and cost reduction were also evaluated.

2. Methodology

In the selected textile industry, dry and wet processing of yarn and fabric is carried out at a large scale. The industry has production capacity of 20,000 kg/d with an equivalent stitching capacity with daily water consumption of 3,000 m^3. Currently, water demand is fulfilled by groundwater, extracted by two turbines with capacity of 1.5 and 2 cusec.

Water network analysis was carried out for the collection of baseline data from all wet processes (bleaching, dyeing, washing, and finishing) for development of process flow diagram (Fig. 1). Blue shaded boxes are showing wet processes of textile industry.

2.1. Sample collection and characterization

All the processes in the industry are batch processes, and each process is carried out once after 12 h. Hence, grab samples from all the wet streams were collected twice for light shades. Collected samples were analyzed for pH, turbidity, color, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), total alkalinity (TA), total hardness (TH) and COD as per procedures laid down in Standard Methods for the Examination of Water and Wastewater [28].

2.2. Water pinch analysis

2.2.1. Contaminant selection for WPA

Three contaminants (COD, TDS and TH) were selected based on effluent quality and process sensitivity. These were analyzed one by one using single contaminant approach of WPA using Water Design software. For these pollutants, mass load was determined for each wastewater stream using Eq. (1).

$$\text{Mass Load (kg/hr)} = \text{Flow (te/hr)} \times (\text{Limiting Outlet Concentration} - \text{Limiting inlet concentration (g/m}^3\text{)}/1000 \quad (1)$$

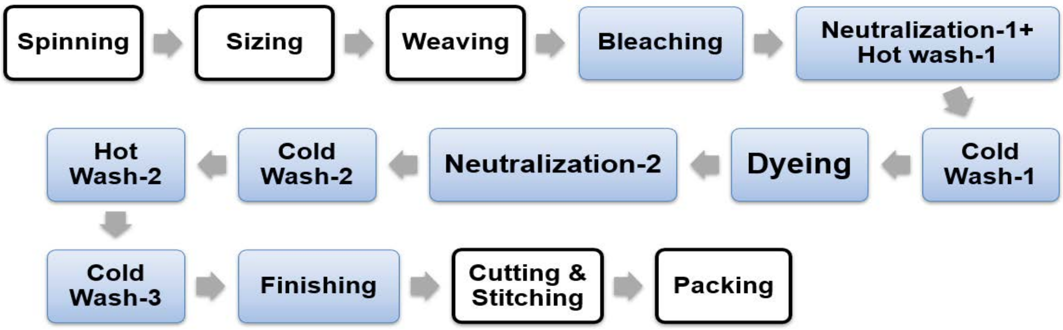

Fig. 1. Process flow diagram in the selected textile industry.

Flow is taken as tons per hour (t/h). While selecting single contaminant for WPA, it is assumed that the system operates as a single contaminant and reuse/recycling is allowed in the system [29].

2.2.2. Collection of limiting concentration data

Limiting concentration data was extracted for all the water using processes. These critical concentrations correspond to maximum inlet and outlet contaminant concentrations, each process units can tolerate and do not affect product quality. These have to be maximized in order to minimize the freshwater requirement [11]. Limiting water data can be evaluated from manufacturer's design data, physical limitations (e.g., flooding flow rate, channeling flow rate, saturation composition), or technical constraints (e.g., to avoid scaling, corrosion, and explosion).

2.2.3. Development of concentration interval diagram

Applying the WPA, concentration interval diagram (CID) was constructed for TDS, TH and COD. CID consists of upward arrows of each water using process separately. Position of arrow represents particular process with flow rate. The arrowhead shows the inlet concentration and arrow tail shows outlet concentration of each process. This enabled the determination of mass load for each process, cumulative mass load and water requirement for each process.

In this concentration interval diagram, all the limiting inlet and outlet concentrations are arranged in increasing order. CID is used to determine mass load transferred in each concentration interval. In each concentration interval, freshwater flow rate required is also calculated. For mass load transferred calculation in each interval, Eq. (2) was used.

$$m_k\left(\frac{\text{kg}}{\text{day}}\right)=\frac{\left(C_{k+1}-C_k\right)\left(\frac{g}{m3}\right)\times\sum_i^o f\ \text{lim}\left(\frac{\text{m}^3}{\text{day}}\right)}{1000} \tag{2}$$

where M_k = mass load in an interval in kg/d; C_{k+1} and C_k = concentration of two consecutive pollutant concentration, g/m^3; $\sum_i^o f$ lim = sum of all flow rates in a particular interval.

2.3. Water network diagram

Water network diagram was developed based on three techniques: wastewater reuse in same process (direct recycle), wastewater reuse in other processes (direct reuse) and use of freshwater. The flow rates were determined by applying mass balance on each process. Distribution of all flow rates was such that it meets the limiting inlet concentration of COD for each water using process.

2.4. Evaluation of proposed options

Two options were proposed using WPA including (1) direct reuse and (2) regeneration reuse. Results obtained from both options were compared with respect to amount of water conserved and the cost benefit analysis for each option. Different treatment technologies for regeneration of wastewater were evaluated based on literature review and the most suitable one was selected. Pollution load calculations were also performed in order to check the feasibility of direct reuse option in terms of environmental benefit.

3. Results and discussion

3.1. Characteristics of effluent streams

Results of characterization for collected samples from various effluent streams are provided in Table 1.

Effluent from bleaching has basic pH due to use of caustic soda in scouring purpose [30]. Similarly, pH of dyeing effluent is highly alkaline, as reactive dyes are used which require basic pH [31]. Effluent from both bleaching and dyeing processes was high in color with color values of 1,834 and 2,165 CU, respectively. It could be attributed to the addition of detergents, caustic soda and other sizing substances in bleaching process [32] and dyes in dyeing process. Also, the TDS of bleaching and dyeing was high, that is, 2,330 and 10,972 ppm, respectively. Different detergents and organic substances get dissolved because of high temperature [30] making the effluents high in TDS.

Similarly, bleaching, and dyeing effluents were high in alkalinity due to use of caustic soda. In dyeing process, soda ash (Na_2CO_3) is also used. In neutralization and washing processes, alkalinity comes from previous processes as water gets absorbed in fabric. The most polluted stream with respect to organic matter is bleaching effluent with COD of 10,000 ppm, followed by dyeing stream with 6,000 ppm COD. In bleaching, it could be because of input material which has sizing substances (starch, acrylic and detergents) [30]. In dyeing process, dyes and salts are used resulting in high amount of COD in the effluent [33].

3.2. Proposed water conservation options

3.2.1. Direct reuse option

After selection of three contaminants (COD, TH, and TDS), the limiting data as inlet and outlet concentrations have been presented in Table 2.

Limiting inlet concentration data for these three contaminants COD, TH and TDS have been taken from literature [4,32] and verified from the plant engineers of subject textile industry. Whereas, limiting outlet concentration data has been calculated by adding the limiting inlet concentration of a particular contaminant into the effluent concentration of that contaminant which has been determined experimentally in laboratory.

Using the limiting concentration data, WPA was performed for the selected contaminants using water design software. The analysis results are presented in Fig. 2 that represents CID for TDS. It can be observed from Fig. 2 that freshwater pinch concentration for TDS is 790 ppm and minimum freshwater requirement needed for all operations is 36.95 t/h. Whereas, actual freshwater consumption was 85 t/h. Freshwater pinch indicates that wastewater process streams having outlet concentration below or equal to pinch concentration can be reused in those process that have outlet concentration above this pinch value.

Fig. 3 shows that freshwater pinch concentration for hardness is 116 ppm and minimum freshwater requirement for all operations is 35.22 t/h, which is less as compared to what was for TDS. This reveals that TH is not as sensitive as TDS because it allows more reuse and recycling of effluent as compared to TDS.

In Fig. 4, CID for contaminant COD represents that freshwater pinch concentration is 950 ppm and minimum freshwater requirement optimized for all operation is 57.16 t/h. It shows minimum reduction for freshwater among all selected contaminants which means it is most critical parameter to consider for water reuse in textile processes. Hence, COD should be selected as limiting/key parameter. Table 3 summarizes the WPA results for all three contaminants.

Table 1
Characteristics of effluent wastewater from various processes

Sr.	Processes	Parameters (Avg. conc.)								
		pH	Turbidity	Color	EC	TDS	TSS	TA	TH	COD
		–	NTU	CU	ds/m	ppm	ppm	ppm as $CaCO_3$	ppm as $CaCO_3$	ppm
1	Bleaching	9.8	9.8	1,834	3.57	2,330	189	1,455	106	10,000
2	Neutralization-1	5.9	7.46	290	1.18	780	140	328	86	2,200
3	Cold wash-1	6.5	9.3	180	0.87	570	114	280	74	1,100
4	Dyeing	10.1	10.2	2,165	17.1	10,972	156	2,440	142	6,000
5	Neutralization-2	7.2	9.4	550	3.79	2,510	105	980	94	1,800
6	Cold wash-2	7.1	13.9	410	2.19	1,520	89	720	68	800
7	Hot wash	6.9	11.2	380	0.97	690	70	360	66	400
8	Cold wash-3	6.6	11.8	225	0.74	500	40	255	56	200
9	Finishing	8.3	12.6	480	0.78	530	80	275	40	900

Table 2
Limiting concentration data for all processes

Sr. no.	Processes	Flow	Limiting inlet concentrations (ppm)			Limiting outlet concentrations (ppm)		
		t/h	COD	TH	TDS	COD	TH	TDS
1	Bleaching	9.00	700	30	1,000	10,700	136	3,040
2	Neutralization-1	9.00	150	60	300	2,350	116	790
3	Cold wash-1	10.00	200	60	300	1,300	104	580
4	Dyeing	9.00	0	30	300	6,000	142	10,982
5	Neutralization-2	9.00	150	60	300	1,950	124	2,520
6	Cold wash-2	10.00	200	60	300	1,000	98	1,530
7	Hot wash	10.00	200	60	300	600	96	700
8	Cold wash-3	10.00	150	60	300	350	86	510
9	Finishing	9.00	50	30	300	950	40	540

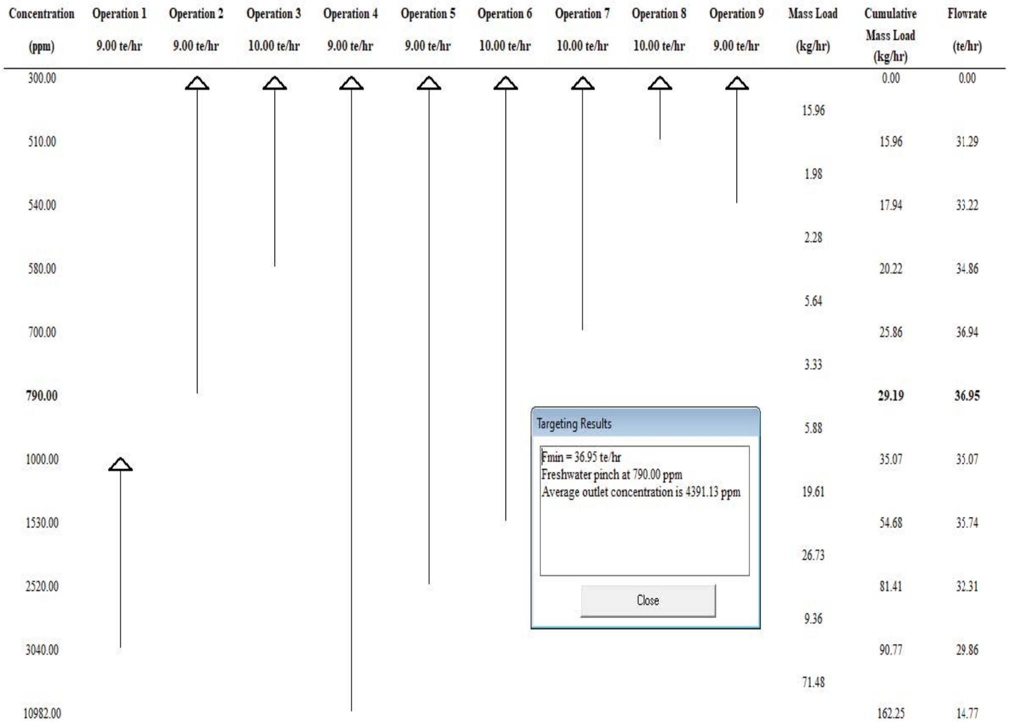

Fig. 2. CID for contaminant TDS.

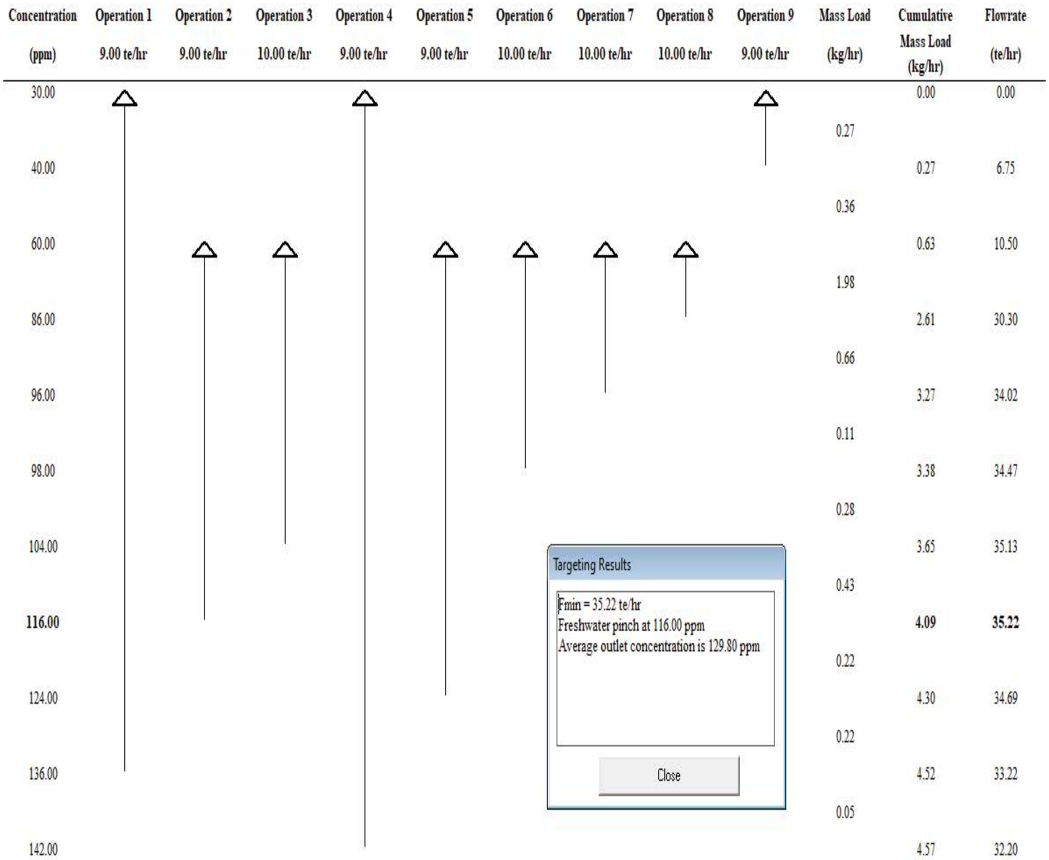

Fig. 3. CID for contaminant TH.

Table 3
Summary of WPA on different contaminants

Contaminant	Minimum flow (t/h)	Freshwater pinch (ppm)	Average outlet concentration (ppm)	Water savings (%)
TDS	36.95	790	4,391.13	56.5
TH	35.22	116	129.8	58.6
COD	57.16	950	3,696.78	32.8

Table 3 shows maximum water savings (58.6%) can be achieved when we take TH as a limiting contaminant, while minimum water savings (32.8%) for COD. COD was selected as a limiting/key contaminant as it is more sensitive that prevents the maximum reuse of freshwater to maintain product quality.

3.2.2. Water network design (direct reuse)

Direct water reuse plan considering COD as limiting contaminant has been shown in Fig. 5. This plan was prepared by applying the law of conservation of mass on various operation streams

As evident from Fig. 5, operation 4 (dyeing process) requires only freshwater. It does not allow reuse or recycling of effluent as it requires high quality water. Operation 7 and 8 (washing processes) produce less polluted effluent having COD of 200 and 150 ppm, respectively. Effluent of these streams can be reused into bleaching and other processes, where limiting COD value is higher.

3.2.3. Pollution load comparison for selected limiting contaminant

The reuse of effluent streams is generally assumed to enhance the COD of wastewater that is not ultimately environmentally friendly. On the contrary, the reuse option reduces the freshwater consumption which ultimately leads to less pollution load and is an environmentally sustainable approach. To weigh out the pros and cons of reuse option in terms of pollution reduction, pollution load has been calculated shown in Table 4.

Table 4 shows that by applying WPA (direct reuse), flow rate decreases from 646,680 to 434,873 t/y and effluent COD increases from 2,685 to 3,697 ppm. It seems like environmentally unfriendly, however in terms of total

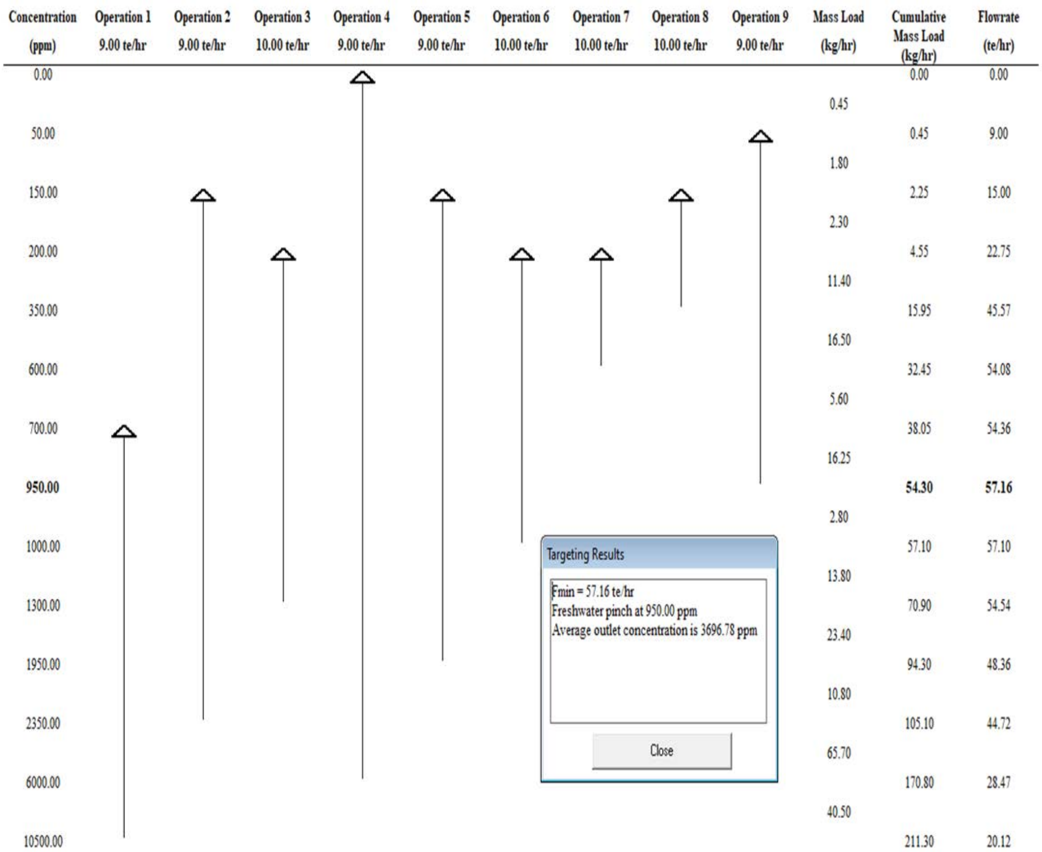

Fig. 4. CID for contaminant COD.

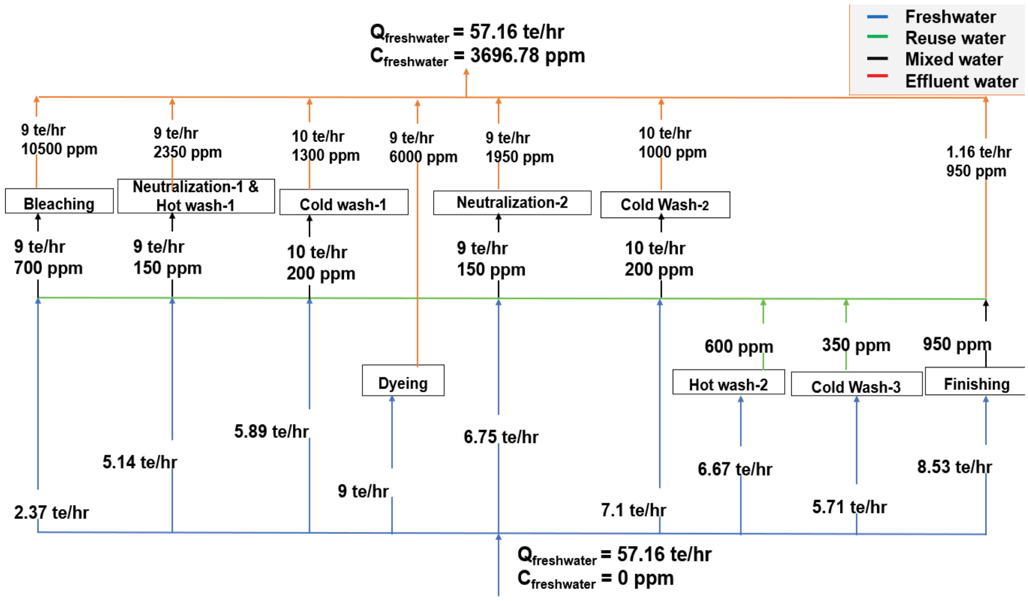

Fig. 5. Water network diagram for contaminant COD.

pollution load, it shows reduction of up to 7.42% which makes it economically and environmentally beneficial.

3.3. Regeneration reuse option

In regeneration reuse option, the effluent streams are treated and hence treated water can be reused in a better way. To evaluate this option, limiting input concentrations of COD for all the processes was set as 200 ppm. It is regeneration outlet concentration from regeneration system and regeneration inlet concentration into various textile processing system. It is an optimum design value to avoid over and under calculations in terms of economics. Since the cumulative effluent concentration of COD (C_{in}) is 1,163 ppm, and the target COD concentration (C_{out}) for regenerated water is 200 ppm, 83% removal will be required.

3.3.1. Treatment technology for regeneration option

Based on selected limiting contaminant, suitable regeneration options were studied from literature are compared. The most suitable option as selected which is more economically feasible and environmentally sustainable.

There are several wastewater treatment technologies like coagulation-flocculation [34], activated sludge process [35] and advance oxidation process [36] etc. that can give COD removal of around 83% and greater. But there are so many technical constraints that restrict their use like area requirement, capital and operational cost, sludge production and other operational problems etc.

After detailed review of literature, MBR and moving bed biofilm reactor (MBBR) were found to be the most popular technologies for the treatment of textile effluent due to their advantages over conventional technologies like conventional activated sludge (CAS) process and coagulation process [37]. According to the economic analysis and LCA study by Yang et al. [38], MBBR is most suitable treatment method for textile wastewater as compared to MBR and conventional activated sludge (CAS) process. MBBR can also treat more organic loading by increasing biomass concentration in same reactor volume [37]. Various studies have reported the COD removal of around 85% by MBBR alone, which could further be enhanced to 91%–95% by post treatment (like ozonation, coagulation) or pretreatment [39–43]. Considering that MBBR can effectively attain required COD removal (80%), it was selected as regeneration technology. After incorporating regeneration, WPA was applied for regeneration recycle option and network diagram was developed.

Fig. 6 represents the CID diagram for regeneration recycle option. It shows that minimum freshwater requirement decreases from 57.16 to 22.75 t/h by adding regenerated flow rate of 45.73 t/h. Whereas freshwater pinch is same at 950 ppm while regenerated water pinch at 6,000 ppm. Regenerated water pinch means regenerated wastewater can be used in process wastewater streams having outlet concentration below or equal to 6,000 ppm.

3.3.2. Network diagram for regeneration recycle option

Network diagram for the regeneration option has been designed by using mass balance concept and is presented in Fig. 7.

Fig. 7 shows the network diagram in which distribution of various flow rates in each process is provided. Flow rate to effluent treatment plant is 25.98 t/h, while remaining effluent is regenerated and reused. Use of freshwater has been reduced from 57.16 t/h (direct reuse) to 25.98 t/h (regeneration recycle) since major part of the effluent is being regenerated to meet water requirement of processes. As, dyeing is a very sensitive process, therefore no regenerated water is being recommended for use in it just like in reuse option.

Table 4
Pollution load calculations for direct reuse option

Parameter	W/O pinch (t/y)	Direct reuse (t/y)	Pollution load (kg/y)		Savings (%)
	Q_{Annual} = 646,680	Q_{Annual} = 434,873	W/o pinch	Direct reuse	
COD (ppm)	2,685.3	3,697	1,736,526	1,607,631	7.42

Table 5
Cost analysis for water usage before and after WPA application

		Freshwater pumping and treatment	Wastewater treatment (existing)	Regenerated water (proposed treatment)
Unit cost ($/m^3)		0.3	0.4	0.3
Option-1 (No reuse)	Annual discharge (m^3/y)	646,680	646,680	0
	Total cost (million US$/y)	0.22	0.26	–
Option-2 (Direct reuse)	Annual discharge (m^3/y)	434,873	434,873	0
	Total cost (million US$/y)	0.15	0.18	–
Option-3 (Regeneration recycle)	Annual discharge (m^3/y)	197,656	197,656	347,914
	Total cost (million US$/y)	0.07	0.08	0.09

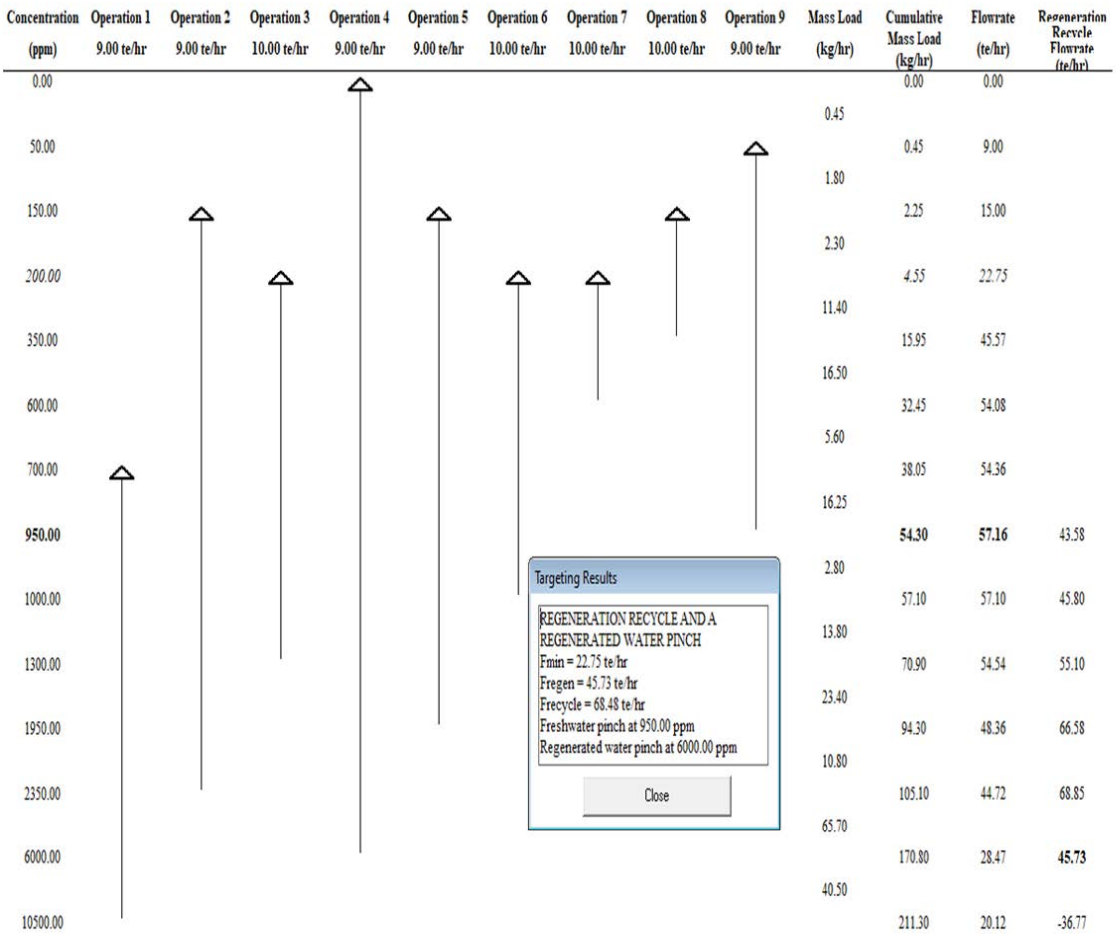

Fig. 6. CID for regeneration recycle option.

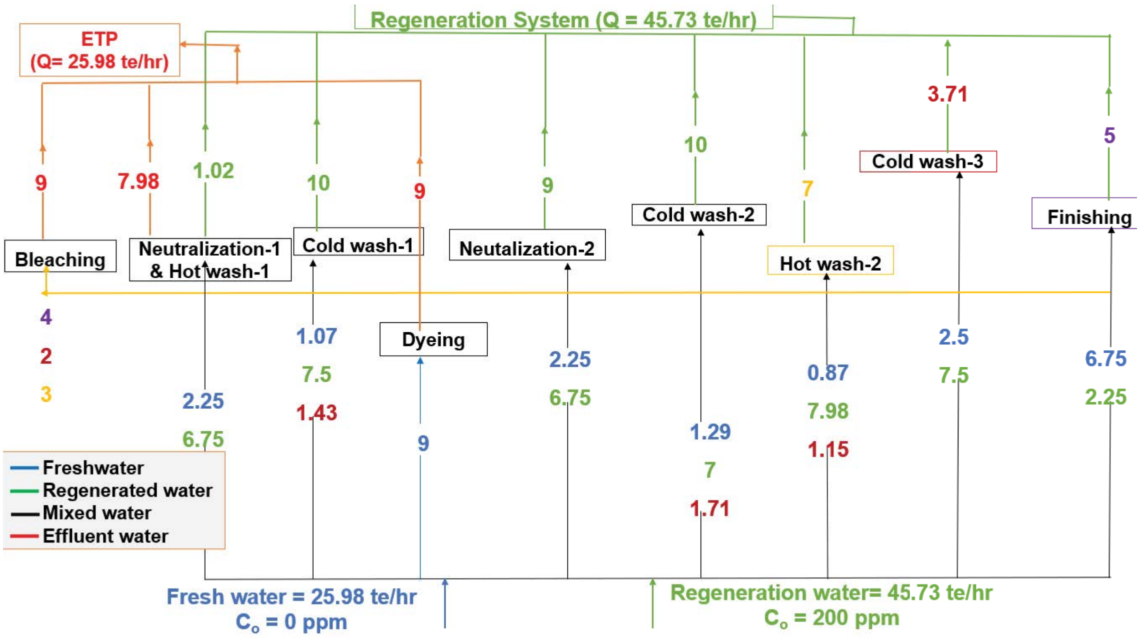

Fig. 7. Water network for regeneration recycle option.

3.3.3. *Cost analysis for water conservation options*

In addition to water conservation, the economics of any suggested system is also important. Therefore, cost analysis was performed for direct reuse and regeneration reuse options, which is presented in Table 5.

Unit cost for freshwater has been estimated from industry by encountering the electricity and chemical cost for withdrawal and treating groundwater for use in the processes. Cost for wastewater treatment has been calculated in similar way, as this textile industry is treating wastewater by means of activated sludge process. MBBR has been selected as a regeneration option that costs 0.3 USD/y [38]. Without WPA, total cost for freshwater withdrawal and wastewater treatment is 0.48 M USD/y that reduced to 0.33 M USD/y and 0.24 M USD/y for WPA direct reuse and regeneration recycle options, respectively. After application of outcomes of WPA, around 31% cost reduction can be achieved for direct reuse and around 50% for regenerated recycle system.

4. Conclusions

In this study, possible reduction for freshwater consumption and wastewater generation have been evaluated for a textile industry using WPA. After choosing multiple contaminants including TDS, TH and COD for single contaminant approach, COD was found most sensitive contaminant for optimization of water network for reuse purposes. After application of WPA, the direct reuse and regeneration recycle options could save 211,807 t/y (32.8%) and 449,024 t/y (69.4%) of freshwater, respectively, as compared to existing water consumption of 646,680 t/y. In addition, the pollution load of 7.4% can be reduced on treatment plant for direct reuse option. The economic analysis of both options have concluded that 31% and 50% of annual cost can be saved by application of direct reuse and regeneration recycle options, respectively.

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