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Computer Aided Selection of the Suitable Treatment Strategy for Industrial Waste Water Utilization and Reuse

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Abstract. In Saudi Arabia, the request for water is increasing annually to fulfill the development requirements in the field of drinking, agriculture and industrial sectors. The only water sources available for these requirements are desalted seawater, which is costly and underground water with its renewal limitations. Hence, more attention has to be given to both wastewater treatment and utilization. Various types of wastewater treatment processes are available in the literature, but most of them are applied to a certain application and a certain waste. No general strategy of treatment appeared in the literature of this field.

In the present work, a design for reliable flow sheet that can handle various industrial and domestic wastewaters has been attempted, and a computer program was developed to enhance the best selection of the suitable treatment strategy for any given wastewater. The program can also deal with more than one type of wastewater stream containing various pollutant concentrations and have different flow rates. The program can also give more than one product from the processed waste and calculates the cost of the produced water in each case.

Moreover, sensitivity analysis runs were carried out to investigate the response of the present program to any expected or sudden changes in the influent streams and it was found that it can give directly the proper action for the treatment strategy in each case.

1. Introduction

In Saudi Arabia, the water sources are limited and water desalination is costly. Meanwhile, the request for water is increasing annually to fulfill the development requirements in the field of drinking, agricultural and industrial sectors.

If present water consumption level per capita is constant, it is expected that underground water will be exhausted within 25 years. Hence, recycling of wastewater will be an attractive alternative for agricultural and industrial uses.

Understanding the nature of wastewater and sources of pollutants is essential in the design and operation of treatment facilities and in the engineering management of environmental quality.

Hence, 39 significant pollutants have been considered during the design of the computer program by which the proper treatment strategy will be obtained. Those selected pollutants are given later.

1.1. Various technologies of wastewater treatment processes

There are different types of wastewater treatment processes available in literature (Smith, 2005; Peters, 2003). Those are usually classified into four levels, i.e. primary, secondary, tertiary and quaternary treatments as shown in Table 1.

Primary treatment involves physical processes like suspended solids removal, while the secondary treatment is usually applied to remove organic pollutants by biological oxidation. Tertiary and quaternary treatments are advanced processing by which specific contaminants like nitrogen, TDS and heavy metals are finally removed from wastewaters (Peters, 2003; Metcalf, 2003). In addition to these four levels of treatment, there are four other classes of treatment technologies, i.e. physical, chemical, biological and thermal processes (Mclaughlin, 1992) as shown in Fig. 1.

Table 1. Waste water treatment technology (Metcalf, 2003)

	Primary Treatment	Secondary Treatment	Advanced Treatment
pH		Neutralization	
SS	Screening Sedimentation	Chemical Precipitation Filtration	
BOD	Sedimentation Chemical precipitation Methane Fermentation	Activated Sludge Trickling Filter	Activated Carbon Chemical precipitation Membrane Filtration
COD	Sedimentation Chemical precipitation Methane Fermentation	Activated Sludge Trickling Filter	Activated Carbon Ozonation Membrane Filtration
Oil	Floatation	Chemical Floatation Filtration	
N Compound	Activated Sludge Trickling Filter	Biological Denitrification	Activated Carbon
Phenol		Activated Sludge	Activated Carbon
CN		Chlorination, Activated Sludge	Catalytic Wet Oxidation
Cr		Reduction Sedimentation	Ion Exchange Electrodialysis
Fe	Sedimentation Chemical precipitation	(Hydroxide) Precipitation Filtration	Ion Exchange Electrodialysis
Heavy Metal		(Hydroxide) Precipitation Filtration	Ion Exchange Electrodialysis
Cl		Neutralization by Sodium Thiosulfate	Activated Carbon
Sulfide		Activated Sludge Chemical Oxidation	Reverse Osmosis
Odor		Activated Sludge Chemical Oxidation	Activated Carbon
Color		Chemical Precipitation Oxyidation & Reduction	Activated Carbon Reverse Osmosis

In the present work, a wide spectrum of treatment processes was considered in order to give a broad chance for the designed computer program to achieve the proper treatment strategy for each type of considered wastewater feed.

These treatment processes, applied in the present work, are:

1. Screening "for debris removal".
2. Neutralization "for pH adjustment".
3. Coagulation, Flocculation and Sedimentation "for fine suspended particles".
4. Flotation "for fine oil particles".
5. Biological Treatment "for BOD and COD".
6. Filtration "for residual fine suspended particles".
7. Air Stripping "for NH_3, phenol and CN".
8. Activated Carbon "for refractory TOC".
9. Membrane Separation "for TDS".
10. Demineralization "by ion exchange or electrodialysis for heavy metal separation and hardness".
11. Disinfection "for taste, odor and microorganisms".

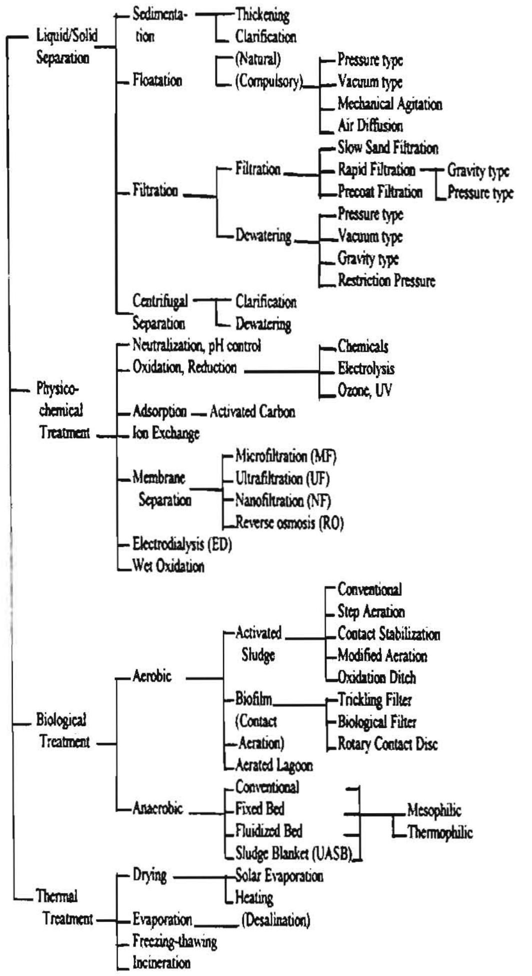

Fig. 1. Classification of treatment processes (Japanese Workshop, 1992).

Figure 2 indicates these treatment steps in a form of generalized flow sheet to be applied in the following computer program.

Moreover, the 39 contaminants considered in the present work are given in Table 1a.

2. Methodology

As the main target of the present work is to establish an engineering strategy by which the suitable treatment flow-sheet can be achieved for each considered wastewater and each desired water product, a computer program was constructed to achieve this goal.

Three qualities of treated water are considered in the present phase of work, i.e. agricultural waste water, industrial waste water and sewage waste water (Metcalf, 2003; Belhatecha, 1995; Eckenfelder, 1980;

Culp, 1980; De Renzo, 1981). Table A (in the appendix) indicates the characterization of these three wastewater qualities.

Table 1a. Wastewater containments for the present work

Pollutant	Significance	Pollutant	Significance
SS	Suspended solids	Nitrate	
TDS	Total dissolved solids	Silica	
BOD	Biochemical oxygen demand	Aluminum	
COD	Chemical oxygen demand	Magnesium	
Oil	Oil content	Manganese	
pH	Power of the hydrogen ion	Calcium	
N	Nitrogen compounds concentrations	Zinc Sulphate	
Phenol	Phenol content	Carbonate hardness	
CN	Cyanide concentration	Bicarbonate	
Cd	Cadmium concentration	Alkalinity	
Cr	Chromium concentration	Mercury	
Fe	Iron content	Nickel	
Cl	Chlorine content	Arsenic	
Heavy metals	Concentration of heavy metals like Cu	Barium	
Odor		Lead	
Color		Selenium	
Turbidity		Silver	
Phosphate		Zinc	
Fluoride		Total Coliform	As an indicator of pathogens

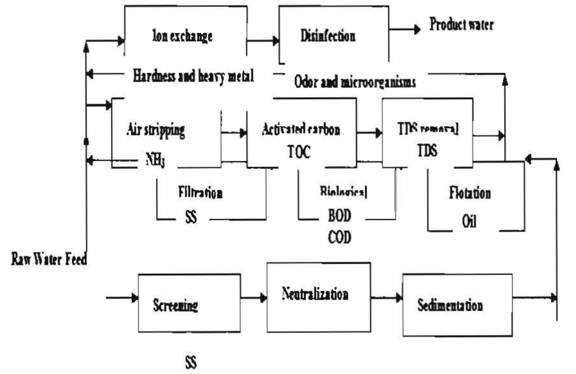

Fig. 2. The general flow sheet diagram.

Thirty-nine pollutants have been selected as previously mentioned. Those pollutants are widely found in various domestic and industrial wastewaters (Metcalf, 2003; Culp, 1980; De Renzo, 1981).

Major treatment methods have been identified as shown in Fig. 2. Each treatment unit will treat only one principal pollutant (this assumption is only considered to avoid complexity and interference between the function of these units), as mentioned in our previous work (Kheder, 1998).

This program starts with reading the wastewater characteristics and the demand water "product specifications". Then, the program compares the level of pollutants in the wastewater feed with that required in the product water. Based on this comparison, the first treatment step is either selected or bypassed. After exiting from this unit, another comparison is conducted to decide for the next step of treatment and so on until the desired water quality is achieved. It is worth mentioning that this numerical program is written in Fortran language (Kheder, 1998). Then, the program will stop and print the details of the required treatment steps and properties of wastewater after each treatment unit.

During the design of this program, the following assumptions are considered:

1. A definite percentage of pollutant removal has been chosen for each treatment method (based on data available in literature and also practical experience) (Culp, 1980; De Renzo, 1981; Kheder, 1998).
2. The specific characteristics of the desired water products are identified according to the regulation rules and given to the computer program.

3. Results and Discussions

3.1. Actual case study for program validation

In order to check the validity of the present designed program, actual data were obtained from one of the wastewater treatment plants in the industrial area of Jubail City in Saudi Arabia. This plant is designed to treat all industrial wastewater generated from the various plants in the area. Its designed capacity is 41,700 m^3/day, while its daily average capacity is 36,957 m^3/day. The treated water produced from this plant is used completely in irrigation. The detailed operating data of this plant are given in Table 2, while its actual flow sheet is given in Fig. 3. The estimated actual cost for water treatment in this plant is 0.87 SR/m^3 treated water (based on average flow rate of 36,957 m^3/day).

When the actual characteristics of this water feed were introduced to the present computer together with the specifications of the required water product for irrigation, the following results were obtained for the characteristics of the treated water and for the selected process flow sheet as in Table 3 and in Fig. 4.

It is clear, from Tables 2 and 3, as well as from Figs. 3 and 4, that either the selected flow sheet or the quality of water produced by the program is similar to or better than that of the actual plant. Moreover, the flow sheet of the treatment obtained by the program and that of the actual plant are almost identical (Figs. 3 and 4) except the location of the neutralization unit which comes before sedimentation and activated sludge to give better control on pH which can improve the performance of both processes. It is also observed that the cost estimation carried out by the program gave a value of 0.94 SR/ m^3 of the treated water which is very close to the actual cost value of this plant which is 0.87 SR/m^3(Kheder, 1998).

Table 2. Actual operating data of the plant

Symbol	Parameter	Average value		Water quality standard for irrigation (Maximum contaminant level mg/L)
		Influent	Effluent	
X(1,j)	S.S mg/L	81	2.6	10
X(2,j)	pH	7.4	7.0	6.5-8.5
X(4,j)	BOD mg/L	116	5	10
X(5,j)	COD mg/L	252	40	150
X(6,j)	Ammonia mg/L	17	3	40
X(2,j)	Sulphide mg/L	3.6	0.0	450
X(13,j)	Chloride mg/L	364	328	110
X(31,j)	Alkalinity mg/L	165	70	-
X(17,j)	Turbidity	5	1.4	2
X(39,j)	Total coliform MPN/100mL	23	< 3	202
X(7,j)	Phenol mg/L	-	-	
X(14,j)	Total dissolved solid mg/L	1070	900	4500

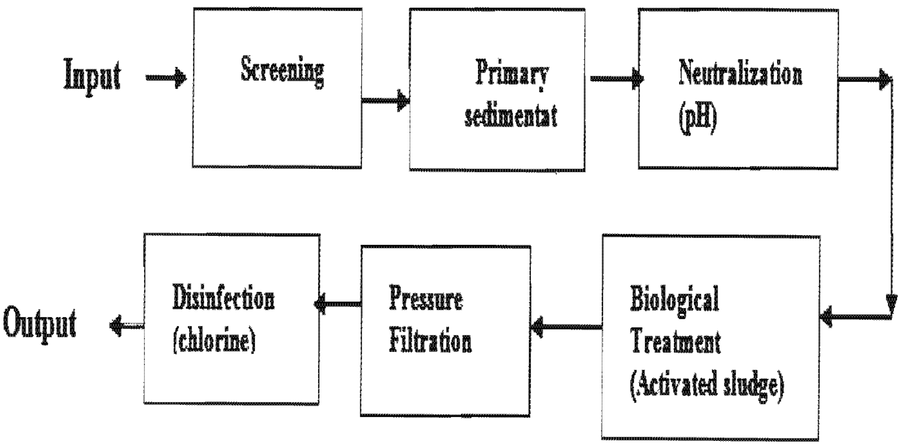

Fig. 3. The actual flow-sheet of the plant.

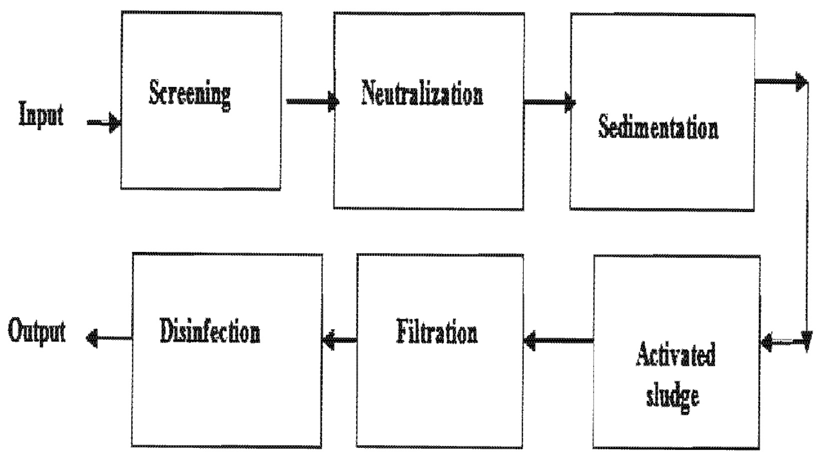

Fig. 4. Flow-sheet of Jubail plant as suggested by the program.

Table 3. Summary of results of the program

Symbol	Parameters	Input	Output	Water quality standard for agriculture
X(1,j)	S.S	81	0.5184	10
X(2,j)	pH	7.4	7.0	6.5-8.5
X(4,j)	BOD	116	1.429	10
X(5,j)	COD	252	1.871	150
X(6,j)	Ammonia	17	2.486	40
X(28,j)	Sulphide	3.6	2.7	450
X(13,j)	Chloride	364	254.8	1100
X(31,j)	Alkalinity	165	13.406	
X(17,j)	Turbidity NTU	5	0.0937	2
X(39,j)	Tot. coliform	23	0.3306	2.2
X(14,j)	TDS	1070	1070	4500

Due to the promising results, obtained by the present designed program in the previous case study of Jubail plant, more applications were suggested in this work. This is to account for the capability of the designed program to deal with more than one input feed stream (Influent), and also to clarify the proper mixing of these influent streams (either at the start or at any point in the flow sheet). For each application, the treatment strategy (or the proper selection of the flow sheet) was obtained by the program as well as the unit cost of the treated water in this case as follows:

3.1.1. Case I: Multi-feed influent streams

In this application, various wastewater streams are considered as multi-feed input streams to the computer program with two main treatment strategies. These various streams are given in Table 4.

The first strategy is to mix all these streams at the start of the flow sheet as shown in Fig. 5a. The second strategy is to introduce each feed at its suitable point of treatment inside the flow sheet as shown in Fig. 5b. These two approaches were investigated by the present program and for each case, the cost of the treatment as well as the suitable treatment flow sheets were obtained. The results of this application as well as the characteristics of the various input streams are given in Table 4. It is clear from this table that the better treatment strategy is not to mix all feed streams at the start of the flow sheet, but to insert each feed at its proper location.

Table 4. Characteristics and flow-rates of each stream

X(1,j)	Parameter	Input					Demand	Output stream	
		Stream (1) X(i,1)	Stream (2) X(i,2)	Stream (3) X(i,3)	Stream (4) X(i,4)	Stream (5) X(i,5)	XD(i)	Mixing at the start	Mixing at the proper site
X(2,j)	SS	0.02	300	0.1	0.1	0.12	0.2	0.0103	0.031
X(3,j)	pH	7.0	6.0	7.0	7.0	7.0	7.0	7.0	7.0
X(1,j)	Oil	7	5.5	0.0	0.0	0.0	0.2	0.001	0.0018
X(4,j)	BOD	180	200	20.	1.0	2.0	3	0.006	0.08
X(5,j)	COD	250	300	4.0	5	4	8	0.007	0.089
X(6,j)	N-com	21.5	210	0.01	0.09	0.04	0.1	0.0014	0.004
X(7,j)	Phenol	3.0	2.0	5.0	0.03	0.02	0.03	0.00008	0.0011
X(14,j)	TDS	1150	1120	1140	1500	100	900	267.5	278.7
X(30,j)	Hardness	340	530	750	700	800	10	3.58	6.53
X(33,j)	Coliform	25	24	23	23.5	22.5	0.1	0.0	0.0
F(j,1)	Flow-rate (mgd)	2.0	3.0	1.0	2.5	1.5		10.0	10.0
Unit Cost in SR / M³								3.250	2.496

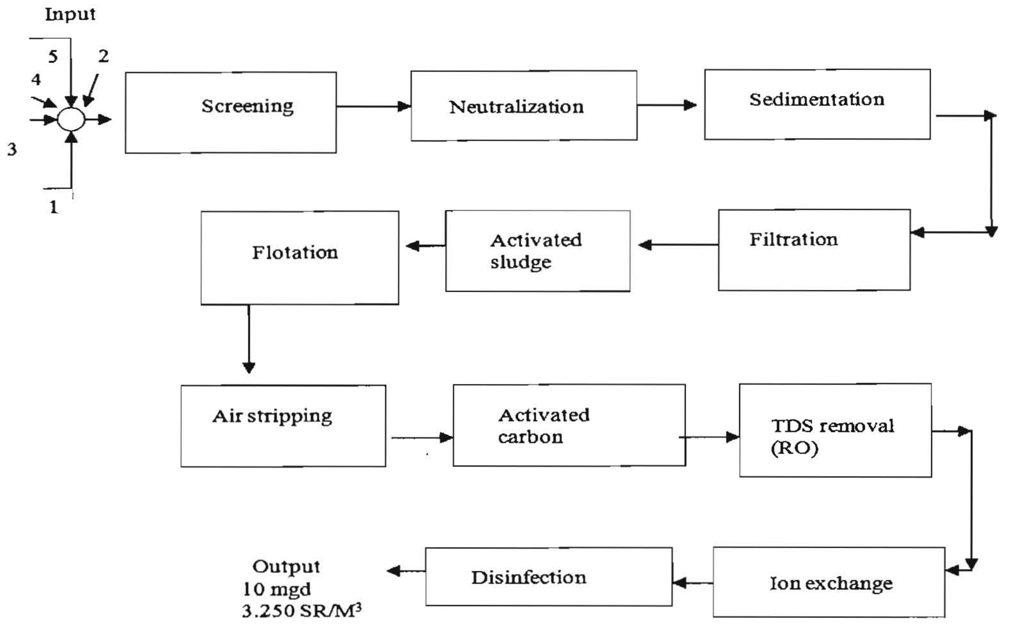

Fig. 5a. Flow-sheet with mixing at the start (Case I).

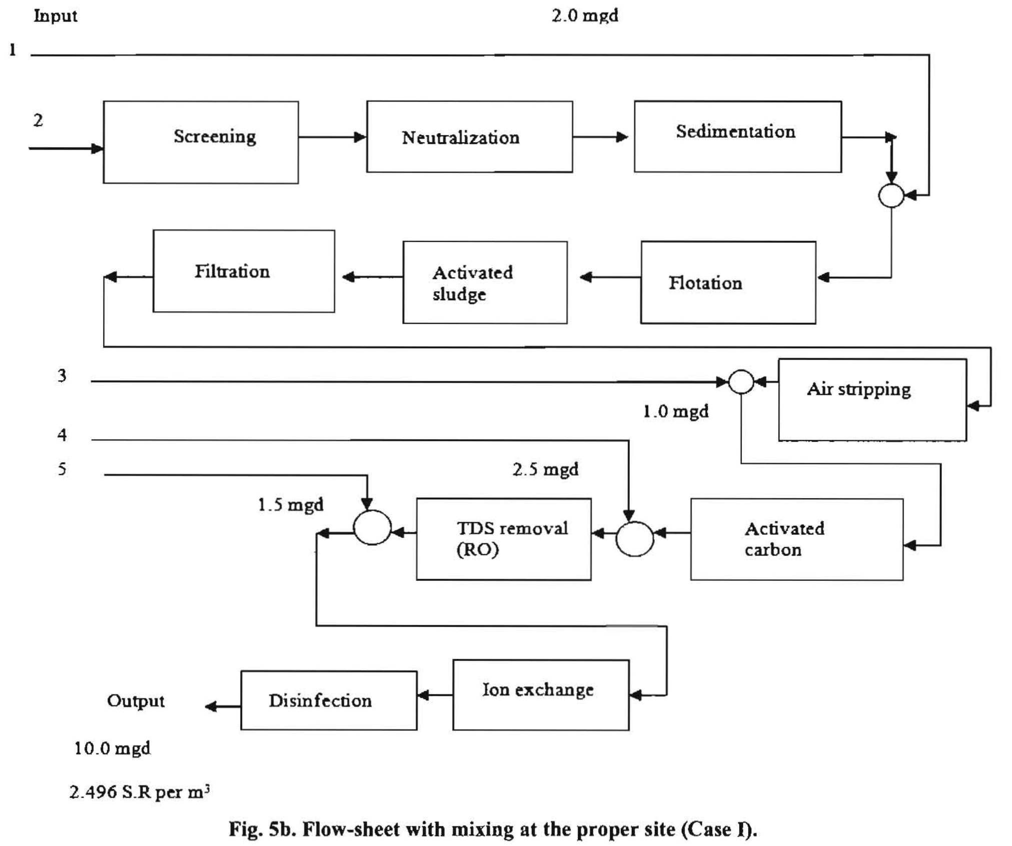

Fig. 5b. Flow-sheet with mixing at the proper site (Case I).

The program also defines this proper location. The cost of each treatment strategy was also calculated by the program and it was equal to 2.496 SR/m^3 for the proper mixing case, compared to 3.250 SR/m^3 for direct mixing at the start of the flow sheet. Hence, the idea of mixing all streams at start is not recommended in this case, especially when feed streams have different types of pollutants.

3.1.2. Case II: The sensitivity of the program to selected input pollutants

In this application, the main aim is to see how the program will behave if some changes occur in the quality of any feed stream, as always occur in practice. This case is identical to the previous Case I, i.e. multi-input streams and single output. The variations are only done in the concentration characteristics of some pollutants in the selected input streams as follows.

3.1.2.1. Case IIa

In Stream 1 and Stream 2, the phenol concentrations have been changed from its previous values (3.0 and 2.0 ppm) to 0.0 ppm, while the TDS were also changed from (1150 and 1120) to (150 and 120) ppm respectively. The computer results of this case are shown in Table 5, while the selected flow sheet for this case is also given by the program as shown in Fig. 6.

3.1.2.2. Case IIb

In this case, phenol and TDS in Streams 1 and 2 were kept constant as in Case I , while BOD and COD in Stream 1 were changed from their previous values in Case I (180 and 250 ppm) to (1 and 4 ppm) respectively. The obtained results by the program for this case are given in Table 6 and Fig. 7 for the flow sheet.

In Case IIa, it is clear from Fig. 6 that Streams 1 and 2 overrun the activated carbon and TDS removal, which is better than the previous flow sheet of Case I (Fig. 5b), where the unit cost is reduced (from 2.496 SR/m^3 to 2.265 SR/m^3).

In Case IIb, it is also clear from Fig. 7 that Stream 2 overruns flotation and Stream 1 overruns the activated sludge and filtration. The summation of Streams 1 and 2 overruns the activated carbon and TDS removal, which is better than the flow sheet of Case IIa.

Moreover, the unit cost is reduced from 2.265 SR/m^3 to 2.153 SR/m^3.

In Case IIc, it is clear from Fig. 8 that Stream 2 overruns flotation and Stream 1 overruns the activated sludge and filtration. The summation of Streams 1 and 2 overruns the activated carbon and TDS removal, which is better than the flow sheet of Case IIa. Moreover, the unit cost could be reduced from 2.265 SR/m^3 to 2.153 SR/m^3. In Case IIc, it is clear from Fig. 8 that Stream 2 overruns flotation and Stream 1 overruns the activated sludge and filtration. The summation of Streams 1 and 2 overruns the activated carbon, TDS removal and ion exchange, also Stream 4 overruns TDS removal. Hence, the flow sheet of this case (Fig. 8) is better than the flow sheet of the previous Case IIb shown in Fig. 7. Moreover, the unit cost of treatment in this case was reduced from 2.153 SR/m^3 to 2.095 SR/m^3.

Table 5. Characteristics and flow-rates of each stream

X(1,j)	Parameter	Input					Demand	
		Stream (1) X(i,1)	Stream (2) X(i,2)	Stream (3) X(i,3)	Stream (4) X(i,4)	Stream (5) X(i,5)	XD(i)	Mixing at the proper site
X(2,j)	SS	0.02	300	0.1	0.1	0.12	0.2	0.366
X(3,j)	pH	7.0	6.0	7.0	7.0	7.0	7.0	7.0
X(1,j)	Oil	7	5.5	0.0	0.0	0.0	0.2	0.024
X(4,j)	BOD	180	200	20.	1.0	2.0	3	0.346
X(5,j)	COD	250	300	4.0	5	4	8	0.431
X(6,j)	N-com	21.5	210	0.01	0.09	0.04	0.1	0.0288
X(7,j)	Phenol	0.0	0.0	5.0	0.03	0.02	0.03	0.0011
X(14,j)	TDS	150	120	1140	1500	100	900	203.25
X(30,j)	Hardness	340	530	750	700	800	10	8.167
X(33,j)	Coliform	25	24	23	23.5	22.5	0.1	0.0
F(j,1)	Flow-rate (mgd)	2.0	3.0	1.0	2.5	1.5		10.0
Unit Cost in SR / M^3								2.265

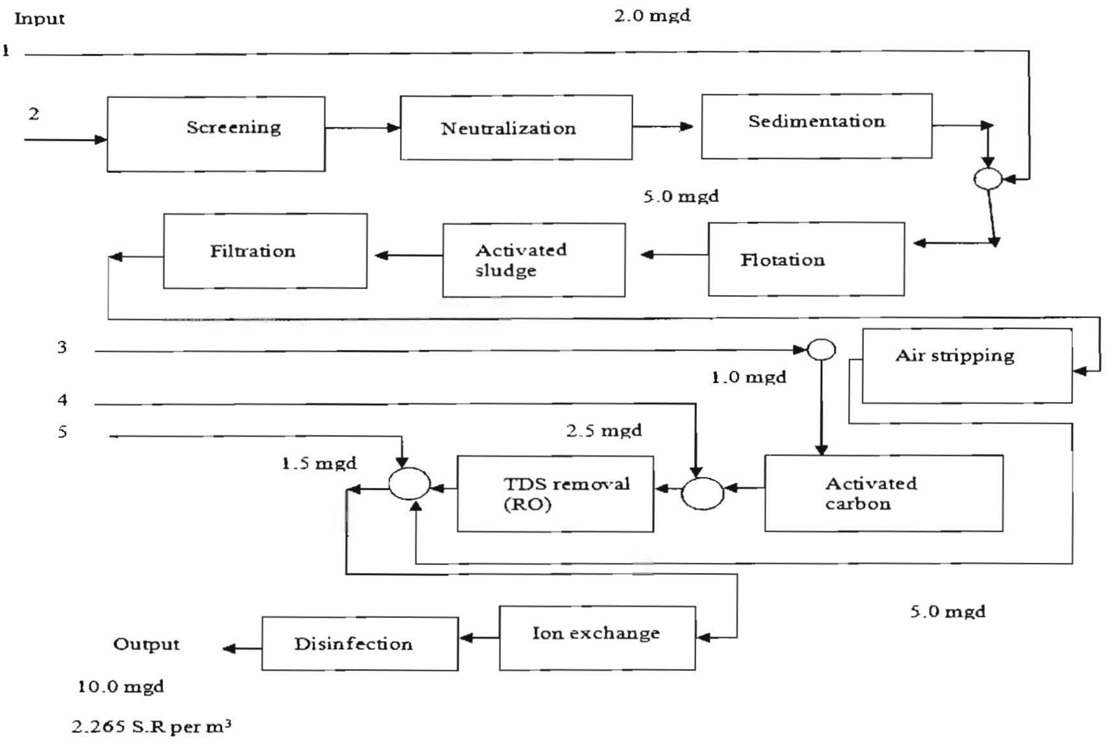

Fig. 6. Flow-sheet with mixing at the proper site for Table 5.

Table 6. Characteristics and flow-rates of each stream

X(1,j)	Parameter	Input					Demand	
		Stream (1) X(i,1)	Stream (2) X(i,2)	Stream (3) X(i,3)	Stream (4) X(i,4)	Stream (5) X(i,5)	XD(i)	Mixing at the proper site
X(2,j)	SS	0.02	300	0.1	0.1	0.12	0.2	0.599
X(3,j)	pH	7.0	6.0	7.0	7.0	7.0	7.0	7.0
X(1,j)	Oil	7	5.5	0.0	0.0	0.0	0.2	0.14
X(4,j)	BOD	1.0	200	20.	1.0	2.0	3	0.235
X(5,j)	COD	4	300	4.0	5	4	8	0.332
X(6,j)	N-com	21.5	210	0.01	0.09	0.04	0.1	0.0678
X(7,j)	Phenol	0.0	0.0	5.0	0.03	0.02	0.03	0.0011
X(14,j)	TDS	150	120	1140	1500	100	900	203.25
X(30,j)	Hardness	340	530	750	700	800	10	8.167
X(33,j)	Coliform	25	24	23	23.5	22.5	0.1	0.0
F(j,1)	Flow-rate (mgd)	2.0	3.0	1.0	2.5	1.5		10.0
Unit Cost in SR / M^3								2.153

Table 7. Characteristics and flow-rates of each stream

X(1,j)	Parameter	Input					Demand	Output stream
		Stream (1) X(i,1)	Stream (2) X(i,2)	Stream (3) X(i,3)	Stream (4) X(i,4)	Stream (5) X(i,5)	XD(i)	Mixing at the proper site
X(2,j)	SS	0.02	300	0.1	0.1	0.12	0.2	0.599
X(3,j)	pH	7.0	6.0	7.0	7.0	7.0	7.0	7.0
X(1,j)	Oil	7	5.5	0.0	0.0	0.0	0.2	0.14
X(4,j)	BOD	1.0	200	20.	1.0	2.0	3	0.936
X(5,j)	COD	4.0	300	4.0	5	4	8	0.742
X(6,j)	N-com	21.5	210	0.01	0.09	0.04	0.1	0.266
X(7,j)	Phenol	0.0	0.0	5.0	0.03	0.02	0.03	0.0233
X(14,j)	TDS	150	120	1140	1500	100	900	203.25
X(30,j)	Hardness	1.0	2.0	3.0	4.0	800	10	3.609
X(33,j)	Coliform	25	24	23	23.5	22.5	0.1	0.0
F(j,1)	Flow-rate (mgd)	2.0	3.0	1.0	2.5	1.5		10.0
Unit Cost in SR / M^3								2.095

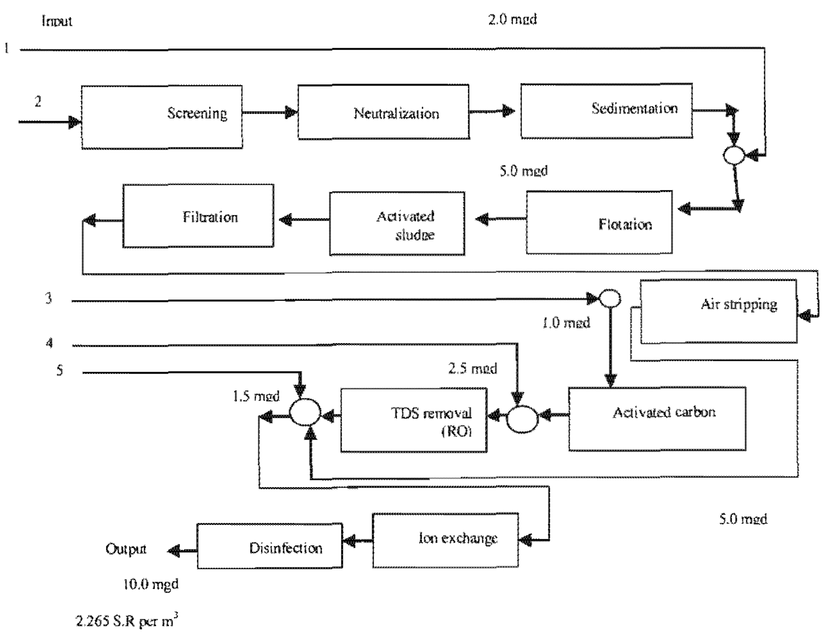

Fig. 7. Flow sheet for Case IIb.

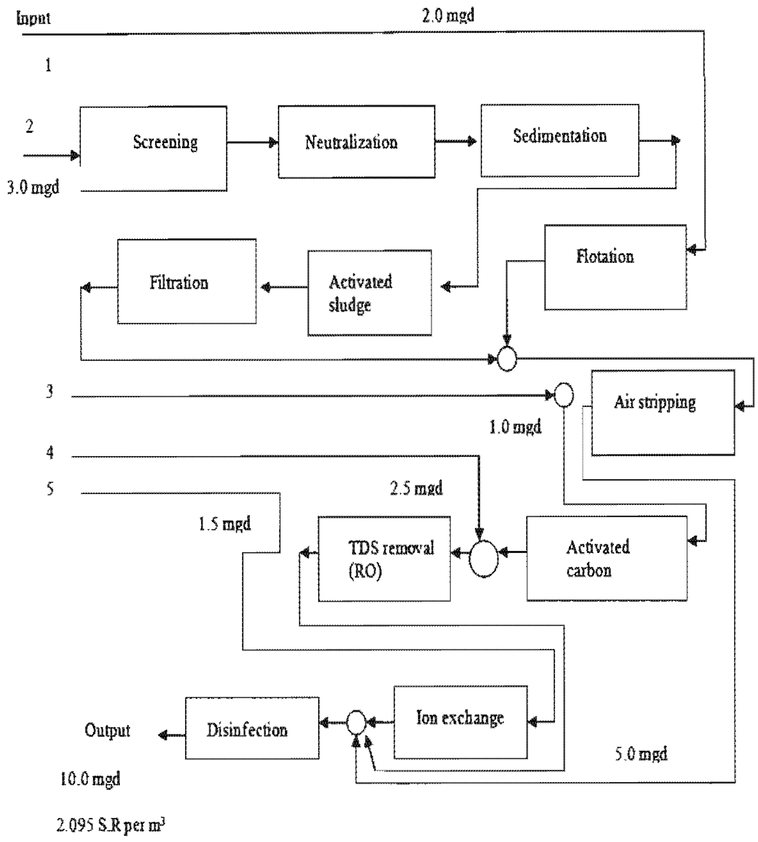

Fig. 8. Flow-sheet with mixing at the proper site for Case IIc.

4. Conclusions

The present work led to the following conclusions:

- The recommended program considered 39 pollutants which accounts for wide applications of waste waters.
- A generalized treatment flow sheet was developed by which the treatment strategy for any type of polluted water can be achieved.
- An actual case study was carried out on the designed program which revealed its accuracy in the selection of the proper treatment flow sheet and the predicted cost of treatment.
- For multi-feed polluted streams, the best treatment strategy obtained by the designed program is to introduce each feed at its proper location in the flow sheet and not to mix them all at the start of the flow sheet.
- The program is also sensitive regarding the pollutant levels like BOD, COD, TDS and hardness. If any sudden change occurs to the influent stream, the program gives directly the proper action concerning the treatment strategy.

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Appendix

Table A. Characteristics of different qualities of water, (in ppm), (Metcalf, 2003; Culp, 1980, De Renzo, 1981)

Contaminants	Agricultural waste water	Sewage waste water	Industrial waste water
BOD	10	100-400	100 - 300
COD	150	200-1000	300 - 2000
Oil & Grease / TPH	<8	<120	15-55
TSS	15	2000	15-45
pH	6.5-8.5	5-10	6-9
N-compound	40(NH_3)	10-50(NH_3)	1-10
Phosphate	1.0	5-20	0.2
Phenol	<0.1	<150	0.1-1.0
Cyanide	<0.05	1.0	0.1
Cd	10	0.5	-
As	0.1	1.0	-
Cr	100	200	-
Cu	200	1.0	-
Pb	5	1.0	-
Hg	0.001	0.001	-
Zn	200	10	-

الاختيار الأمثل باستخدام الحاسوب لإستراتيجية معالجة المياه الصناعية المبتذلة من أجل إعادة الاستخدام

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الكلمات المفتاحية: مياه ملوثة ، مياه صناعية ، معالجة مياه، إعادة استخدام المياه المبتذلة.

ملخص البحث. إن الحاجة إلى المياه في السعودية عالية لتحقيق أغراض التطورات المدنية وذلك في الشرب والزراعة والصناعة. والمصدر الرئيس هو تحلية مياه البحر المالحة وهي عملية مكلفة، وأيضاً المياه الجوفية وهي قابلة للنضوب. لذا فإنه من المهم الاستفادة من المياه المبتذلة لإعادة استخدامها. هناك العديد من الطرق للمعالجة لكنها تطبق على نوع واحد محدد من المياه ولا يوجد حل عام لجميع أنواع المياه المبتذلة.

تم في هذا البحث تصميم حل شامل باستخدام الحاسوب من خلال إستراتيجية شاملة للتعامل مع كافة أنواع المياه المبتذلة بما فيها الصناعية والمنزلية. إن البرنامج قادر على التعامل مع عدة أنواع من المياه في وقت واحد مع اختلاف في طبيعة الملوثات وتركيزاتها. ويضع البرنامج حلولاً شاملة تتضمن أكثر من منتج من المياه المعالجة مع حساب تكاليف المعالجة لكل خيار.

أيضاً يمكن عمل حساب للحساسية بحسب التغيرات المتوقعة في خصائص المياه المبتذلة مع اقتراح الإستراتيجية التي ينبغي اعتمادها والحلول المناسبة لها.