An Optimization-based Approach for design Ion Exchange Treatment Unit

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***Abstract*- The objective function is to satisfy certain constraints and achieve minimum capital, maintenance, and operation costs. Ion exchange unit was used in this study. This study includes development of computer program for advanced wastewater treatment plants design adopting genetic algorithm. The program was developed using Matlab software. The output of the genetic algorithm includes the finding of optimum design criteria for advanced wastewater treatment plants. The obtained design criteria are satisfying the required effluent quality with minimum treatment cost.**

Based on results of applying GA on ion exchange treatment plant, it was found that the optimum values of bed depth, service flowrate, regenerate flowrate, and back wash rate are 0.71m, 25m3/m3.hr, 8 m3/m3.hr, and 55 m/hr respectively.

1. Introduction

Water is the first element of sustaining life on earth. In addition, it is crucial for the economy. Virtually every industry agriculture, electric power and industrial manufacturing to beverage, apparel, and tourism relies on it to grow and ultimately sustain their business.

In the last years, water drought occurred due to the shortage in rainfall. This is a problem in arid and semi-arid countries such as Iraq. During droughts, water available in streams, rivers, and wells can be severely diminished. On the other hand rapidly growing population with associated changes in lifestyle and consumption patterns; competition between sectors, such as industry, agriculture and energy for precious land and water resources increases the rate of water demand for the different water use figures [1]. Thus, the planners are forced to consider any sources of water which might be used economically and effectively in satisfying the increasing water demand of water. Treated wastewater is now being considered and used in many countries throughout the world, as a new additional, renewable and reliable source of water, which can be used for agricultural production. By releasing freshwater sources of potable water supply and other priority uses, treated wastewater reuse makes a contribution of water conservation and expansion of irrigated agriculture, taking on an economic dimension. It also solves disposal problems aimed at protecting the environment and public health and prevents surfaces water pollution by the direct discharge of pollutants into inland and coastal waters. This increases the need of water reuse and converts the reuse wastewater management from conventional disposal strategy into value added product [2].

Ion Exchange

Ion exchange is a reaction between a solid and a liquid resulting in replacement of an ion of the solid with an ion from the liquid which can be used to remove hardness from water (water softening) [3]. Hardness is caused by the presence of any metallic cation, the most prevalent of these species are the divalent cations calcium and magnesium. As a result, hardness is usually defined as the total concentration of calcium and magnesium ions and is usually expressed as mg/l of CaCO3.

During the softening process the sodium ions are replaced by the hardness ions (calcium and magnesium) until the resin becomes exhausted and the feed water passes through the resin without a significant reduction in hardness as shown in fig.(1). At that point, it becomes necessary to regenerate the resin. This is accomplished by washing with a strong salt solution. The high concentration of sodium ions in the salt solution drives the reaction to the left and regenerates the resin bed. After the regeneration process, the bed is backwashed to remove the excess salt of regeneration. During the backwash process, the resin bed is decompacted (expanded) for 5 to 15 minutes with an upward flow of water. The backwash flow rate must be adjusted to get an expansion of at least 50%. Water softening reactions during the operation and regeneration are shown below [4].

Operation:

$$2Na^{+}R^{-} + Ca^{+2} \leftrightarrow Ca^{+2}R2^{-} + 2Na^{+} \quad (1)$$

$$2Na^{+}R^{-} + Mg^{+2} \leftrightarrow Mg^{+2}R_2^{-} + 2Na^{+} \quad (2)$$

Regeneration:

$$2NaCl + Ca^{+2}R_2^{-} \leftrightarrow 2Na^{+}R^{-} + CaCl_2 \quad (3)$$

$$2NaCl + Mg^{+2}R_2^{-} \leftrightarrow 2Na^{+}R^{-} + MgCl_2 \quad (4)$$

Where R= Resin.

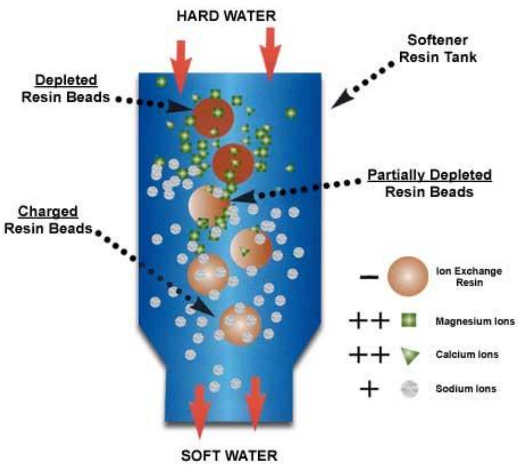
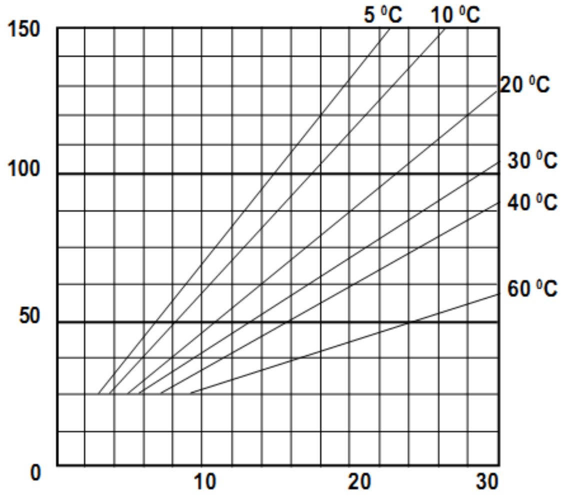


Fig.1 Ion exchange treatment unit

The design of ion exchange depends on the choices of process type, resin type, the amount of resin and the size and the number of exchangers [4,5]. In this study the ion exchange is used for hardness removal. For this purpose, different types of resin are available. In this study, Duolite C20 shall be used. Thus the operating conditions of this resin shall applied.

Duolite C20 is gel type strongly acidic cation exchange resin of the sulphonated polystyrene type. It can be used for softening (in Na+ form) as well as for water demineralization and other chemical process (in H+ form). Its principal characteristics are excellent physical, chemical and thermal stability, good ion exchange kinetics and high exchange capacity [6, 7].

The sodium leakage and operating capacity of Duolite C20 used with reverse flow (counter current) regeneration with NaCl are calculated in the following sections. During the backwash process, the bed expansion of DOULITE C20, as a function of backwash flow rate and water temperature, is shown in Fig.(2).



Backwash rate (m/hr)
Fig.2 Bed expansion verses backwash flowrate for Duolite C20, [6].

In order to apply the relations shown in Fig.(1) into the developed genetic algorithm (GA), it is necessary to find the equation describing each line. That was done by using EXCEL data sheets, and the obtained equations for the relation between the expansion ratio at temperature=T in °C (ERT) and backwash rate(BWR) in m3/m2.hr are [1];

and backwash rate(BWR) in m^3/m^2.hr are [1];

$$ER_5 = 6.9803 \times BWR + 2.0766 \quad (5)$$

$$ER_{10} = 5.5914 \times BWR + 3.5999 \quad (6)$$

$$ER_{20} = 3.9881 \times BWR + 5.5678 \quad (7)$$

$$ER_{30} = 3.3112 \times BWR + 4.8646 \quad (8)$$

$$ER_{40} = 2.8022 \times BWR + 6.1878 \quad (9)$$

$$ER_{60} = 1.6896 \times BWR + 9.6045 \quad (10)$$

Determination of Total Resin Volume

The total required volume of resin is calculated as [3];

$$V_T = \frac{Q_t}{SFR} \quad (11)$$

where; SFR is the service flowrate which depends on resin type. The volume of resin in one column is obtained as;

$$V_c = A_c \times BD \quad (12)$$

where;
A_C = cross sectional area of ion exchange bed, m^2
BD = bed depth which is dependent on resin type, m

The number of ion exchange columns (N_c) is calculated as;

$$N_c = \frac{V_T}{V_c} \quad (13)$$

Determination of Regeneration Cycle Time

The cycle time (Tc) of regeneration is calculated as;

$$T_C = T_S + T_R + T_B + T_{RS} \quad (14)$$

where; T_S, T_R, T_B, and T_{RS} are the times of service, regeneration, backwash, and rinse, respectively. T_B and T_{RS} are dependent on resin type, while, T_S and T_R are calculated as [8];

$$T_S = \frac{C_C\, N_C}{TRH} \quad (15)$$

$$T_R = \frac{V_S}{REG \times V_C} \quad (16)$$

where; V_S is the volume of salt solution, (L^3), and REG is the regenerant flowrate which is dependent on resin type. The volume of salt solution is obtained as;

$$V_S = \frac{M_S}{G \times \rho_W} \quad (17)$$

$$M_S = \frac{Msalt}{Csalt} \quad (18)$$

where; M_S is mass of solution (M), Msalt is mass of salt (M), Csalt is the concentration of salt (%), G is the specific gravity of salt solution which is usually taken to be 1.07, and ρ_w is the water density, (M/L^3).

Determination of Total Removed Hardness

The total removed hardness by an ion exchange is determined as [3];

$$TRH = (H_{in} - H_{ef}) \times Q_t \quad (19)$$

where;
H_{in} = influent hardness, ($M/L^{3)}$
H_{ef} = effluent hardness, ($M/L^{3)}$
H_L = leakage hardness, (M/L^3)

Q_t = actual treated water flowrate, (L^3/T)
and H_L and Q_t are defined as;

$$H_L = H_{in} \times L \tag{20}$$

$$Q_t = Q - Q_b \tag{21}$$

where;
L = percent of leakage.
Q = influent flowrate, (L^3T^{-1})
Q_b = bypass flowrate, (L^3T^{-1})
The bypass flowrate is obtained as;

$$Q_b = F \times Q \tag{22}$$

where;
F = bypass fraction which varied over the range (10-50)%

Advanced Wastewater Treatment

Advanced wastewater treatment (AWWT) refers to those additional treatment techniques needed to further reduce suspended, colloidal, and dissolved constituents remaining after conventional secondary treatment. It is used to improve the effluent quality to meet stringent effluent standards and to reclaim wastewater for reuse as a valuable water resource [9].

The purpose of AWWT is to remove one or more of the following constituents [4];

1- Organic matter and total suspended solids beyond what can be accomplished by conventional secondary treatment processes to meet more stringent discharge and reuse requirements.

2- Residual total suspended solids to condition the treated wastewater for more effective disinfection.

3- Nutrients beyond what can be accomplished by conventional secondary treatment process to limit eutrophication of sensitive water bodies.

4- Specific inorganic and organic constituents to meet more stringent discharge and reuse requirements and inorganic constituents for industrial reuse.

Genetic Algorithm

The genetic algorithm (GA) is an optimization and search technique based on the principles of genetics and natural selection. A GA allows a population composed of many individuals to evolve under specified selection rules to a state that maximizes the “fitness” (i.e., minimizes the cost function). The method was developed by [10] over the course of the [11,12] and finally popularized by one of his students. The analogy between natural genetics and GA terms, often used interchangeably, is shown in Table 1 [13]

Table (1) Genetic terminology

Natural Genetics	Genetic Algorithm
Chromosome	String
Gene	Feature or bit
Allele	Feature or bit value
Locus	String position
Genotype	Structure of an individual in the GA population
phenotype	Decode individual giving a possible solution to the problem

Some of the advantages of a GA include that it[9]:
1-Optimizes with continuous or discrete variables,
2-Doesn’t require derivative information,
3-Simultaneously searches from a wide sampling of the cost surface,
4-Deals with a large number of variables,
5-Is well suited for parallel computers,
6-Optimizes variables with extremely complex cost surfaces (they can jump out of a local minimum),
7-Provides a list of optimum variables, not just a single solution,
8-May encode the variables so that the optimization is done with the encoded variables, and
9-Works with numerically generated data, experimental data, or analytical functions.

The population of strings is randomly initialized giving a diverse range of possible solution. Each of these solutions is evaluated and given a fitness score. At this point the population is examined to see if a suitable solution has been found or improvement gas slowed to such an extent that is not worth searching further. This could be when a given goal has been reached or a certain level of improvement has not been achieved over a fixed number of generations. If the stopping criteria have been reached the GA enters loop involving three stages. The first stage is to select a new population based on fitness. This is, in Darwinian terms, performing a 'survival of the fittest' operation on the population. The selected population, which is usually the same size as the initial population, then forms the basis of a mating pool and enters the second stage of the loop. In the stage, two genetic operations are applied to the mating pool crossover and mutation. Crossover randomly selects pairs of strings called parents and combines their properties into offspring strings. This is done by choosing crossing points and swapping the genetic material between these points. The principle behind this is the good genetic material from each parent will thus be combined in a favorable manner in the offspring. Mutation makes random changes to individual genes in order that genetic material is not completely lost and to introduce new material to encourage diversity. The operator aids in preventing the population converging into local maxima or minima. It should be noted that both crossover and mutation are applied with associated probabilities Pc and Pm respectively, so that not all pairs will be crossed and not all strings will be mutated. The final stage of the loop re-evaluates the evolved population and then the loop return to the start where the stopping criteria are examined. If they are not met the population re-enters the loop, otherwise, the GA exits and the best solution found from the search is chosen.

Basic components of a genetic algorithm

By the application of a genetic operator□s selection, crossover, and mutation processes, a GA transition from one generation to another generation takes place. The following sections describe the three components of a genetic algorithm [9].

Selection

The selection process chooses the fittest individual from a population to continue into the next generation. Based on Darwin's principle of natural selection "survival the fittest" the selection component chooses the fittest individuals. It can be a deterministic operation, but in most implementations it has random components. The selection component judges against the fitness of one individual in relation to other individuals and chooses which individual goes on to next generation. Through selection, "good individuals" are favored to advance with a high probability, while "bad individuals" advance with low probability to the next generation.

Crossover

Crossover is the process of taking two parent solutions and producing from them a child. After the selection (reproduction) process, the population is enriched with better individuals. Reproduction makes clones of good strings but does not create new ones. Crossover operator is applied to the mating pool with the hope that it creates a better offspring. Crossover is a recombination operator that proceeds in three steps [9]:

1.The reproduction operator selects at random a pair of two individual strings for the mating.
2.A cross site is selected at random along the string length.
3.Finally, the position values are swapped between the two strings following the cross site.

That is, the simplest way how to do that is to choose randomly some crossover point and copy everything before this point from the first parent and then copy everything after the crossover point from the other parent.

Mutation

After crossover, the strings are subjected to mutation. Mutation prevents the algorithm to be trapped in a local minimum. Mutation plays the role of recovering the lost genetic materials as well as for randomly disturbing genetic information. It is an insurance policy against the irreversible loss of genetic material. Mutation has traditionally considered as a simple search operator. If crossover is supposed to exploit the current solution to find better ones, mutation is supposed to help for the exploration of the whole search space. Mutation is viewed as a background operator to maintain genetic diversity in the population. It introduces new genetic structures in the population by randomly modifying some of its building blocks. Mutation helps escape from local minima’s trap and maintains diversity in the population. It also keeps the gene pool well stocked, and thus ensuring ergodicity. A search space is said to be ergodic if there is a non-zero probability of generating any solution from any population state.

Specification of Objective Function

The objective function of each AWWT plant in the current population is taken as the sum of the annual costs, which is to be minimized. A general form of the applied objective function is;

$$\text{Minimize } f(x_1,\ldots,x_j) = \sum_1^N C_i \qquad (23)$$

where:
f (xj) = objective function in terms of the total costs.
Ci = annual cost of individual unit that includes capital, land and operation and maintenance costs.
N = number of treatment units in AWWT
x = decision variables
j = number of decision variables in each train.

Formulation of Cost Function

The annual cost of water treatment includes the annualized capital cost, annual operation and maintenance cost, and land requirement cost."Capital costs" refers to the investment required to construct and begin the operation of the plant, principally materials, labor, and interest. Operation and maintenance costs include the costs associated with the labor, material, and energy required to operate and maintain the treatment plant [14]. The annual cost function for treatment unit-i can be written as:

$$C_i = ACC_i + LC_i + OMC_i \qquad (24)$$

where:
ACCi = annualized capital cost of treatment unit-i, $
LCi = land cost of treatment unit-i, $
OMCi = annual operation and maintenance cost of treatment unit-i, $.

The annualized capital cost can be determined by spreading out the capital cost over a given number of years at a specific interest rate, and is defined as [14];

$$ACC_i = CC_i \times CRF \qquad (25)$$

$$CRF = \frac{m(1+m)^n}{[(1+m)^n - 1]} \qquad (26)$$

where CCi is the capital cost of treatment unit-i, CRF is capital recovery factor, m is the interest rate per year, and n is the number of years over which the cost will be spread. In this study, all the capital costs shall be spread over a period of 20 years at a 8 percent annual rate of interest.

This train incorporates ion exchange process. For this treatment plant, Eq.(25) can be rewritten as;

$$f(x_{1,\ldots,}x_j) = C_{ion} \qquad (27)$$

where; j=1,…..,5 and x6j ϵ { F, BD, SFR, REG, BWR }

For ion exchange unit, the annual cost function is rewritten as;

$$C_{ion} = ACC_{ion} + LC_{ion} + OMC_{ion} \qquad (28)$$

$$CC_{ion} = P_R \times V_T + P_{co} \times A_T + P_{BP} \times N_{BP} + P_{RP} \times N_{RP} + P_{salt} \times M_s \qquad (29)$$

where:
PR = unit Price of Duolite C20 resin, $/m3
VT = total volume of the resin, m3
Pco = unit price of ion exchange column, $/m2
AT = total area required for ion exchange, m2
PBP= price of backwash pumps, $/pump
NBP = No. of backwash pumps
PRP = unit Price of regeneration pumps, $/pump
NRP = No. of regeneration pumps
Psalt = price of salt for regeneration, $/Kg
Ms = total mass of salt used for regeneration, kg

The land and annual operation and maintenance costs were calculated as;

$$LC_{io} = N_c \times C_c \times A_c \qquad (30)$$

where AC is the cross sectional area of ion exchange bed (m2) and Nc is the number of ion exchange columns. While, the operation and maintenance cost was determined as;

$$OM_{io} = \frac{1.1 \times 8760}{T_C} \left(IP_{BP} \times N_{BP} + IP_{RP} \times N_{RP} \right) \times P_p \quad (31)$$

where IPBP and IPRP are input of backwash and regeneration pumps (kW), respectively, and Tc is the total cycle time .

Specification of Design Variable Constraints

The objective functions were subjected to a set of design and behavioral constraints. These constraints define the physical boundaries of the decision variables and are written in the form of equality or inequality functions, and as shown below:

The constraints of this plant can be stated as follows:

a) The hardness of the ion exchange effluent is not exceeding 50mg/l. The effluent hardness (Hef) was calculated using the following equation [3];

$$H_{ef} = H_{in} \times F + L \times H_{in} \times (1 - F) \quad (32)$$

b) The ratio of bed expansion during the backwash process is not exceeding 60%.

c) The time of the ion exchange backwash (TB) is not exceeding 30min. The value of TB was calculated using the following equation [3];

$$T_B = \frac{V_{salt}}{BWR \times N_c} \quad (33)$$

Bounds of the Design Criteria

The bounds (or boundary limits) of any problem are the minimum and maximum values of all decision variables, which are in this study, the design criteria of the different AWWT units. The boundary limits of the problem under consideration were chosen to be the most frequent applied criteria. These limits are presented in Table (2).

Table (2) the boundary limits of design criteria

Design criteria	Minimum value	Maximum value	Unit
F	0.1	0.5	
BD	0.7	0.9	m
SFR	5	40	hr
REG	2	8	m^3/m^3.hr
BWR	48	64	m/hr

F: Fraction, BD: Bed depth, SFR: Service flowrate, REG: regeneration rate, BWR: Backwash rate

2. Results and Discussion

AWWT plant includes ion exchange unit only. Here, five design criteria govern the design of this unit; F, BD, SFR, REG, and BWR.

During the application of GA in designing AWWT, the effect of varying the concentrations of influent and effluent hardness (Hin, and Hef) on optimum design criteria was studied. This was done by considering Hin values of 184, 220, and 256 mg/l and Hef values of 10, 20, 30, 40, and 50mg/l. The adopted values of Hef were selected to be within the accepted range of total hardness in water to be reused for industrial purposes. Also, the effect of varying the influent flowrate on the optimum values of design criteria was studied.

The results of GA application for the optimum design of AWWT were plotted in terms of each design criterion verses Hef for different Hin and influent flowrate values. Table (3) shows the Fig.numbers with the applied conditions and the obtained optimum values of fraction (F), service flow rate (SFR), and backwash rate (BWR). The values of other design criteria, bed depth (BD) and regeneration rate (REG), are not affected by the variation of Hin, Hef, and the influent flowrate and they are 0.71m and 8 m3/m3.hr, respectively.

Table (3) Optimum design criteria of AWWT at different influent flowrate values.

Influent flowrate	Design Criteria	Optimum values range*	Refrence figures
1.62	F	0.1-0.27	3
	SFR	7-39	4
	BWR	48-57	5
0.81	F	0.11-0.27	6
	SFR	7-40	7
	BWR	48-55	8
0.54	F	0.11-0.27	9
	SFR	6-39	10
	REG	48-60	11

*SFR in m3/m3.hr and BWR in m3/m2.hr

For the optimum design of AWWT train, the treatment cost was plotted verses Hef for the three considered values of Hin at the three values of influent flowrate. The results are shown in Figs. (12) through (14). From these figures, it can be seen that:

- The maximum cost of AWWT is obtained for minimum Hef values which are 10 and 20 mg/l at maximum Hin value.
- The treatment cost values vary over the ranges (2.1E07 -2.5E07), (4.35E07- 4.8E07), and (4.5E07- 1.0E08) $ for the minimum, average, and maximum influent flowrate, respectively. Therefore, the treatment cost
- decreases with the decrease of influent flowrate which is a reasonable logical result.

3. Conclusions

The development and application of genetic algorithm (GA) for the design of different alternatives of advanced wastewater treatment (AWWT) plant, reveal the following conclusions:

1- Genetic Algorithm was found to be powerful technique for operating and defining optimum values of the parameters used in design of the advanced wastewater treatment system.

2- A penalty function can be used to find the global optimum design of constrained problems such as of advanced wastewater treatment design and in conjugation with the genetic algorithm developed in this study.

3-Matlab was found to be a very useful tool for use as an incubator for the genetic algorithm.

4-The treatment cost increases with the increase of influent hardness and decrease of effluent hardness.

5-The optimum values of bed depth, service flowrate, regenerate flowrate, and back wash rate are 0.71m, 25m3/m3.hr, 8 m3/m3.hr, and 55 m/hr, respectively.

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List of Symbols

Symbol	**Description**
Ac	cross-section area of Ion Exchange
Acc	Annualized capital cost of treatment unit-i
AT	total area required for ion Exchange
BD	Bed depth of resin
BWR	Backwash rate
H_{if}	concentration of influent hardness
H_{ef}	concentration of effluent Hardness
hp	The pump head
IP_{bw}	Input power of backwash Pumps
L	leakage hardness
Ms	Total mass of salt used for regeneration
M_{salt}	Mass of salt
P_R	Unit price of Duolite C20 resin
Psalt	price of salt for regeneration
P	Power Input
P_{1i}	The input power
P_{co}	Unit price of ion exchange column, S/m2
PI	The unit price of land
Pp	The unit price of power
Q	Water flowrate
Qb	By pass flowrate
Qt	Actual treated flow rate
REG	Regenerant flow rate
SFR	Service flowrate
T	Temperature
T_B	Time of backwash
T_C	Cycle time
Ts	Time of service
T_R	Time of regenerant
T_{RS}	Time of rinse
V	Volume of water
V_b	Volume of resin in one column
Vs	Volume of salt solution
V_T	Total volume of the resin
ρ_W	Density of water
R	Resin

ABBREVIATIONS

AWT	Advanced wastewater treatment
ER_T	Expansion ration at temperature
GA	Genetic Algorithm
TRH	Total removed hardness
WWTP	Wastewater Treatment Plant

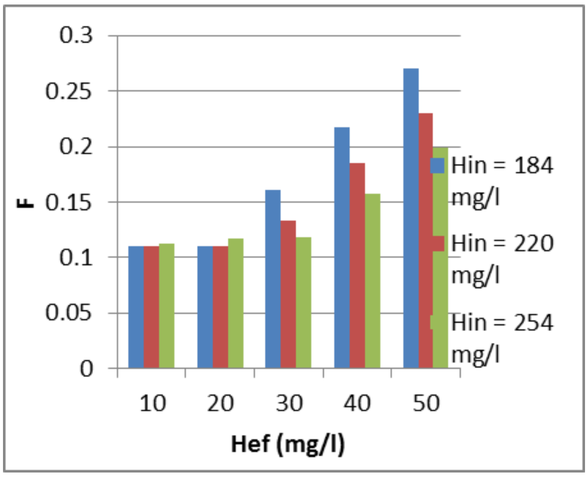

Fig.3 Effect of H_{in} and H_{ef} on F for max influent flowrate

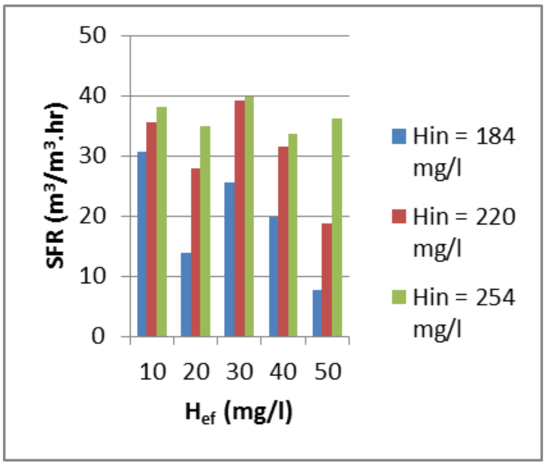

Fig.4 Effect of H_{in} and H_{ef} on SFR for max influent flowrate

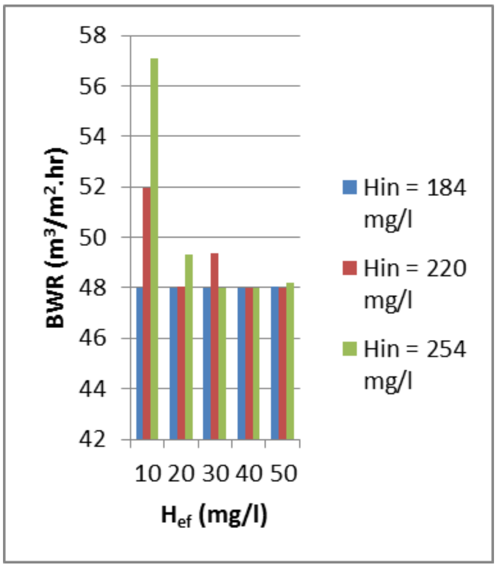

Fig.5 Effect of H_{in} and H_{ef} on BWR for max influent flowrate

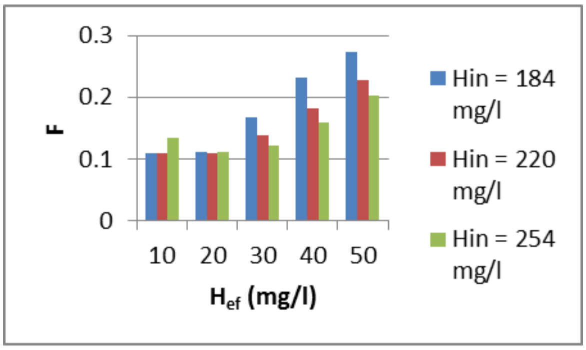

Fig.6 Effect of H_{in} and H_{ef} on F for avg. influent flowrate

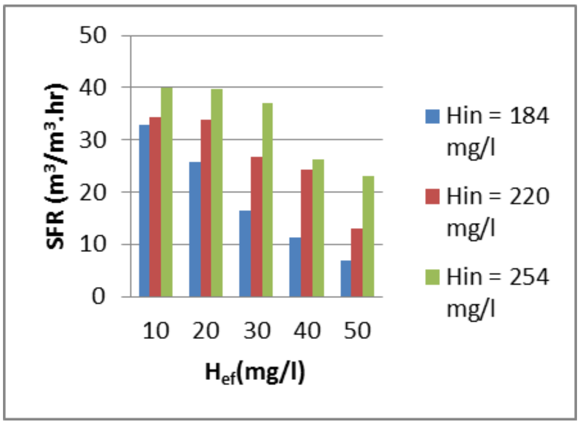

Fig.7 Effect of H_{in} and H_{ef} on SFR for avg. influent flowrate

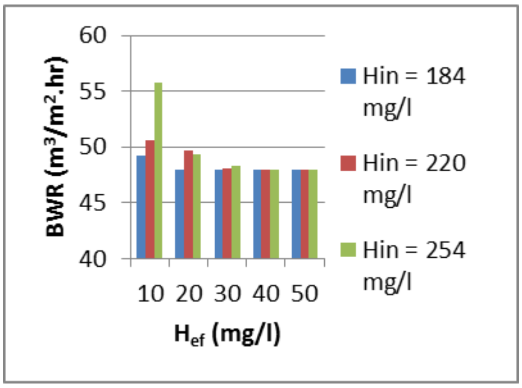

Fig.8 Effect of H_{in} and H_{ef} on BWR for avg. influent flowrate

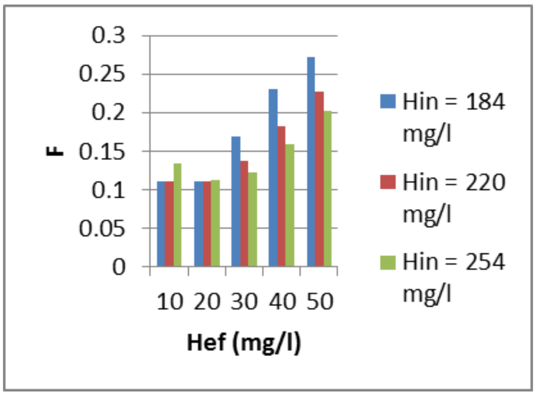

Fig.9 Effect of H_{in} and H_{ef} on F for min. influent flowrate

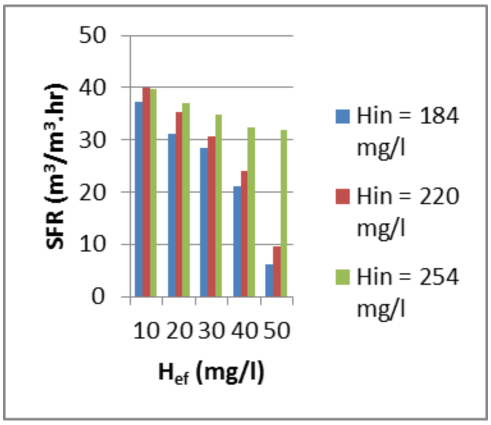

Fig.10 Effect of H_{in} and H_{ef} on SFR for min. influent flowrate

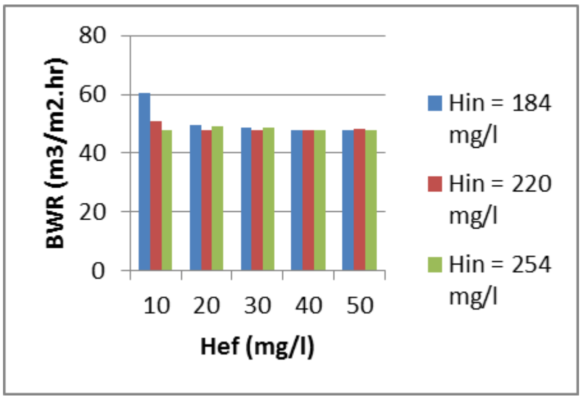

Fig.11 Effect of H_{in} and H_{ef} on BWR for max. influent flowrate.

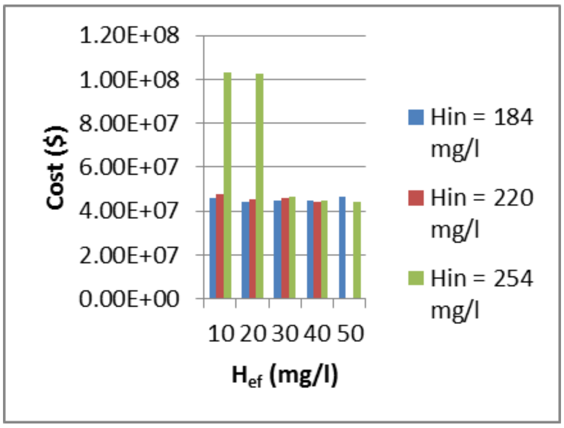

Fig.12 Effect of Hin and Hef on cost for max. influent flowrate.

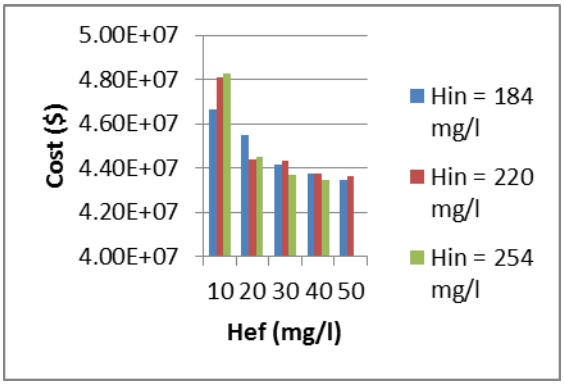

Fig.13 Effect of H_{in} and H_{ef} on cost for avg. influent flowrate

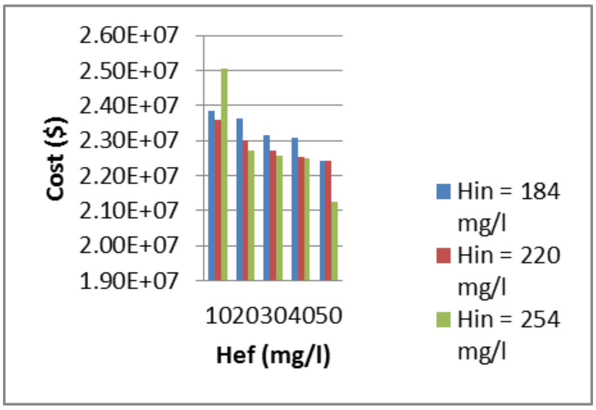

Fig.14 Effect of H_{in} and H_{ef} on cost for min. influent flowrate