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**IMPROVEMENT OF FILTRATION OPERATION BY
CHLORINATION-FILTRATION PROCESS FOR IRON REMOVAL**

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by

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Engineering

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ABSTRACT

Chlorination followed by filtration was recently reported to be one of the most efficient and economical method for iron removal compared to the other treatment methods. Based on the above findings, this study was conducted to determine the effects of both chemicals and physical parameters on the removal efficiency of the filter by this process. The study indicate about 30 percent of the stoichiometric value of the hypochlorite concentration is required for complete oxidation of ferrous to insoluble ferric state. No pH adjustment of the water is found to be necessary. It was also found that the optimum sand size for iron removal was 0.85 to 1.00 mm and the removal efficiency is dependent on the influent and effluent iron concentration and rate of filtration.

SAATCI'S (BDST) and MINT'S equation can be successfully used to predict the efficiency of the filter performance and provides a means for rational design of filter with the help of limited number of pilot-scale experiments.

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1. INTRODUCTION

1.1 General

It has been noted for a long period, that iron creates serious problems in public water supplies especially when groundwater is used for this purpose. Although human suffers no harmful effects from drinking waters containing iron, such waters are highly unacceptable from the aesthetic point of view. It should not be forgotten that iron is essential to human life. It is an element required for the formation of haemoglobin which is needed in transporting oxygen from the lungs to tissue cells. For proper nutrition, human adults require 10 to 20 mg/l of iron intake per day and that deficiency of iron in human body will cause anemia (UNDERWOOD, 1971).

The presence of iron in water causes what is commonly called "red water" which makes the water reddish brown in color (because of the hydrate oxidised iron). The presence of iron in water will also produce an astringent, metallic or bitter taste and imparts bad odor. This metal is objectionable owing to the production of discoloration, turbidity, and staining of laundry and porcelain. This effect is detectable even at very low concentrations. Its presence in water also tends to favor the growth of iron microorganisms popularly lumped together with other elements, especially manganese, under the designation "crenothrix". This form of life may thrive and cause slimes which will take up chlorine (SHAIR, 1975). These growth often develop in the distribution systems, when difficulty such as blocking of mains, meters, pipes, etc are accentuated and complaints of discolored, turbid and unpalatable water become more serious. For these aesthetic reasons and not on any other physiological considerations, the International Drinking Water Standards of the World Health Organization (WHO, 1971) recommends the permissible limits of iron for potable water to be 0.1 mg/l and a concentration of 1 mg/l is reported to be excessive. The industries on the other hand, may have more demanding requirements as to the critical concentration of the iron in their processes. Many of the industries require water which is entirely free from iron.

The present of iron, even at a very low concentration is highly unacceptable and treatment is therefore a necessity although expensive. Three common processes for removing iron as given by WONG (1984) are;

- (1) aeration-filtration,
- (2) chlorination-filtration and
- (3) potassium permanganate-manganese green sand filtration.

Various modification of this processes have been tried and developed in an effort to meet the required standards. Whatever treatment method is employed, difficulties and incomplete iron removal are often encountered (GHOSH, 1965).

1.2 Objectives of the Study

In this study, the suitability of the process of prechlorination- filtration in removing iron has been investigated. The study was conducted in three parts:

- An extensive experimental investigation was made with laboratory-scale unit to study the effects of chlorine dose, filter depth, filtration rate, filter media size and pH on removal of iron from water.
- Based on the experiments conducted, semi-empirical relationships was formulated to relate the iron removed with the physical and chemical parameters.
- Since this process is not at present widely used and design details are not available, a practical operational chart was made based on the results to guide engineers in designing such unit.

1.3 Scope of the Study

A laboratory-scale experimental unit was constructed to study the performance of chlorination-filtration process. The performance of this process was studied in terms of iron removal at different operating parameters like chlorine dose, pH, chlorination time, filter media size, filter depth and filtration rate.

- Since the Fe concentration in AIT groundwater is not sufficient, Fe at known concentration was added. This was used as raw water.
- Chlorine was added in the form of NaOCl.
- Hydrochloric acid and calcium hydroxide was added to adjust the pH at required level.
- Narrowly graded sand was used as filter medium.
- The filter run time was limited to a maximum of 8 hours only due to the time limitation. However few experiments with longer filtration time was carried out in order to observe the temporal variation of iron removal and headloss development.

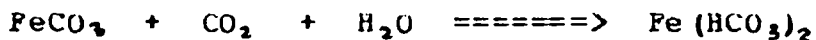
II LITERATURE REVIEW

2.1 Iron

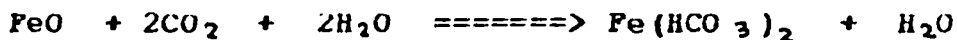
2.1.1 Sources of Iron

Iron in ground water commonly exist in soluble ferrous state, usually as ferrous carbonate. The mechanism by which iron enters water as soluble contaminant according to GHOSH (1965) is as follows:

- (1) The FeCO_3 solution in the presence of CO_2 undergoes the following reaction:

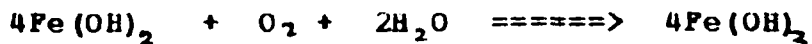
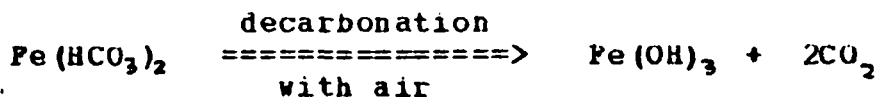


- (2) The FeCO_3 solution under anaerobic conditions, possibly facilitated by bacterial action which reduces the ferric iron to the ferrous form which then dissolved by CO_2 as shown in the following reactions:



- (3) Solution or infusion of organic colour bodies from wood, leaves and so forth. Iron is a constituent of several group of stable compounds. These compounds are not usually regarded as iron sources although they might aesthetically objectionable due to their colour.

Iron introduced by the first two mechanisms is largely responsible for the problems resulting from iron in water supplies. Ferrous iron, in general, is precipitated from solution by the oxidation to insoluble ferric hydrate, $\text{FeO} \cdot 3\text{H}_2\text{O}$, commonly denoted by $\text{Fe}(\text{OH})_3$. The precipitation process by oxidation is represented by the following reactions (BELL, 1965):



2.1.2 Chemistry of Iron

2.1.2.1 Aqueous Chemistry

The aqueous chemistry of iron is rather complex, since this metal enters into several protolysis and oxidation-reduction reaction. Figure 1.1 shows the pE-pH stability diagram and the construction details for this figure was discussed by FAUST and ALY (1981). Briefly explained, the pE-pH diagram gives the boundaries in which Fe(II) is oxidized to Fe(III) with O_2 as the electron acceptor, and is subsequently precipitated as $Fe(OH)_3$. Most natural waters have pH values ranging from 5.0 to 8.5, and pE values ranging from +2 to +12. Thus Fe(II) would be predominant iron species in the absence of an electron acceptor such as O_2 . In order to oxidize Fe(II) to Fe(III), it is necessary to raise both pE and pH values. The former maybe raised by adding such an electron acceptor like O_2 , Cl_2 or $KMnO_4$, whereas the pH value is increased through the addition of OH from $Ca(OH)_2$ or NaOH. This diagram also shows that the pE value required for oxidation is lowered as the pH value is increased. This interpretation has very pragmatic operational applications in iron removal from natural waters.

2.1.2.2 Solubility

In natural groundwater, soluble iron exists in the bivalent state. But some trivalent iron may also exist in solution especially in aquifers where low pH values are encountered. In alkaline waters devoid of sulphides, phosphates and organic compounds, iron will precipitate from aqueous solution as ferrous hydroxide, ferrous carbonate, ferric hydroxide or mixture thereof depending upon the concentration of oxidizing agent and pH (GHOSH, 1965).

The solubility of ferrous iron is reduced by any form of alkalinity. The ferrous iron existing in a carbonate bearing water has more tendency to form crystal nuclei and precipitate than when iron is in a non-carbonate bearing water at the same pH. However, $Fe(OH)_3$ has more tendency to precipitate than ferrous iron in a carbonate-bearing water. The iron is oxidized from the ferrous to ferric form by aeration or by addition of oxidizing agents. Once oxidized, the solubility of iron is limited over the range of 4 to 13 by the solubility of ferric hydroxide (GHOSH and O'CONNOR, 1966).

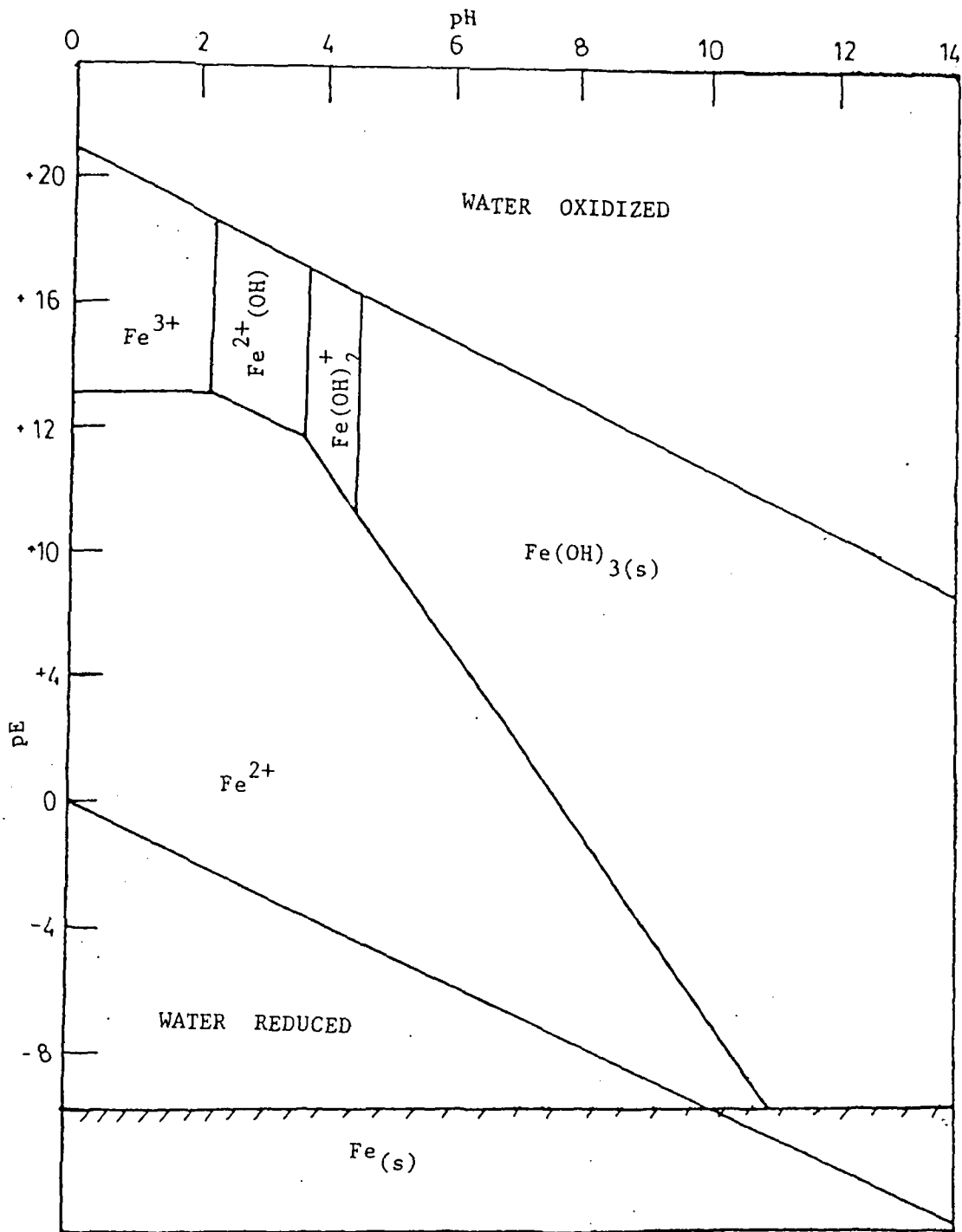


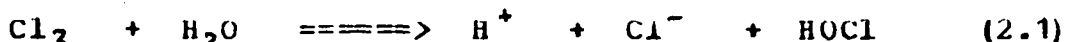
Figure 2.1 - pE - pH diagram for the iron system
(Source; Faust and Aly, 1981)

2.2 Chlorination

Chlorination is the application of chlorine either in the form of free chlorine or hypochlorite to water mainly for the purpose of disinfection. However, being a very strong oxidizing agent, it will react rapidly with many reducing substances and with organic material as well as with the bacteria.

2.2.1 Reaction with Water

When chlorine gas is dissolved in water, the hydrolysis reaction occurs rapidly to form hypochlorous acid (SAWYER and McCARTY, 1978).



The hydrolysis constant for this reaction is given by;

$$K = \frac{[\text{H}^+] [\text{Cl}^-] [\text{HOCl}]}{[\text{Cl}_2]} \quad (2.2)$$

CONNICK and CHIA (1956) studied the reaction of the above equation at different temperatures and found out that the equilibrium constant value, K , increases with increase in temperature.

PAUST and ALY (1983) stated that the extent of chlorine hydrolysis is controlled by H^+ in equation (1). At pH values greater than 3 and with Cl^- less than 100 mg/L, very little molecular chlorine is present as shown in Figure 2.2.

Hypochlorous acid which is classified as a "weak" acid, tends to undergo partial dissociation as:



to produce a hypochlorite ion and a hydrogen ion. The amount of hypochlorite ion becomes appreciable above pH 6, while molecular chlorine is non-existent. When the pH value of the chlorinated water is 7.5, 50 percent of the chlorine concentration present will be undissociated hypochlorous acid (HOCl) and 50 percent will be the hypochlorite ion, OCl^- . The higher the pH values, the greater the concentration of OCl^- ion, while the amount of HOCl becomes proportionately less as shown in Figure 2.3.

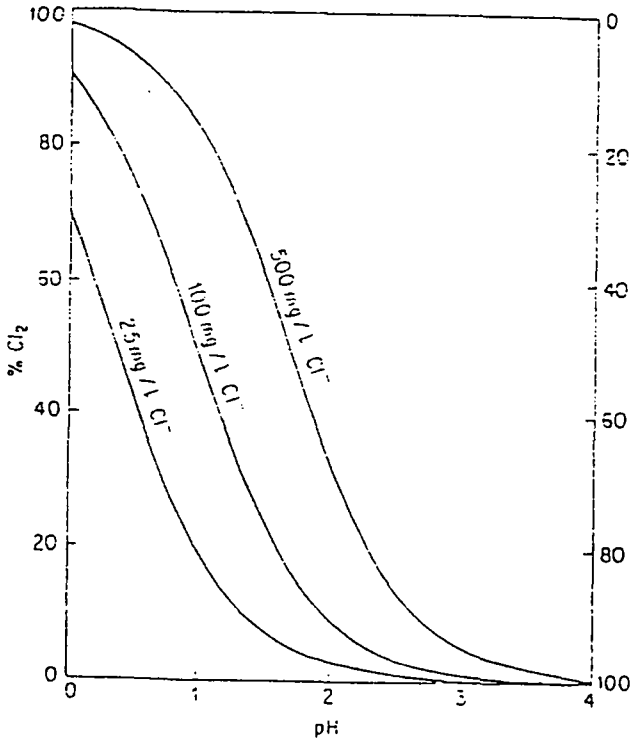


FIGURE 2.2 - Effect of pH and chloride concentration on the distribution of chlorine and hypochlorous acid in water at 25 C. (Source: SAWYER and McCARTY, 1978)

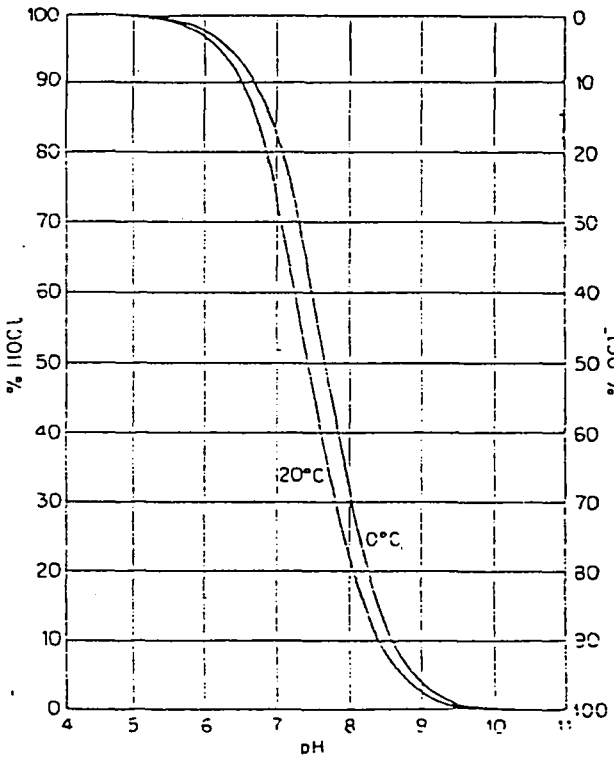


FIGURE 2.3 - Effect of pH on the distribution of hypochlorous acid and hypochlorite ion in water. (Source: SAWYER and McCARTY, 1978)

2.2.2 Reaction with Impurities in Water

Chlorine and hypochlorous acids react with wide variety of substances like ammonia and many other inorganic reducing agents like iron, manganese, etc. Ammonia reacts with chlorine forming monochloramines, dichloramines and trichloramines depending upon the relative amounts of each and to some extent upon the pH (SAWIER and McCARTY, 1978).

The reaction of chlorine with iron will be discussed in Chapter 3. WHITE (1972) stated that if the iron present is in the complex form, free residual chlorine is more effective than combined chlorine in breaking up the iron complex so that oxidation by chlorine can proceed.

Chlorine also reacts with organic compounds in water such as fulvic and humic acids forming a variety of chlorinate products (KOOK, 1971). Much of the concern is chloroform which is carcinogenic. BURSILL (1982) found out that the level of trihalomethanes in most South Australian water supplies are much higher than the standard set by the WHO (30 µg/L). This led to the concern of over the public health significance of the use of chlorine in water supplies. He stated that the factors affecting the formation of trihalomethanes are (1) the amount of chlorine dose, (2) temperature, (3) pH and, (4) type and concentration of precursor level.

2.2.3 Chlorine and Hypochlorite

Exactly the same phenomenon occurs when hypochlorite is used instead of gaseous chlorine. They are used in the form of solutions of hypochlorite and are used where local supplies are available or on-site generation from salt solutions is feasible. This compound will ionize in water to yield hypochlorite ion as illustrated below:



This ion, of course, establishes an equilibrium with hydrogen ions in accordance to equation (3). Thus, it may be concluded that the same equilibria are established in water regardless of whether chlorine or hypochlorites are added. The significant difference would be in pH effects and its influence in the relative amounts of OCl^- and HOCl in equilibrium. Chlorine tends to decrease the pH, whereas hypochlorites tend to increase the pH (SAWYER and McCARTY, 1978).

2.3 Filtration

Filtration is the process of removing solids from a fluid by passing it through a porous medium. It is widely used in water treatment to remove solids, including bacteria present in surface water, precipitated hardness from lime-softened waters and precipitated iron and manganese. It is normally preceded by coagulation and sedimentation.

2.3.1 Mechanisms of Filtration

O'MELLIA and STUMM (1964) described that the particle removal at the filter pore is given by two mechanisms:

(a) Transport Mechanism - move the particle in a filter pore so that it comes in contact with the filter media (or existing deposits of particle).

(b) Attachment Mechanism - cause the particle to adhere to the grain surface.

(a) Transport Mechanism - IVES (1961) reported that there are several transport mechanisms available which all act simultaneously during filtration. However, their relative importance depend on the characteristics of the particles (principally size, density and shape), the characteristics of flow (principally velocity, viscosity, and temperature) and characteristics of the filter media (primarily surface area, pore size, shape and volume).

The transport mechanisms that may occur are interception, diffusion and sedimentation. Interception is characterized by the ratio (e/d) , where e and d are particle and grain diameters, respectively. Diffusion is represented by the Peclet No. $(3\mu v e d / kT)$, where μ is the viscosity of water, v is the velocity of filtration, kT is the thermal energy. The smaller is this number, the better is the particle retention. This mechanism is only significant when the particle size is less than 1μ . Sedimentation is represented by the dimensionless group $g(\rho_p - \rho_w)d / 18\mu$, where ρ is the water density and ρ_p is the particle density. The larger is the group, the better is the retention.

GHOSH (1965) reported that the insoluble ferric hydrate can exist in two forms, namely, the sol form and the floc form. Sol particles can grow to larger agglomerates, i.e.,

flocs. Both are present after hydrolysis but soil particles offer much more resistance to filtration than flocs do.

(b) Attachment Mechanism - IVES (1961) defined the three principal factors that affect particle attachment to a given surface or to existing deposits of particles. These are molecular (van der Waal's) forces, electric double layer and mutual adsorption.

- (i) Molecular (van der Waal's) forces lead to attraction between particles and filter grain surface in water, although they are of extremely limited range (usually less than 50 nm).
- (ii) Electric double layer which exist at every interface between a solid and an aqueous phase. This solid side assumes an electrostatic charge which may either be positive or negative. An equivalent number of counter ions of opposite charge form a diffuse layer in the aqueous phase. When a suspended particle approaches the surface of the filter, the two diffused ion atmosphere begin to interact. If both double layers are of the same sign, this interaction will result to the formation of a repulsive potential energy.
- (iii) Mutual adsorption of polymers or hydrolysis products of aluminum or ferric salts which can form links or bridges where one end is attached to the grain, the other to the particle. In some cases, a cation can act as a link between an anionic polymers and a negative site on a surface: this has been observed with Ca^{2+} .

CLEASBY, et. al. (1962) examined detachment is a function of an increase in filtration rate. As this rate is increased, the hydrolytic shearing forces also increase, which disturbs the existing hydraulic equilibrium between the deposited solids in water.

JORDEN (1963) studied the filtration of clay through a coarse grained media. His results showed that the process primarily responsible for the removal of the suspended matter is adsorption. In addition, the removal of material of colloidal size inspite of the large pore spaces and the absence of head loss through the filter suggest removal by some processes other than straining. It is then possible that in his experiment, the adsorption was caused by an

electric interaction between the negatively charged clay material and the Schmutzdecke which is positively charged.

O'MELIA and STUMM (1964) reported that van der Waal's attractive forces increase as the particles approach each other. If the double layers of the suspended particle and the filter media are of similar signs, the interaction between the two results in the formation of repulsive potential energy, V_R , that varies approximately inversely in an exponential manner with separating distance. Summation of repulsive potential energy, V_R , and attractive potential energy, V_A , yields a curve describing the variation in net interaction energy ($V_R - V_A$) as a function of the distance.

IVES (1961) showed schematically in Figure 2.4 the net interaction energy, ($V_R - V_A$), with a repulsion hump referred to as the energy barrier. It can be seen that if any approaching particle has sufficient kinetic energy to overcome the energy barrier, it will be strongly attracted and bound to the grain surface. Also, if the barrier is reduced by diminishing the electrostatic repulsion (zeta potential) between the particle and the grain, rapid attraction is possible. These hold true for the grain with potential of the same sign.

In 1937, a mathematical evaluation of filtration was proposed by IWASAKI (1937). This is still the predominant concept of filtration based on the fact that the rate of removal per unit depth of the filter is proportional to the local concentration of the suspended solids. The following were developed by IWASAKI:

$$\frac{\partial c}{\partial L} = -\tau c \quad \dots \dots \dots (2.6)$$

$$\tau = \tau_0 + ks \quad \dots \dots \dots (2.7)$$

$$\frac{\partial c}{\partial L} + \frac{\partial s}{\partial Y} = 0 \quad \dots \dots \dots (2.8)$$

- where, C = concentration of the suspended matter in the flow
- L = depth of any point in a filter
- τ = filter coefficient
- τ_0 = initial filter coefficient
- S = amount of suspended matter arrested
- Y = filtration time

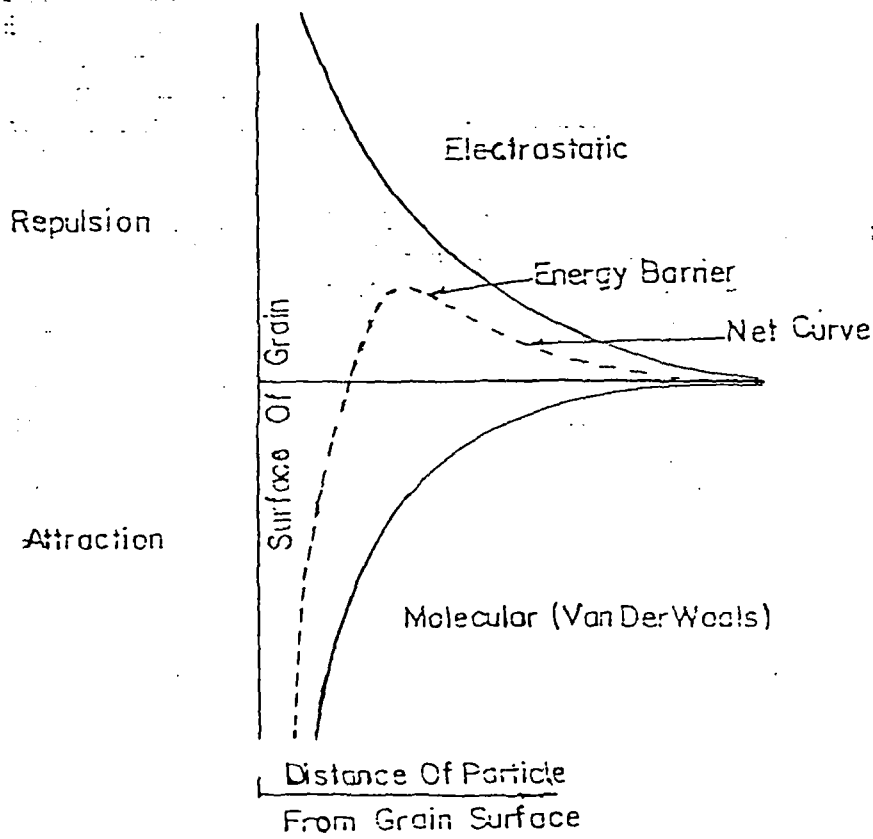


FIGURE 2.4 - Diagram of Surface Forces between Sand Grain and Particle in Suspension (After IVES, 1971)

It can be noted in equation (2.6) that the amount of suspended matter in a given layer of the filter media is proportional to the concentration of the suspended matter entering the media.

Equation (2.7) states that the proportionality factor, (length) changes with time, and as the voids of the filter become filled, the change in directly proportional to the amount of the matter filling the voids.

Equation (2.8) is a continuity equation. This states that inert matter can neither be created nor destroyed, or that the decrease in concentration of the suspended matter in the flow through the lamina is directly accounted for by the increase in the amount of the matter deposited through the lamina.

2.3.2 Hydraulics of Filtration

Under conditions commonly employed in water treatment, the hydraulics of flow in a filter are the same as the hydraulics of groundwater flow. Thus, flow in a clean and even clogged, filter bed is laminar, and Darcy's law applies (WEBER, 1972). This law states that the water velocity in a porous medium is proportional to the slope of the hydraulic gradient (CLARK and VIESSMAN, 1966) or:

$$v = K_p S, \quad (2.9)$$

where v = superficial flow velocity (L/t)
 K_p = coefficient of permeability (L/t)
 S = hydraulic gradient = hf/L (dimensionless)
 hf = head loss (L)
 L = length (depth) of filter (L)
 t = time

The consideration of head loss or energy loss during the filtration process is important. As solid particles are removed, the void spaces available for the flow decrease. Since these void spaces can be considered analogous to small pipes, any conventional expression for head or energy loss can be applied, of which an example is the Darcy-Weisbach relationship (STREETER and WYLIE, 1979).

$$hf = f \frac{L}{D} \frac{v^2}{2g} \quad (2.10)$$

where f = Darcy-Weisbach friction factor (dimensionless)
 D = pipe diameter (L)
 V = mean pipe flow velocity (L/t)
 g = gravitational acceleration (L/t²)

It can be noted that as the pipe diameter decreases, the head loss increases. It is likewise true in filtration: as filtration proceeds, the solids fill up the void spaces and the head loss increases. Application of equation (2.10) to porous media yields the classical Carman-Koozney equation (CLARK and VIESMAN, 1966)

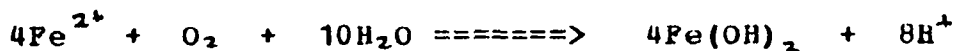
$$hf = f \frac{L}{\phi d} \frac{1 - E}{E^3} \frac{v^2}{g} \quad (2.11)$$

where f = friction factor = $150 (1 - E)/N_R + 1.75$ (ft)
 ϕ = particle shape factor (dimensionless);
 = 1 for spherical particles
 E = bed porosity (dimensionless)
 N_R = Reynolds Number = $\phi (vd)/\mu$ (dimensionless)
 d = media particle diameter (L)
 ρ = density of water (M/L)
 μ = absolute viscosity of water (M/LT)

2.4 Methods of Iron Removal

2.4.1 Aeration-Filtration

The basic equation describing the oxidation of ferrous ion by oxygen is given by



Stoichiometrically, 1mg/L of oxygen will oxidize 7 mg/L of ferrous iron. In an investigation made by STUMM and LEE (1961) on the oxygenation of ferrous ion, they found that the rate of oxygenation is a function of the ferrous ion concentration and partial pressure of oxygen (P):

$$\frac{-d(Fe)}{dt} = k^0 (Fe^{2+}) P_{O_2} \quad (2.12)$$

where k^0 is strongly dependent of pH. Their data indicated that a 100-fold increase in the rate of oxidation of ferrous ion with an increase of one pH unit.

The use of several cations has been investigated relative to their catalytic effect on the rate of oxidation. STUMM and LEE (1961) made an investigation on the catalytic effect of cupric ion on the oxygenation of ferrous ion in acid solutions. The cupric ion has been found to have pronounced effect in the reaction rate. Laboratory results also suggest that other metal ions, Mn^{2+} and Co^{2+} , are also effective catalysts.

OLDHAM and GLOYNA (1969) stated that the first approach to iron removal was put forward in 1850 when the study of dissolved iron in water was first gained importance. The research led to the development of the aeration and filtration process of removing iron from water supplies.

BROWN (1952) reported that an experimental work on the carbon dioxide and iron with the use of six coke trays aerator and sand filtration at Memphis, Tenn. The sand filter 25 cm square was constructed and the effluent from the aerator was filtered through it at the rate of 3.32 L/m²-s. The aerator dosing rate was 10.2 L/m²-s and no other chemical was added. After filtration, it was found out that only a trace amount of iron remained in the filtered water.

BRELAND and ROBINSON (1967) studied iron removal by aeration, sedimentation and filtration of five ground water in Mississippi and Alabama which has low content of alkalinity. They found out that iron removal was difficult if ground waters contain natural bicarbonate alkalinities of less than 50 mg/L as CaCO₃, even if it is left for 20 hours after aeration. The apparent cause is the failure of the ferrous ion to oxidize. However, if the alkalinity is raised above 100 mg/L as CaCO₃, complete oxidation occurs in less than one hour after oxidation.

GHOSH, O'CONNOR and ENGELBRECHT (1966) studied factors that governed the kinetics of iron precipitation in natural waters concluded that filtration has a significant role in the removal of iron from water supplies. There is often a depletion of DO in the water as it is filtered, resulting in a high iron content, in the form of ferrous, in the finished water. The depletion of DO is due to the bacterial growth which create a reducing environment of the filters. It was also observed that this reaction is accompanied by a slow decrease in the oxidation potential within the filter with increasing filtration time. This condition is probably

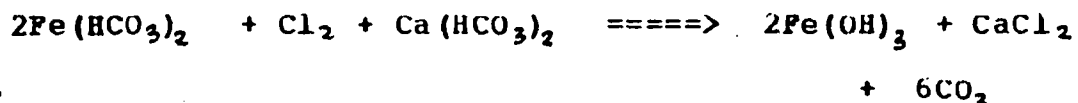
responsible for the reduction of iron from the ferric to ferrous form.

GEORGE and CHAUDHURI (1977) made the study to compare performance of coal and sand as filter media in iron removal at different filtration rates under otherwise identical condition. The result indicated that coal filter is more effective than sand filter in removing the soluble ferrous form of iron, while the effectiveness of both are comparable in removing the ferric and insoluble ferrous form. He also conducted that for comparable head-loss development and effluent quality, coal filter can be operated at a filtration rate three to four times the conventional sand-filtration rate.

OLSON and TWARDOWSKI (1975) made a study to determine if precipitation of something other than ferric hydroxide is feasible in a water treatment plant and if the filterability of this other material could be expected to be different from the filterability of ferric hydroxide. From the result, they concluded that precipitation of ferrous carbonate may occur in plants treating hard water especially when the contact time is short. Ferrous carbonate was also found to have higher filterability than ferric hydroxide. This results are consistent with studies done by ROBINSON and BRELAND (1967).

2.4.2 Chlorination-Filtration

Iron which is in the form of ferrous bicarbonate reacts with chlorine, either in the form of free or combined available, converts it to the ferric form. Depending upon the hydroxyl ion activity, the ferric chlorine formed will quickly hydrolyse to ferric hydroxide. the latter precipitates as a reddish fluffy mass, depending on the concentration of ferric ion. Omitting the intermediate reaction of the formation of ferric chloride, the reaction follows:



This reaction produces a rapid release of carbon dioxide which causes a significant rise in pH. The soluble ferrous bicarbonate is oxidized to the insoluble ferric hydroxide, which can be removed by sedimentation and/or filtration, depending on how heavy a floc is produced.

GRIFPIN and BAKER (1959) reported that this reaction will take place over a wide range of pH, i.e., 4 to 10 but the optimum pH is 7 and the maximum time it takes for complete oxidation is one hour. Stoichiometrically, each part of iron as Fe oxidized requires 0.62, 0.64, 0.67 ppm of chlorine in terms of chlorine (gas), calcium hypochlorite and sodium hypochlorite, respectively (PICEK, 1978). This reaction consumes 0.9 ppm alkalinity as calcium carbonate (CaCO_3) for each ppm iron as Fe oxidized.

The fact that chlorine can aid in the removal of iron in water has been known for a long time. BRICKSON and VEATH (1937) reported the iron removal plant in the city of Lincoln, Nebraska using chlorination process reduces the iron up to 99%. The method employed consists of aeration, chlorination, upward flow contact filters of coke or gravel, two hour sedimentation and filtration at rates of 4 $\text{g/ft}^2\text{-min}$. As a matter of operating procedure, the amount of chlorine to add to the plant is determined by the chlorine residual of the plant effluent, which is held as nearly as possible to a maximum of 0.5 ppm. After eighteen months of operation, this process is found to be entirely feasible and it is the most economical one available for the particular water at Lincoln.

MATTHEWS (1947) reported that a 9.5 ppm dosage of chlorine "completely removed" 4.5 ppm iron and yet maintaining a residual chlorine of 0.5 ppm. The flow rate was given as 11 gpm. The experimental plant consists of an aerator, contact filter, settling basin and sand filter. Efficiency of each unit was measured in terms of percentage of iron removal. It was found out that the settling basin was not an essential unit in this process, since by-passing the water iron was still completely removed but filter runs were appreciably shortened, indicating that the detention time provided by the settling basin aided in coagulating the colloidal particles, even though little sedimentation would take place. It was evident that, with small amounts of iron, the need for sedimentation would be slight, but that, with waters high in this material, provisions for a short detention time would be warranted. It was also found out that contact filter need not be used for same removal efficiency provided that sand filtration rates were held below 2 gpm.

WONG (1984) made a comparative study on the prechlorination-filtration process for iron removal using dual filter media (300 mm (0.1-1.5mm) of anthracite and 300 mm (0.5-0.7mm) of silica sand) and single media (600 mm (1.0-1.5mm) anthracite). He reported that at pH above 8.5,

chlorine reaction time of 20 minutes and filtration rate of 3.4 mm/s, the performance of dual media filter was excellent achieving more than 90 percent removal most of the time and producing iron concentration much below the recommended unit. The removal efficiency of the anthracite filter during the first few runs was relatively poor indicating that the material used were probably too coarse. However, as more particles were deposited, the efficiency increased dramatically to about 85 percent.

In an attempt to find the best chemical for iron removal, McCBAREN (1960) found out using chlorine as an oxidizing agent and lime as pH control, the iron content in the effluent was about 0.05 mg/L. The amount of chlorine and lime used were 9 mg/L and 22 mg/L respectively which produced a pH quite close to the pHs indicated for corrosion control. The unit consist of chemical feeding apparatus, a flocculation tank, a sedimentation basin and a rapid sand filter column.

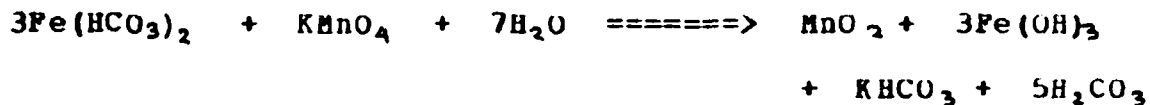
RUSSEL (1977) made the pilot study on the use of chlorination-filtration process for the removal of iron in water. The filter media used were the anthracite and sand of size 0.5-0.7mm. His results indicated that the process is very effective in removing this element at pH 8.5 and above without causing greater pressure drops. He also concluded that major savings can be achieved using this process especially for a large municipal system.

NORDELL (1961) reported that "with chlorine it is possible to oxidize iron rapidly at a lower pH than with dissolved oxygen." A rather qualitative laboratory study indicate that the chlorine, 10 ppm of Fe "was completely oxidized in less than 15 minutes at a pH of 5 whereas with air a pH of 7 was required" in a pilot plant test.

The application of chlorine to iron-bearing water is imperative regardless of whether or not it is considered a part of the iron removal process, simply to prevent and control the growth of the creniform organisms, which if allowed to proliferate, can devastate the entire system and render the iron removal process useless. It should also be emphasized that when iron is present in small quantities (0.3 ppm) where iron removal is not a factor, chlorine should be used to prevent the growth of organisms, which have been known to proliferate in water containing iron as low as 0.1 ppm (WHITE, 1971). WONG (1984) recommended that the chlorination-filtration process is to be used for removal of low iron concentration (<2.0 mg/L).

2.4.3 Potassium Permanganate - Greensand Filtration

Removal of divalent iron by oxidation with potassium permanganate has been successfully popularized in this decade. The oxidation reactions of soluble ferrous iron with potassium permanganate is as follows:



WILLEY and JENNINGS (1963), in their study using this process concluded that "dissolved iron can be effectively removed from water by continuous feeding of KMnO_4 to a water before it is passed through a manganese greensand filter."

Normally, 1-4 percent solution of potassium permanganate (KMnO_4) is continuously fed into the raw water line prior to filtration to reduce the soluble iron going to the filter. The greensand filter has the ability to oxidize as well as to filter. However, its oxidative capacity is limited, and eventually the bed must be regenerated with KMnO_4 after backwashing (WONG, 1984).

This process has the advantage in that the greensand can act as a buffer. If the feed of KMnO_4 does not oxidize all the soluble iron, the greensand will oxidize and filter this metal. Stoichiometrically, 0.92 mg of KMnO_4 is required to oxidize 1.0 mg of iron (PICEK, 1978). However, the quantity necessary to effect total oxidation of soluble iron is always less than the theoretical quantity due to the formation of secondary oxidation reaction (WELCH, 1963).

This process is generally recommended for iron concentration of less than 5 mg/L. The major disadvantages of this process are high operational cost associated with the chemical requirements and filter bed deterioration if the pH falls below 7.1 (WONG, 1984).

2.4.4 Other Methods of Iron Removal

Not all the water supplies respond to the simple method of iron removal. Due to this fact, various methods have been developed to determine the feasibility and most economical method of iron removal. Most of these methods are the modifications of the oxidation-filtration processes as mentioned above.

BOLAS (1965) for example describe the use of catalytic blankets in an upflow sedimentation tank for iron removal. His plant consisted of an aerator, a contact tank, three

upflow sedimentation tanks and filters. Lime was used as coagulant and was applied at two consecutive points between the aerator and the upflow sedimentation tanks. He reported that the plant was able to remove iron completely even when the influent concentration exceeds 15 mg/L. HUM (1978) use the same model for different coagulants to determine the most efficient and economical chemicals to be used. He concluded that the methods adapted are expensive and suggested the use of a pressure filter either of sand or diatomaceous earth for more practical alternative.

EQUINA (1979) made a study to determine whether pretreatment method of using horizontal-flow filter with crushed stones can effectively remove iron contents in water. Her results showed that the length of the filter is the most important factor for iron removal. She also showed that at filtration rate of $0.4 \text{ m}^3/\text{m}^2\text{-h}$ the influent iron concentration of 1.24 mg/L can be removed up to 47 percent.

Ferrous iron can also be removed by ion-exchanged method. Regeneration is accomplished with NaCl. It is necessary to consider the hardness content when sizing and designing the capacity of the ion exchanger for the ferrous removal. A "rule of thumb" is 0.5 ppm Fe/ppm of hardness up to maximum of 50 ppm (NORDELL, 1961). No preaeration is allowed to prevent the precipitation of ferric hydroxide which will foul the bed.

COOGAN (1963) studied the removal of iron using diatomite filtration to treat groundwaters at Massachusetts. Aeration and KMnO_4 was used to oxidize the ferrous iron before the diatomite filtration. The pressure filter was precoated with 0.15 lb/ft^2 of diatomaceous earth and was operated at a flow of 1 gpm/ft^2 . His result showed that the influent iron concentration of 6-11 mg/L was reduced to 0.02 mg/L at least 50 percent of the time. One of the operational difficulties arose from the use of lime for the alkalinity control. Filter runs as measured by headloss were short with lime but were lengthened considerably when soda ash was employed. BELL (1965) also reported upon the diatomite filtration removal of iron from groundwaters. Pilot-plant experiment with several "filter aids" (body feeds) supplemented with MgO produced substantial reductions in iron contents ($< 0.01 \text{ ppm}$). Filter runs up to 400 hours were obtained and preaeration was not needed for this process.

III EXPERIMENTAL INVESTIGATION

3.1 Description of Experimental Set-Up

The schematic diagram of the experimental set-up is shown in Fig. 3.1. This system was designed to provide a constant head above the filter bed and a constant as well as steady oxidant dosage. The main unit consists of the following:

- a) Ground raw water tank with electric stirrer.

A 100 liter tank with a stirrer rotating at a speed of 17.5 rpm was installed.

- b) Constant Head Tank.

A feeding pump was used to supply the raw water from the raw water tank into this tank. For keeping a constant level, an overflow arrangement was provided.

- c) Hypochlorite Addition

Sodium hypochlorite in the form of solution of known concentration was pumped into the pipe carrying iron containing water continuously in order to oxidize the iron present in the water before going to the filter.

- d) Filter Column

A 10 cm. in diameter and 1 meter long of perspex tubing was used as the filter column. Sampling facilities and headloss measurement arrangements were made for every 10 cm. intervals.

- e) Flow Controller

A rotameter was installed at the effluent end of the column for maintaining the constant flow throughout the filter run. The filtration rate was adjusted manually by adjusting either the rotameter or the gate valve installed on top of the filter column.

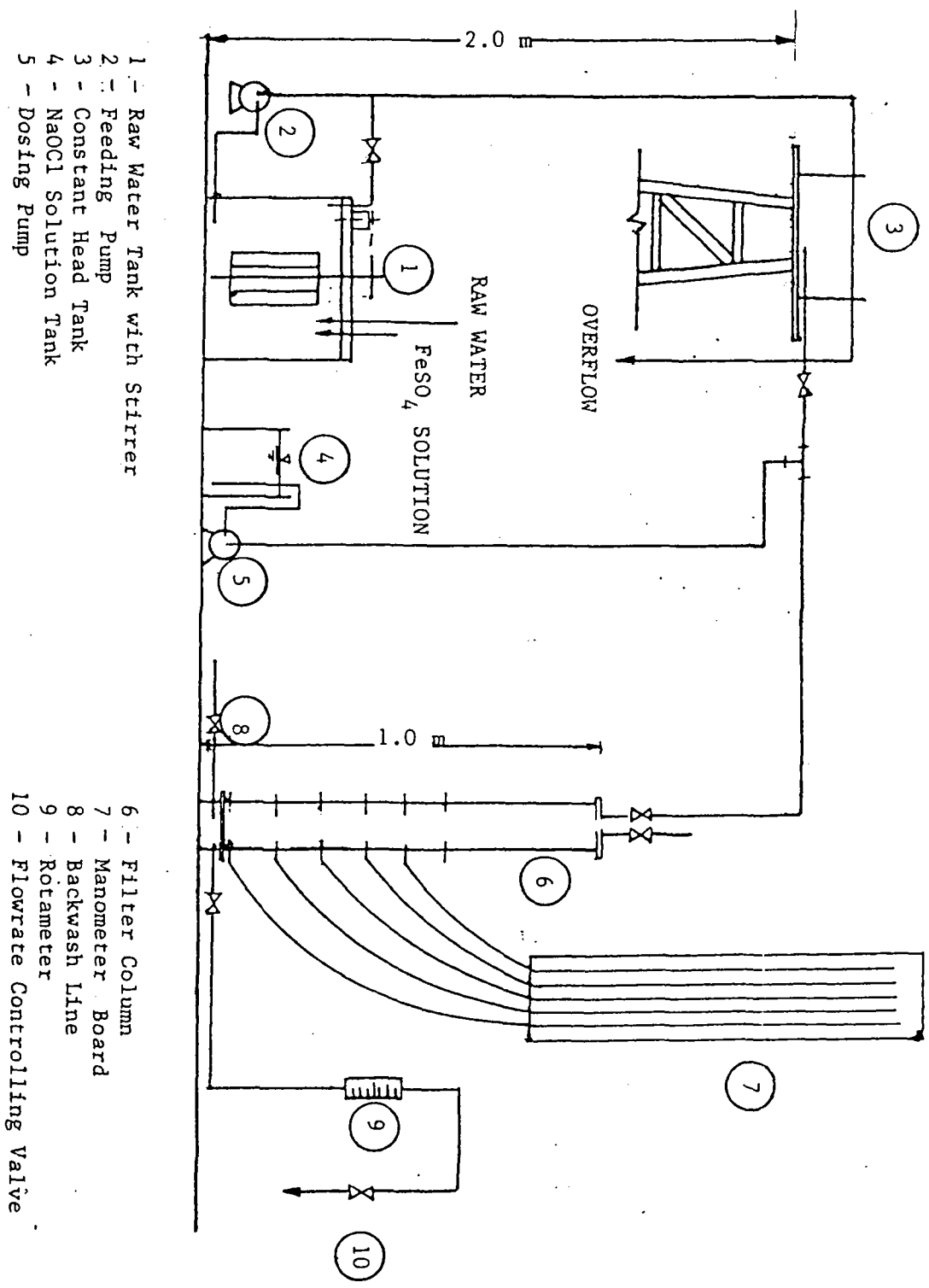


FIGURE 3.1 - EXPERIMENTAL SET - UP

3.2 Chemicals and Materials Used

3.2.1 Chemicals

The chemicals used in this study were:

1) Ferrous Sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) Solution

This chemical was used to increase the required iron concentration of the influent. It was prepared by dissolving ferrous sulphate salt in distilled water acidified with hydrochloric acid to prevent the formation of ferric hydroxide precipitation. This solution was fed continuously in the raw water tank.

2) Sodium Hydroxide (NaOH) Solution

6N of sodium hydroxide solution was prepared and added to the raw water tank to maintain the pH when studying the effect of pH on iron removal.

3) Sodium Hypochlorite (NaOCl) Solution

This chemical was added as the source of chlorine. It was used as an oxidant which oxidized the soluble ferrous iron into an insoluble ferric hydroxide which then precipitated and filtered in the following filtration column.

4) The other chemicals used in this study are for the determination of iron concentration (Standard Methods, 1982).

3.2.2 Materials

The materials used in this study were:

3.2.2a Filter Medium

Three different sizes of narrowly graded sand were used as filter medium. The characteristics of the sand is shown in Table 3.2. The sand was rinsed with acid, thoroughly washed and dried before it was filled inside the filter column.

Table 3.2 Characteristics of Sand Used as Filter Media

Sand Size (mm)		Geometric Mean Size (mm)	Porosity
> Sieve Size	< Sieve Size		
0.50	0.60	$\sqrt{0.5 \times 0.6} = 0.55$	0.45
0.85	1.00	$\sqrt{0.85 \times 1} = 0.92$	0.44
1.20	1.40	$\sqrt{1.2 \times 1.4} = 1.33$	0.45

3.2.2b Water

AIT raw water was used in all the experiments. This is from the groundwater supply. The chemical composition of the water is shown in Table 4.1. Since the iron content of this water was not appreciable, appropriate quantities of ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) was added to give the desired influent iron concentration.

3.3 Measurement

3.3.1 Iron Concentration

The measurement of iron concentrations was done by Orthophenanthroline Method as outlined in the Standard Methods. The influent iron concentration was measured several instances and the average value was taken. Sampling of the filtered water was done hourly and was accomplished by collecting the effluent from the five sampling points along the depth of the columns at the rate of approximately 5 ml per minute. The continuous dripping technique was used so that sampling would not cause any disturbances to the filter or the accumulated deposits in the filter pores.

3.3.2 Sodium Hypochlorite Concentration

The stock solution (concentration = 12%) provided was diluted to required concentration in distilled water and standardized periodically to determine the exact concentration using Ideometric Method as outlined in Standard Methods (1982).

3.3.3 pH

The pH of the influent water was measured several times to determine the average pH. An hourly determination of pH was also made for the effluent water. It was measured using a digital pH meter.

3.3.4 Headloss

The headloss was measured directly from the manometer board every thirty minutes during the first four hours and hourly measurements were carried out thereafter.

IV PRESENTATION OF RESULTS AND DISCUSSION

4.1 Characteristics of Groundwater

The results of the laboratory investigation on the characteristics of groundwater is given in Table 4.1. The dissolved oxygen present is significant which is in the range of 3.5 to 4.2 mg/l and this will definitely have an effect on the ferrous content of the groundwater. The observed total iron concentration is not completely in the form of ferrous iron which means that oxidation to the ferric state has taken place. The groundwater used is not in the very hard range. SAWYER (1960) classified very hard waters to have total hardness greater than 300 mg/l. The alkalinity values are in excess of hardness which according to LONGLEY, et. al. (1962), will favor more rapid oxidation of the ferrous iron.

Table 4.1 - Chemical Analyses of the Groundwater

Parameter	Values
Total Iron	0.20 - 0.50 mg/l
Ferrous Iron	0.16 - 0.45 mg/l
pH	7.5 - 7.8
Alkalinity (as CaCO ₃)	370 - 394 mg/l
Total Hardness (as CaCO ₃)	130 - 142 mg/l
Dissolved Oxygen	3.5 - 4.2 mg/l
Carbon Dioxide	22 - 23 mg/l
Ammonia Nitrogen	nil

4.2 Results of the Jar Test

A series of Jar Test experiments were conducted to determine the optimum dosage of hypochlorite for maximum precipitation. This test is necessary to find the correct amount of hypochlorite concentration that is to be used in the filtration process. Figure 4.1 shows the percentage

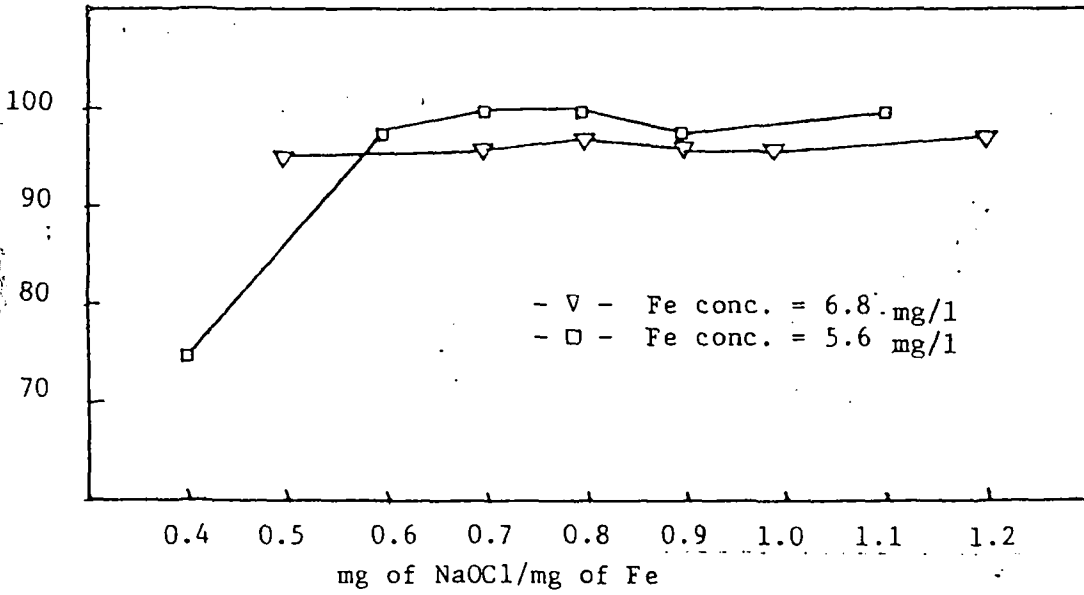


Figure 4.1 - The Optimum NaOCl Dosage Determination by Jar Test (Initial pH = 6.5)

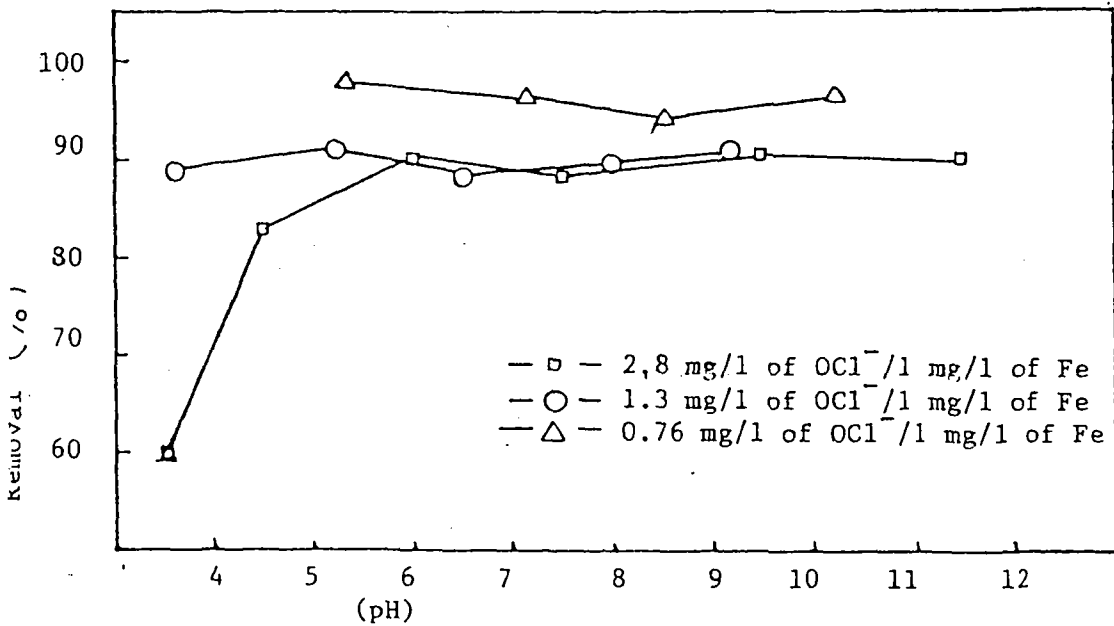


Figure 4.2 - The Optimum pH Determination by Jar Test

removal on the iron in the water for different hypochlorite dosage at pH of 6.5. The contact time is 15 minutes and the speed of the stirrer is set at 15 rpm. It can be seen that the maximum precipitation occurs when 0.7 mg of NaOCl was added per 1 mg of Fe⁺⁺. Initial iron concentration was 5.6 mg/l. When the iron concentration was increased to 6.8 mg/l the percentage removal was slightly reduced. The removal efficiency was practically constant when the hypochlorite dosage was varied (Above the dose of 0.7 mg of NaOCl per mg of iron.)

Figure 4.2 shows the results of another series of Jar Test experiments used to determine the range of pH for the oxidation of soluble ferrous iron to insoluble ferric form. This figure shows that there is no optimum pH and the oxidation takes place at a wide pH range; i. e., from pH 6 onwards. It was visually observed that at higher pH, a gelatinous type of floc was formed and this settled very slowly. Based on this results, a pH of the raw water was maintained greater than 6 for techno-economical reasons.

Table 4.2 shows the variation of the pH during the Jar Test when hypochlorite was added. It can be seen that the increase is significant for lower pH values and remain the same when the initial pH is high.

Table 4.2 - Effect of pH

Initial pH	pH after reacting with NaOCl
3.4	4.6
4.8	5.9
7.3	7.8
9.3	9.2
10.6	10.4

(When 0.7 ppm of NaOCl solution was added to water containing 1 ppm of iron)

4.3 Filter Run Results

4.3.1 Effects of NaOCl Dosage on Iron Removal

The effects of NaOCl on iron removal is illustrated in Fig. 4.3. As can be seen from this figure, the efficiency removal increased with the increase in NaOCl. This is due to the fact that only a portion of the iron in the water is oxidized when low NaOCl doses were used. It is to be mentioned here that when NaOCl dosage is increased to 3.5, 5.0 and 6.5 mg/l (0.83, 1.21 and 1.55 mg/l of NaOCl per 1 mg/l of iron respectively) the quality of effluent is almost the same in the context of iron removal.

The equal removal at dosage of 3.5, 5.0 and 6.0 mg/l is due to the fact that the oxidation of soluble ferrous to insoluble ferric has already been completed. No additional hypochlorite is then required above this concentration since the saturation point has been reached.

As far as the headloss is concerned, Figure 4.3b shows that the headloss for NaOCl dosage of 0.48 mg per 1 mg/l of Fe is less than the other higher dosages although the initial headloss is almost the same for all doses.

In general the headloss development was higher at higher hypochlorite doses. For optimum and economic reasons, it is therefore suggested that the minimum of 0.83 mg/l of NaOCl should be applied to the water containing 1 mg/l of iron for total oxidation to take place. (Note: the stoichiometric value for complete oxidation is 0.67 mg of NaOCl per 1 mg of iron).

4.3.2 Effects of pH on Iron Removal

Throughout the whole period of the experiment, no attempt has been made to adjust the pH of the raw water since the daily fluctuation is not very significant. From the Jar Test experiment carried out, it was found out that the oxidation takes place on a wide range of pH. However, one experiment was conducted at pH of 9.5 to compare the iron removal efficiency with other test done at pH of 7.7 (Figure 4.4). It can be seen that the quality of the effluent is better at pH 9.5 than that at pH 7.8. On the other hand, the headloss development was higher for pH 9.5 than 7.8. This may be due to the thick gelatinous type of flocs formation at higher pH. These flocs enter into the pores in between the grain thus reducing the passage of ferric iron through the filter. Although the removal efficiency is high because of the greater headloss development (i.e., almost 3 times than the headloss developed at pH 7.8 in 8 hours), the idea to increase the pH for iron removal is not recommended. WONG (1984) reported that the use of high pH (above 8.5) was necessary for treating

iron and manganese by these process. This may be true if manganese is also present in the water. Methods which are

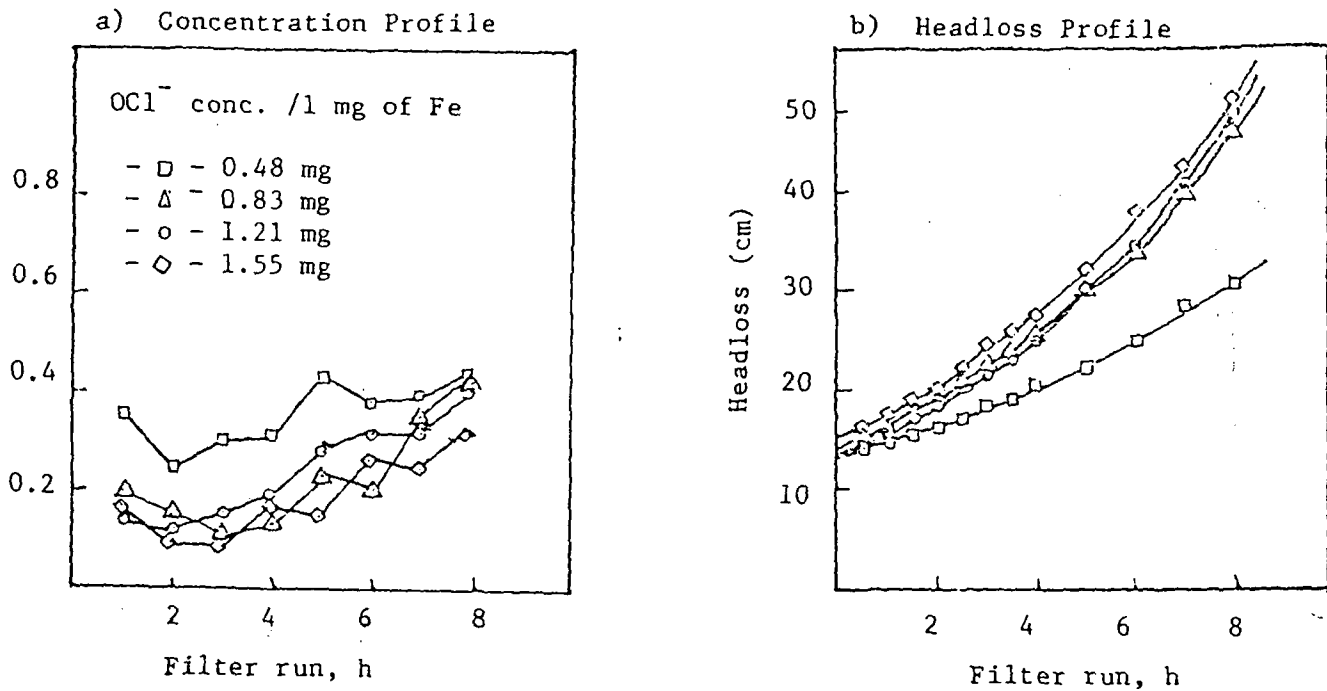


Figure 4.3 - Effect of NaOCl dosages on Iron Removal (Inf. Fe = 4.15 mg/l, pH = 7.7, depth = 40 cm, filtration rate = 10 m³/m²-h, sand size = 0.85 - 1.00 mm)

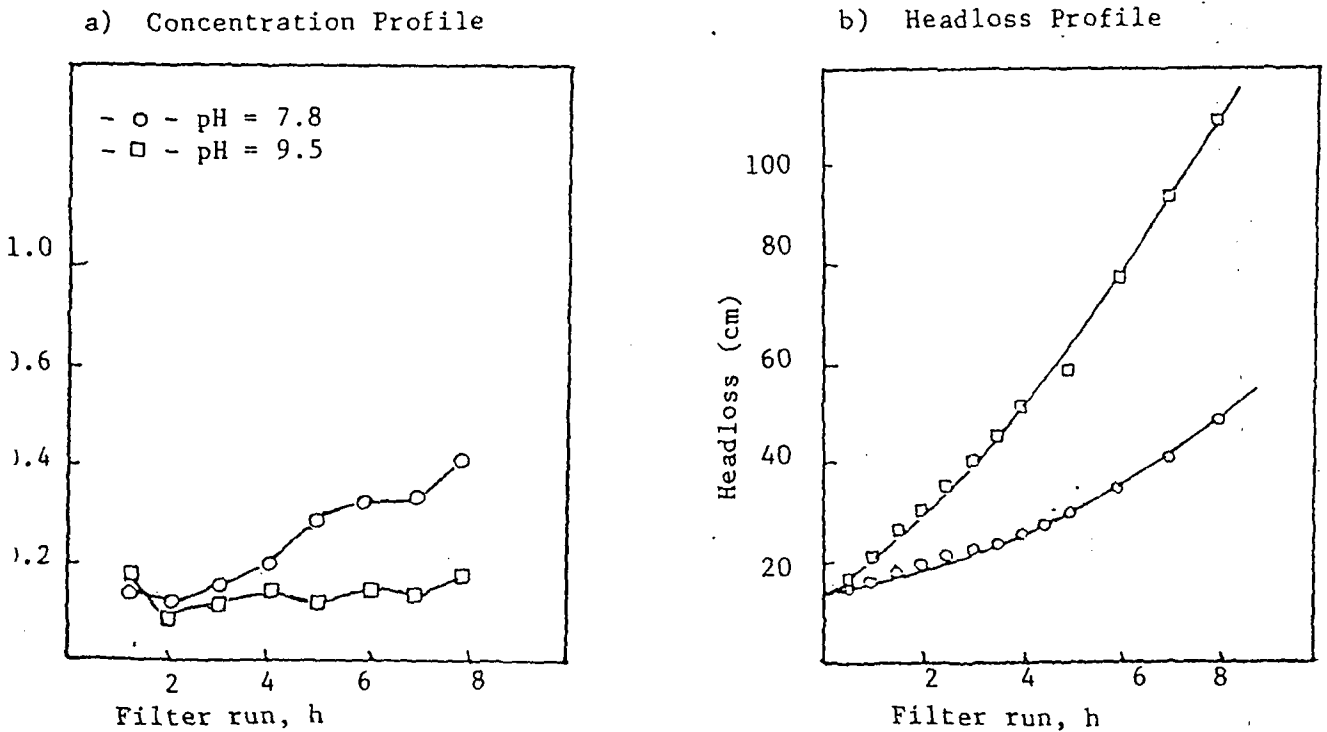


Figure 4.4 - Effect of pH on Iron Removal (Inf. Fe = 4.2 mg/l, NaOCl ≈ 5 mg/l, depth = 40 cm, filtration rate = 10 m³/m²-h, sand size = 0.85 - 1.00 mm)

successful in removing manganese are also effective in removing iron, but the reverse is not true. MATTHEWS (1947) reported that a large number of iron removal plants employing aeration, sedimentation, filtration and ordinary chlorination do not remove manganese.

4.3.3 Effect of Filtration Rate on Iron Removal

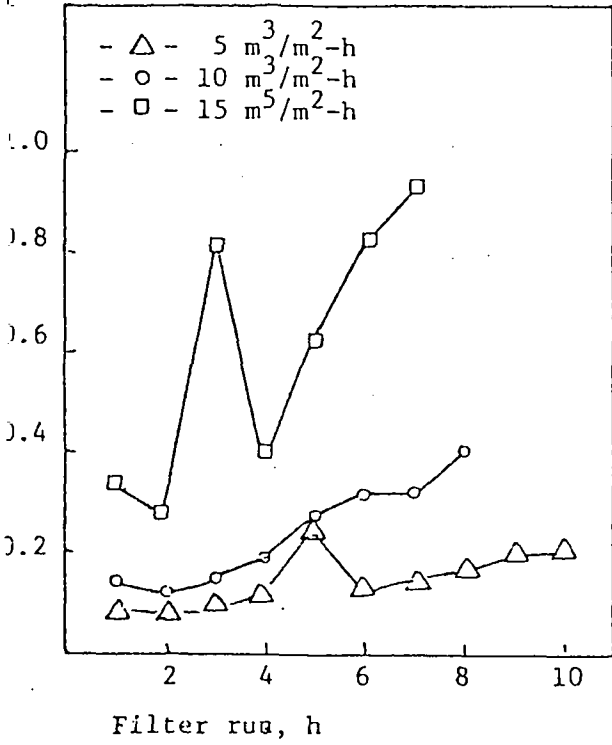
Experiments were conducted with three different filtration rates to determine their effect on the iron removal. The filtration rates used were 5, 10 and 15 $\text{m}^3/\text{m}^2\text{-h}$ where the average influent iron concentration were kept at 4.20, 4.12 and 4.24 mg/l respectively. The hypochlorite dosage was maintained at 5 mg/l and the sampling point was at 40 cm of filter depth for all the different filtration rates tested. The effect of filtration rate is shown in Figure 4.5. It can be seen that when the filtration rate is set at 5 $\text{m}^3/\text{m}^2\text{-h}$, the effluent concentration was within the maximum desirable level of 0.3 ppm even after 10 hours of filter run. The corresponding headloss was found to be only 22 cm. When the filtration rate was doubled, the effluent quality deteriorated slightly and the concentration exceeded the maximum allowable of 0.3 ppm in 5 1/2 hours of filter run. The headloss was noted to be about 65 cm in 8 hours of run. When the filtration rate was set to 15 $\text{m}^3/\text{m}^2\text{-h}$ within 7 hours of filter run, the headloss reached up to 90 cm and the deterioration in the effluent quality seemed to be quite rapid. Higher filtration rate on the other hand, will reduce the area considerably, thus the filter construction costs. Therefore, it is necessary to choose the optimum filtration rate in techno-economical manner.

4.3.4 Effects of Filter Medium Sizes on Iron Removal

Three different filter medium sizes were used to study the effect of medium size on iron removal. The medium sizes used are 0.5 - 0.6 mm, 0.85 - 1.00 mm and 1.2 - 1.4 mm. The result of the run is shown in Figure 4.6. It can be seen clearly that for the medium size of 0.50 - 0.60 mm, the concentration of iron in the effluent was less than 0.1 mg/l for most of the time. However, the run has to be terminated after 6 hours since the headloss development was very high. The flow showed faster declining trend. Therefore, the run was continued until the time there was no way to maintain the filtration rate at 10 $\text{m}^3/\text{m}^2\text{-h}$. It can also be seen that the headloss development was at the rate of 200 mm/h, compared to the rate of headloss for medium size of 0.85 - 1.0 mm which is only 44 mm/h. When 1.2 - 1.4 mm of medium size was used, the concentration in the effluent was increased to 0.4 mg/l after the third hour of the run, whose concentration was 0.6 mg/l at the beginning of the run. The decrease in the effluent quality at the later stage indicates that the medium used was probably too coarse. The total headloss after 8 hours of the run

was only 10 cm. The headloss developed, for this medium size was at the rate of about 10 mm/h which was much less than the other

a) Concentration profile



b) Headloss profile

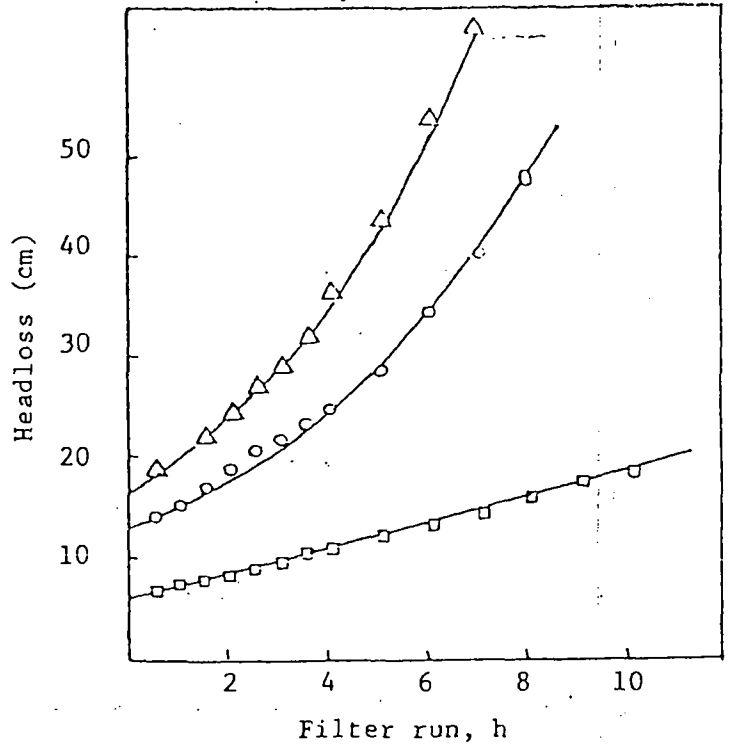
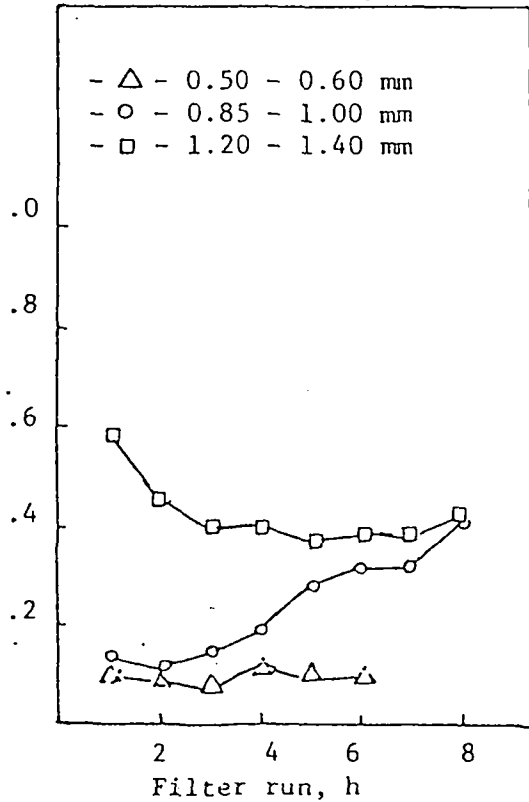


Figure 4.5 - Effect of Filtration Rate on Removal of Iron. (Inf. Fe = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8, depth = 40 cm, media size = 0.85 - 1.00 mm)

a) Concentration profile



b) Headloss profile

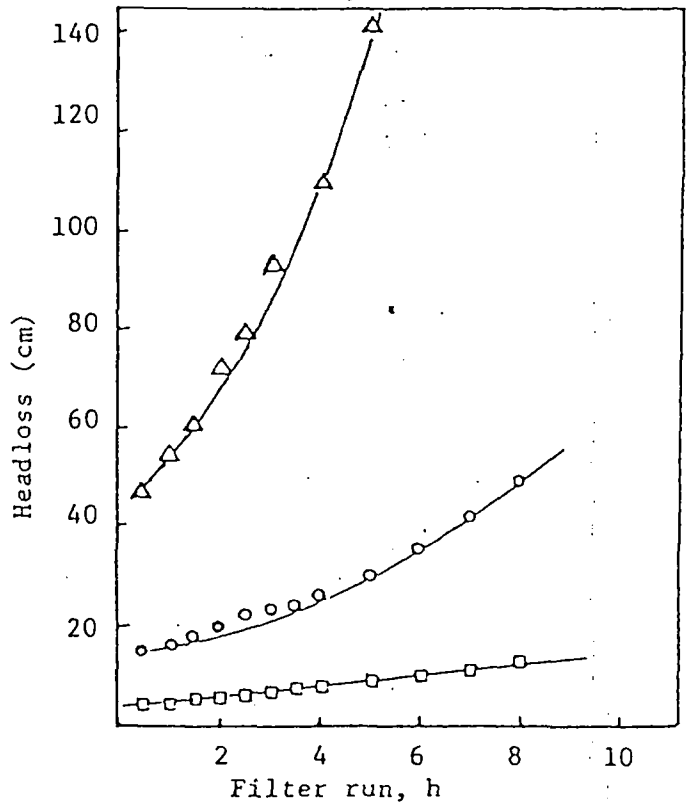


Figure 4.6 - Effect of Media Sizes on Iron Removal. (Inf. Fe = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.7, depth = 40 cm, filtration rate = $10 \text{ m}^3/\text{m}^2\text{-h}$)

two finer media used. By looking at the removal efficiency and headloss development, the medium size of 0.85 - 1.00 mm looks appropriate and this is the reason why the other experiments were conducted with 0.85 - 1.00 mm sand medium.

4.3.5 Effect of Depth on Iron Removal

The effect of depth for different operating parameters was also determined in terms of efficiency of iron removal and headloss development. Sampling points and headloss measurement points were provided at four different depths of 10 cm apart. The effluent from the 4 different depths were analyzed for total iron both when filtration rate and media sizes were varied. The results of the analysis are presented from Figure 4.7.1 through Figure 4.7.5.

Figures 4.7.1 to Figure 4.7.3 shows the effect of depth at different filtration rate. When the filtration rate was $5 \text{ m}^3/\text{m}^2\text{-h}$, it can be seen that the effluent concentration at 30 cm and 40 cm was almost the same which means that no increase in depth beyond 30 cm is required. The effluent at the depth of 10 cm seemed to deteriorate faster. The headloss was found to increase linearly for every depth measured and developed at the rate of 12 mm/h. When the filtration rate was set at $10 \text{ m}^3/\text{m}^2\text{-h}$, it was observed that the quality of the effluent not only decreased initially with the increase in depth but also the rate of deterioration at 10 cm depth was much faster than at 40 cm. The headloss development at each depth was found to develop linearly at the early hours of the run but increased exponentially afterwards. The average headloss development for each layer was found to be 44 mm/h. When the filtration rate was further increased to $15 \text{ m}^3/\text{m}^2\text{-h}$, it was observed that the effluent quality improved as the depth was increased. It can also be seen that even at the depth of 40 cm, the filter was still insufficient to provide effluent quality of desired level. The headloss development was found to be at the rate of 64 mm/h. Based on these results, it is therefore neither economical nor technically feasible to operate at $15 \text{ m}^3/\text{m}^2\text{-h}$.

The effects of depth for varying medium sizes were also investigated. As shown in Figure 4.7.4, the effluent quality for the medium size of 0.5 - 0.6 mm used was well below the allowable concentration even at the depth of 20 cm. However, this medium size resulted in very high headloss development at the rate of 200 mm/h even at the depth of 10 cm. The rate of development was found to be the same for all the depths. Due to this reason it is therefore impracticable to run the filter using this medium size especially when longer run time is needed. When 1.2 - 1.4 mm of media size was used, although it provided less headloss it did not yield sufficient iron removal even for the filter depth of 40 cm. Increasing the filter depth is possible since the headloss

development is only 10 mm/h at 40 cm depth. Figure 4.7.5 also shows that the rate of headloss development increases with the

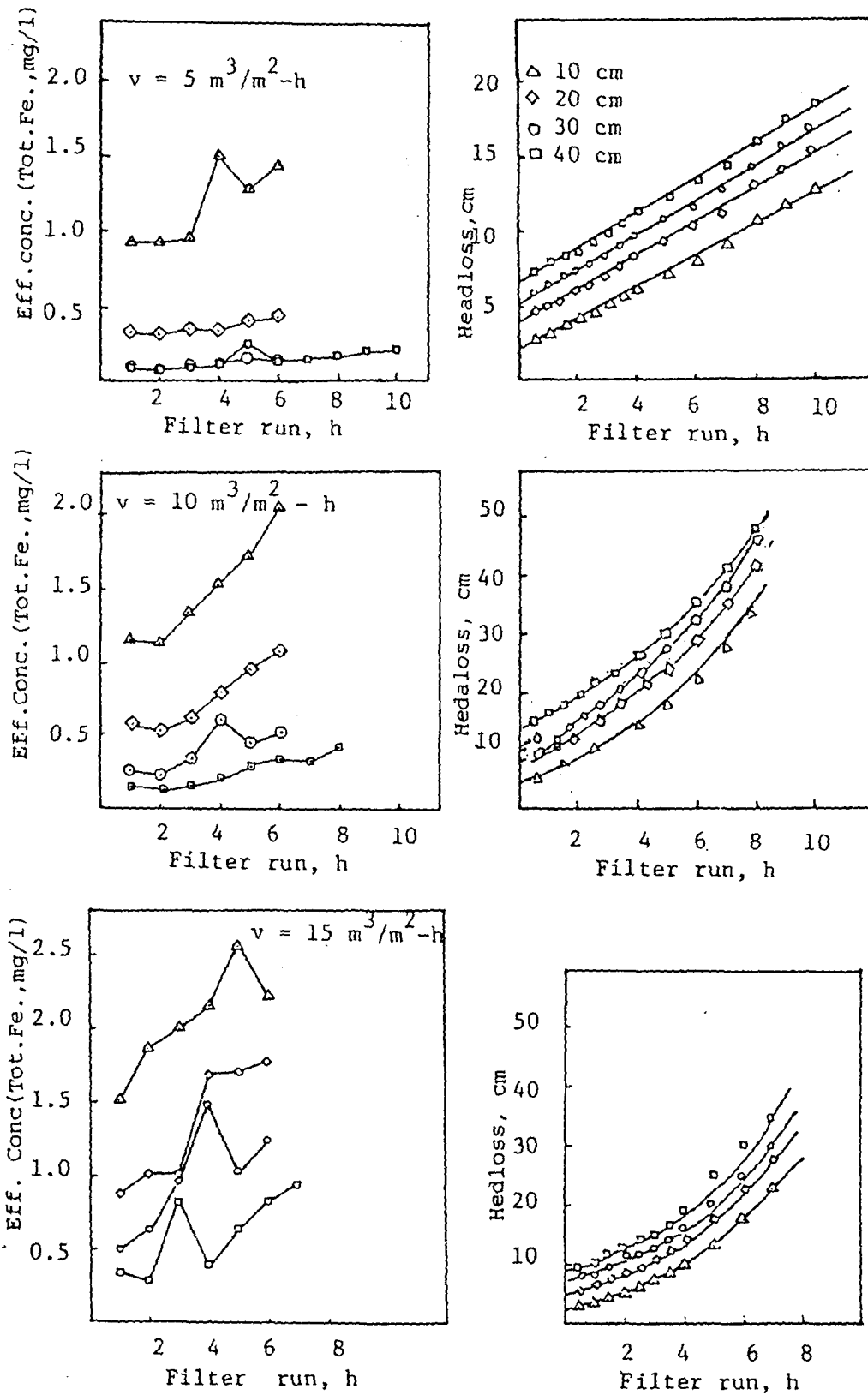
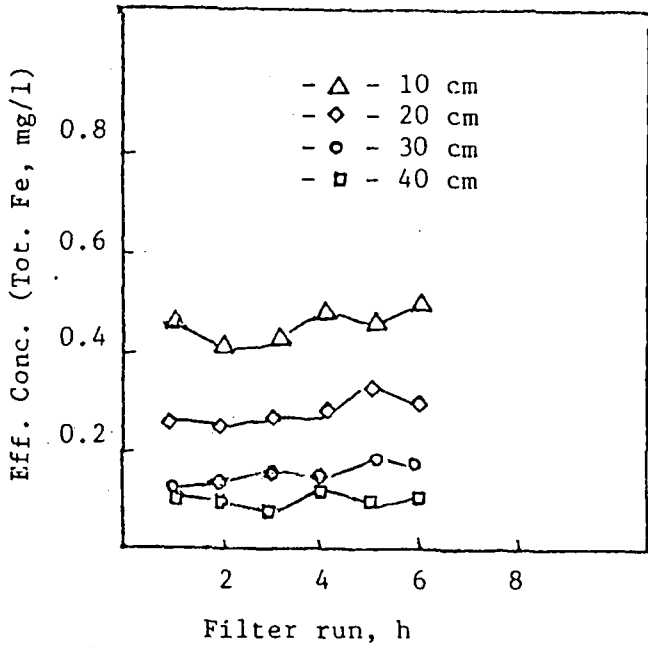


Figure 4.7 - Effect of depth on iron removal for different filtration rates and depths. (Inf. Fe = 4.24 mg/l, NaOCl = 5 mg/l, pH = 7.8, media size = 0.85 - 1.00 mm).

a) Concentration profile



b) Headloss profile

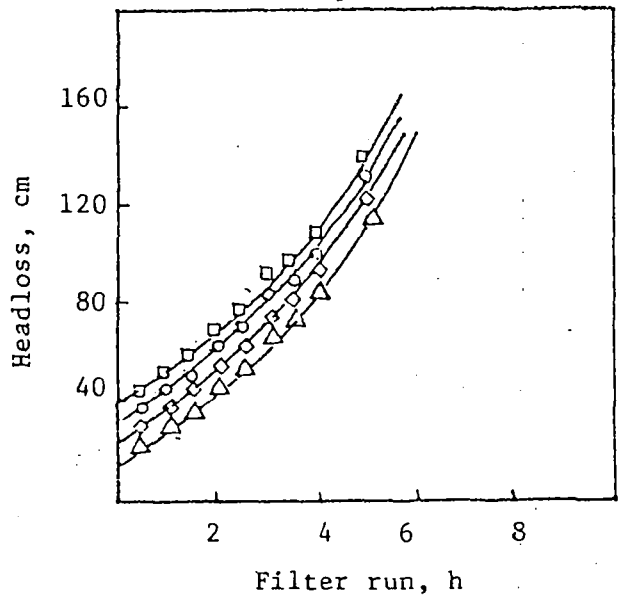
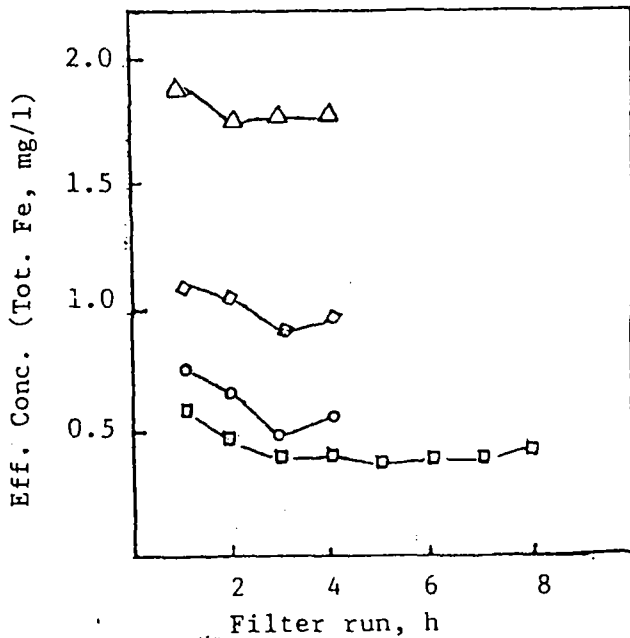


Figure 4.7.4 - Effect of Depth on Iron Removal for Media Size 0.50 - 0.60 mm
(Inf. Fe = 4.35 mg/l, NaOCl = 5 mg/l, pH = 7.8, Flow = 10 m³/m²-h)

a) Concentration profile



b) Headloss profile

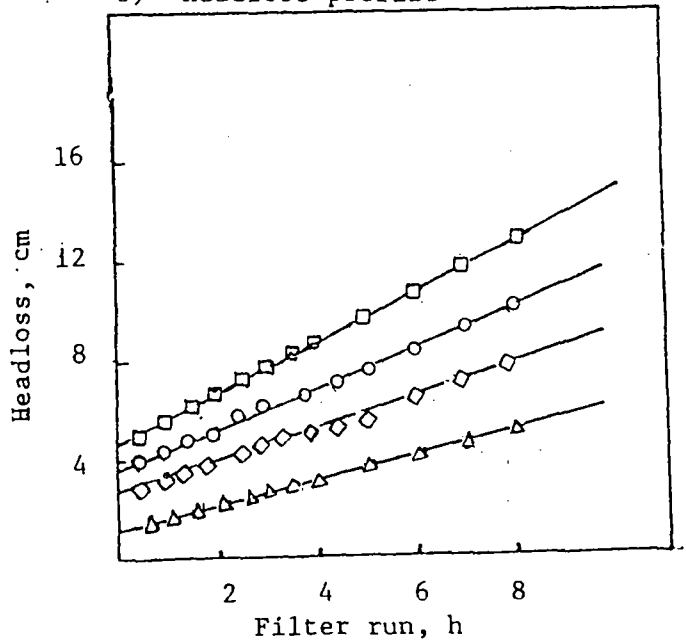


Figure 4.7.5 - Effect of filter Depth on Iron Removal for Sand Size =
1.20 - 1.40 mm. (Inf. Fe = 4.21 mg/l, NaOCl = 5 mg/l,
pH = 7.6, Flow = 10 m³/m²-h)

increase in depth. The effluent quality was also found to decrease when depth was reduced. It could not be seen how the deterioration in effluent quality took place since the effluent was only measured during the first four hours of the filter run.

V SIMULATION OF RESULTS

5.1 Mathematical Formulation for Iron Removal in the Filter

The design method described in this paper includes an analytical solution for one part of the overall problem - that of meeting the water quality criteria. The related problems of meeting the headloss and the optimization of the length of the filter run both depend on the effluent history curve (Figure 5.1) and headloss profile (Figure 5.2). The optimization based on the effluent quality breakthrough can be achieved by using Bed Depth Service Time (BDST) Method. This was developed by SAATCHI and BAUMANN (1983) to design a deep bed filter. This method provides a simple means for evaluating the coefficients needed in filter design which can provide a rational basis for the filter design of a deep bed filter.

5.1.1 Bed Depth Service Time Method

The BDST equation is based on the fact that the time for the effluent quality to exceed the desirable effluent concentration limit (i. e., to breakthrough (t) for a given maximum effluent suspended solids concentration (Cc)) depends on the depth of the filter (L), the rate of filtration (V) and the concentration of the solids in the influent (Co).

If the filter is sufficiently deep, one can formulate the following relationship between time and depth which yields a given effluent quality:

$$t = a + bL \quad (5.1)$$

where:

a = intercept

b = slope

The particle removal mechanisms in deep bed filtration is very much similar to particle adsorption in packed bed column. SAATCHI and OULMAN (1979) used the Bohart-Adam's equation (Equation 5.2) for adsorption to predict the performance of deep bed filtration where they defined

k = attachment coefficient

No = storage coefficient

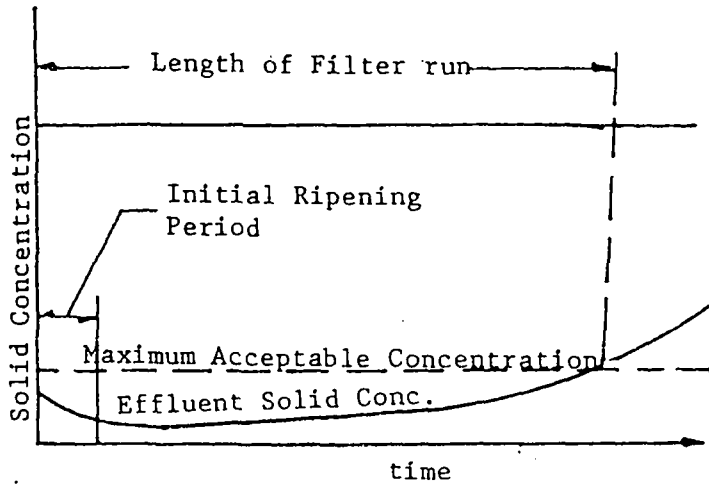


Fig. 5.1 - Effluent Quality as a Function of Time

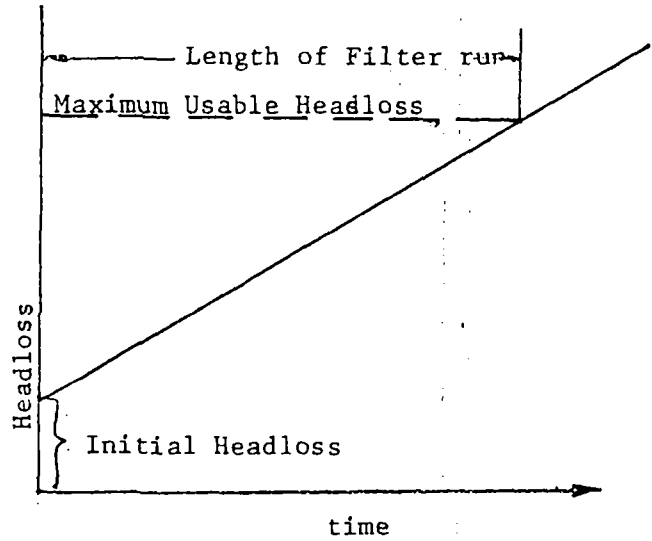


Fig. 5.2 - Headloss as a Function of Time

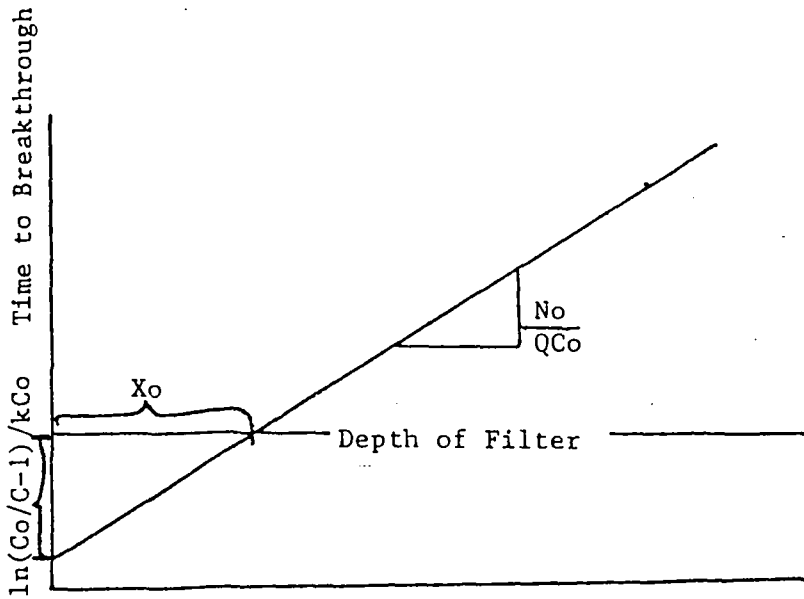


Fig. 5.3 - Time- Depth Relationship

SAATCHI's method is based on the Bohart-Adam's equation for adsorption. Bohart-Adam's equation was derived from the experimental studies to calculate the service life of activated carbon used in gas masks to remove chlorine from air. ECKENFELDER then used the equation for granular activated carbon adsorption columns. The Bohart-Adam's equation is:

$$\frac{C}{C_0} = \left[\frac{\ln(e^{kN_0L/V} - 1) - kC_0t}{+ 1} \right]^{-1} \quad (5.2)$$

where:

- C_0 = filter influent concentration, mg/l
- C = filter effluent concentration, mg/l
- k = attachment coefficient, mg/l-min
- L = filter media depth, mm
- N_0 = storage coefficient, mg/l
- V = filtration rate, mm/min
- t = filtration time, min

When L is sufficiently large,

$$\exp(kN_0L/V) \gg 1$$

and the equation 5.2 is simplified as:

$$\frac{C}{C_0} = (\exp(kN_0L/V - kC_0t) + 1)^{-1} \quad (5.3)$$

or in logarithmic form,

$$\ln(C_0/C - 1) = (kN_0L/V) - kC_0t \quad (5.4)$$

or

$$Y = A - Bt$$

Equation 5.4 can also be rewritten in the following form:

$$t = - \frac{\ln(C_0/C - 1)}{kC_0} + \frac{N_0}{VC_0} L \quad (5.5)$$

i.e.,

$$t = m + nL$$

This equation can be represented graphically as given in Figure 5.3. If t is set to zero, equation 5.5 becomes

$$X_0 = - \frac{\ln (C_0/C - 1)}{k N_0/V} \quad (5.6)$$

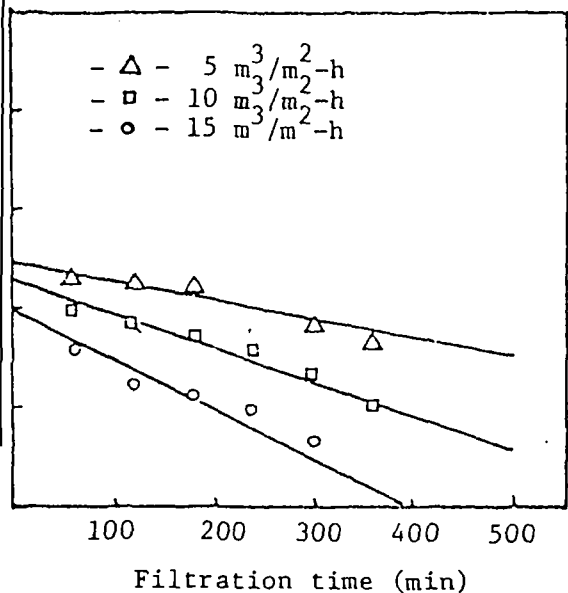
The intercept on the abscissa (X_0) represents the minimum depth of filter that would just meet the breakthrough criteria at time zero.

5.1.1.1 Determination of Storage Coefficient (N_0) and Attachment Coefficient (k)

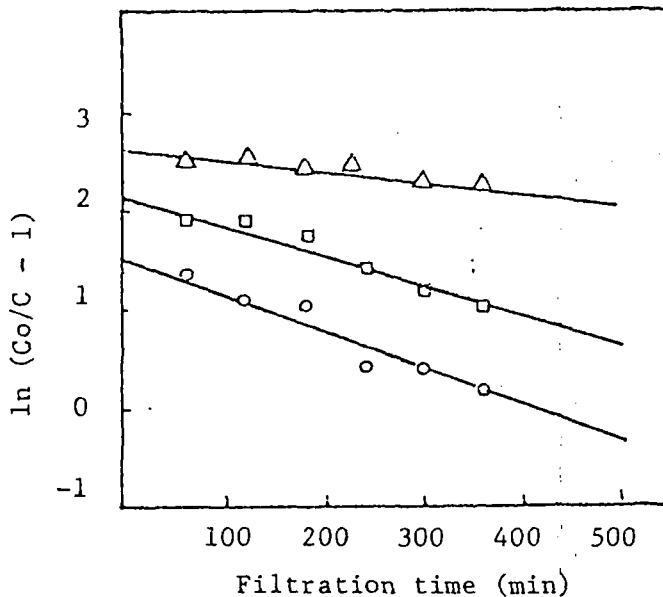
In order to determine the storage coefficient (N_0) and attachment coefficient (k), the graphs between $\ln (C_0/C - 1)$ and t were first made for different depths and filtration rates (Figure 5.4).

The gradient (B) and the intercept (A) values obtained for different filter depths are given in Table 5.1. The storage coefficient (N_0) and attachment coefficient (k) were then calculated for every depths and filtration rates and also presented in Table 5.1. In theory, the values of N_0 and k should be independent of the depth, although it varied slightly in the present experiments. The average values of N_0 and k calculated for different filtration rates are presented in Table 5.2. These values are used in subsequent calculations to derive equations which are to be used to model the complete breakthrough curve.

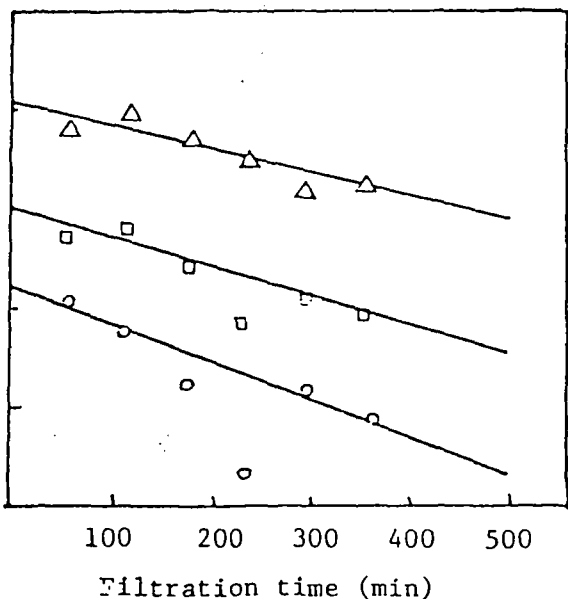
a) Depth = 10 cm



b) Depth = 20 cm



c) Depth = 30 cm



d) Depth = 40 cm

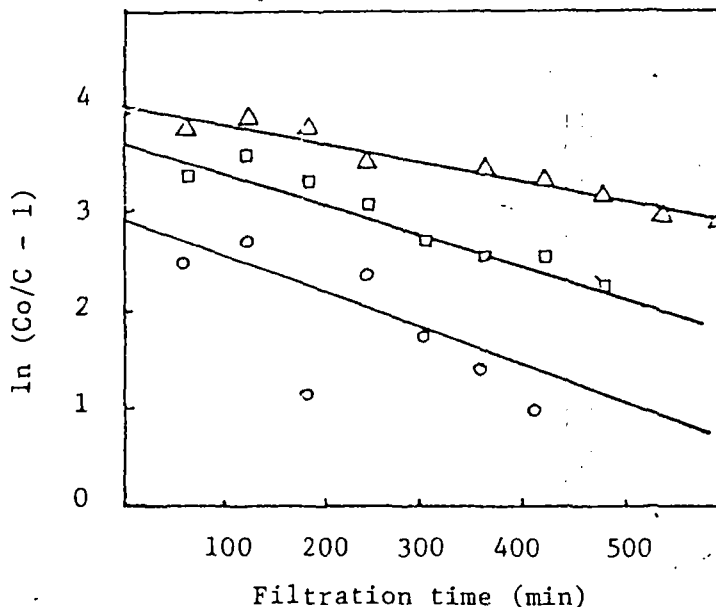


Figure 5.4 - The Relationship of $\ln (C_o/C - 1)$ with Filtration Time for Different Filtration Rates and Depths (Inf. Fe. Conc. (avg) = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8, Sand size = 0.85 - 1.00 mm)

Table 5.1 - Values of Coefficients A, B, k, and No

Flow m^3/m^2 h	Inf. Fe. conc (Co) mg/l	Depth (cm)	A	B $\times 10^{-3}$	Coeff. of Corre.	Attachment Coeff. $k \times 10^{-4}$ (mg/l-min) ⁻¹	Storage Coeff. No mg/l
5	4.20	10	1.478	-1.900	0.942	4.523	2794
		20	2.165	-1.128	0.918	2.686	3357
		30	4.072	-2.324	0.940	5.533	2043
		40	4.065	-1.839	0.977	4.378	1934
10	4.12	10	1.275	-3.247	0.971	7.881	2697
		20	2.157	-2.995	0.952	7.269	2473
		30	3.001	-2.870	0.960	6.967	2401
		40	3.704	-3.120	0.959	5.593	2033
15	4.24	10	0.954	-4.990	0.944	11.772	2026
		20	1.534	-3.660	0.943	8.631	2221
		30	2.211	-3.730	0.991	8.797	2093
		40	2.930	-3.861	0.932	9.106	2011

(Sand size : 0.85 - 1.00 mm,
NaOCl concentration : 5 mg/l, pH : 7.8)

Table 5.2 - Average Values of k and No
at Different Filtration Rates

Filtration Rate ($\text{m}^3/\text{m}^2\text{-h}$)	Attachment Coefficient $k \times 10^{-4}$ (mg/l-min) ⁻¹	Storage Coeff. No (mg/l)
5	4.280	2532
10	7.430	2401
15	9.576	2088

Once the average values of k and No for different filtration rates are known, the graph of filtration rates against their corresponding values of k and No was plotted and is presented in Figure 5.5. This figure will then be used to interpolate the values of k and No for other filtration rates.

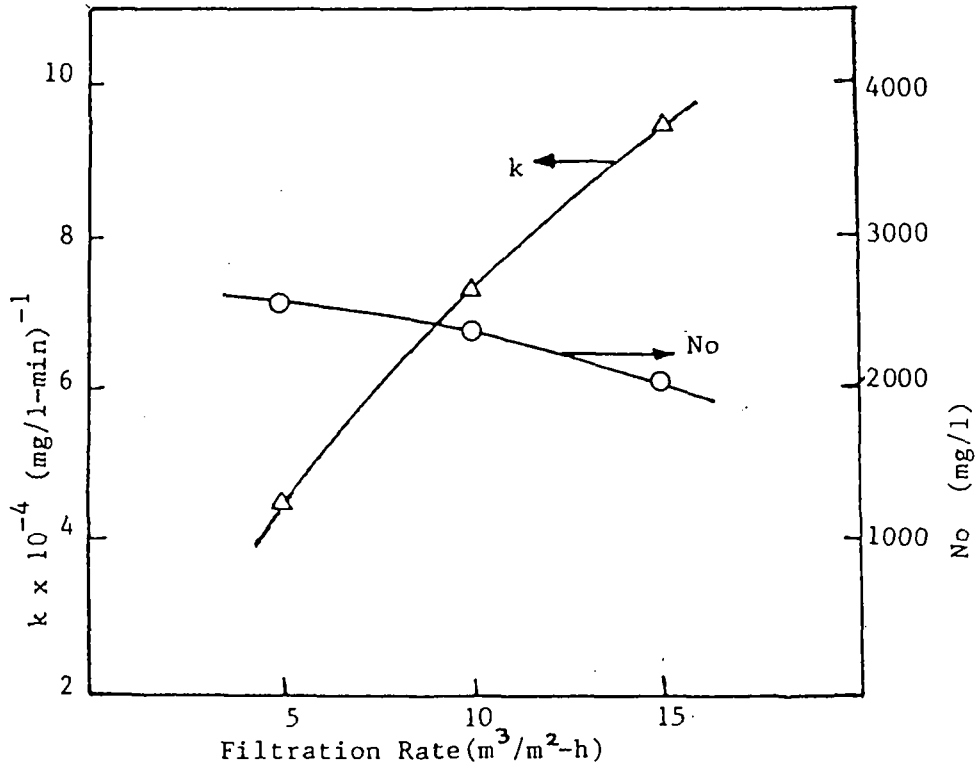


Figure 5.5 - The values of k and No at different filtration rates.
(Inf. Fe=4.2 mg/l, NaOCl=5 mg/l, pH=7.8, sand size 0.85-1.00 mm)

5.1.1.2 Verification of Iron Concentration Profile

Before the coefficients k and N_0 to be use for designing purposes, it is necessary to determine its validity. This is done by deriving semi-empirical relationships between attachment coefficients (k), storage coefficients (N_0), filtration rates (V), depth (L) and time (t) for different filtration rates as given in Table 5.3.

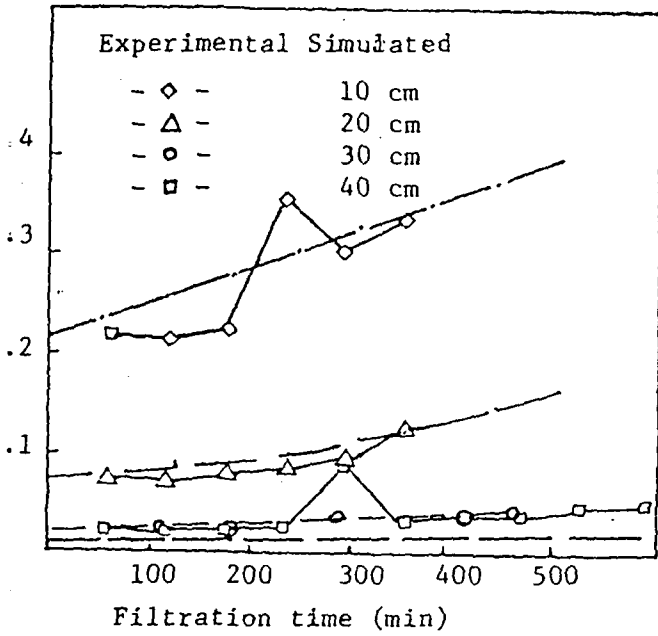
This empirical relationships given in Table 5.3 were derived by simply substituting the values for k , N_0 , and V in equation 5.3.

Table 5.3 - Semi-Empirical Relationships for Different Filtration Rates

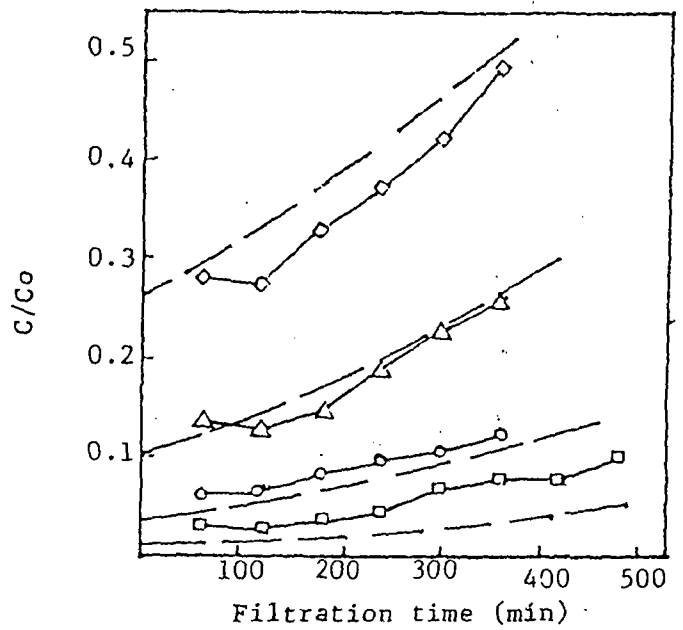
Flow (m^3/m^2-h)	Semi-Empirical Relationships
5	$C = C_0 (\exp(0.13L - 0.0018t) + 1)^{-1}$
10	$C = C_0 (\exp(0.107L - 0.0031t) + 1)^{-1}$
15	$C = C_0 (\exp(0.08L - 0.0041t) + 1)^{-1}$

Using this equation, the Fe concentration profile at different depths were calculated. The theoretical values calculated are presented in Figure 5.6 along with the corresponding experimental values. It can be seen from the figure that the simulated values agree quite well with the experimental values.

a) Filtration Rate = $5 \text{ m}^3/\text{m}^2\text{-h}$



b) Filtration Rate = $10 \text{ m}^3/\text{m}^2\text{-h}$



c) Filtration Rate = $15 \text{ m}^3/\text{m}^2\text{-h}$

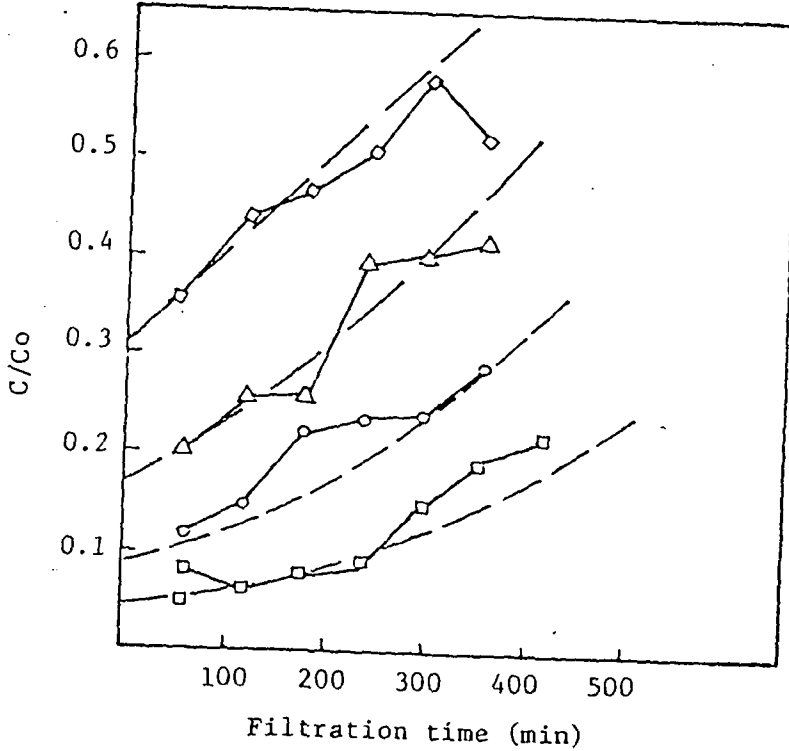


Figure 5.6 - Comparison between the Simulated and Experimental Results for Different Filtration Rates and Depths.

5.1.1.3 Simulation of Concentration Profile

In this study, as an example, the concentration simulation procedure for different filtration rates and depths are discussed. To do this, the following procedure has been used:

- from Figure 5.5, one can read directly the k and N_0 values for any filtration rates.
- once the k and N_0 values are known for the required filtration rates, the C/C_0 profile can be simulated for different filter depths using equation 5.3.

For example, if it is required to determine the concentration profile of $12 \text{ m}^3/\text{m}^2\text{-h}$ for water containing 4 mg/l of Fe. From Figure 5.5, k and N_0 values at this filtration rates can be calculated as $8.22 \times 10^{-4} (\text{mg/l-min})^{-1}$ and 2270 mg/l respectively. Substituting these values and the values of filtration rate and influent iron concentration, equation 5.3 becomes

$$C = 4 (\exp(0.093L - 0.00329t) + 1)^{-1} \quad (5.7)$$

where:

C = effluent iron concentration, mg/l

L = filter depth, cm

t = filter run time, min

The simulation of the concentration profile of the above equation is presented in Figure 5.7.

5.1.2 Simulation of Iron Concentration by Macroscopic Filtration Mathematical Model

IMASAKI (1937) proposed the first equation in deep bed filtration based on first order kinetics relating the change of concentration of suspended particles with filter depth and the local concentration as:

$$\frac{-\partial C}{\partial L} = \lambda C \quad (5.8)$$

in which, C = local concentration of suspended particles

L = filter depth

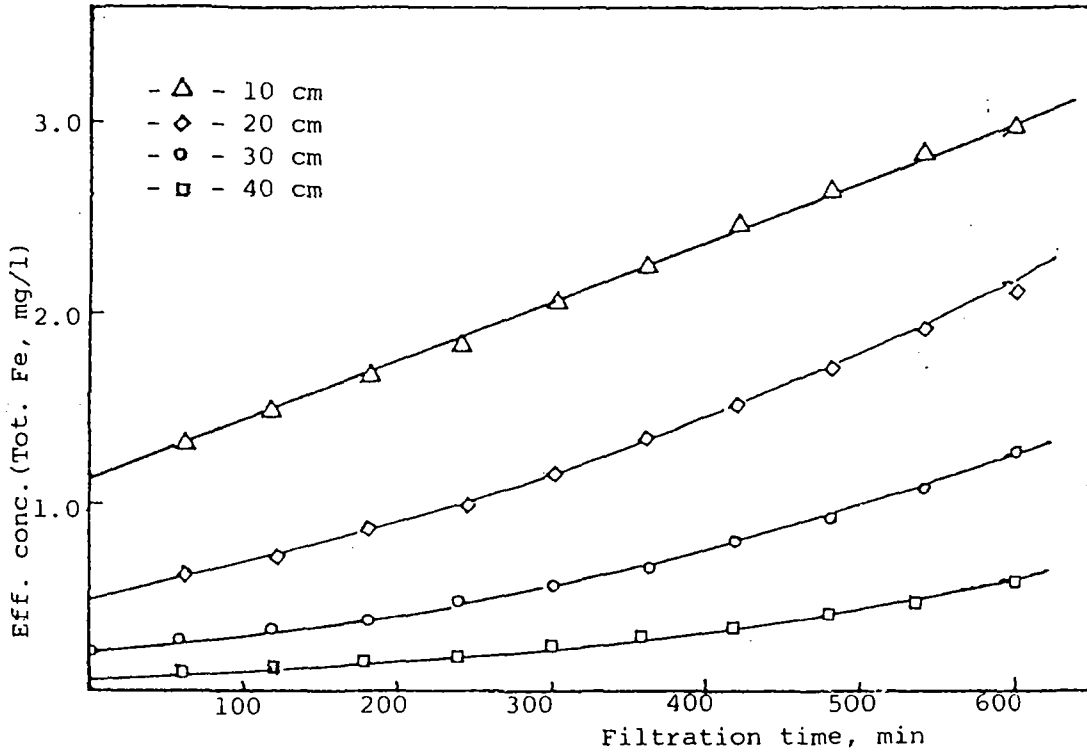


Figure 5.7 - Simulation of Concentration Profile for Filtration Rate of $12 \text{ m}^3/\text{m}^2\text{-h.}$ (Inf. Fe = 4.2 mg/l , sand size = $0.85 - 1.00 \text{ mm}$, pH = 7.8 , NaOCl = 5 mg/l)

λ = filter coefficient (which varies with filter depth and time)

From the mass balance of suspended solids (i.e. the volume of particles removed from flowing suspension is equal to the particles accumulated in the pores), the following relationship can be established.

$$-v \frac{\partial c}{\partial L} = \frac{\partial \sigma}{\partial t} + \frac{\partial c}{\partial t} (f - \sigma) \quad (5.9)$$

in which, f = porosity of filter

t = filtration time

v = approach velocity of filtration

σ = specific deposit

Since the change in concentration of particles in the pores with time is very small compared to specific deposit except in the beginning of filter run, the equation 5.8 can be simplified as follows:

$$-v \frac{\partial c}{\partial L} = \frac{\partial \sigma}{\partial t} \quad (5.10)$$

To predict the local suspended solids concentration the relationship between c and σ should also be known. There are many equations relating these two parameters. In the present study the following relationship is used (IVES, 1960)

$$\lambda = \lambda_0 + c \sigma - \lambda \sigma^2 / (f_0 - \sigma) \quad (5.11)$$

in which c , λ_0 and f_0 are constants for a particular suspension and filter medium.

5.1.2.1 Calculation of λ and σ

The specific deposit can be calculated from the following formula (FOX and CLEASBY, 1966) which is derived directly from its definition:

$$\text{total} = \left[\sum_{i=1}^{i=t} \frac{(C_1 - C_2)_{i-1} + (C_1 - C_2) (t_1 - t_{i-1})}{2} \right] \frac{v}{L_2 - L_1} \quad (5.12)$$

where:

σ_{total} = total specific deposit between depth L_1 & L_2 at time t

$(C_1 - C_2)_{i-1}$ = difference in concentration between depth L_1 & L_2 at time t_{i-1}

$(C_1 - C_2)_i$ = difference in concentration between depth L_1 & L_2 at time t_i

The calculation of specific deposit is easily done by simple computer programming and is given in Appendix F. It should be noted that it has a unit of mg/cm^2 and the methodology of conversion to the unit of volume/volume is made by the method given by FOX and CLEASBY (1966).

The filter coefficient (λ) can be calculated at a particular time between two layers from the following formula which is a rearranged form of equation 5.8.

$$\lambda = \frac{-(C_1 - C_2) / L_1 - L_2}{(C_1)} \quad (5.13)$$

5.1.2.2 Calculation of λ_0 , c and ϕ

Once the values of λ and σ are determined from the above equations using experimental local concentration values, the values of λ_0 , c and ϕ can be calculated from multiple linear regression method.

Table 5.4 shows the values of λ_0 , c and ϕ obtained for different conditions. It can be seen that all the coefficients in general decreased when the filtration rate and depth are increased.

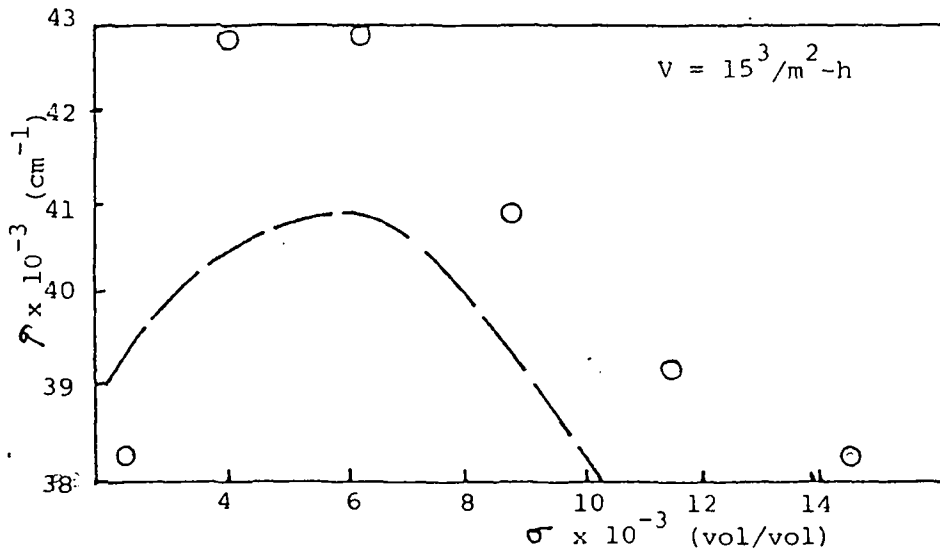
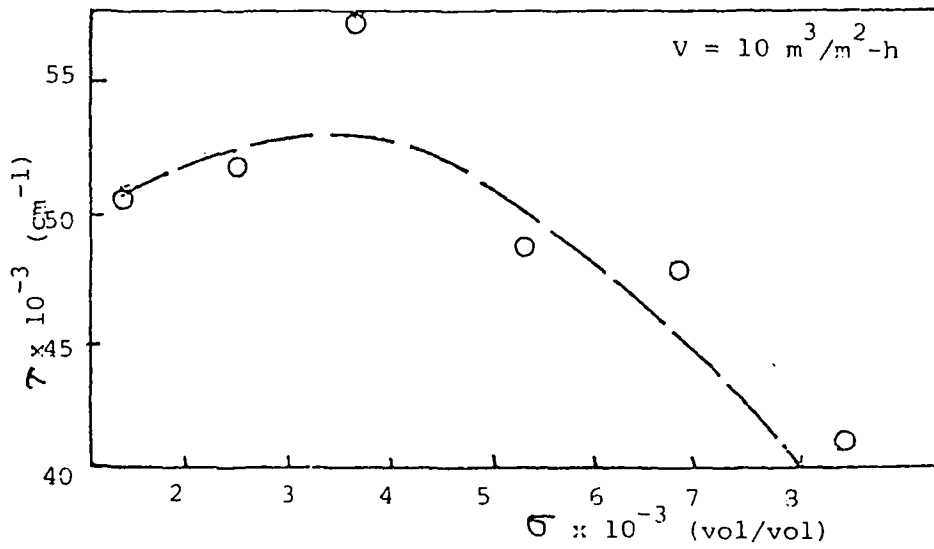
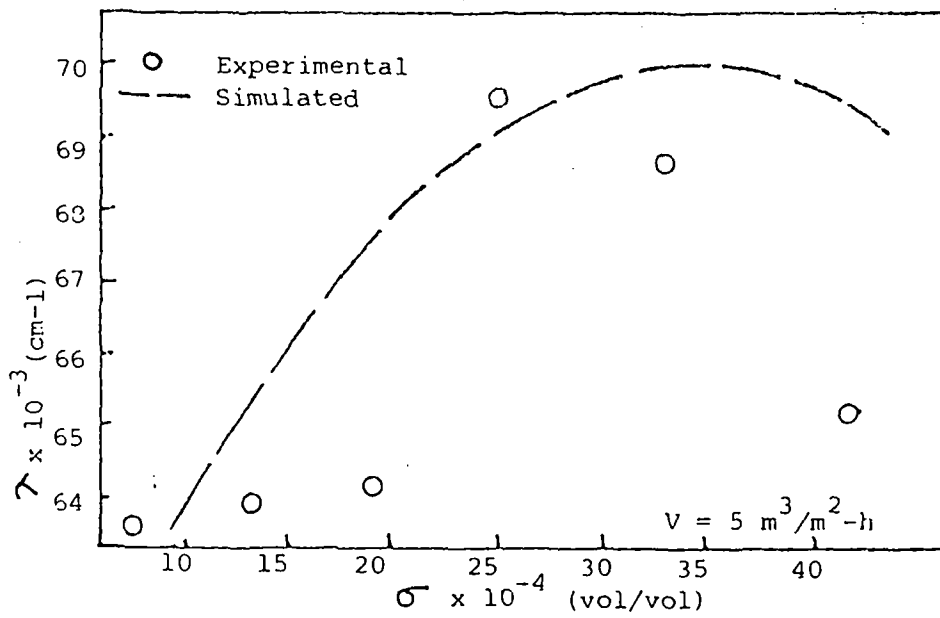


Figure 5.8 - Comparison Between the Experimental and Simulated Results for Different Filtration rate at Filter Depth of 10 - 20 cm (Inf. Fe. = 4.2 mg/l, NaOCl = 5mg/l, pH = 7.3, sand size = 0.35 - 1.00 mm)

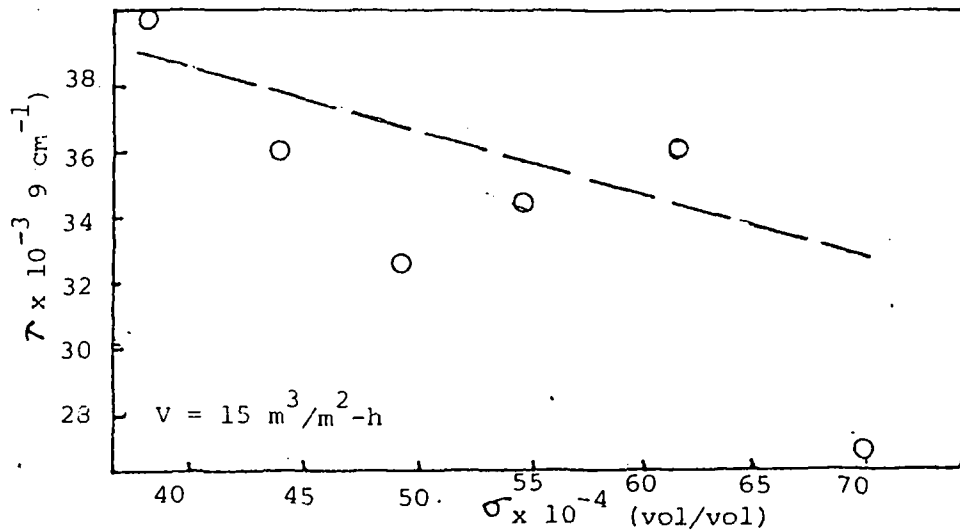
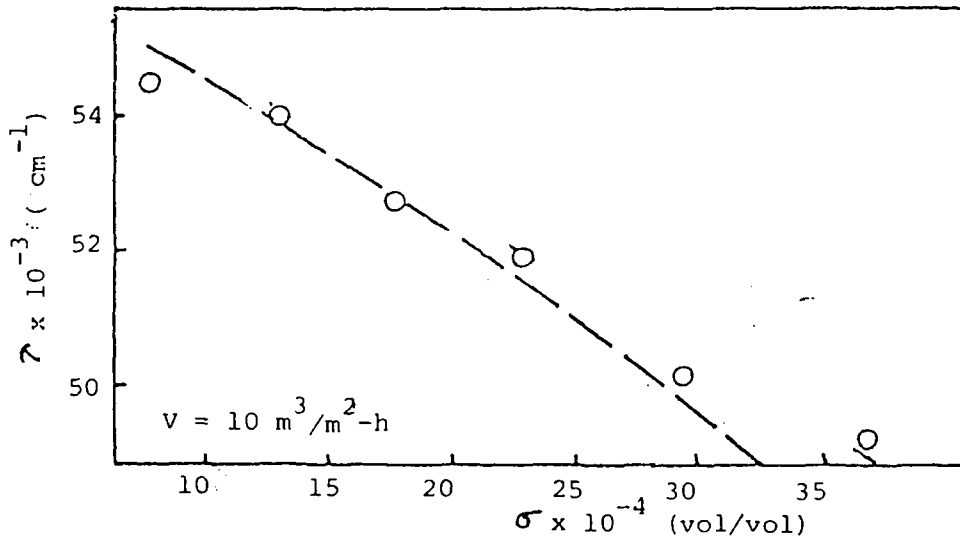
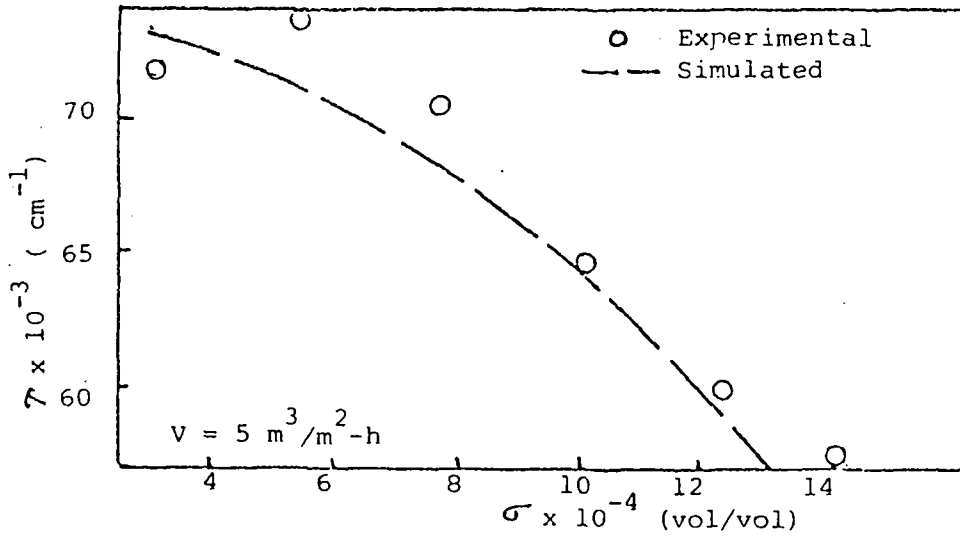


Figure 5.9 - Comparison Between the Simulated and Experimental Results of Different Filtration Rates at Filter Depth of 20 - 30 cm. (Inf. Fe. = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8, sand size = 0.85 - 1.00 mm)

Table 5.4 - Values of τ_0 , c and ϕ for Different Filtration Rates and Depths (Influent Fe = 4.12 mg/l, NaOCl = 5 mg/l, pH = 7.8, medium size = 0.85 to 1.00 mm)

Depth (cm)	Flow m^3/m^2-h	τ_0	c	ϕ	Coeff. of corell.
10 - 20	5	0.0577	7.035	440	0.774
	10	0.0468	3.748	248	0.896
	15	0.0371	1.349	53	0.77
20 - 30	5	0.0741	0.309	4400	0.963
	10	0.0586	-1.788	50	0.950
	15	0.0400	-0.785	5.5	0.80

Knowing these coefficients, the theoretical concentration profile can be simulated by using equations 5.8, 5.9 and 5.11. Fig. 5.8 and 5.9 shows the experimental and theoretical values of for different filtration rates as well as different depths.

This method although can be used to simulate concentration profiles by known τ_0 , c , and ϕ , it is not preferred because the coefficients of τ_0 , c , ϕ in general do not follow any regular trend with the operating parameters. In the present study also, these coefficients calculated for different filtration rates did not have any particular trend in order to facilitate the simulation at different filtration rates. Due to this reason, the model developed by SAAICI (BDST) was used in the present study to predict the filter performance for other operating conditions.

5.2 Mathematical Formulation for Headloss Development in the Filter

5.2.1 Relationships Between Initial Headloss and Filtration Rate

From DARCY's equation, it is clear that the relationship between clean bed headloss and filtration rate is linear for a given size of sand. Therefore in this study, the following equation has been used and the value of S (L/kp) was calculated for different sand layers.

$$V = kp \times H_0/L$$

or

$$H_0 = (L/kp) V = SV \quad (5.14)$$

where : V = superficial flow velocity, m^3/m^2-h

k_p = coefficient of permeability

H_o = headloss of clean bed, m

L = filter depth, m

S = headloss - velocity coefficient, h

The values of V and H_o were plotted for different depths as shown in Figure 5.10 in order to calculate the S values. The values of S calculated for different filter depths are summarized in Table 5.5.

Table 5.5 - Values of S for Different Filter Depths.

Bed Depth (cm)	S (h)	Coefficient of Correlation
10	0.00354	0.97
20	0.00670	0.99
30	0.00920	0.99
40	0.01210	0.99

The value of S was found to increase with the increase in filter bed. The values of S calculated for different filter depth are related by a linear empirical equation of the following form:

$$S = JL \quad (5.15)$$

Where: L = filter depth, m

J = constant, h/m

Thus, if S and L are plotted (as shown in Fig.5.11), the gradient J can be determined. The value of J was found to be equal to 0.03 for sand size of 0.85 - 1.00 mm. The initial headloss which is a function of filter depth (or filter media size) and filtration rate, can thus be written as:

$$H_o = 0.03 LV \quad (5.16)$$

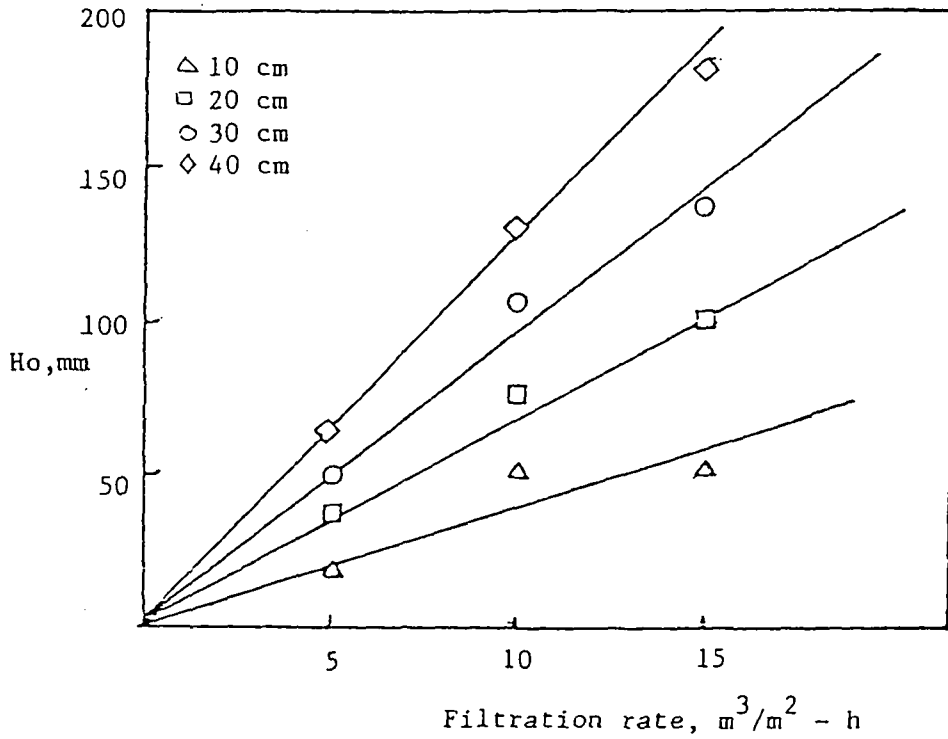


Figure 5.10 - Relationship of Initial Headloss and Filtration Rate. (media size = 0.85 - 1.00 mm, Inf. Fe. Conc, = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8)

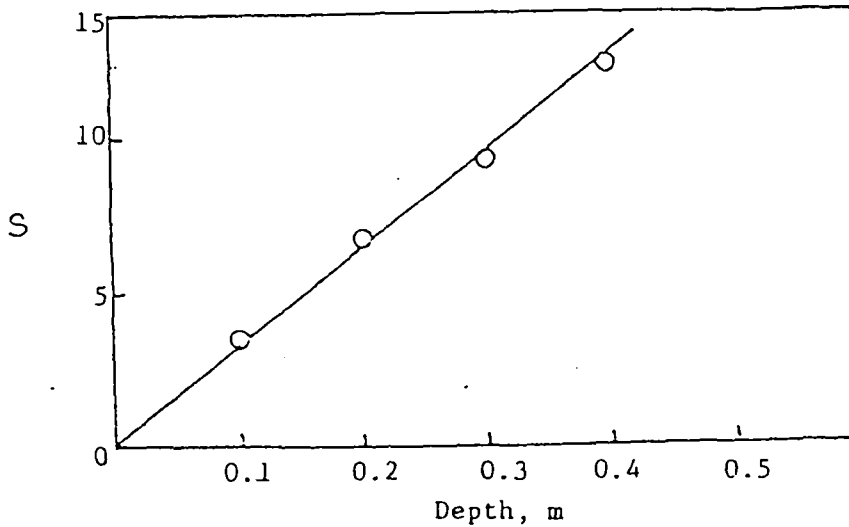


Figure 5.11 - Relationship between S and Filter Depth (Media size = 0.85 - 1.00, Inf. Fe. = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8).

5.2.2 Mathematical Relationships of Headloss with Specific Deposit

The clean bed headloss depends on the hydraulic characteristics of the filter bed and is quantified by KOZNEY as follows:

$$\frac{H_0}{L} = \frac{K_0}{g} (\nu) V \frac{(1-f)^2}{f^3} \left[\frac{6}{\psi d} \right]^2 \quad (5.17)$$

where:

K_0 = KOZNEY's coefficient

g = acceleration due to gravity, cm/s^2

ψ = sphericity

d = sand size, cm

f = porosity

ν = kinematic viscosity of water, cm^2/s

V = superficial flow velocity, cm/s

But as the filtration proceeds, the headloss is developed because of the clogging of particles retained in the bed. MINTS (1966) put forward an equation to relate the headloss development with specific deposit as follows:

$$\frac{H}{H_0} = 1 + k\sigma \quad (5.18)$$

where:

H = headloss at time t , m

k = coefficient, dimensionless

σ = mean specific deposit over the filter depth at time t

The definition of specific deposit, σ and its calculation was given in the preceding discussions.

5.2.3 Calculation of k

The $H/H_0 - 1$ values were plotted against specific deposit for different filter depths and filtration rates and is shown in Figure 5.12. The gradient k , can therefore be obtained from this figure and are summarized in Table 5.6.

Table 5.6 - Values of k for Different Filtration Rates and Filter Depths

Filtration Rate (m^3/m^2-h)	Influent Fe concentration (mg/l)	Depth (cm)	k Values	Coefficient of Correlation
5	4.20	10	121	0.97
		20	144	0.99
		30	164	0.99
		40	187	0.99
10	4.12	10	114	0.98
		20	127	0.98
		30	138	0.99
		40	150	0.98
15	4.24	10	108	0.96
		20	121	0.97
		30	130	0.97
		40	135	0.97

It can be seen that the value of k decreases with the increase in filtration rate and the following empirical relationships between k and filtration rate (V) has been established as follows:

$$k = a + b V^2$$

where :

k = coefficient developed by MINTZ, dimensionless

a = coefficient of zero degree, dimensionless

b = coefficient of second degree, (h/m)

The values of a and b were calculated from linear regression method and shown in Figure 5.13 and listed in Table 5.7. It can be seen that the values of a increases with the increase in filter depth.

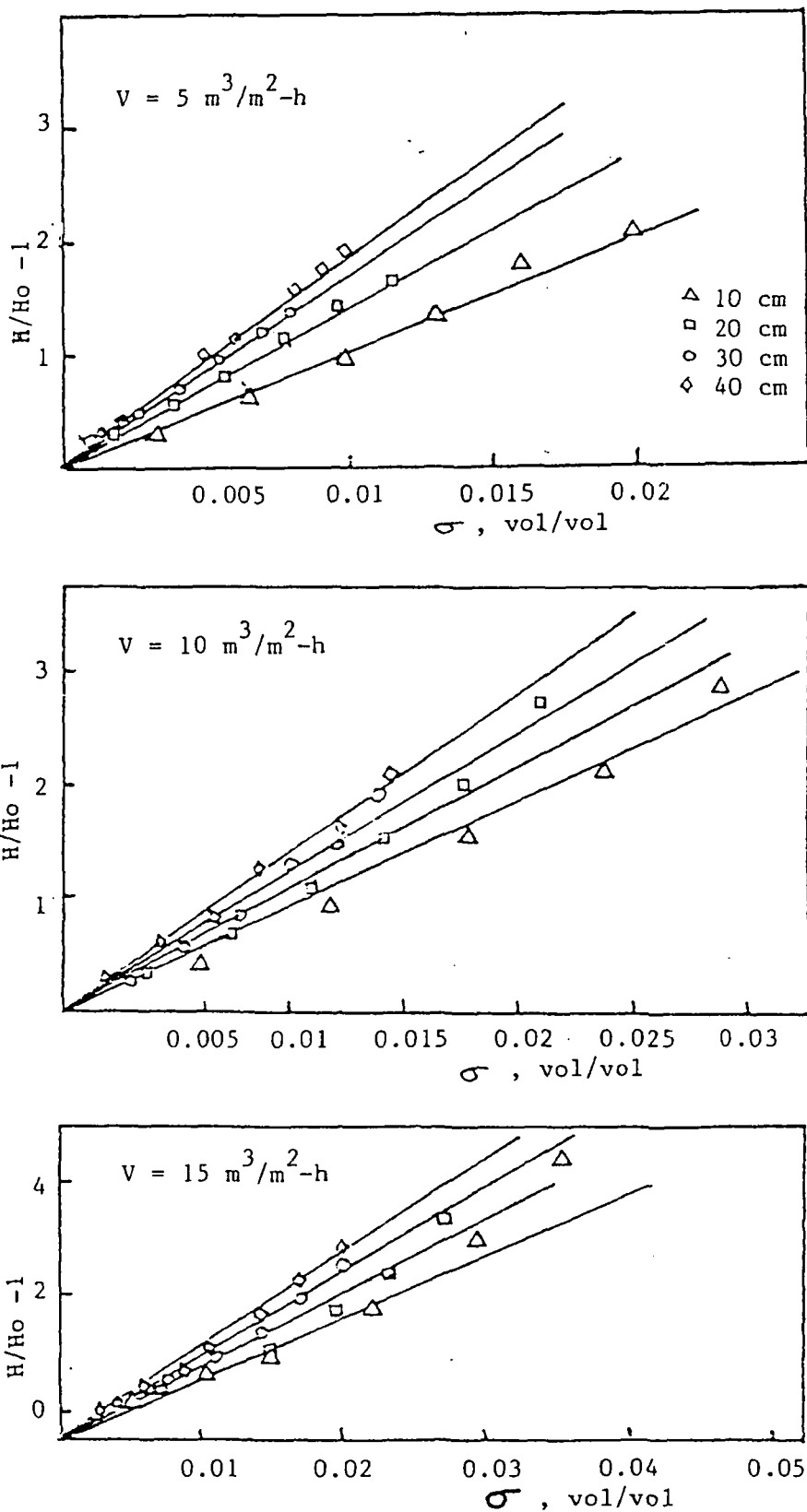


Figure 5.12- Relationship between $H/H_o - 1$ and σ for Different Filter Depth and Filtration Rates. (Inf. Fe.=4.2 mg/l, NaOCl =5 mg/l, pH=7.8, Media size=0.85 to 1.0 mm)

Table 5.7 - Values of a and b for Different Filter Depths

Bed Depth (cm)	Values of a	Values of b	Coefficient of Correlation
10	121	-0.0632	0.98
20	143	-0.1080	0.92
30	162	-0.1590	0.90
40	185	-0.2410	0.93

An empirical relationship was also assumed to relate the coefficient of a and b with filter depth (L) as follows:

$$a = a_1 + a_2 L \quad (5.20)$$

$$b = b_1 + b_2 L \quad (5.21)$$

The values of a_1 , a_2 , b_1 and b_2 calculated are listed in Table 5.8 and shown in Figure 5.14.

Table 5.8 - Values of a_1 , a_2 , b_1 and b_2

Influent Fe Concentration (mg/l)	Coefficients					
	a_1	a_2	correl'n	b_1	b_2	correl'n
4.2	101	211	0.99	0.0033	-0.58	0.99

Thus the headloss equation for the experimental condition studied can be given as follows:

$$H = 0.03VL + 0.03VL ((101+211) - (0.58L - 0.0033)) V^2 \sigma \quad (5.22)$$

It is to be noted that the above equation is only applicable for influent iron concentration of about 4.2 mg/l, NaOCl dosage of 5 mg/l, pH 7.8 and sand size of 0.85 - 1.00 mm. If any of the values of these parameters are varied, the coefficient of the above equations will be changed.

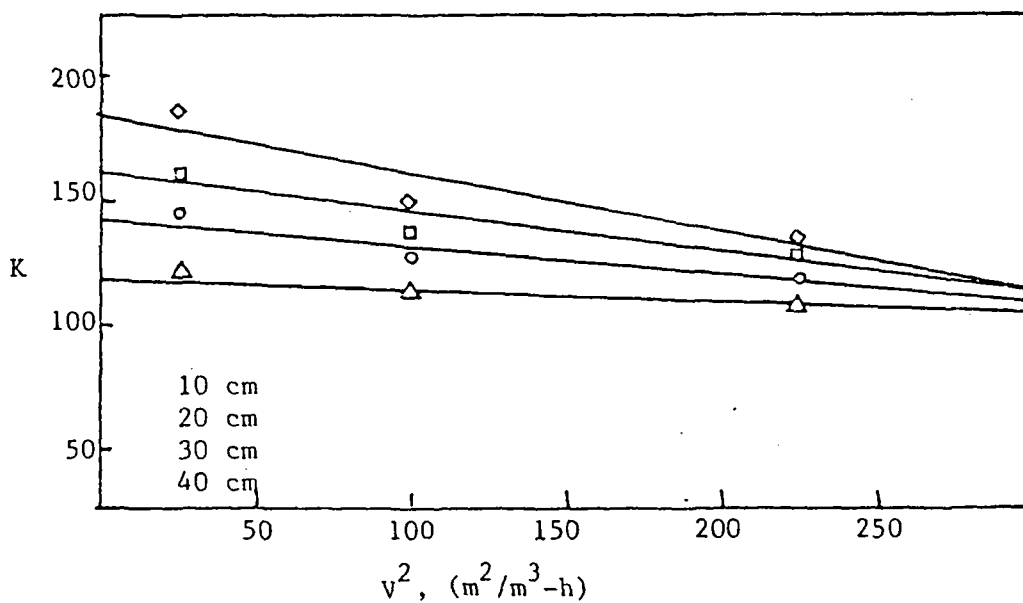


Figure 5.13 - Variation of k with V^2 for Different Filter Depths
 (Inf. Fe = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8
 media size = 0.85 - 1.00 mm)

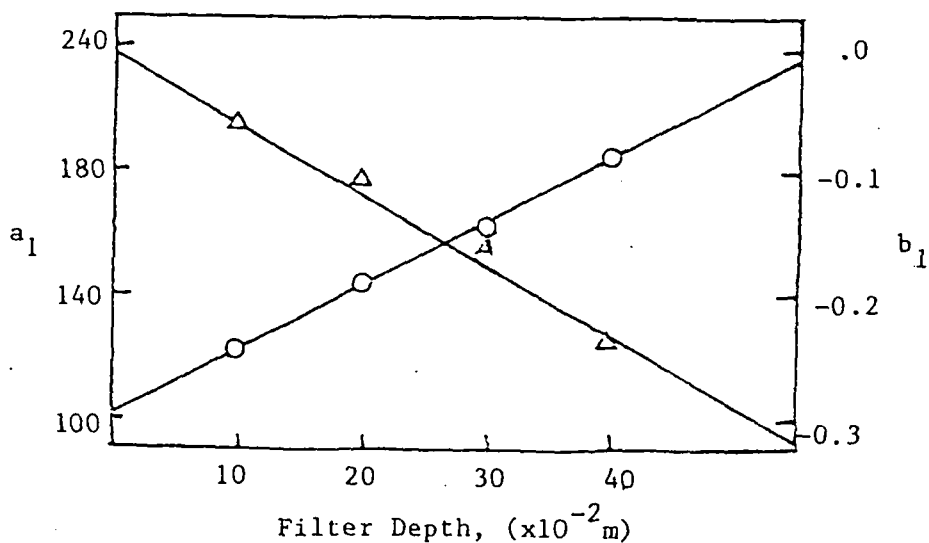


Figure 5.14 - Variation of a_1 and b_1 with Filter Medium Depth
 (Inf. Fe = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8,
 Media Size = 0.85 to 1.00 mm)

5.3 Development of Operational Chart

5.3.1 Relationship of Iron Concentration with NaOCl Concentration

The amount of NaOCl concentration used is 0.85 times the amount of iron present in the water and the relationship is shown in Figure 5.15.

5.3.2 Relationship of Filtration Rates and Filter Depth with Influent iron concentration

1. From Figure 5.5, the values of k and N_0 for other filtration rates can be interpolated as listed in Table 5.9.

Table 5.9 - Interpolated Values of k and N_0 for Different Filtration Rates

Filtration Rate (m^3/m^2-h)	$k \times 10^{-4}$ ($mg/l-min$) ⁻¹	N_0 (mg/l)
5	4.280	2532
7	5.850	2500
9	6.900	2450
11	7.800	2340
13	8.650	2200
15	9.576	2088

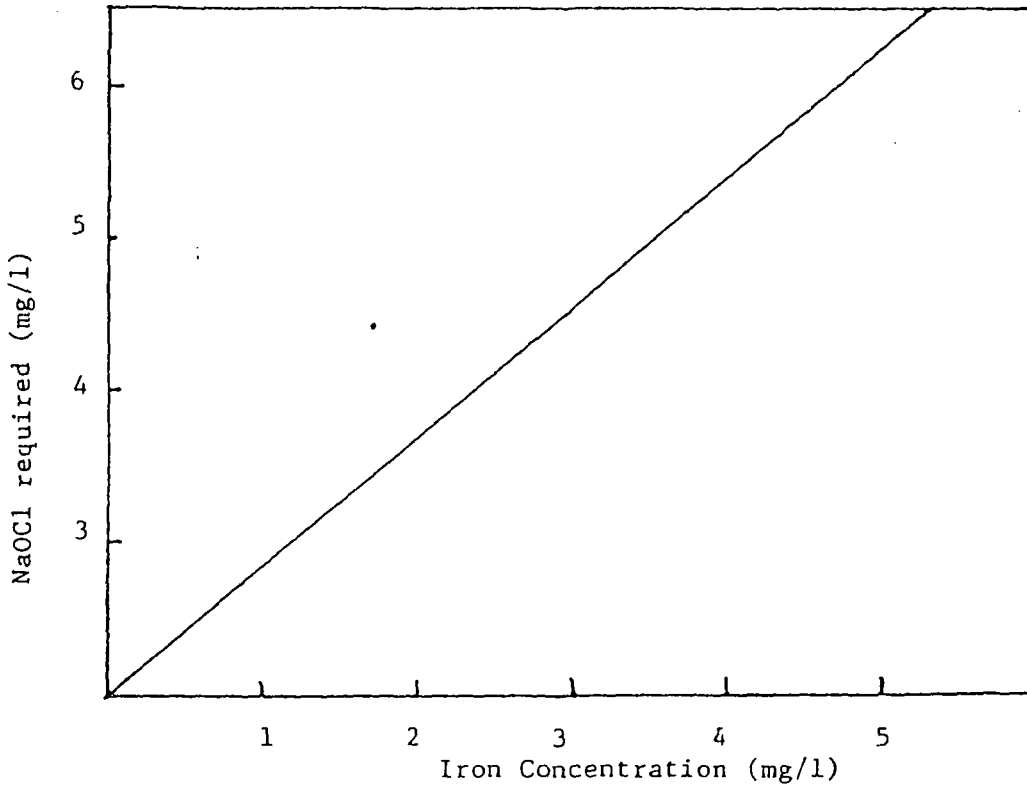


Figure 5.15 - Relationship between Iron present in water and amount of NaOCl required for complete oxidation (pH = 7.8, Sand size = 0.85 - 1.00 mm, Filtration rate = $10 \text{ m}^3/\text{m}^2\text{-h}$)

Table 5.10 - Values of Optimum Depth for Different Filtration Rates and Influent Iron Concentration

Influent Fe Co, mg/l	Filtration Rate m ³ /m ² -h	Optimum Depth (cm)	Influent Fe Co, mg/l	Filtration Rate m ³ /m ² -h	Optimum Depth (cm)
1	5	8.1	6	5	31.2
	7	10.0		7	36.9
	9	10.5		9	43.7
	11	12.3		11	52.1
	13	14.4		13	61.8
	15	16.3		15	71.2
2	5	16.5	8	5	37.6
	7	18.0		7	43.8
	9	21.3		9	52.3
	11	24.9		11	62.7
	13	29.2		13	74.8
	15	33.2		15	86.6
4	5	25.62	10	5	42.5
	7	29.0		7	50.1
	9	34.0		9	60.2
	11	40.3		11	72.5
	13	47.5		13	86.9
	15	54.4		15	100.9

- ii. Knowing these values and keeping the maximum allowable concentration at 0.3 mg/l (WHO Standards for Potable Water), and setting the filtration time to 8 hours, the optimum depth of filter (X_0) can be calculated for different filtration rates and influent iron concentration using Equation 5.3. The optimum depth values calculated in this manner are listed in Table 5.10 and presented in Figure 5.16.
- iii. Equation 5.3 can also be used to calculate the influent iron concentration to be treated for different filter depths and filtration rates by iterative procedure. The results of the iteration is shown in Table 5.11 and presented in Figure 5.17.

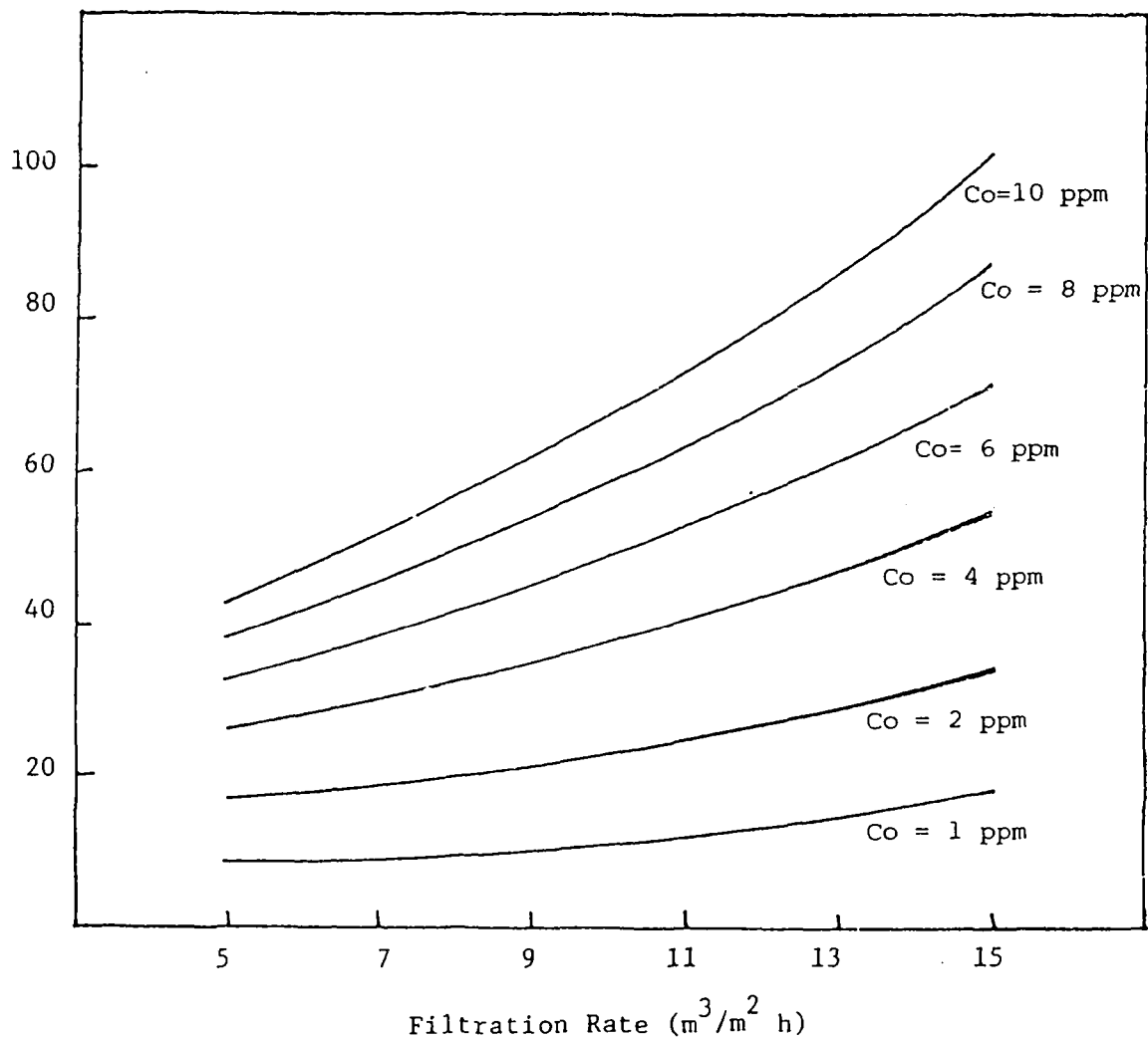


Figure 5.16 - Optimum Filter Depth Values for Different Filtration Rates and Influent Concentrations for 8 hours filter Run (Allowable Effluent Fe Concentration = 0.3 ppm)

Table 5.11 - Relationship of Influent Iron Concentration with Filter Depth and Filtration Rate (NaOCl = 5 mg/l, pH = 7.8, Sand size = 0.85-1.00 mm)

Filtration Rate V, m ³ /m ² -h	Depth L cm	Inf. Iron Concentration mg/l
5.0	10	1.17
	20	2.65
	30	5.30
	40	8.95
	50	13.30
7.0	10	1.08
	20	2.25
	30	4.23
	40	6.87
	50	9.96
9.0	10	0.97
	20	1.84
	30	3.28
	40	5.18
	50	7.44
11.0	10	0.88
	20	1.54
	30	2.57
	40	3.96
	50	5.62
	60	7.47
13.0	10	0.81
	20	1.31
	30	2.07
	40	3.09
	50	4.32
	60	5.72
	70	7.24
15.0	10	0.78
	20	1.17
	30	1.77
	40	2.56
	50	3.53
	60	4.63
	70	5.84

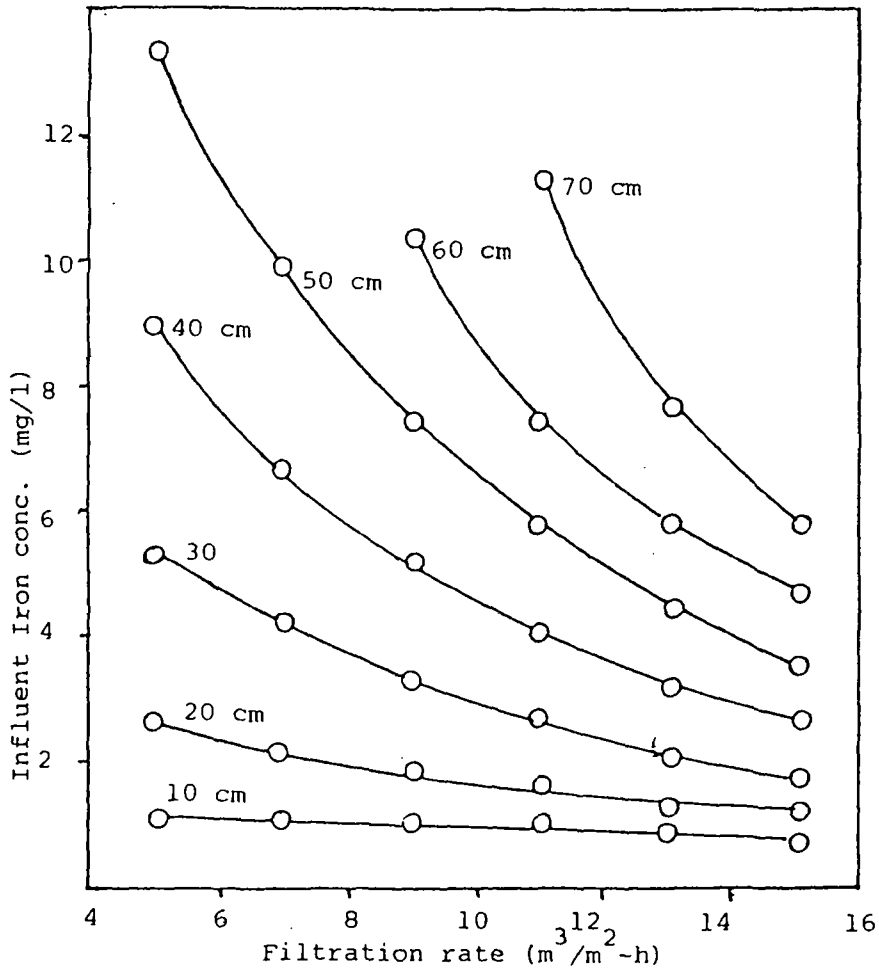


Figure 5.17 - Relationship between Influent Iron Concentration with Different Filtration Rates and Depth (NaOCl = 5 mg/l, pH = 7.8, Sand Size = 0.85 - 1.00 mm)

5.3.3 Relationship of Filtration Rate and Filter Depth with Headloss

Equation 5.22 can be used to predict the headloss of the filter for a given filtration rate and filter depth at any given filter time. To do this, it is necessary to determine the value of the total specific deposit (σ_{total}) at the required filter run time. For 8 hours of filter run time has to be extrapolated since in this study their values, for different filter depth and filtration rate, are only known only at the sixth hour of the filtration time. Substituting all the variables in the equation, the headloss values can finally be determined and its relationship with filtration rate and depth is presented in Figure 5.18.

5.3.4 Application of the Nomograph

Figure 5.19 is a combination of Figure 5.15, Figure 5.17 and Figure 5.18. It is superimposed to proper scale so that it can be conveniently used as a guide to designing engineers when designing such kind of unit. The procedure to use this nomograph is as follows:

- a) For example, let the iron content of the water is 4 mg/l and the required filtration rate be $8 \text{ m}^3/\text{m}^2\text{-h}$. From the figure, the NaOCl concentration is 3.4 mg/l and is obtained by projecting the intersection point of the iron concentration line with the diagonal upward.
- b) The point of intersection of the iron concentration and the rate of filtration will determine the required filter depth and was found to be 32 cm. This is minimum depth of the filter in order to achieve the effluent concentration of 0.3 mg/l for 8 hours filter run time.
- c) Projecting the intersection point upward till reaching the same depth for headloss line, the headloss of the filter at 32 cm height can be determined by simply reading the scale on the right and was found to be 35 cm.

It is to be noted that this nomograph is only applicable for treating iron with NaOCl at pH of about 7 to 8 and the filter media is of river sand of size 0.85 - 1.00 mm. Its use is also limited to treating the raw water whose characteristics is more or less similar to the one shown in Table 4.2.

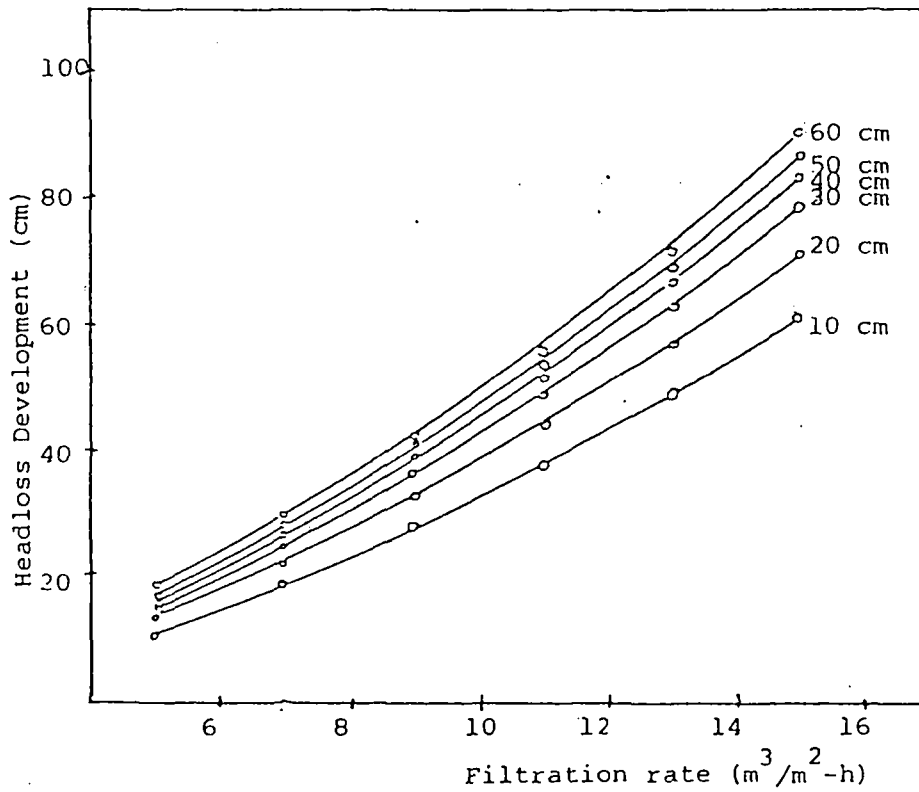


Figure 5.18 - Relationship Between Headloss Development with Different Filtration Rates and Filter Depth
(Inf. Fe = 4.2 mg/l, NaOCl = 5 mg/l, pH = 7.8, Sand Size = 0.85 - 1.00 mm)

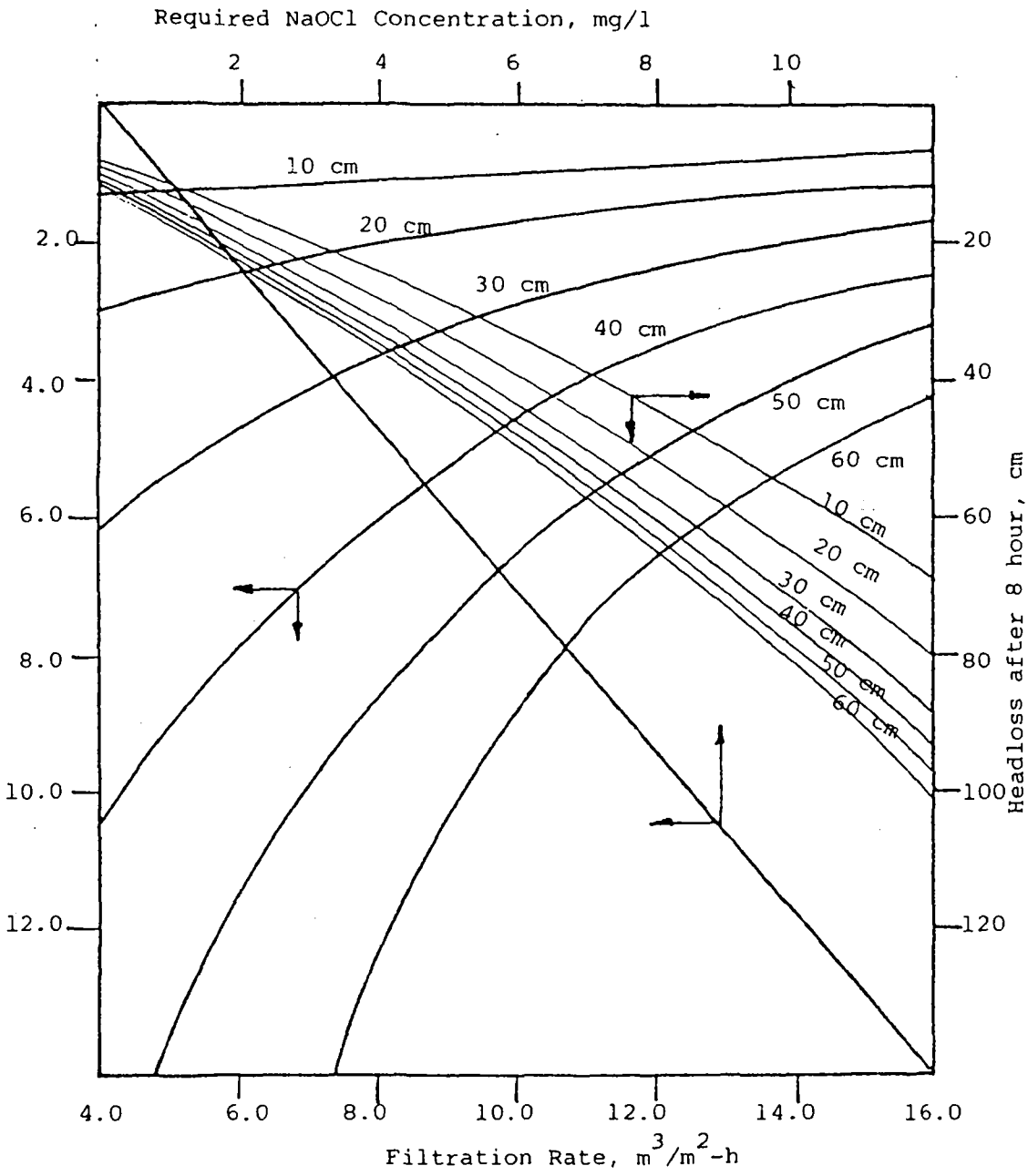


Figure 5.19 - Operational Chart for Removal of Iron by Chlorination Filtration Process. (only applicable when pH = 7 -8, sand size = 0.85 - 1.00 mm, NaOCl is used as the source chlorine, filter run time = 8 hrs, eff. conc. = 0.3 mg/l)

VI CONCLUSION

1. The chlorination followed by filtration was found to be very effective method to remove the iron to a large extent especially when filtration rate is less than $10 \text{ m}^3/\text{m}^2\text{-h}$ using media size of 0.85 - 1.00 mm.
2. The iron removal efficiency increased from 90 to 95% when pH was increased from 7.8 to 9.5. However, the headloss development was 120 cm at a pH of 9.5 after 8 hours of run compared to 48 cm at pH of 7 after the same filtration time. Therefore, the pH increase does not have significant advantage on the removal of iron. In addition this pH adjustment would also add to cost on the purchase of chemicals which is again not economical.
3. The minimum NaOCl concentration required for complete oxidation is about 0.85 mg/l per 1 mg/l of iron present. Higher dosage of NaOCl was found to have only little improvement in iron removal. (The stoichiometric calculations showed that 1 mg/l of iron would require 0.67 mg/l of NaOCl).
4. The BDST Method was found to be a powerful tool to evaluate the optimum filter depth and filter time when the parameters like filtration rate, influent iron concentration and allowable effluent quality were varied. Thus this method becomes useful in deciding the rational design criteria with the limited number of experimental results which is used to find the relationship between model coefficients, k and N_0 with operational parameters.

VII RECOMMENDATIONS FOR FUTURE WORKS

This study has shown that it is feasible to use prechlorination followed by filtration process to remove considerable amount of iron from the water. However, the study was only limited to see the iron removal with operating parameters. The following works appear attractive for future study:

1. Incorporation of reactions between iron and hypochlorite ion to evaluate the ferric precipitation and the removal in the filter.
2. The detailed study on the hydraulic parameter to achieve optimum mixing (for example hydraulic gradient (G) and detention time (td)) for successful precipitation of iron on subsequent removal in the filter.
3. The detailed study on the amount of chlorine escaping with the effluent from aesthetic and public health point of view.

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APPENDIX A

CALCULATION OF STOICHIOMETRIC VALUE OF SODIUM HYPOCHLORITE
CONCENTRATION FOR COMPLETE OXIDATION WITH IRON

Calculation of Stoichiometric Value of Hypochlorite Concentration for Complete Oxidation with Iron

Using ionic equations;



Fe^{2+} will have to be oxidized to Fe^{3+} for precipitation to occur.



OCl^{-} having 0 valency $2 = -2$

Cl_2 valency $1 = +1$

Therefore,

$$\text{OCl}^{-} = -2 + 1 = -1$$

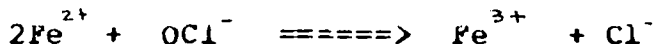
Thus,

Cl_2 from (+1) to Cl^{-} (-1) requires 2e.

Combining equations (1) and (2),



Therefore,

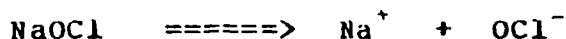


To balance the equation,

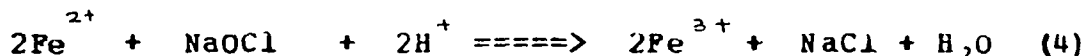


From equation (3), it appears that in order for complete oxidation to occur, the solution must be kept in acidic condition.

If NaOCl is used, then it will yield



Thus, equation (3) becomes



Stoichiometrically,

112 mg of Fe^{2+} requires 74.5 mg of NaOCl to be oxidized into Fe^{3+} .

thus,

1 mg of Fe^{2+} requires $112/74.5 = 0.67$ mg of NaOCl

Therefore, the equation to calculate the theoretical amount of OCl is

$$y = 0.67 x \quad (5)$$

where y = amount of iron to be removed (mg/l)
 x = amount of NaOCl required for oxidation (mg/l)

APPENDIX B

RESULTS OF THE JAR TEST

Results of the Jar Test

RUN A - To determine the optimum NaOCl dosage
(Initial pH = 6.5)

Inf. Iron conc., Co (mg/l)	NaOCl conc. (mg/l)	mg. NaOCl per 1 mg. of Fe	Soluble Iron Remaining (mg/l)
5.60	2.24	0.4	1.40
	3.36	0.6	0.22
	3.92	0.7	0.06
	4.48	0.8	0.06
	5.04	0.9	0.17
	6.16	1.1	0.11
6.80	3.40	0.5	0.31
	4.76	0.7	0.21
	5.44	0.8	0.20
	6.12	0.9	0.24
	6.80	1.0	0.24
	8.16	1.2	0.20

RUN B - To determine the optimum pH

Initial Fe conc.	NaOcl (mg/l)	mg of NaOCl per mg of Fe	pH	Fe Remaining (mg/l)
4.03	11.28	2.8	3.5	1.61
			4.5	0.69
			6.0	0.38
			7.5	0.48
			9.5	0.38
			11.5	0.40
5.48	12.6	1.3	3.6	0.60
			5.2	0.49
			6.5	0.63
			8.0	0.57
			9.2	0.49
6.41	6.15	0.76	5.3	0.13
			6.1	0.19
			7.1	0.22
			8.5	0.38
			10.4	0.22

APPENDIX C

RESULTS OF THE FILTER RUN

Appendix C.1.1 - PARAMETER VARIED : HYPOCHLORITE CONCENTRATION

Run 1.1 Sodium hypochlorite concentration is set to 2 mg/l;
other operational parameters are fixed at:

- a) Influent iron concentration = 4.1 mg/l
- b) Influent pH (average) = 7.7
- c) Media size = 0.85 - 1.00 mm
- d) Flowrate = 10 m³/m²-h

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h)	Depth (cm)			pH at 40 cm
	10	20	40	
1	-	-	0.35	7.7
2	-	-	0.24	7.8
3	-	-	0.30	7.7
4	-	-	0.32	7.8
5	-	-	0.43	7.8
6	-	-	0.38	7.8
7	-	-	0.39	7.7
8	-	-	0.44	7.8

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (cm)			
	10	20	30	40
0.5	42	83	108	143
1.0	44	94	118	153
1.5	45	95	120	154
2.0	64	104	128	163
2.5	76	116	142	174
3.0	85	126	151	185
3.5	92	130	155	190
4.0	100	140	170	205
5.0	121	160	186	222
6.0	145	187	210	246
7.0	181	222	247	282
8.0	209	250	274	308

Appendix C.1.2 - PARAMETER VARIED : HYPOCHLORITE CONCENTRATION

Run 1.2 Sodium hypochlorite concentration is set to 35 mg/l;
other operational parameters are fixed at:

- a) Influent iron concentration = 4.18 mg/l
- b) Influent pH (average) = 7.8
- c) Media size = 0.85 - 1.00 mm
- d) Flowrate = 10 m³/m²-h

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h) Time	Depth (cm)			pH at 40 cm
	10	20	40	
1	-	-	0.20	7.8
2	-	-	0.15	7.8
3	-	-	0.11	7.8
4	-	-	0.13	7.8
5	-	-	0.23	7.8
6	-	-	0.20	7.9
7	-	-	0.35	7.8
8	-	-	0.42	7.8

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (cm)			
	10	20	30	40
0.5	40	95	120	156
1.0	46	106	133	169
1.5	70	135	139	175
2.0	64	134	160	196
2.5	71	146	172	208
3.0	84	164	190	226
3.5	94	179	205	241
4.0	105	195	220	256
5.0	145	240	266	302
6.0	174	274	299	335
7.0	232	335	361	397
8.0	297	402	427	463

Appendix C.1.3 - PARAMETER VARIED : HYPOCHLORITE CONCENTRATION

Run 1.3 Sodium hypochlorite concentration is set to 6.5 mg/l; other operational parameters are fixed at:

- a) Influent iron concentration = 4.1 mg/l
- b) Influent pH (average) = 7.7
- c) Media size = 0.85 - 1.00 mm
- d) Flowrate = 10 m³/m²-h

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h) Time	Depth (cm)			pH at 40 cm
	10	20	30	
1	-	-	0.16	7.8
2	-	-	0.09	7.8
3	-	-	0.08	7.9
4	-	-	0.17	7.9
5	-	-	0.15	7.8
6	-	-	0.26	7.8
7	-	-	0.25	7.9
8	-	-	0.32	7.8

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (cm)			
	10	20	30	40
0.5	45	99	125	161
1.0	52	109	122	172
1.5	64	122	147	182
2.0	82	144	169	204
2.5	95	160	186	221
3.0	118	188	214	249
3.5	129	202	228	264
4.0	142	218	243	279
5.0	189	276	304	320
6.0	217	309	337	377
7.0	299	396	423	459
8.0	321	424	451	486

Appendix C.2.1 - PARAMETER VARIED : pH

Run 2.1 pH is set to 9.5

other operational parameters are fixed at:

- a) Influent iron concentration = 4.25 mg/l
- b) Hypochlorite concentration = 5 mg/l
- c) Media size = 0.85 - 1.00 mm
- d) Flowrate = $10 \text{ m}^3/\text{m}^2\text{-h}$

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h) Time	Depth (cm)			pH at 40 cm
	10	20	40	
1	-	-	0.20	9.5
2	-	-	0.09	9.5
3	-	-	0.12	9.5
4	-	-	0.13	9.4
5	-	-	0.11	9.5
6	-	-	0.14	9.5
7	-	-	0.13	9.6
8	-	-	0.18	9.7

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (cm)			
	10	20	30	40
0.5	78	112	142	167
1.0	112	150	182	209
1.5	154	197	231	261
2.0	190	243	277	307
2.5	230	286	321	351
3.0	270	332	370	401
3.5	315	383	421	452
4.0	367	445	486	518
5.0	406	506	549	581
6.0	564	693	742	776
7.0	681	840	898	935
8.0	778	987	1058	1098

Appendix C.3.1 - PARAMETER VARIED : FLOWRATE

Run 3.1 Flowrate is set to $5 \text{ m}^3/\text{m}^2\text{-h}$

other operational parameters are fixed at:

- a) Influent iron concentration = 4.2 mg/l
- b) Hypochlorite concentration = 5 mg/l
- c) Media size = 0.85 - 1.00 mm
- d) Influent pH (average) = 7.7

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h) Time	Depth (cm)				pH at 40 cm
	100	200	300	400	
1	0.93	0.32	0.09	0.09	7.7
2	0.93	0.31	0.08	0.08	7.8
3	0.95	0.34	0.10	0.09	7.8
4	1.52	0.34	0.12	0.12	7.7
5	1.28	0.40	0.16	0.25	7.8
6	1.44	0.43	0.15	0.13	7.8
7	-	-	-	0.15	7.9
8	-	-	-	0.17	7.8
9	-	-	-	0.20	7.8
10	-	-	-	0.21	7.8

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (mm)			
	100	200	300	400
0.5	27	44	60	74
1.0	31	48	64	78
1.5	36	53	69	83
2.0	40	58	74	86
2.5	43	62	78	92
3.0	48	67	83	97
3.5	54	75	91	105
4.0	59	80	97	112
5.0	70	92	109	124
6.0	78	100	117	132
7.0	89	111	128	143
8.0	102	130	147	163
9.0	113	141	158	174
10.0	129	152	169	185

Appendix C.3.2 - PARAMETER VARIED : FLOWRATE

Run 3.1 Flowrate is set to $10 \text{ m}^3/\text{m}^2\text{-h}$

other operational parameters are fixed at:

- a) Influent iron concentration = 4.12 mg/l
- b) Hypochlorite concentration = 5 mg/l
- c) Media size = 0.85 - 1.00 mm
- d) Influent pH (average) = 7.7

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h)	Depth (cm)				pH at 40 cm
	100	200	300	400	
1	1.15	0.57	0.25	0.14	7.8
2	1.12	0.53	0.23	0.12	7.7
3	1.34	0.61	0.34	0.15	7.7
4	1.52	0.79	0.59	0.19	7.8
5	1.72	0.95	0.44	0.28	7.8
6	2.04	1.07	0.50	0.32	7.9
7	-	-	-	0.32	7.8
8	-	-	-	0.41	7.8

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (mm)			
	10	20	30	40
0.5	53	88	118	145
1.0	64	101	132	159
1.5	75	114	147	175
2.0	85	127	161	191
2.5	101	147	182	213
3.0	114	160	194	223
3.5	125	173	207	236
4.0	140	189	244	253
5.0	176	227	263	291
6.0	224	281	318	348
7.0	274	338	376	406
8.0	341	412	450	480

Appendix C.3.3 - PARAMETER VARIED : FLOWRATE

Run 3.3 Flowrate is set to $15 \text{ m}^3/\text{m}^2\text{-h}$
 other operational parameters are fixed at:
 a) Influent iron concentration = 4.24 mg/l
 b) Hypochlorite concentration = 5 mg/l
 c) Media size = 0.85 - 1.00 mm
 d) Influent pH (average) = 7.8

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h) Time	Depth (cm)				pH at 40 cm
	10	20	30	40	
1	1.52	0.87	0.49	0.34	7.8
2	1.87	1.10	0.63	0.28	7.9
3	1.99	1.10	0.96	0.83	7.9
4	2.14	1.68	1.49	0.38	7.8
5	2.57	1.70	1.02	0.63	7.8
6	2.21	1.77	1.24	0.82	7.9
7	-	-	-	0.94	7.8

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (cm)			
	10	20	30	40
0.5	64	114	156	191
1.0	71	122	165	200
1.5	90	148	193	229
2.0	106	167	214	251
2.5	124	189	237	274
3.0	142	209	257	294
3.5	164	236	285	322
4.0	200	280	332	372
5.0	272	342	405	494
6.0	351	440	492	593
7.0	450	539	600	690

Appendix C.4.1 - PARAMETER VARIED : MEDIA SIZE

Run 4.1 The size of the filter media is 0.5 - 0.6 mm
 other operational parameters are fixed at:
 a) Influent iron concentration = 4.35 mg/l
 b) Hypochlorite concentration = 5 mg/l
 c) Flowrate = 10 m³/m²-h
 d) Influent pH (average) = 7.8

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h) Time	Depth (cm)				pH at 40 cm
	10	20	30	40	
1	0.46	0.26	0.12	0.10	7.8
2	0.40	0.24	0.13	0.09	7.9
3	0.41	0.27	0.16	0.07	7.8
4	0.47	0.26	0.14	0.12	7.8
5	0.45	0.35	0.18	0.09	7.9
6	0.49	0.28	0.16	0.10	7.8
7	-	-	-	-	-
8	-	-	-	-	-

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (mm)			
	10	20	30	40
0.5	213	303	387	460
1.0	288	378	462	537
1.5	351	442	517	601
2.0	457	552	638	714
2.5	523	623	710	788
3.0	664	761	848	928
3.5	720	813	897	974
4.0	832	929	1015	1092
5.0	1138	1236	1326	1406

Appendix C.4.2 - PARAMETER VARIED : MEDIA SIZE

Run 4.2 Media size is set to 1.20 - 1.40 mm
 other operational parameters are fixed at:
 a) Influent iron concentration = 4.12 mg/l
 b) Hypochlorite concentration = 5 mg/l
 c) Flow rate = 10 m³/m²-h
 d) Influent pH (average) = 7.7

Results:

A. Effluent Iron Concentration (mg/l) and pH

Time (h) Time	Depth (cm)				pH at 40 cm
	10	20	30	40	
1	1.91	1.10	0.76	0.60	7.7
2	1.76	1.04	0.66	0.47	7.7
3	1.78	0.91	0.48	0.40	7.6
4	1.76	0.94	0.44	0.41	7.7
5	-	-	-	0.38	-
6	-	-	-	0.38	-
7	-	-	-	0.37	-
8	-	-	-	0.39	-

B. Headloss Development (mm)

Time of Run (h)	Depth of Filter Media (mm)			
	10	20	30	40
0.5	14	30	39	50
1.0	17	34	42	56
1.5	20	36	48	60
2.0	22	39	51	64
2.5	25	42	57	72
3.0	26	47	61	75
3.5	27	49	63	78
4.0	29	52	65	82
5.0	37	55	70	95
6.0	40	64	77	102
7.0	47	70	84	115
8.0	52	77	92	132

APPENDIX D

DATA FOR CALCULATION OF k AND N_0

Table D.1 - Data for the Calculation of k and No
(for Depth = 100 mm)

Flow m^3/m^2-h	Inf. Fe Conc. (Co, mg/l)	Time (min)	Eff. Fe Conc. (C, mg/l)	Co/C	C/Co -1	ln (C/Co -1)
5	4.20	60	0.93	4.490	3.490	1.250
		120	0.93	4.490	3.490	1.250
		180	0.95	4.425	3.425	1.231
		240	*1.52	2.763	1.763	0.567
		300	1.28	3.273	2.273	0.821
		360	1.44	2.914	1.914	0.649
10	4.12	60	1.15	3.583	2.583	0.949
		120	1.12	3.679	2.679	0.985
		180	1.34	3.075	2.075	0.730
		240	1.52	2.711	1.711	0.537
		300	1.72	2.396	1.396	0.333
		360	2.04	2.020	1.020	0.019
15	4.24	60	1.52	2.789	1.789	0.582
		120	1.87	2.267	1.267	0.237
		180	1.99	2.131	1.131	0.123
		240	2.14	1.981	0.981	-0.019
		300	*2.47	1.716	0.716	-0.333
		360	2.21	1.919	0.919	-0.085

* : outlier - not considered in regression analysis
(Media size = 0.85 - 1.00 mm; NaOCl = 5 mg/l; pH 7.8)

Table D.2 - Data for the Calculation of k and No
(for Depth = 200 mm)

Flow m^3/m^2-h	Inf. Fe Conc. ($C_0, mg/l$)	Time (min)	Eff. Fe Conc. ($C, mg/l$)	C_0/C	$C/C_0 - 1$	$\ln (C/C_0 - 1)$
5	4.20	60	0.32	13.125	12.125	2.495
		120	0.31	13.548	12.548	2.529
		180	0.34	12.353	11.353	2.429
		240	0.34	12.353	11.353	2.429
		300	0.40	10.500	9.500	2.251
		360	0.43	9.767	8.767	2.171
10	4.12	60	0.57	7.228	6.228	1.829
		120	0.53	7.773	6.773	1.913
		180	0.61	6.754	5.754	1.750
		240	0.79	5.15	4.215	1.439
		300	0.95	4.337	3.337	1.205
		360	1.07	3.850	2.850	1.047
15	4.24	60	0.87	4.873	3.873	1.354
		120	1.10	3.854	3.854	1.049
		180	1.10	3.854	3.854	1.049
		240	1.68	2.524	1.524	0.421
		300	1.70	2.494	1.494	0.402
		360	1.77	2.395	1.395	0.333

* : outlier - not considered in regression analysis
(Media size = 0.85 - 1.00 mm; NaOCl = 5 mg/l; pH 7.8)

Table D.3 - Data for the Calculation of k and No
(for Depth = 300 mm)

Flow m^3/m^2-h	Inf. Fe Conc. (Co,mg/l)	Time (min)	Eff.Fe Conc. (C,mg/l)	Co/C	C/Co -1	ln (C/Co -1)
5	4.20	60	0.09	46.667	45.667	3.821
		120	0.08	52.500	51.500	3.942
		180	0.10	42.000	41.000	3.714
		240	0.12	35.000	34.000	3.526
		300	0.16	26.250	25.250	3.229
		360	0.15	28.000	27.000	3.296
10	4.12	60	0.25	16.480	15.480	2.740
		120	0.23	17.913	16.913	2.828
		180	0.34	12.118	11.118	2.409
		240	*0.59	8.983	7.983	1.789
		300	0.44	9.364	8.364	2.124
		360	0.50	8.240	7.240	1.980
15	4.24	60	0.49	8.653	7.653	2.035
		120	0.63	6.730	5.730	1.706
		180	0.96	4.417	3.417	1.229
		240	*1.41	3.007	2.007	0.697
		300	1.02	4.157	3.157	1.150
		360	1.24	3.419	2.419	0.884

* : outlier - not considered in regression analysis
(Media size = 0.85 - 1.00 mm; NaOCl = 5 mg/l; pH 7.8)

Table D.4 - Data for the Calculation of k and No
(for Depth = 400 mm)

Flow m^3/m^2-h	Inf. Fe Conc. ($C_0, mg/l$)	Time (min)	Eff. Fe Conc. ($C, mg/l$)	C_0/C	$C/C_0 - 1$	$\ln (C/C_0 - 1)$
5	4.20	60	0.09	46.667	45.667	3.821
		120	0.08	52.500	51.500	3.942
		180	0.09	46.667	45.667	3.821
		240	0.12	35.000	34.000	3.526
		300	*0.25	16.800	15.800	2.760
		360	0.13	32.308	31.308	3.444
		420	0.15	28.000	27.000	3.296
		480	0.17	24.706	23.706	3.166
		500	0.20	21.000	20.000	2.996
		600	0.21	20.200	19.000	2.944
10	4.12	60	0.14	29.432	28.432	3.347
		120	0.12	34.333	33.333	3.507
		180	0.15	27.467	26.467	3.276
		240	0.19	21.684	20.684	3.029
		300	0.28	14.714	13.714	2.618
		360	0.32	12.875	11.875	2.474
		420	0.32	12.875	11.875	2.474
		480	0.41	10.049	9.049	2.203
15	4.24	60	0.34	12.471	11.471	2.440
		120	0.28	15.143	14.143	2.649
		180	*0.83	5.108	4.108	1.413
		240	0.38	11.158	10.158	2.318
		300	0.63	6.730	5.730	1.746
		360	0.82	5.171	4.171	1.428
		420	0.94	4.511	3.511	0.921

* : outlier - not considered in regression analysis
(Media size = 0.85 - 1.00 mm; NaOCl = 5 mg/l; pH 7.8)

APPENDIX E

DATA FOR CALCULATION OF $H/H_0 - 1$ WITH SPECIFIC DEPOSITS
AT VARIOUS FILTRATION RATES

Table E.1 - Relationship of H/Ho - 1 with Specific Deposit at Filtration Rate of 5 m³/m²-h

Depth (cm)	Initial Headloss Ho, mm	Filtration time (h)	H/Ho	H/Ho - 1	Specific Deposit vol/vol
10	18	1	1.24	0.24	0.0033
		2	1.60	0.60	0.0065
		3	1.92	0.92	0.0098
		4	2.36	1.36	0.0131
		5	2.80	1.80	0.0161
		6	3.12	2.12	0.0190
20	38	1	1.263	0.263	0.0019
		2	1.526	0.526	0.0039
		3	1.763	0.763	0.0058
		4	2.105	1.105	0.0077
		5	2.421	1.421	0.0097
		6	2.632	1.632	0.0116
30	50	1	1.280	0.280	0.0014
		2	1.480	0.480	0.0027
		3	1.660	0.660	0.0041
		4	1.940	0.940	0.0055
		5	2.180	1.180	0.0068
		6	2.340	1.340	0.0082
40	64	1	1.219	0.219	0.00103
		2	1.344	0.344	0.0021
		3	1.516	0.516	0.0031
		4	1.750	0.750	0.0041
		5	1.938	0.938	0.0051
		6	2.063	1.063	0.0062
		7	2.234	1.234	0.0072
		8	2.547	1.547	0.0082
		9	2.719	1.719	0.0092
		10	2.891	1.891	0.0102

(Influent Fe = 4.2 mg/l, pH 7.8, NaOCl = 5 mg/l)

Table E.2 - Relationship of $H/H_0 - 1$ with Specific Deposit at Filtration Rate of $10 \text{ m}^3/\text{m}^2\text{-h}$

Depth (cm)	Initial Headloss H_0 , mm	Filtration time (h)	H/H_0	$H/H_0 - 1$	Specific Deposit vol/vol
10	45	1	1.422	0.422	0.0060
		2	1.889	0.889	0.0119
		3	2.533	1.533	0.0179
		4	3.111	2.111	0.0234
		5	3.911	2.911	0.0286
		6	4.978	3.978	0.0334
20	75	1	1.347	0.347	0.0035
		2	1.693	0.693	0.0071
		3	2.133	1.133	0.0107
		4	2.520	1.520	0.0142
		5	3.027	2.027	0.0175
		6	3.747	2.747	0.0207
30	105	1	1.257	0.257	0.0026
		2	1.533	0.533	0.0052
		3	1.848	0.848	0.0078
		4	2.324	1.324	0.0103
		5	2.505	1.505	0.0128
		6	3.029	2.029	0.0152
40	130	1	1.223	0.223	0.0020
		2	1.469	0.469	0.0040
		3	1.715	0.715	0.0060
		4	1.946	0.946	0.0080
		5	2.238	1.238	0.0100
		6	2.677	1.677	0.0119
		7	3.123	2.123	0.0138
		8	3.692	2.692	0.0157

(Influent Fe = 4.2 mg/l, pH 7.8, NaOCl = 5 mg/l)

Table E.3 - Relationship of H/Ho - 1 with Specific Deposit at Filtration Rate of $15^3 \text{m}^3/\text{m}^2\text{-h}$

Depth (cm)	Initial Headloss Ho, mm	Filtration time (h)	H/Ho	H/Ho - 1	Specific Deposit vol/vol
10	50	1	1.42	0.42	0.00711
		2	2.12	1.12	0.01527
		3	2.84	1.84	0.02240
		4	4.00	3.00	0.02910
		5	5.44	4.44	0.05340
		6	7.02	6.02	0.04150
20	100	1	1.22	0.22	0.0051
		2	1.67	0.67	0.0101
		3	2.09	1.09	0.0148
		4	2.80	1.80	0.0195
		5	3.42	2.42	0.0234
		6	4.40	3.40	0.0272
30	135	1	1.222	0.222	0.0038
		2	1.585	0.585	0.0075
		3	1.904	0.904	0.0111
		4	2.460	1.460	0.0144
		5	3.000	2.000	0.0168
		6	3.644	2.644	0.0200
40	185	1	1.081	0.081	0.0029
		2	1.357	0.357	0.0058
		3	1.589	0.589	0.0088
		4	2.011	1.011	0.0117
		5	2.670	1.670	0.0146
		6	3.205	2.205	0.0174
		7	3.730	2.730	0.0199

(Influent Fe = 4.2 mg/l, pH 7.8, NaOCl = 5 mg/l)

APPENDIX F

COMPUTER PROGRAM FOR CALCULATION OF SPECIFIC DEPOSITS
AND FILTER COEFFICIENT

DLIST

```
10 DIM C1(30),C2(30),N(30)
15 PRINT "FILTER RUN TIME (H)"
16 INPUT N
20 PRINT "ENTER C1 AND C2 STARTI
    NG WHEN T=0"
35 FOR I = 0 TO N
40 INPUT C1(I),C2(I)
50 NEXT I
55 PRINT "FLOWRATE IN CM/HR"
56 INPUT VA
60 PRINT "DEPTH (L1-L2) IN CM"
70 INPUT B
72 SUM = 0.0
73 PRN 1
75 PRINT "FLOW= "VA,"DEPTH= "B
77 PRN 1
78 PRINT "LAMBDA (7CM)      SIGMA
    (VOL/VOL)
79 PRINT "====="      "====="
    "====="
80 FOR I = 1 TO N
82 SAM = ((C1(I) - C2(I)) / B)
84 TAM = SAM / C1(I)
90 AX = (C1(I - 1) - C2(I - 1)) /
    2.0
100 SX = AX * .00004 * VA / B
110 SUM = SUM + SX
112 PRN 1
125 PRINT TAM,SUM
130 NEXT I
```