Impact of process variables on nutrient removal in slow sand filters

Shuaib Salman

Civil Engineering

December 1995

Abstract

This study is a field evaluation of slow sand filtration as a tertiary treatment at pilot scale level. Three slow sand filters were constructed at Al-Khobar STP site and were operated for about 15 months. Four different flow rates of 8, 10, 16 and 20 1/min at three different sand depths of 150, 80 and 50 cms and two different size of sand of 0.5 and 0.3mm were used. The effect of flow rates, sand depth and sand size on percent removal of BOD, SS, turbidity and nitrogen species were investigated. At these operating conditions the results from the pilot scale filters proved slow sand filtration to be an eefective wastewater treatment technology. The average removal efficiencies of BOD, SS, turbidity as well as nitrification, denitrification and nitrogen removal efficiencies ranged from 41.8 to 83.4%, 21.6 to 71.0%, 37.7 to 62.8%, 42.4 to 78.2%, 58.1 to 82.1% and 34.7 to 67.5% respectively. Statistical analysis was performed on the average means using 't-test' on the experimental data. It was confirmed that the removal efficiencies decreased with the increase in flow rate, decrease in sand depth and increase in sand size.

Impact of Process Variables on Nutrient Removal in Slow Sand Filters

by

Shuaib Salman

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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COLLEGE OF GRADUATE STUDIES

بسم الله الرحمن الرحيم

(In the name of Allah the Most Beneficent, The Most Merciful)

سبحنك لا علم لنا إلا ما علمتنا انك أنت
العليم الحكيم ۝

Glory be to You, We have no knowledge except what You have taught us. Verily, It's You, The all Knower, The all Wise. (Holy Qura'n 2:32)

صدق الله العظيم

Dedication

This Thesis is Dedicated To My Family

Acknowledgment

First and foremost, praise and thanks be to Almighty Allah, the most Gracious, the most merciful;

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THESIS ABSTRACT

NAME OF STUDENT	Shuaib Salman
TITLE OF STUDY	Impact of Process Variables on Nutrient Removal in Slow Sand Filters
MAJOR FIELD	Civil Engineering
DATE OF DEGREE	December, 1995

This study is a field evaluation of slow sand filtration as a tertiary treatment at pilot scale level. Three slow sand filters were constructed at Al - Khobar STP site and were operated for about 15 months. Four different flow rates of 8, 10, 16 and 20 l/min at three different sand depths of 150, 80, and 50 cms and two different size of sand of 0.5 and 0.3mm were used. The effect of flow rates, sand depth and sand size on percent removal of BOD, SS, turbidity and nitrogen species were investigated. At these operating conditions the results from the pilot scale filters proved slow sand filtration to be an effective wastewater treatment technology. The average removal efficiencies of BOD, SS, turbidity as well as nitrification, denitrification and nitrogen removal efficiencies ranged from 41.8 to 83.4%, 21.6 to 71.0%, 37.7 to 62.8%, 42.4 to 78.2%, 58.1 to 82.1% and 34.7 to 67.5% respectively. Statistical analysis was performed on the average means using 't - test' on the experimental data. It was confirmed that the removal efficiencies decreased with the increase in flow rate, decrease in sand depth and increase in sand size.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

Dhahran, Saudi Arabia
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خلاصة

إسم الطالب : شعيب سلمان

عنوان الدراسة : تأثير متغيرات عملية الترشيح الرملي على إزالة المغذيات

القسم : الهندسة المدنية

تاريخ : ديسمبر ١٩٩٥م

تعني هذه الدراسة بتجربة ميدانية للمعالجة الثلاثية لمياه الصرف الصحي بواسطة مرشحات رملية . لهذا الغرض تم إنشاء ثلاثة مرشحات رملية بمحطة معالجة مياه الصرف الصحي بالخبر وتشغيلها لفترة خمسة عشر شهراً . لقد تم التشغيل تحت معدلات متغيرة من التدفق وهي ٨ , ١٠, ١٦, ٢٠ لتراً في الدقيقة بأعماق رمل متباينة وهي ١٥٠ , ٨٠ و ٥٠ سنتمتراً لنوعين من الرمل بحجم ٠,٥ مم و ٠,٣ مم ودرست معدلات إزالة الأوكسجين الحيوي ، المواد العالقة ، الكدارة والنيتروجين . نتائج التجربة أثبتت فعالية الترشيح الرملي لمعالجة مياه الصرف الصحي تحت ظروف التشغيل الموضحة أعلاه . تراوحت معدلات إزالة الأكسجين الحيوي ، المواد العالقة ، الكدارة من ٤١,٨ إلى ٨٣,٤ ٪ ،٢١,٦ إلى ٧١,٠ ٪ ، ٣٧,٧ إلى ٦٢,٨ ٪ على التوالي .كذلك تراوحت كفاءة النترتة نزع النترتة ، إزالة مجمل النتروجين من ٤٢,٤ إلى ٧٨,٢ ٪ ، ٥٨,١ إلى ٨٢,١ ٪ ، ٣٤,٧ إلى ٦٧,٥ ٪ على التوالي . لقد حللت النتائج إحصائياً وأكدت أن كفاءة الإزالة نقصت بزيادة معدل التدفق ، خفض عمق الرمل الترشيحي وزيادة حجم الرمل .

درجة ماجستير

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

CHAPTER # 1

1. INTRODUCTION

For many years, wastewater treatment plant effluent quality was measured in terms of two parameters namely suspended solids (SS) and biochemical oxygen demand (BOD). However this philosophy has changed and now more stringent effluent standards are imposed by the regulatory agencies. In some areas, high quality effluents are required before discharge to receiving waters or before land application.

The removal of nitrogen and nitrogenous compounds is receiving great attention in most of the wastewater management programs in order to prevent it from entering the receiving waters or land disposal site. Nitrogen, in its various forms can deplete dissolved oxygen in receiving waters. It has been found, that for the conversion of the ammonia to nitrate of 4.5mg oxygen per mg ammonia oxidized would be required. Additional reasons for the removal include,

1. NH_3 at low concentrations can be toxic to fish.
2. NH_3 is corrosive for copper fittings; and
3. NH_3 increases chlorine breakpoint requirement and contact time for adequate disinfection.

The major concern in wastewater reuse is related to health aspects. Nitrate contamination of ground water resources is becoming an ever increasing problem. In some parts of Europe nitrate concentrations in ground water reached serious levels 20 years ago and have continued to increase. The United States, Canada, the European Economic Community (EEC) and the World Health Organisation have set maximum acceptable limits for nitrates of 10mg/l. Because of the adverse health effects associated with nitrate in the drinking water (METHEMOGLOBINEMIA) and the concerns regarding diminishing water quality, interest is increasing in nitrate removal technologies.

Nitrogen concentrations in raw municipal wastewaters are well documented by (Martin, 32., Reeves, 44). Nitrogen concentrations range from 15 to 50 mg/l, out of which approximately 60% is ammonia-N, 40% is organic-N and a negligible amount about 1% is nitrite and nitrate nitrogen. An estimate for the total nitrogen discharged into sewerage systems in domestic wastewater is 0.84 million tons/year in the United States.

While conventional technology is well developed for removing organics from wastewater, the processes for the control of nitrogen in wastewater effluents are under going fast development. Tertiary treatment is a third stage to remove more nutrients and other contaminants from wasteswater that are usually removed by the conventional secondary wastewater treatment. This includes microstrainers, filtration (Slow or Rapid), chemical precipitation, carbon adsorption etc. The selection of the type of tertiary treatment process that is to be employed depends on a number of factors such as cost, availability of land, and most important among these is the water quality that is desired.

One of the most promising, versatile,and attractive techniques proposed to treat the secondary effluent in this study is *"Slow Sand Filtration"* as a tertiary treatment.

Though slow sand filtration is very promising little work has been done on determining the impact of the process variables, depth, flow rate and sand size on the removal of nutrients by a slow sand filter. The objective of this study is to determine the impact of the nutrient removal in slow sand filters.

CHAPTER # 2

2. LITERATURE REVIEW

2.1 Environmental Impact Of Nitrogen

The presence of various compounds containing the element nitrogen is becoming increasingly important in wastewater management because of many effects that nitrogenous material in wastewater effluents, have on the environment. Nitrogen results largely from human sanitary wastes. Also kitchen garbage grinders and food processing industries make significant contributions. The nitrogen in raw sewage is almost totally in the form of ammonia and organic nitrogen, with negligible nitrate. Total content in typical municipal wastewater approximates 10 pounds of nitrogen per capita per year.

Bliss, (8) in his literature review has stated that nitrogen is of concern with regards to the management of water quality in many countries. Many streams and groundwaters are becoming enriched with various forms of nitrogen as a result of greatly increased nitrogen discharges arising from man's urban and rural activities. Sources of nitrogen reaching surface and groundwaters include wastewater effluent discharges, urban runoff, agricultural and irrigation drainage, and atmospheric emissions which eventually reach the

aquatic environment as a result of precipitation or dust-fall. Environmental problems such as algal growth (eutrophication), toxic effects in streams, lakes and water distribution systems, also result from the significant discharge of nitrogen. Also there will be decrease in dissolved oxygen level due to oxidation of ammonia nitrogen (Hammer, 23).

Impact of nitrogen on water resources depends on:

1. The amount and type of nitrogen discharges
2. The characteristics of, and the biochemical transformations which take place in the aquatic environment, and
3. The required beneficial uses of the receiving waters.

Hence considering all the above problems associated with nitrogen , the removal is being considered in most parts of the world. So nitrogen removal processes have recently become an extremely important part of wastewater treatment technology. It is nearly certain that nitrogen removal processes will be at the forefront in wastewater treatment systems because of increasing removal requirements of nitrogenous oxygen demand (NOD). Stiochiometrically, to accomplish nitrification, each 1 mg of nitrogen requires approximately 4.5 mg of oxygen, thus it can exhibit a great oxygen demand on a receiving watercourse.

Conventional primary and secondary treatment normally remove 40 percent or less. In some areas of Denmark nutrient removal is required even for very small wastewater plants. Wide areas of lakes in Denmark suffer from severe oxygen deficits. As one of several steps a strict plan for the nutrient removal from sewage plant outlets has

been introduced for instance in the Limfiord area in Northern Jutland and the counties have agreed upon a plan for the removal of nutrients (Niels, 39).

2.2 NITROGEN REMOVAL PROCESSES

Nitrogen in untreated wastewaters is principally in the form of ammonia or organic nitrogen, both soluble and particulate. Soluble organic nitrogen is mainly in the form of urea and amino acids. Untreated wastewater usually contains little or no nitrite or nitrate. In primary and secondary treatment a portion of the organic particulate matter is removed by primary sedimentation. During the secondary biological treatment, most of the particulate organic nitrogen is transformed into ammonium and other inorganic forms. A portion of the ammonium is assimilated into the cell material of the biomass. Most of the nitrogen in treated wastewater is thus in the ammonium form. Less than 30 percent of the total nitrogen is removed by conventional secondary treatment.

For further removal of the nitrogen in the tertiary stage a number of physical, chemical and biological processes are available. Each of the processes has a different effect on organic-nitrogen , ammonia-nitrogen and nitrate nitrogen in the wastewater.

The decision of which process is finally used depends on the characteristics of the untreated wastewater, the existing treatment being given to the wastewater, the level of nutrient control required, and the flexibility in operations and cost.

2.2.1 Physical And Chemical Removal Processes

There are many physical and chemical processes for the removal of nitrogen. The physical processes are *filtration, air stripping, electrodialysis* and *reverse osmosis*, whereas the chemical processes are *breakpoint chlorination, chemical coagulation, selective ion exchange* for ammonium and nitrate. Of these, the principle physical and chemical processes used for nitrogen removal are air stripping , breakpoint chlorination and selective ion exchange. Each of these processes has its advantages and disadvantages which have made these three the most used of all the physical and chemical nitrogen removal processes available.

The applications of these processes are usually under special conditions when biological processes cannot be used for one reason or the other as for example where the climatic conditions inhibit biological nitrification (Metcalf and Eddy, 33a).

2.2.2 Chemistry Of Nitrification And Denitrification

Most of the nitrogen present in sewage is in the form of ammonium ion or other compounds (e.g., urea) from which ammonium ion is readily derived by hydrolysis. A relation between the various compounds and the transformation which occur are presented schematically in Fig 2.1 known as nitrogen cycle. *Nitrification* and *Denitrification* are respectively the biological oxidation and reduction of ammonia-N to nitrate-N and nitrite-N to nitrogen gas. The reaction, considered in detail in the following discussion is known to proceed as follows.

1. Oxidation of ammonia to nitrate-N

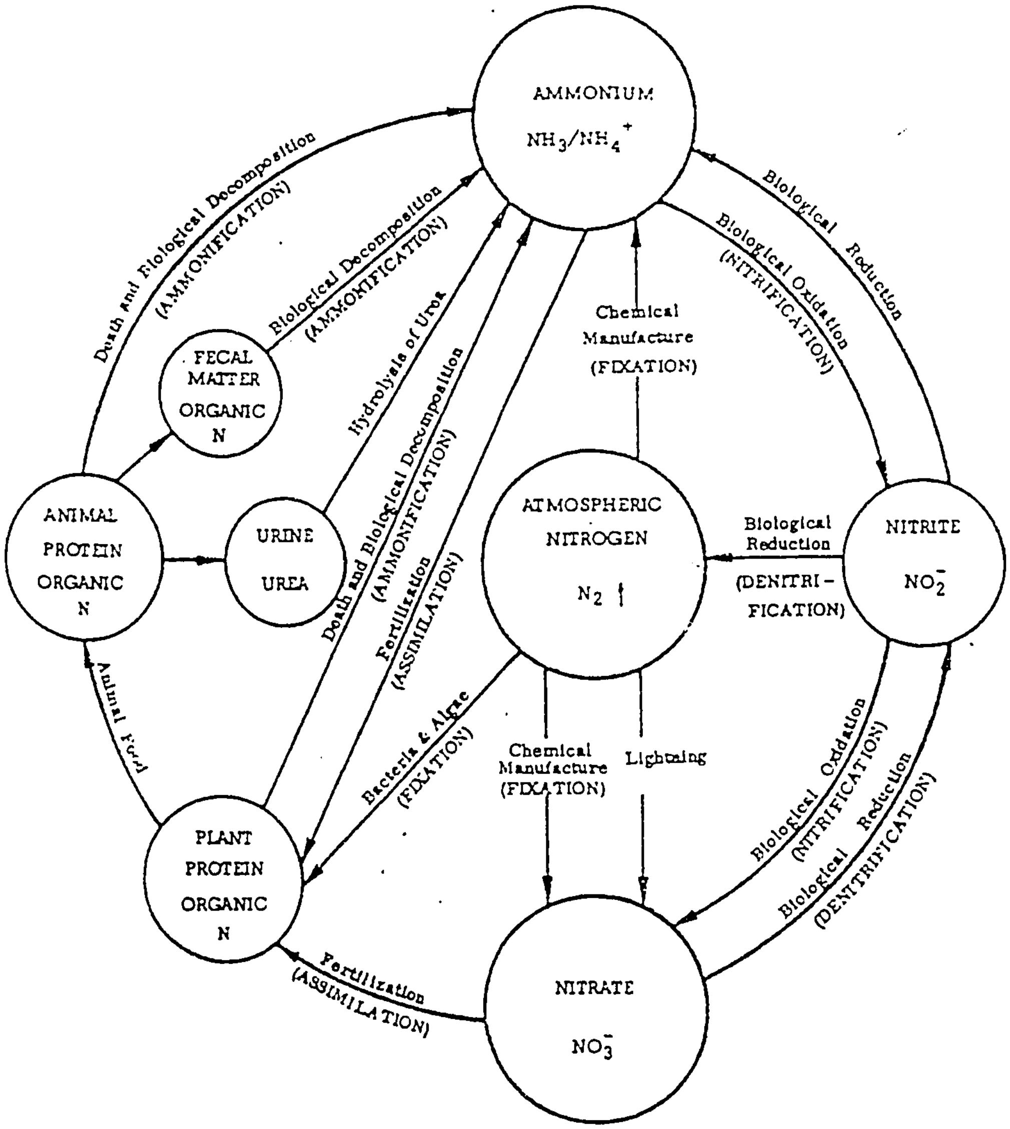


Figure 2.1 Nitrogen Cycle

2. Oxidation of nitrite-N to nitrate-N

3. Reduction of nitrate-N to nitrite-N

4. Reduction of nitrite-N to nitrogen gas

The above reactions are part of the nitrogen cycle in nature and are understood to be mediated by chemoautotrophic bacteria of the genera *Nitrosomonas Nitrobacter Pseudomonas, Micrococcus* respectively, for their energy, growth and maintenance. Although heterotrophic micro-organisms have been known to effect nitrification (Vertracte and Alexander, 55), their relative contribution is believed to be minimal. Features of Nitrosomonas and Nitrobacter are shown below (Sharma, 47).

Morphology	**Nitrosomonas**	**Nitrobacter**
Cell Shape	Oval to rod - shaped	Oval to rod - shaped
Cell size	1x1.5μ	0.5x1.0μ
Motile	May or May not be	May or May not be
Gram test	Negative	Negative
Dissolved Oxygen requirement to Nitrify	Strict Aerobes	Strict Aerobes
Autotrophs	Obilgate	Facultative

Parameters that affect the biological nitrification and denitrification reactions and other process schemes employed via biological means are listed in the following discussion.

Transformation reactions of importance include, fixation , ammonification, nitrification, and denitrification (EPA, 43). Fixation of nitrogen from nitrogen gas to organic nitrogen is accomplished biologically by specialised microorganisms. Biological fixation accounts for the natural transformation of nitrogen to compounds which can be used by plants and animals.

Ammonification is the change from organic nitrogen to the ammonia (NH_3/NH_4^-) form. This results from dead animals and plant tissue.

Protein ÷ micro-organisms ------------------- NH_3/NH_4^+ -------(a)

Nitrogen in rain exists principly as urea, which is hydrolysed by enzyme urease to ammonium carbonate

$$H_2CONH_2 + 2H_2O \xrightarrow[urease]{eneyme} (NH_4)_2CO_3 \text{--------------------------------(b)}$$

Assimilation is the consumption of nitrate compounds to form plant protein and other nitrogen containing compounds

$$NO_3^- + CO_2 + greenplants + sunlight \rightarrow protein \text{------------------------(c)}$$

$$NH_3 / NH_4^- + CO_2 + greenplants + sunlight \rightarrow protein \text{----------------(d)}$$

The term nitrification as mentioned in the literature is the biological oxidation of ammonium, to nitrite and then to nitrate. The bacteria responsible for these reactions are called as chemoautotrophs as they use inorganic chemicals as their source of energy

$$NH_4^- + 1.5O_2 \xrightarrow{bacteria(Nitrosomonas)} NO_2^- + 2H^+ + H_2O \text{------------}2.1$$

The nitrates are in turn oxidised to nitrites according to the following equation.

$$NO_4^- + 0.5O_2 \xrightarrow{bacteria(Nitrobacter)} 2NO_3^- \text{------------------------------}2.2$$

Reactions 2.1 and 2.2 are believed to serve as energy yielding reactions for the two autotrophic bacteria, represented by the genera Nitrosomonas and Nitrobacter, respectively.

Denitrification is a two-step biological process in which the first step is a conversion of nitrate to nitrite,. The second step carriers nitrite through two intermediate steps to nitrogen gas. Bacterial genera that are known to contain denitrifying species include, Microccous, Bacillus, Chromobacter and Pseudomonas (Gayle, 20) can accomplish nitrate reduction by what is known as nitrate dissimilation in which nitrate or nitrite replaces oxygen in the respiratory process of the organism under anoxic condition. This two - step process is normally termed as dissimilation. The exact sequence of biological denitrification is not well known. Different routes have been reported by different researchers. According to Fewson and Nicholas (18), dissimilatory nitrate metabolism occurs in a series of enzymes catalysed reaction similar to the route:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow NOH \rightarrow NH_2OH \rightarrow NH_3$$

The NOH (amine) produced yields N_2 gas in an enzymatic environment. In an nonenzymatic environment NOH produces N_2O_2 (nitrite oxide) which yields N_2O (nitrous oxide). The reaction sequence is partially confirmed through few enzymes found in denitrifying bacteria. Payne, (41), however reported that denitrification simply proceeded in the sequence as shown in eq 2.3.

Whatever is the sequence, the conversion of nitrate (NO_3^-) to nitrite (NO_2^-) and nitrite to nitrogen gas (N_2) proceeds in a sequence described below:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow NO_2 \rightarrow N_2 \quad \text{--}2.3$$

2.2.3 Biological Processes

There are many biological processes for the removal of nitrogen. The processes are i) Bacterial assimilation ii) Harvesting algae iii) Oxidation ponds iv) Nitrification and Denitrification (Metcalf and Eddy, 33b).

The biological transformations of nitrogen that occur in wastewater treatment processes have been described by Ludzak (31), Barnard (5), and Balakrishnan (4), that all forms of nitrogen can be reduced by biological processes through stages of ammonification-nitrification and denitrification. The first two stages require the presence of oxygen, the last stage (denitrification) requires absence of oxygen.

Ammonification is the change from organic nitrogen to the ammonia (NH_3 / NH_4^-) form. This results from dead animals and plant tissue. The two distinct mechanisms responsible for the reduction of nitrites and nitrates are: (a) formation of ammonia followed by transfer of ammonia into the anabolic cell-metabolism.

Nitrification has no effect on NO^{-}_{3}, limited effect on organic nitrogen and NH_3 - NH_4^+ is converted to NO^{-}_{3}. The net nitrogen removal varies from a mere 5 to 20 %.

Denitrification is reduction of nitrates to nitrites and finally to nitrogen gas in the absence of oxygen by a group of bacteria. It has no effect on either organic nitrogen or NH_3 -NH_4^+ but removes between 70 to 95 % of NO^{-}_{3}. Thus the net removal of total nitrogen entering the process varies from 70 to 95 %.

The nitrate produced during nitrification can be reduced to nitrogen gas by a variety of facultative bacteria under anaerobic conditions (Denitrification). Because nitrified effluent contains little carbonaceous BOD for cell synthesis, an organic carbon source is required to act as a electron donor and to supply carbon for biological synthesis of the denitrifying organisms. Numerous reduced organic chemicals have been successfully tested as a carbon source, including acetic acid , acetone, ethanol, methanol and sugar. Methanol is the most preferred substance in most applications as it is one of the least expensive of the synthetic compounds.

The biological nitrification and denitrification may be carried out in a number of systems. The systems can either be separate stage where the nitrification/ denitrification occur in separate reactors (Two Stage System) or they can be Combined nitrification / denitrification systems. The two stage systems may be attached or suspended growth systems (Metcalf and Eddy, 33b).

A number af attached-growth denitrification processes, many of them proprietary, have been developed. Fludized-bed reactors and rotating biological contactors (RBCs) are

the most commonly used processes. The design of suspended-growth denitrification systems is similar in many respects to the design of the activated-sludge systems used to remove organic carbon. Both complete-mix and plug-flow reactors have been used.

Since nitrification converts NH_3 -NH_4^+ to NO^-_3. and denitification removes between 70 to 95 % of NO^-_3 combined nitrification and denitrification is the most popular process for the removal of nitrogen. It has a high potential removal efficiency, high process stability and reliability, relatively easy process control , low land area requirements, and a moderate cost. Most of these systems are capable of removing 60 to 80 % of the total nitrogen (Metclf and Eddy, 33c).

Combined nitrification / denitrification systems may be oxidation ponds or slow sand filtration. However oxidation ponds have the disadvantage of being energy intensive while slow sand filters offer the advantage of not being energy intensive.

Tertiary treatment (frequently referred to as effluent polishing) can mean different things on opposuite sides of the Atlantic. In Britain, tertiary treatment is usually referred to those processes which primarily reduce the suspended solids content of a secondary effluent and by doing so, also reduce the level of the BOD. This is not a comprehensive definition as some processes may be used to reduce the BOD, to some extent, by biological activity and one specific process (nitrifying filtration) employs biological activity not to remove material from the water but merely to change its form.

Generally the techniques of tertiary wastewater treatment can be listed as: microstrainers , grass plots, lagoons, sand filtration (slow filtration, rapid gravity filtration, upward flow filtration), upward flow clarifiers, and nitrifying filters.

Of these, microstrainers and rapid gravity filtration go right back to the inception of tertiary sewage treatment at the East Hyde treatment work, Luton, in the early 1950s. They are still effective and popular. Grass plots and lagoons are also widely employed and have definite advantages for specific situations. Upward - flow clarifiers are widly employed, with varying success, usually on the effluents from small and remote works. Nitrifying filters operate merely to reduce the ammonia content in an otherwise acceptable effluent. Upward-flow, deep - bed filtration is a popular and effective form of polishing process. Slow sand filtration is rarely employed and this represents an enigma to those aware of its effectiveness in the potable water industry.

Ellis (12) has shown that these slow sand filters can be applied effectively as tertiary treatment for relatively clean secondary effluents. His study showed that 88% removal of suspended solids, 76% removal of BOD and 97% removal of coliform organisms were all remarkably superior to the 35-45% removal of BOD and 60 % removal of suspended solids suggested in published results (Truesdale, 54, HMSO, 25, Black, 7,) of slow sand filter operation.

The slow sand filters operate very largely by a straining action through the formation of a layer of inert deposits and biological matter at the surface of the sand. This layer is referred to as the *Schmutzdecke* (a German word meaning "dirty layer"). There is appreciable microbiological activity within the sand itself as colloidal and soluble organic

materials are degraded and stabilized and as ammonia is converted to nitrate. This view is supported by the evidence of nitrification through the filter which has been observed in full scale and in laboratory scale work (Ellis, 13).

Ellis (12) in his literature review has reported that fundamentally the slow sand filters employed in tertiary wastewater treatment are typically the same as those used for the purification of drinking water. The salient features of a slow sand filter have been elaborately presented earlier in the introduction.

Farooq et al. (16) conducted a study for about a year on slow sand filtration of chlorinated secondary effluents from North Aramco Wastewater Treatment Plant, Dhahran. The study was conducted at a hydraulic loading of 0.16 m/h i.e., at a flow rate of 2 l/m using two different sand sizes of 0.3mm and 0.51mm to determine the efficiency. It was found that the effluent turbidity levels ranged from 0.08 to 0.43 NTU. The average percentage removal of BOD, nitrate, phosphate, and turbidity ranged from 79-92%, 17-30%, 83-84%, and 87-92% through different sizes and depths of sand. They found that a greater depth of sand was better for the removal of turbidity and nutrients.

At Tampa, Florida, advanced wastewater treatment plant studies carried out on sand filters at a hydraulic loading rate of 3.4 - 11m/d have proved that the addition of methanol in the influent is effective for wastewater denitrification (Koopman et al., 29). The wastewater treatment plant has consistently reduced efluent concentrations to 1.2 g/m^3 on a yearly average basis for a mean flow of over 2.2 m^3 /s.

Al - Adham (1) in his research on slow sand filter as a tertiary process on the secondary effluent pointed out that nitrification is probably taking place at the upper layers of the sand bed. This observation may be reasonable since adequate oxygen is present at the upper layers of the filter bed. He also pointed out that denitrification is taking place, when he observed that the concentration of $NO_2^- + NO_3^-$ in the filtrate is lower than that in the sampling port. This is probably true, since the dissolved oxygen concentration in deeper layer is decreasing, thus denitrification is more likely to occur.

Ellis (13) concluded that no nitrification was taking place during filtration even when the dissolved oxygen content of the influent was increased by aeration. He thought that denitrification was taking place due to low dissolved oxygen content of influent (1.5mg/l). But the denitrification continued at unreduced rate even when the dissolved oxygen content was increased to 8mg/l via diffused aeration. Scutt (46) raised an interesting point on this subject. He pointed out, because Ellis's observation is based on the reduction in nitrate concentration during filtration, the possibility of nitrification taking place should not be eliminated. In other words, he stated that it is possible to have nitrification taking place in the upper aerobic layers of the sand bed followed by denitrification due to absence of oxygen in the lower layers.

Ellis (14) conducted his study using slow sand filtration for treating tertiary sewage with four filters and found that when samples were taken during first and second stages from the points immediately below the surface sand of slower filter, 50% of the denitrification achieved was accounted for in the surface layers and the remainder through the total depth of the sand. In the second stage faster filter removed 22% of the nitrate

(mean value in secondary effluent 18 mg/l) while the slower filter (3.5m/d) removed 41% of the nitrate.

Prior to the commencement of the investigation continuing nitrification was expected but this was not the case as denitrification was the most predominant feature. More oxygen was diffused into the secondary effluent thinking that denitrification is resulting due to low dissolved oxygen. Even then there was no additional nitrification. This indicates that the intensity of biological activity was quite substantial on and within the sand bed resulting in consumption of oxygen.

Koopman et al. (29) achieved denitrification in sand filters with methanol as a carbon source. The hydraulic loading rates were varied between 3.4 and 11m/d and influent NO_2 + NO_3 -N concentrations of up to 22 g/m^3 were tested. The turnover rate of the sand bed ranged between 0.4 and 3.8 bed volume/d and complete denitrification i.e.effluent NO_2 + NO_3-N of 1.0 g/m^3 was obtained at daily loading of up to 2.7 kg/ m^3 total equivalent nitrate nitrogen (NO_3-N). To achieve complete denitrification the amount of methanol required was very nominal 3.3 to 3.5 g C H_3OH /g NO $_3$.

Clarence (10) conducted a study on soil columns packed into PVC pipe. Each column was a 2.75m length of 10cms diameter PVC pipe filled with 6cms of pea gravel at the bottom and 250cms of loamy sand on top. Column samples were analysed for NO_2^- , NO_3^- NH_4^+ and organic nitrogen. Net nitrogen removal averaged 30% when soil columns were intermittently flooded with secondary sewage effluent at infiltration rates that resulted in total annual infiltration of 85meters of water. Most of the nitrogen remaining in

the water was concentrated in a nitrate peak measured at the begining of each flooding period.

A survey of 27 slow sand filtration plants in the U S indicated that most of these plants are currently serving communities of fewer than 10,000 people, are more than 50 years old, and are effective and inexpensive to operate (Stezak and Sims, 50). In addition the major advantages over the other processes are:

1. Can be built with local materials using local skill and labour
2. It is very stable and effective in removing suspended solids and other nutrients.
3. No Chemicals are used so hazard of transporting and storing the chemicals is eliminated.
4. Maintenance is cheap as no mechanical and electrical equipment are used.

In addition to the above no backwashing is required, the cleaning of the filters being done by scraping the top 2-4 cms of the sand bed (*that is Schmutzdecke*) upon termination of the filtration phase.

Slow sand filters are quite different from rapid sand filters in terms of several aspects. However slow sand filters require less maintenance cost than rapid sand filters. Furthermore a detailed comparison is presented in the Table 2.1.

Table 2.1 *General Features of Slow Sand Filter versus Rapid Sand Filter(14)*

Description	Slow Sand Filers	Rapid sand Filters
Rate of filtration	0.1-0.4 m/h	4 to 21 m/hr
Cost of operation	Relatively low	Relatively high
Cost of Construction	Relatively low	Relatively high
Method of Cleaning	Scraping off surface layer	Backwashing
Water required off cleaning	0.2 to 0.6% of water filtered	1 to 6% of water filtered
Length of run between cleaning	20 to 60 days	12 to 72 hours
Size of Sand	ES 0.15 to 0.35 mm UC 3 or less	ES 0.35 mm or more, UC 1.5 or less
Grain size distribution of sand	Unstratified	Stratified
Depth of bed	30 cm of gravel , 90 to 110cm of sand	30 cm to 45 cm of gravel 60 to 70 cm of sand
Area of the filter	Requires large area of 2000 m^2	Requires less area of 40-400 m^2
Loss of head	6 cm initial to 120 cm final	30 cm initial to 275 cm final

2.3 SLOW SAND FILTRATION

Slow sand filters consist of the following basic elements.

I. Filter box : The filter box is usually made up of reinforced concrete or steel in rectangular or cylindrical shape. It has a concrete floor with over 3m in height, the filter box essentially acts or serves as a container for housing the: (a) Supernatant (b) Filter medium and Sand Depth (c) Gravel (d) Underdrain (e) Out-let Chamber

(a) Supernatant : As table 2.2 shows the water above the sand media is usually kept at about 1-1.5m which provides a pressure or head to obtain the desired filtration rate for an appreciable length of filter run. Various researchers have recommended different depth of water to be maintained above the sand bed.

(b) Filter Medium and Sand Depth : Although various materials have been employed as a filter medium in slow sand filters, sand is by far the most common material selected for its durability, inexpensiveness, and wide availability. The type of sand that is to be used should be free from dirt and clay. The sand that is to be used is characterised by its effective size (E S), d_{10}, which is defined as the diameter for which 10 % of the sand is finer by weight, and its UC which is defined as the ratio of d_{60} to d_{10} (Holtz, 27). Sand used in slow sand filters should be relatively fine with an effective size of 0.15mm to 0.3mm and an UC of less than 3 (Ellis, 12). Filter media that are sized too large will allow deposits to be driven deeper into the filter, thereby increasing the amount of medium to be scraped. On the other hand finer sand will increase head loss, and reduce filter runs. Table 2.3 shows the filter bed depth suggested by the following researchers. Ellis (12)

Table:2.2 Depth of water above the sand bed

Researchers	Depth (m)
Fox et al (19)	1.25
Gummerman et al (22)	1-1.25
Montegomery (36)	1.2-1.5
Paramasivan et al (42)	1-1.13
Weber (58)	0.9-1.5

Table:2.3 Depth of sand suggested by following researchers

Researchers	Depth (m)
Bellamy et al (6)	0.6-1.2
Ellis (14)	0.95
Gummerman (22)	0.6-1.4
Stezak et al (50)	0.38-1.83
Paramasivam et al (42)	1.0
Fox et at (19)	0.76

indicated that it is better to use deeper beds than tyo reduce grain size if an additional margin of safety is required. The depth of the filter bed needed for proper functioning of the purification process before resanding should be over 0.5 to 0.6m. The initial depth should be 0.9 to 1.0 m (Visscher, 57) to allow for sufficient number of scrapings before resanding. The filter depth is normally 1.0- 2.0m thick.

(c) Gravel : A gravel layer is laid over the under drainage system in order to support the overlaying sand. It helps in preventing the sand getting into the underdrainage system and also ensures uniform abstraction of the filtered water. The gravel bed consists of larger size gravel at the bottom and corresponding smaller size at the top. Generally four layers of gravel in descending order with respect to the size from the bottom will be provided. The depth of gravel ranges from 20-50cms (Bellamy, et al., 6).

(d) Underdrain : The bottom layer of the filter consists of the underdrain system. It is constructed with open joint hollow concrete blocks or with perforated pipes. The main function of the underdrain system is to support the overlaying gravel and to provide unobstructed passage of filtered effluent directly to the outlet channel or pipe.

(e) Outlet Chamber : The outlet chamber usually consists of two sections separated by a wall, on top of which a weir is placed with its overflow slightly above the top of the sand bed to prevent the development of negative pressure in the filter bed, and ensure that the filter operates independently of fluctuations in the level of the clear- water reservoir. By allowing the free fall of water over the weir, the dissolved oxygen concentration in the filtered water increases.

Typical design criteria for slow sand filtration provided in the Ten States Standard (51) and the International Research Center (IRC) Manual (21) are summarized in Table 2.4. The minimum number of units is set at two to ensure uninterrupted supply and facilitate maintenance. In larger plants the number of units may be increased to ensure greater flexibility often at little additional cost. It can be seen from the table that the more comprehensive design criteria formulated by the IRC reflects the longer experience of the European countries with slow sand filtration. As there is hardly any economy of scale in the cost of slow sand filter construction, short design periods of 10-15 years can be adopted to prevent overdesign and subsequently unnecessary eroding of resources in many developing countries.

II. Control Valves: The control valves form the most important part of the slow sand filter, as these valves regulate the flow of the water in and out of the filter. These valves should be provided with great precision as the quality depends on the regulation of these valves. In practice it is upto the discretion of the designer to provide the minimum number of valves needed for an effective operation of the filter. Basically the slow sand filter is equipped with the following valves.

1. Inlet valve which delivers the unfiltered water to the filter
2. Flow controlled regulating valve to provide constant head .
3. Drain off valve from the filter box.
4. Flow regulating valve.

Table 2.4: General design criteria for slow sand filters

Criterion	Ten State Standards	IRC Manual
Design period		10-15 years
Period of operation		24h/d
Filtration rate	0.08-0.24 m/h	0.1-0.2 m/h
	(0.03-0.10 gpm/sq ft)	(0.04-0.08 gpm/sq ft)
Height of underdrains including gravel	-	0.3- 0.5 m
Number of filter bed units	2 minimum	2 minimum
Filter bed depth	> 80 cm (30 in.)	50-90 cm (18-35 in.)
Filter bed area	-	5-200 m^2 per filter
Sand medium specification		
Effective size	0.3 - 0.45mm	0.15- 0.3mm
Uniformity coefficient	< 2.5	<3.5

2.3.1 The Purification Mechanisms

The method of purification through slow sand filters is not completely understood though it is the most popular method of water treatment. Letterman (30), suggested mechanical straining, sedimentation, adsorption , chemical and biological activity as the important processes of slow sand filtration. The following mechanisms are believed to take place within the filter.

(a) ***Sedimentation and Straining*** : When the filter is commissioned the initial mechanism that takes place within the filter is sedimentation and straining. The sample will remain above the sand depending upon the filtration rate. The heavier particles of suspended matter start to settle, while the lighter particles are drawn into the interstices of the sand particles. With time a deposit of biological matter forms on the top of the sand bed which is referred to as Schmutzdecke. The Schmutzdecke layer and the biological growth have significant effect on the purification mechanism. (Bellamy 6, Ellis 12, Huisman 28, Letterman 30, Guidelines for O&M of SSF Plant in Rural Areas of Developing Countries, 21.)

(b) ***Chemical and Bacteriological Action*** : As stated earlier a thin layer called the Schmutzdecke is formed on the surface of the filter bed which consists of alluvial mud, organic matter, and other forms of life such as fungi, bacteria, actinomycetes, plankton, including algae. Suspended matter and organic material is retained by this layer as the water passes through this layer. With time the amount of organic matter will not be sufficient to support the bacterial population in the Schmutzdecke layer which in turn

slowly die or may be eaten by other protozoa. This is a chain reaction as the death of organisms will increase the organic matter available for other organisms to feed upon, due to which additional organic matter available which will serve as the food for bacteria at lower depths. At lower depths the food is minimal due to the biochemical decomposition of organic matter which leads to the die off of bacteria. All the coming impurities will stick to the bacterial slime and are subsequently broken done by biochemical action and finally discharged with the effluent.

2.3.2 Effect Of Algae

Algae are unicellular or multicellular found in all natural waters where there is presence of light and nutrients. They are green and the most common species namely *chlamydomonas, scenedesmus, novicula* (Standard Methods, 49) are phototrophs, that is they derive their energy from sunlight and use inorganic compounds as their source. It has been known that algal blooms can develop in places where the water is stagnant or moving slowly (Mitchel, 34). Algae have significant effect on the functioning of the filters, they may be advantageous or disadvantageous. It has been stated by Ellis, (12) that high concentrations of the algae will cause anaerobic biological activity within the filter, giving rise to problems such as early clogging of the filter, and also increase the concentration of soluble and biodegradable organics. Their presence in the filter is not totally disadvantageous as moderate concentrations will be beneficial in building the filter skin and also provide the water with oxygen needed for the aerobic activity.

However in order to have a trouble free operation and to enhance the efficiency of the filter they should be controlled either by chemicals or physical methods. Chemical methods include the addition of chemical such as chlorine, copper sulphate or pre-ozonation. In case where chemical addition is not recommended, physical control methods such as centrifugation, and by simply covering the filters with sheets which prevent the passage of light.

2.3.3 Flow Control

Filters may be operated by control of either the outlet or the inlet flow. In outlet-controlled filters, the rate of flow is controlled by an outlet valve which has to be opened a bit further as the filter run progresses, to compensate for the increased hydraulic resistance of the filter bed thereby forcing the operator to visit the plant at least every day.

In an inlet-controlled filter, the rate of filtration is set at the desired level without further manipulation. At first the water level over the filter will be low but will rise continuously to compensate for the increased resistance. Once the level has reached the scum outlet, the filter has to be taken out of service for cleaning.

2.3.4 Head Loss Development

When a clean filter is put into operation floc accumulation will be in the first few inches of the sand and as the time of operation increases, simultaneously the floc accumulation will also start increasing and extend deeper into the filter bed. The accumulated floc causes an increase in the hydraulic headloss.

The filter run is characterised by the headloss which is directly proportional to flow. The headloss is corrected to a standard flow to produce normalised headloss (Tom & Bagley, 52). When normalised headloss is plotted against total quantity of water treated per unit area of sand (Q in m), three distinct phases are identified:

(a) It usually falls in the first few days of the run.

(b) Thereafter, it usually increases exponentially at rates which depend on season.

(c) Its rate of increase (slope) may sometimes change very rapidly, which is dependent on season.

It has been observed that the normalised headloss is initially a function of sand quality and water temperature and increases with time. This pattern is observed in winter when biological activity is low. The headloss increases by 0.4-0.5% for each meter of water filtered.

During the early stage of the run headloss builds up gradually but suddenly the rate of increase in headloss itself increases by a factor between 5 and 10. This discontinuity depends mainly on the season varying from over 200 days in winter to less than 12 days in spring. Carman Kozeny, Fair and Hatch, Rose and Hazen (Hammer, 23) have proposed the following expression .

$$\frac{h}{l} = \frac{36kv(1-n)^2 V}{gn^3 w^2} \sum \frac{Pi}{d_i^2}$$

h/l= head loss per unit depth of filter bed m/m

k = empirical constant equal to 5.0, dimensionless

ν = Kinematic viscosity m^2/s

n = porosity dimensionless

V = filtration velocity m/s

g = gravitational accelaration m^2/s

w = Sphericity of grain (0.8 for rounded and 0.7 for angular)

P_i = fraction of total weight of filter grains in layer I, dimensionless.

d_i = geometric mean diameter of grain in layer i, m

CHAPTER # 3

3. RESEARCH OBJECTIVES

Most of the previous studies conducted on slow sand filtration have not studied the effect of higher flow rates, and sand sizes, on nitrification and denitrification over the range that were covered in this study. In this study higher flow rates were used for different size of sand and at different depths than previously studied. Futhermore the effect of flow rates were studied for different sand sizes and sand depths.

The overall objective of this research is to test the hypothesis that nitrification and denitrification occur in a slow sand filters as a result of the dissolved oxygen variation's within the filter and the ensuing predominance of oxic and anoxic zones.

The specific objectives of this study were:

1. To investigate the effect of grain size on nitrification and denitrification.

2. To study nitrification and denitrification process under different regimes of flow and different depths of sand.

3. Determination of spatial variation of various nitrogen species at the different loading conditions.

4. To assess the hypothesis that nitrification and denitrification will be carried in a single unit.

5. Determination of nitrogen balance.

Chapter # 4

4. EXPERIMENTAL WORK

4.1 EXPERIMENTAL SET-UP

Slow sand pilot filters were constructed at Al-Khobar Wastewater sewerage Treatment Plant. The Treatment Plant is serving Al-Khobar community, carrousel system operating satisfactorily yielding a good percentage of nitrification and denitrification. Secondary effluent from the channels connected to the clarifiers is stored in a sump from where it is pumped for chlorination

4.1.1 Construction Of Filter Units

The filtration plant was located on the premises of Al-Khobar Wastewater Treatment Plant on a 15m x 15m plot bordered in the east by the secondary clarifiers to facilitate the conveyance of unchlorinated secondary effluent to the filters. The plant consists of 3 modular units of slow sand filters with the necessary connections enabling them to be operated in series or parallel. The filtrate from the 3 units is directed to a common basin adjacent to the filters. The general layout of the plant is illustrated in Figure4.1

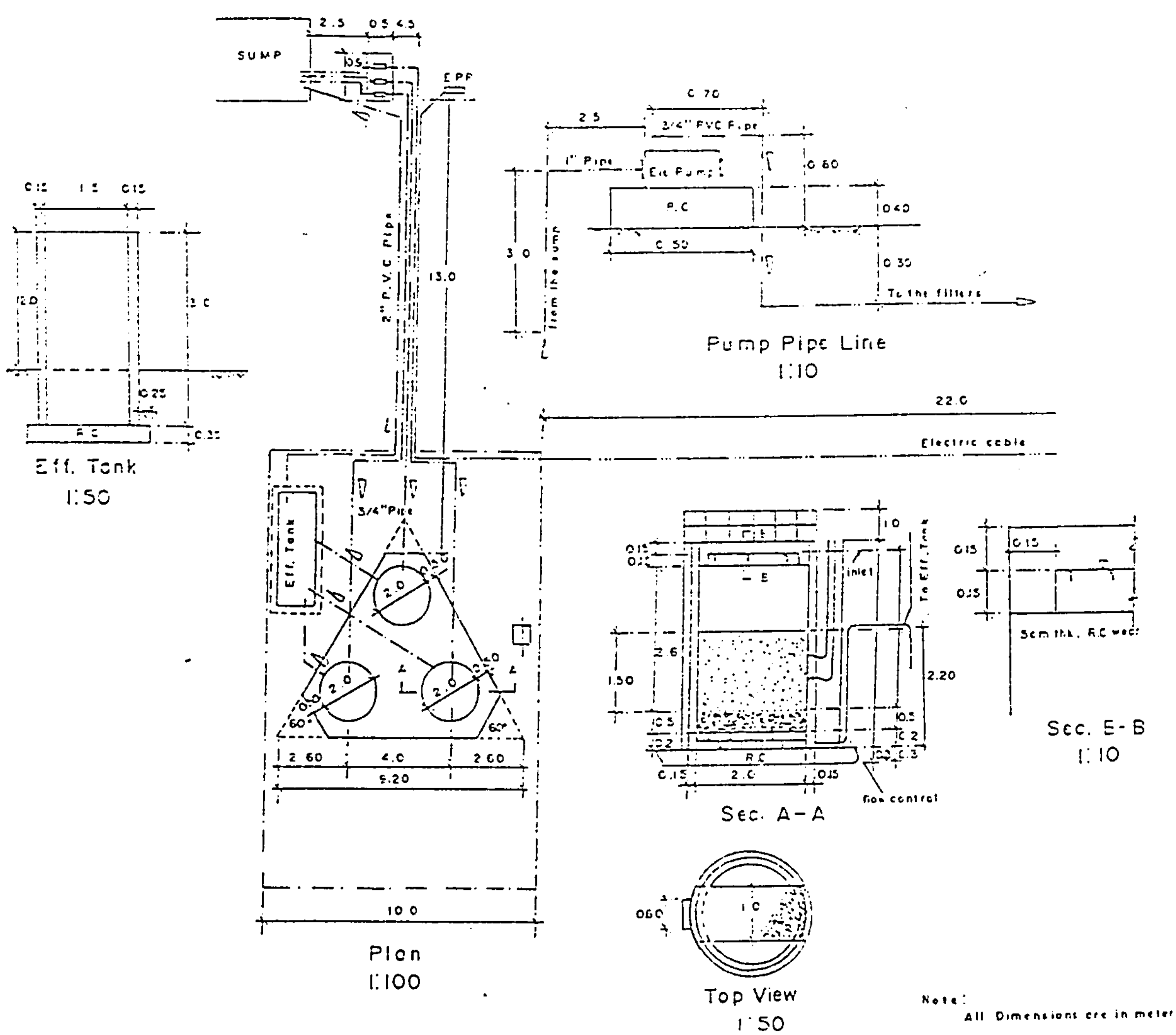
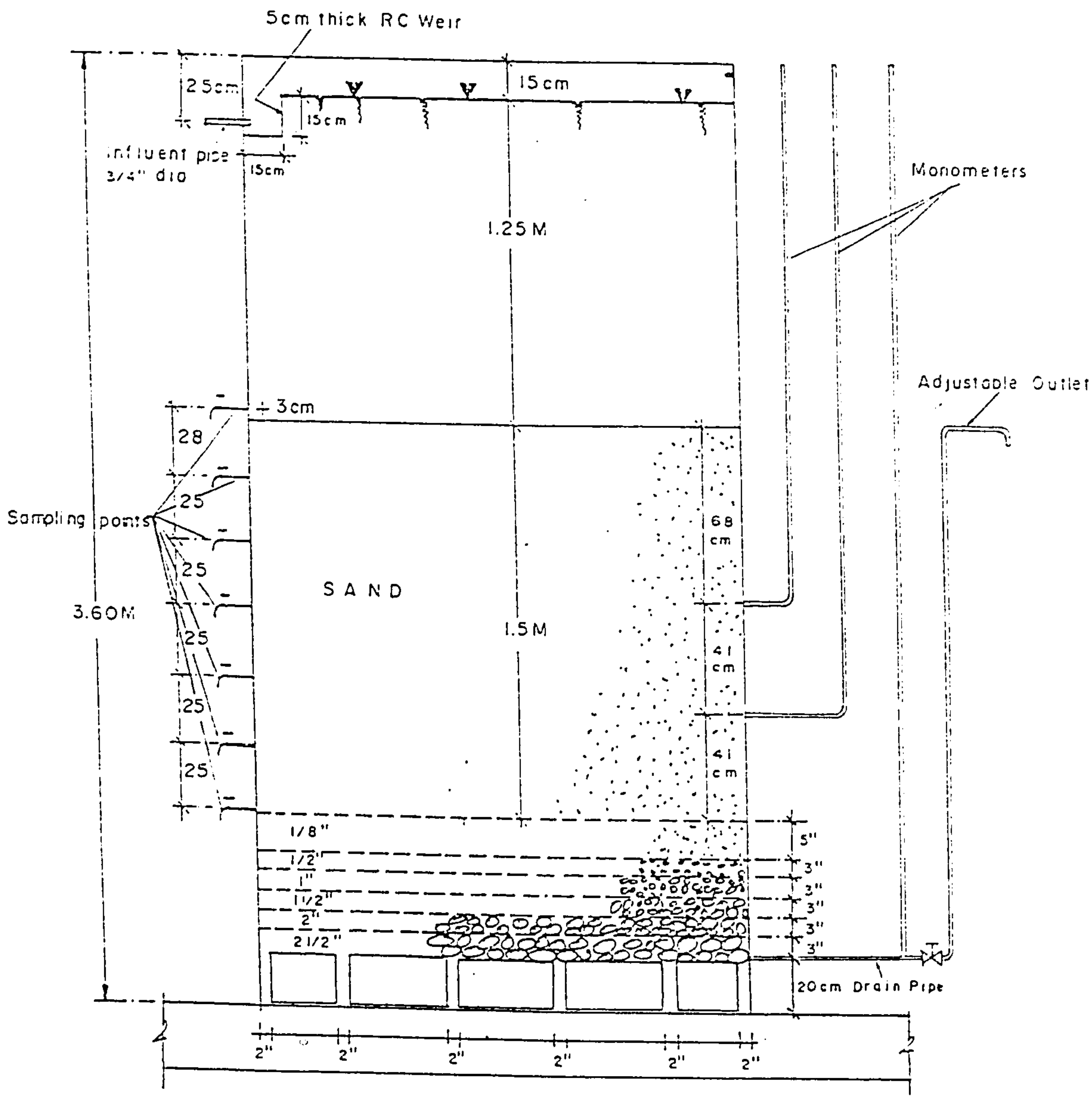


Figure 4.1: General layout of the Plant

The three identical filter modules are symmetrically placed on the truncated 9.2-m equilateral triangular base constructed of 30-cm thick 3500 psi reinforced concrete with its upper surface at ground level. Figure 4.2 shows the details of the filter unit. The 2-m internal diameter, 3.65 m high filter units were constructed of 15 cm thick 3500 psi reinforced concrete walls with a 1m wide steel walkway centrally placed on the top and a ladder on the outside. A 15-cm high circular weir was constructed of 5 cm thick RC, 15 cm away from the inner wall and the filter top to minimise disturbance of the supernatant water and subsequent erosion of the sand bed by the feed. Each filter was also fitted with a 2 " overflow pipe 5 cm from the top. Seven sampling ports located at 0.70, 0.95, 1.21, 1.48, 1.72, 1.95, and 2.20 m above the filter floor were used to assess the removal efficiency of various layers of the sand bed. Furthermore, to measure head loss, three manometers were installed at depths of 2.23, 2.64, and 3.56m. All sampling ports and manometers utilise 1/2 " schedule 80 PVC pipes whereas the influent and effluent lines were constructed of 3/4 " and 2 " schedule 80 PVC pipes respectively. Figure 4.3 shows the layout of underdrain system constructed of 20cm x 20cm x 40cm concrete blocks. To ensure unimpeded discharge of collected filtrate, the blocks were cemented to the floor 2" apart with the entire pore volume interconnected. The 2" effluent pipe placed 20 cm above the floor and supported on the concrete blocks extends to the centre of the filter. To prevent the potential accumulation of particulate matter in the pipe, particularly during breakthrough, the pipe was inverted downwards to a depth of 10 cm below the blocks as shown. To ensure that sand does not clog the underdrain, several layers of supporting reversely graded gravel are provided in sizes ranging from 2-1/2" at the bottom to 1/8 " at



Plan for Gravel Layers

1:20

Figure 4.2: Details of Filter Bed And Supporting Gravel.

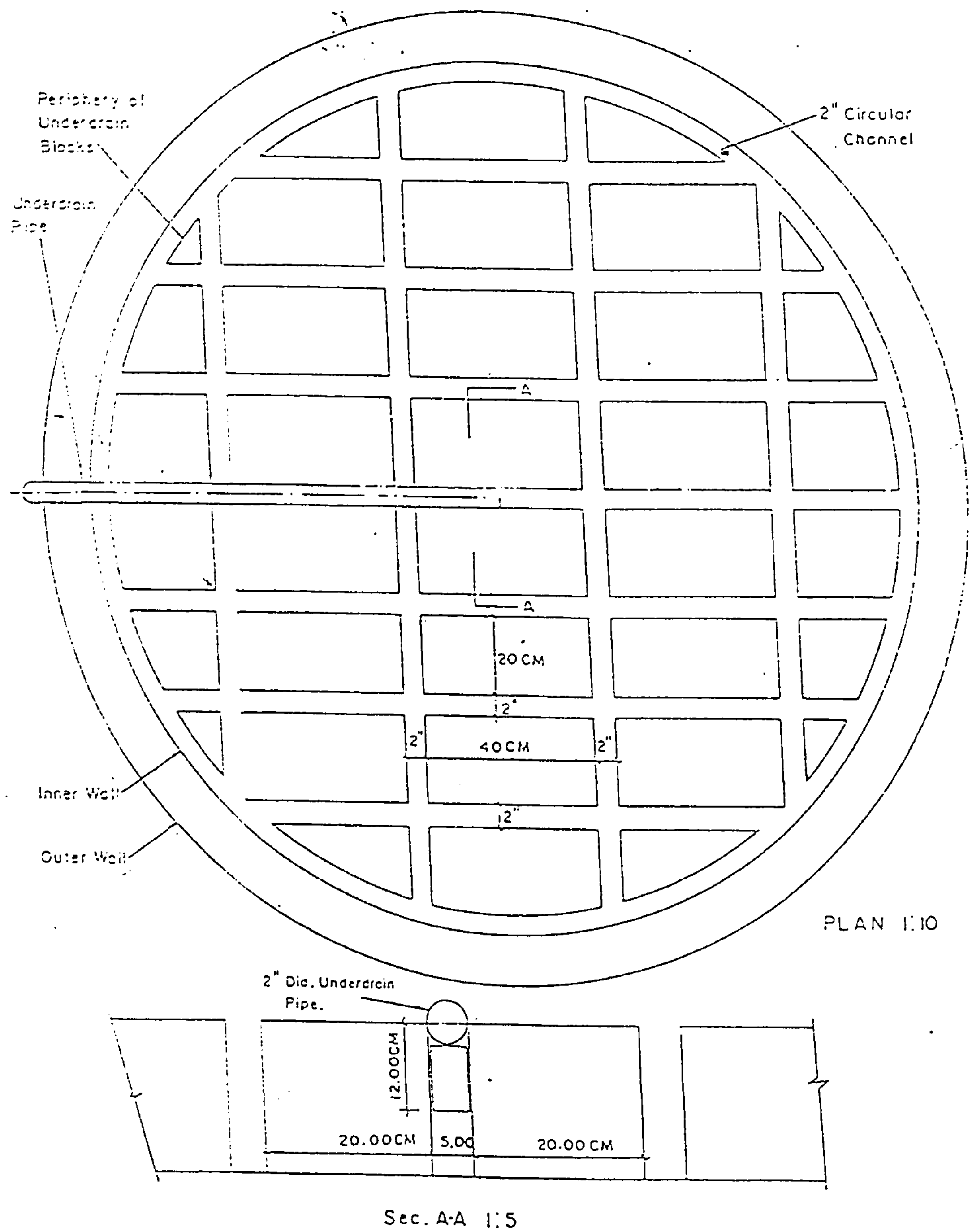


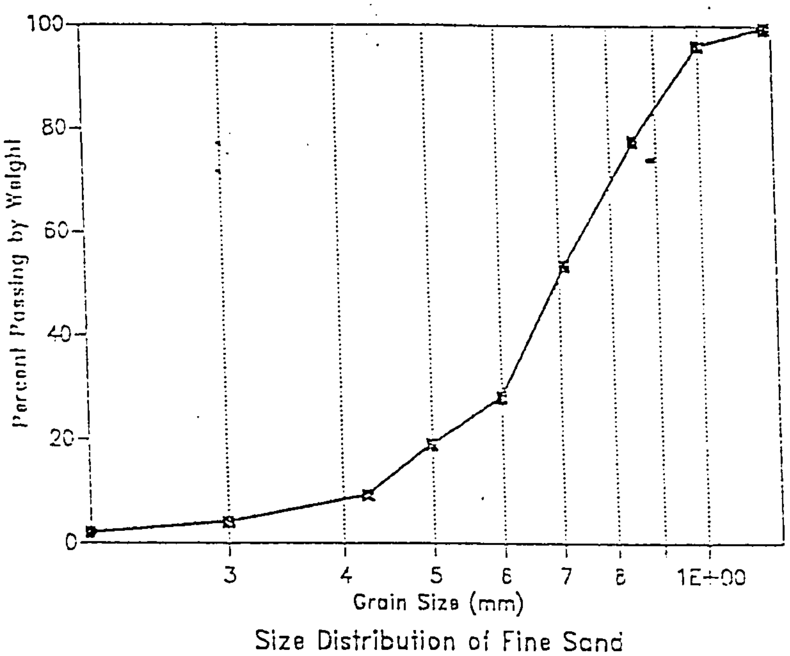
Figure 4.3: Layout of Underdrain System

the bottom of the sand. Five layers of each 3" thick of gravel effective sizes of 2-1/2 ", 2 ", 1-1/2 ", 1 ", 1/2 " are underlying 5" of 1/8" effective size gravel such that the total depth of supporting gravel is 20 " (50 cm).

The common effluent tank was constructed of 3500 psi RC 15-cm thick walls with internal dimensions of 4 m x 1.5 m x 3.0 m (length x breadth x height) and with an outer steel ladder. The foundation for this rectangular tank was constructed of 3500 psi RC such that there is a 0.2 m border all around the outside walls of the tank and as such has a length of 4.8 m by a breadth of 2.3 m. The foundation slab is 0.3 m thick with its underside at a depth of 1.3 m below ground level. A 2 " grade 80 PVC located at a depth of 0.4 m below ground retains the treated effluent to the treatment plant secondary effluent collection sump. Another 2 " grade 80 PVC pipe fitted with a gate valve was provided to drain the tank for cleaning and emergency. It is worth mentioning that all surfaces in contact with water were coated with epoxy to preclude leaks. Furthermore, all exterior walls of the 4 units (3 filter modules and effluent tank) were plastered and painted. Two of the filters were filled with sand of the size distribution shown in Figure 4.4 and effective diameter of 0.45 mm and a uniformity coefficient of 1.6 to a depth of 1.5 m above the gravel. The third filter was filled with the sand, characterised by the distribution presented in Figure 4.5 resulting in an effective diameter of 0.3 mm and a uniformity coefficient of 2.2, to the maximum depth of 1.5 m.

Each filter module was equipped with 1-hp, 60 Hz, single-phase pump with corrosion-resistant plastic impellers that draws unchlorinated secondary effluent from the collection sump. All three pumps were mounted on a 40-cm thick plain concrete base

founded at ground level about 2.5 m from the sump. The 1" grade 80 PVC suction pipe draws the secondary effluent from the sump at a depth of about 3m. The 3/4" grade 80 PVC discharge lines were all buried, along with the return filtrate from the effluent basin and the electrical connection to the power supply in a 0.3-m wide and deep trench beneath the asphalt road as shown in Fig 4.1. All discharge lines from the pump ran completely underground up to the triangular base of the filter modules after which they were laid to grade and along the filter wall to a height of 3.35 m above the floor. Table 4.1 and 4.2 gives the details of gravel and the filter unit.



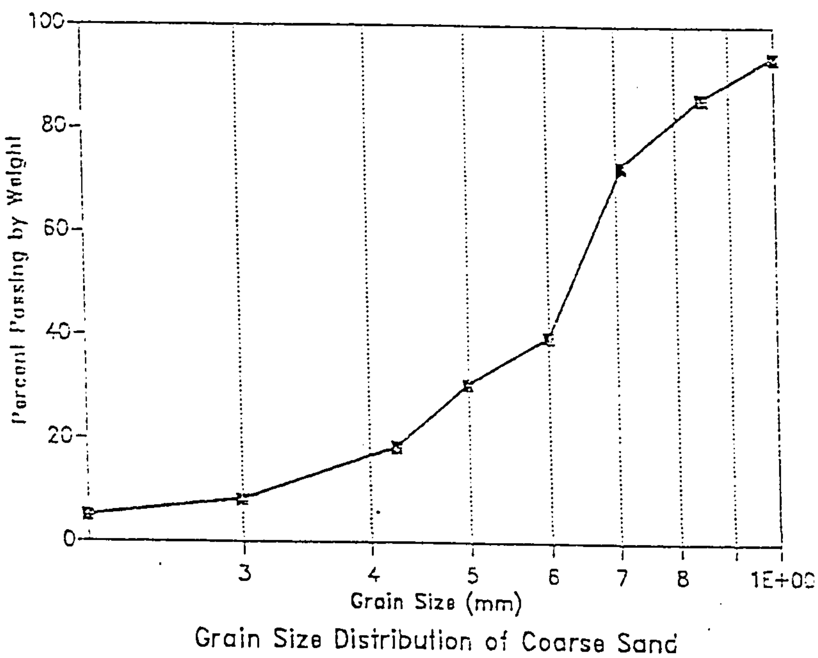


Figure 4.4 Grain Size Distribution of Fine and Coarse Sand

Table 4.1: Depth & Size of Gravel Layers in the Filter

Layer	Depth (in)	Size (in)
Top	5	1/8
First	3	1/2
Second	3	1
Third	3	1-1/2
Fourth	3	2
Fifth	3	2 -1/2

Table 4.2: Details of Filter Unit

Element	Selected (cm)
Free board	15
Supernatant water	125
Sand	150
Supporting Gravel	50
Underdrain	20

4.2 Experimental Methodoloy

The slow sand filters were started in June 1994. First all the valves were closed, filtered water was introduced from the bottom to flow upwards through the drainage system, gravel and sand bed to a level of about 30 cms above the sand bed. This was done in order to ensure that no air is entrapped or accumulated in the system. After this the inlet valve was opened allowing the water to flow on top to the bed. The filters were run continuously for few weeks to allow for "ripening" with the outlet valve opened. Filter # 1 and Filter # 3 employing 0.5mm effective sand size were operated under a hydraulic loading rate of 0.15 - 0.19m/hr and 0.3 - 0.38m/hr while Filter # 2 employing effective sand size = 0.3mm was operated under a hydraulic loading rate of 0.3 - 0.38m/hr all set to treat the secondary effluents. The experimental work of this project was divided into fourteen operational conditions in all the three filters each condition being run at different flow rate and sand depth. During the operation the filtration rate and sand depth were altered which enabled us to collect data covering a wide range of filtration rates from 0.15 to 0.375 and sand depths of 150 to 50 cms respectively. The different conditions of experimental work will help in evaluating the effects of filtration rate and sand depth on filtrate quality.

4.2.1 Daily And Weekly Operation

Daily operation was done by visiting the treatment plant for checking and possibly adjusting the rate of filtration, and to monitor the plant performance. Samples of influent and effluent were collected on grab basis for the analysis of pH, alkalinity and dissolved

oxygen. Furthermore for weekly analysis of various parameters automatic samplers were used to collect composite samples, both for influent as well as effluent.

4.2.2 Cleaning Of Filter Bed

Generally the criteria for terminating slow sand filter run is either break through or turbidity. However during the phases of operation the criteria for terminating filter run was based on the ability to maintain the design filtration rate irrespective of the head loss. When the filtration rate decreased the filter run was terminated, to clean the filter by lowering the water level to about 5-10 cms above to top of the sand. The inlet valves were closed and outlet valves opened to drain the water to the required level. The outlet valve was closed and filter bed cleaning was accomplished by scraping the top 2-4 cms of the bed. In order to reduce the time taken between two runs due to cleaning siphoning was employed to drain the water from the filter.

After cleaning, the filters were put back into service by opening the inlet valve, when the water is filled up to the required level the outlet valve was opened and the required flow was adjusted.

4.3 ANALYTICAL METHODS

The nitrogen species such as Total Kjeldahl nitrogen (TKN), Ammonia -N , Organic Nitrogen , Nitrates, and Nitrites were analysed according to Standard Methods for the examination of water and wastewater (Standard Methods 50).

TKN was analysed using macro Kjeldahl method (Method 420 A - Standard Methods, 50). Distillation method (Method 417 D - Standard Methods, 50) was used for the determination of ammonia nitrogen. The concentration of organic nitrogen was determined by difference between the Kjeldahl nitrogen and ammonia nitrogen. Nitrate was determined by the cadmium reduction method (Method 418 C - Standard Methods, 50), and nitrite was found through the formation of reddish purple azo dye produced at pH 2.0 to 2.5 by coupling diazotized sulfalinic acid with N-(1-naphthyl)-ethylnediamine dihydrochloride (NED - dihydrochloride) and measuring the absorbance at 543nm (Method 419- Standard Methods, 50). The concentration of alkalinity was determined using indicator method (Method 102 - Standard Method, 50) Dichromate reflux method (Method 220 - Standard Method, 50) was used to determined chemical oxygen demand (COD) and biological oxygen demand (BOD) was determined by the five day BOD method (Method 219 - Standard Method, 50).

CHAPTER # 5

5. RESULTS AND DISCUSSIONS

5.1 GENERAL OPERATION AND PERFORMANCE

5.1.1 Hydraulics:

Water quality parameters of daily interest during the operation of filters were turbidity, headloss, and filtration rate. Generally the criteria for terminating slow sand filter runs is either the breakthrough of turbidity or attainment of terminal head loss, which subsequently results in a very dramatic decline of effluent flow rates. For the purpose of this work however, due to the very low influent turbidity and the availability of substantial head approximately of around 3.4m of which 1.25m is free board above the sand, a significant head loss could still sustain the desired filtration rate. Therefore the criteria for terminating the filter runs was based on the ability to maintain the design filtration rate.

During the initial operation of filters there was a heavy growth of algae which were in the range of 10000 to 15000 forms / ml. This is a natural phenomena due to the presence of nutrients and also because the filters were exposed to sun light. The filters were being clogged which could be attributed to significant algal blooms, leading to short filter runs. Consequently to prolong the filter runs, the filters were covered at the top with wooden board sheets to preclude sun light and the ensuing proliferation of algal growth.

This protective measure resulted in a significant extension of filter runs from the previously observed runs of short duration.

The headloss build up was recorded at the three manometers for all the three filters through out the study. The head loss is equal to the vertical distance between the surface of the water on the filter and the water level in the manometer. (Monk , 35).

A typical headloss build up at the three manometers is shown in Fig 5. H1 is the headloss as measured in the bottom peizometer and is thus indicative of the total resistance to flow in the entire sand bed. While H2 and H3 are the headlosses in the top 68cms and 109cms of the 1.5m deep sand bed. It is apparent that during periods of regular operation no significant differences between the three peizometeric heights were observed in any of the filters, thus indicating that most of the resistance to flow is attributed to the Schmutzdecke layer, on the surface of the bed. From the figure the headloss increased with the length of the filter run with some fluctuation during the middle of the run.

As the length of the filter runs increased, the build up of suspended material in the interstices of the filter medium increases. In order to maintain the design hydraulic loading in the respective filters the outlet valves were opened proportionally to compensate for the headloss. This was done until the valve was fully open. In some instances, operation was facilitated by 'combing' the surfacial layer thus decreasing headloss. The fluctuations in the headloss could be attributed to the combing operation. In all the three filters the desired flow could not be maintained with the underdrain valve fully open at headlosses in excess of 60-70 inches. At this stage the filter runs were terminated. Hence, when the headlosses exceeded 70 inches the filter runs were terminated for cleaning.

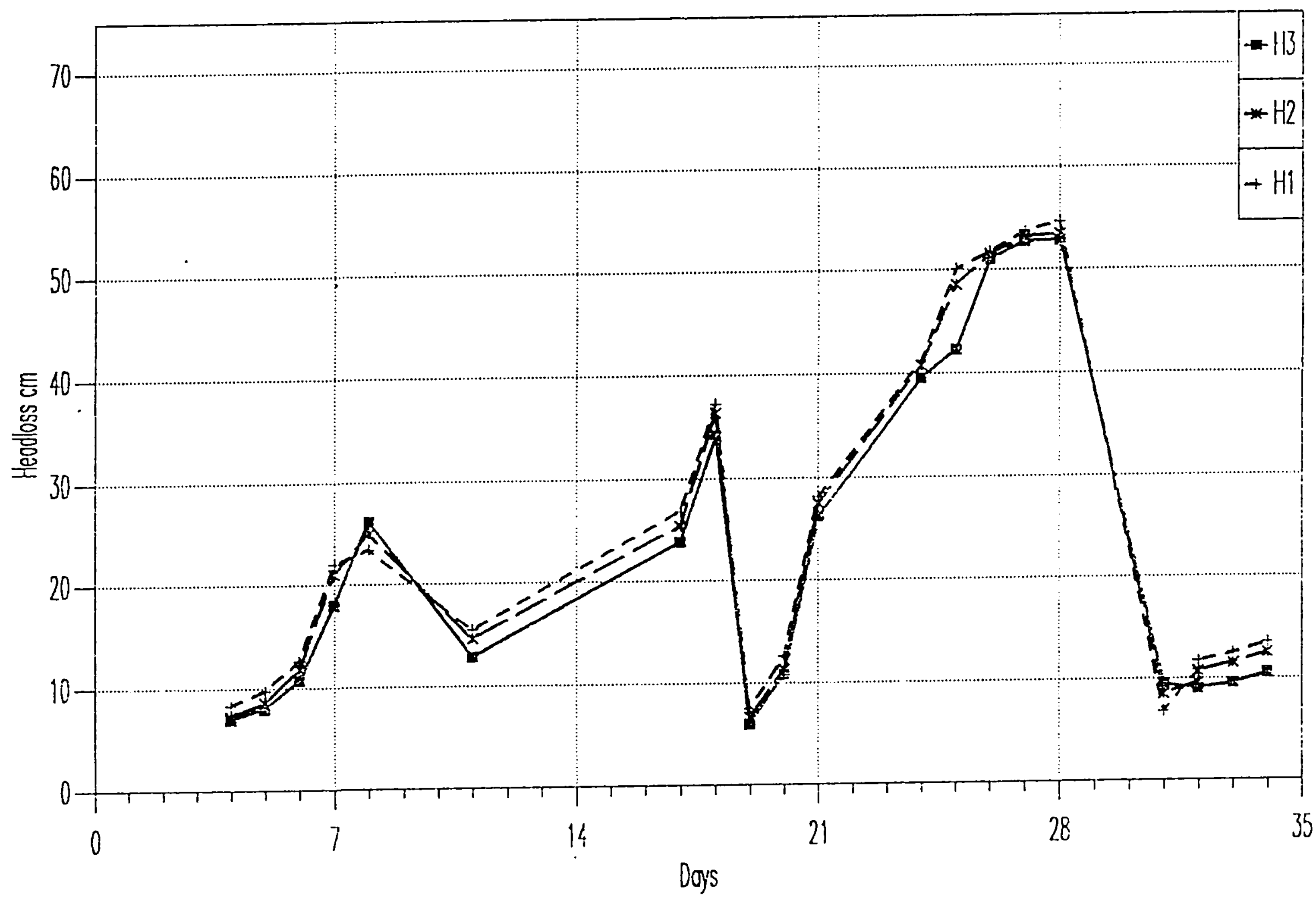


Figure 5: Variation of Headloss

5.1.2 Operational Conditions

The entire research operation was divided into the fourteen operational conditions designated as C1 - C14 in all the three filters shown in Table 5. Filter 1 having coarse sand consisted of four conditions in which condition # 1 (C1) was operated at a flow rate of 8 l/min and a sand depth of 150cms. Condition # 2 (C2) was operated at higher flow rate of 10l/min with the sand depth being 150cm. In condition # 3 (C3) and condition # 4 (C4), sand depth was reduced to 80cms and 50cms respectively with the flow rate being maintained at 10l/min.

F2 consisted of five conditions in which C5 of filter 2 was operated at a flow rate of 16l/min and a sand depth of 150cms. In C6 the flow rate was increased by 25% to 20l/min with the sand depth being 150cm. During C7 and C8 the depth of sand was reduced to 80cms and 50cms respectively maintaining the flow rate constant at 20l/min. In C9 the flow rate was reduced by 50% to 10l/min with the sand depth being 50cm.

Similarly F3 having coarse sand consisted of five conditions. C10 was operated at a flow rate of 16l/min and a sand depth of 150cms. In C11 the flow rate was increased to 20l/min while the sand depth was 150cm. During C12 and C13 the sand depth was reduced to 80cms and 50cms respectively maintaining a constant flow rate of 20l/min in each of the conditions respectively. Furthermore in order to assess the removal at lower flow rate the flow rate was reduced by 50% to 10l/min during C14 with the sand depth being maintained at 50cm. F1 and F3 were operated with same type of sand (coarse sand). This provided us with added flexibility to operate them under different experimental conditions, which was not possible with one filter over 12 months period.

Table 5: Operational Schedule Of Slow Sand Filters

Filter Number	Flow (l/min)	Sand Depth (cm)	Sand Size (mm)	Starting Date	Termination Date	Total Days of Operation	Total Days of Suspension	Condition Number (C)
F1	8	150	0.5	7 - 6 - 94	30 - 11 - 94	177	32	1
F1	10	150	0.5	1 - 12 - 94	4 - 1 - 95	35	1	2
F1	10	80	0.5	4 - 1 - 95	13 - 4 - 95	99	2	3
F1	10	50	0.5	14 - 4 - 95	28 - 6 - 95	76	2	4
F2	16	150	0.3	7 - 6 - 94	14 - 12 - 94	191	39	5
F2	20	150	0.3	14 - 12 - 94	4 - 1 - 95	21	1	6
F2	20	80	0.3	4 - 1 - 95	13 - 4 - 95	99	3	7
F2	20	50	0.3	14 - 4 - 95	1 - 7 - 95	79	3	8
F2	10	50	0.3	2 - 7 - 95	19 - 7 - 95	18	0	9
F3	16	150	0.5	7 - 6 - 94	14 - 12 - 94	191	55	10
F3	20	150	0.5	14 - 12 - 94	11 - 2 - 95	60	1	11
F3	20	80	0.5	11 - 2 - 95	13 - 4 - 95	60	2	12
F3	20	50	0.5	14 - 4 - 95	1 - 7 - 95	79	6	13
F3	10	50	0.5	2 - 7 - 95	19 - 7 - 95	18	0	14

5.1.3 Suspended Solids And Turbidity

It is essential to remove suspended solids from the wastewater as they lead to the development of sludge deposits and create anaerobic conditions when untreated wastewater is discharged in the aquatic environment. Filtration is a well established operation used extensively for achieving supplemental removal of suspended solids (including particulate BOD) from wastewater effluents of biological treatment processes. Typically the suspended solids concentration in the effluents from activated sludge and trickling filters plants varies between 6 and 30mg/l. It is interesting to note that the AL-Khobar WasteWater Treatment Plant has a low effluent suspended solids concentration of 15mg/l. On the other hand turbidity is often used as a practical means of monitoring the filtration process. It is believed that turbidity serves as a carrier for nutrients that can result in biological activity. In water and wastewater industry the use of slow sand filters has been limited by the turbidity of the influent. Normally suggested limits vary from 10 to 50 NTU (Cox, 11., Huisman 28, Thanh and Hittiaratchi 53, Paramasivan et al, 42).

In the present study removal of suspended solids and turbidity was monitored over the period of about 15 months. Samples were analyzed for suspended solids on weekly basis and turbidity on daily basis. The three slow sand filters F1, F2 and F3 consisting of coarse sand (F1 & F3) and fine sand (F2) were run under different flow rate and sand depths during the course of operation.

(a) Filter operation at flowrates of 8l/min, 10l/min, 16l/min and 20l/min at sand depth of 150cms:

In F1 the weekly and diurnal variation of influent and effluent concentration of suspended solids and turbidity are shown in Fig 5.1 and 5.2 for C1. The concentrations ranged from 10 to 22mg/l and 6 to 12mg/l, 0.2 to 0.9NTU and 0.1 to 0.7NTU respectively. The average percent removal of suspended solids and turbidity was found to be 38% (5.5mg/l) and 37.7 % (0.3 NTU). The maximum and minimum removal ranged from 55 to 10% and 66.7 to 0% of suspended solids and turbidity. In case of F2 during C5 the influent and effluent concentration of suspended solids and turbidity are illustrated in Fig 5.3 and 5.4. The influent and effluent concentrations varied between 10 to 22 mg/l and 4 to 12 mg/l , 0.2 to 0.9 NTU and 0.1 to 0.7 NTU. The average percent removal of suspended solids and turbidity was calculated to be 55 % (8 mg/l) and 49.4 % (0.32 NTU). The maximum and minimum removal of SS and turbidity ranged from 72 to 35.7% and 85.7 to 28.3% respectively.

Similarly Fig 5.5 and 5.6 depict the variation of influent and effluent concentrations of SS and turbidity in F3 for C10. The influent and effluent concentrations of suspended solids and turbidity ranged from 10 to 22 mg/l and 6 to 14 mg/l , 0.2 to 0.9 NTU and 0.1 to 0.6 NTU respectively. The average percent removal of suspended solids and turbidity was calculated to be 31.4% (4.6 mg/l) and 48.7% (0.3NTU). The corresponding maximum and minimum removals ranged from 63.7 to 10% and 57.2 to 11% respectively. It can be observed from Fig 5.1, 5.2 & 5.3 that the effluent followed the influent quite closely with the elimination of few odd points, thus exhibiting a discernable trend. While

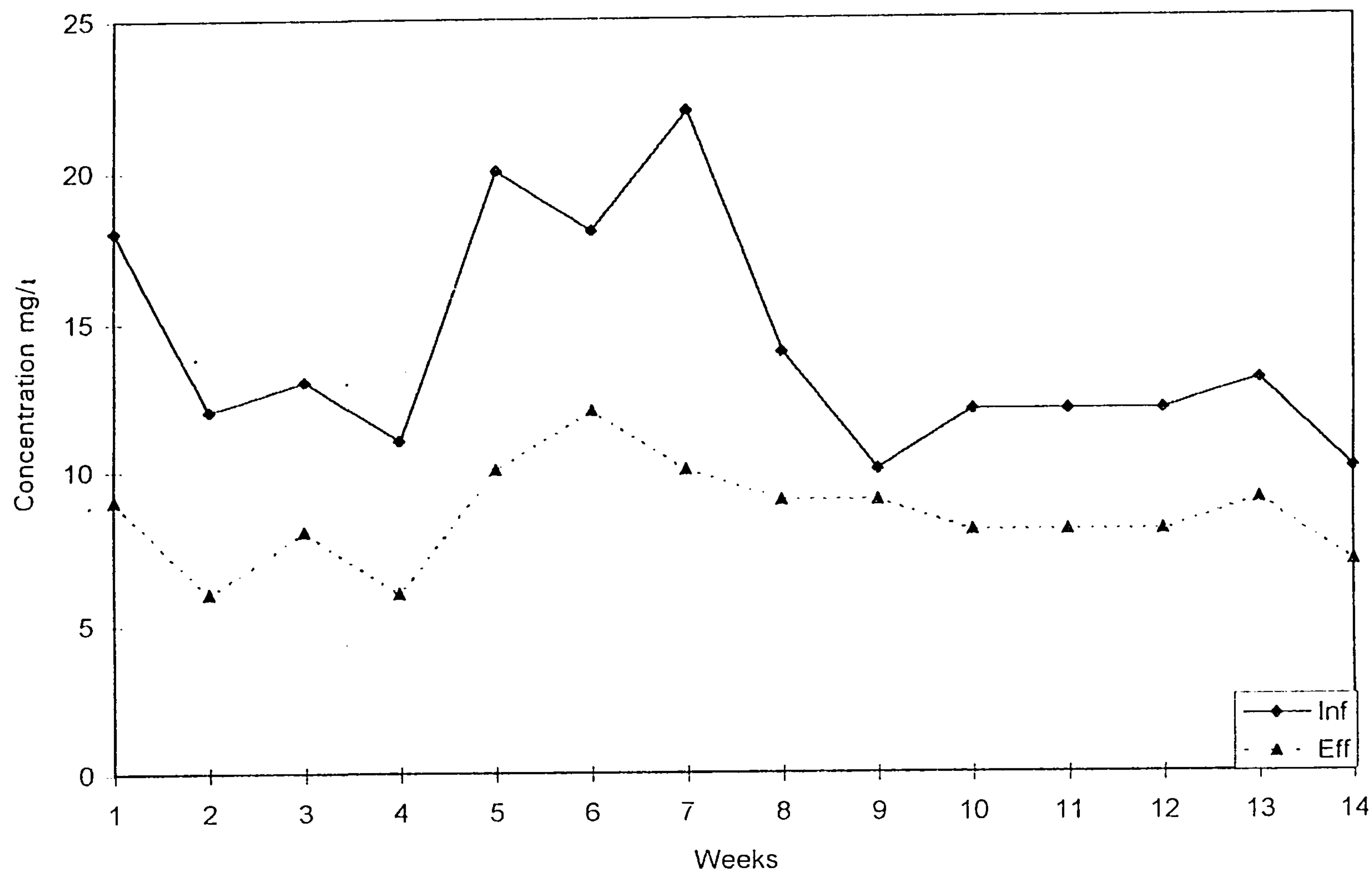


Figure 5.1: Variation of SS in Condition 1

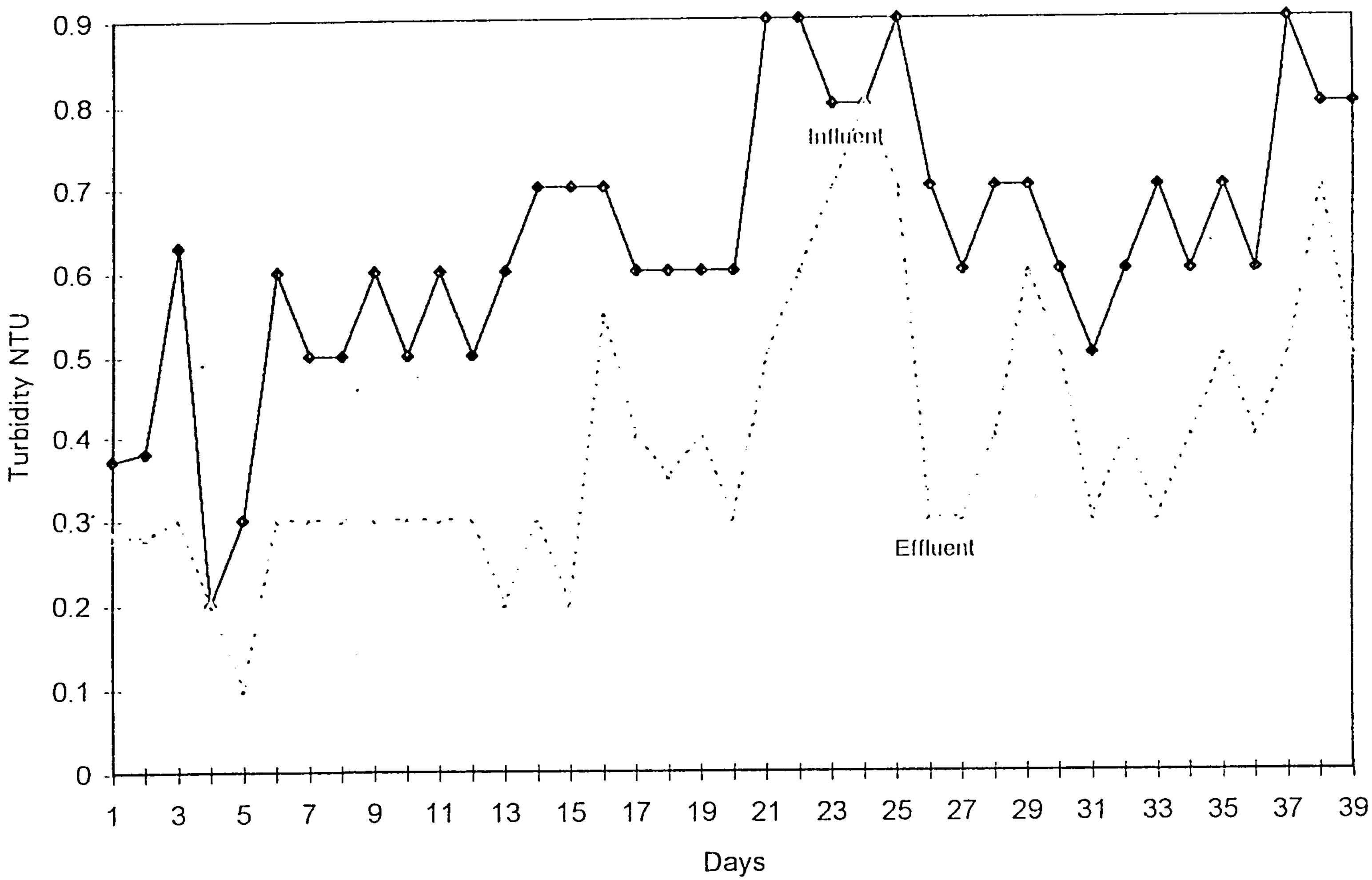


Figure 5.2: Variation of Turbidity in Condition 1

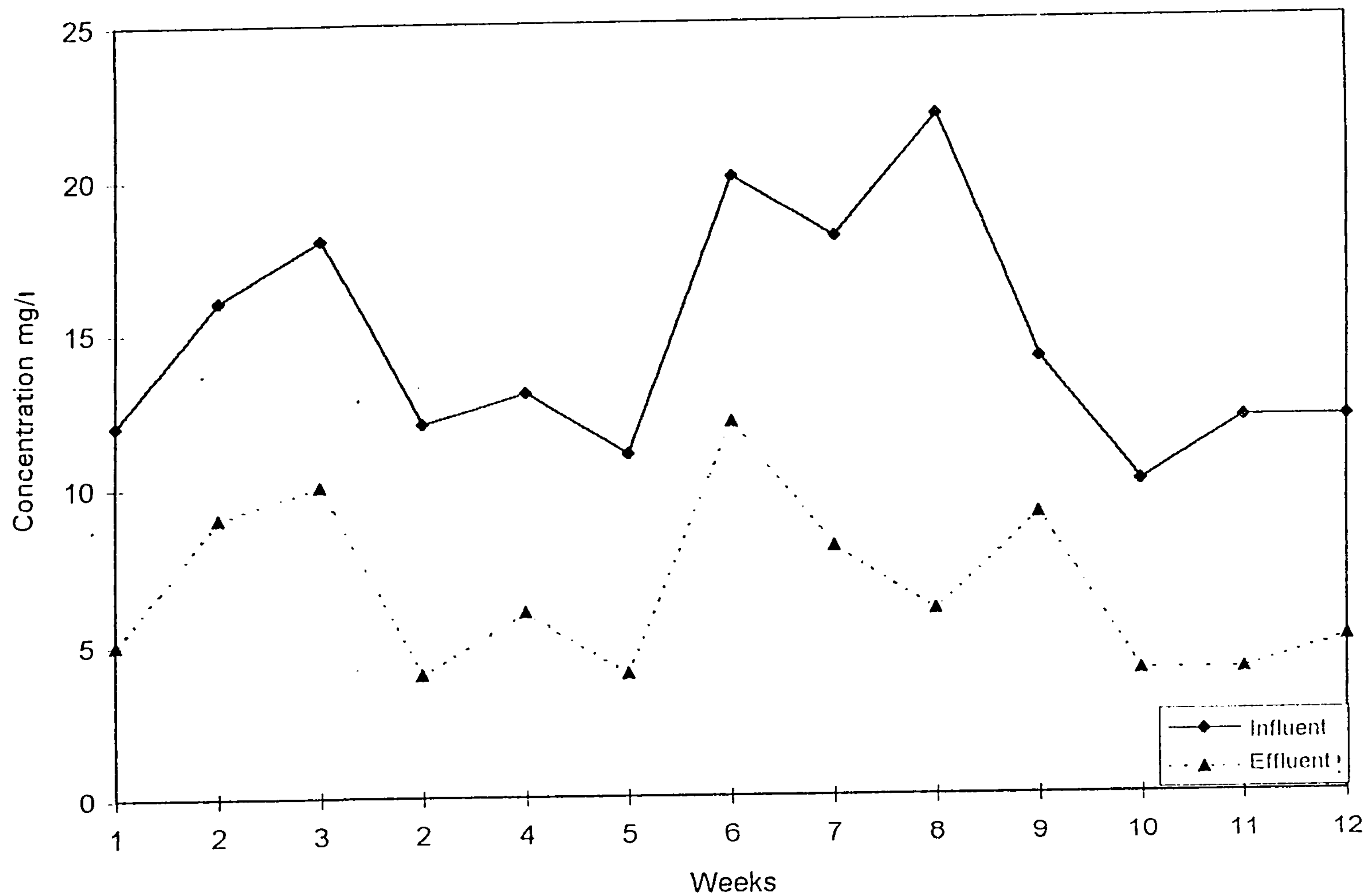


Figure 5.3: Variation of SS in Condition 5

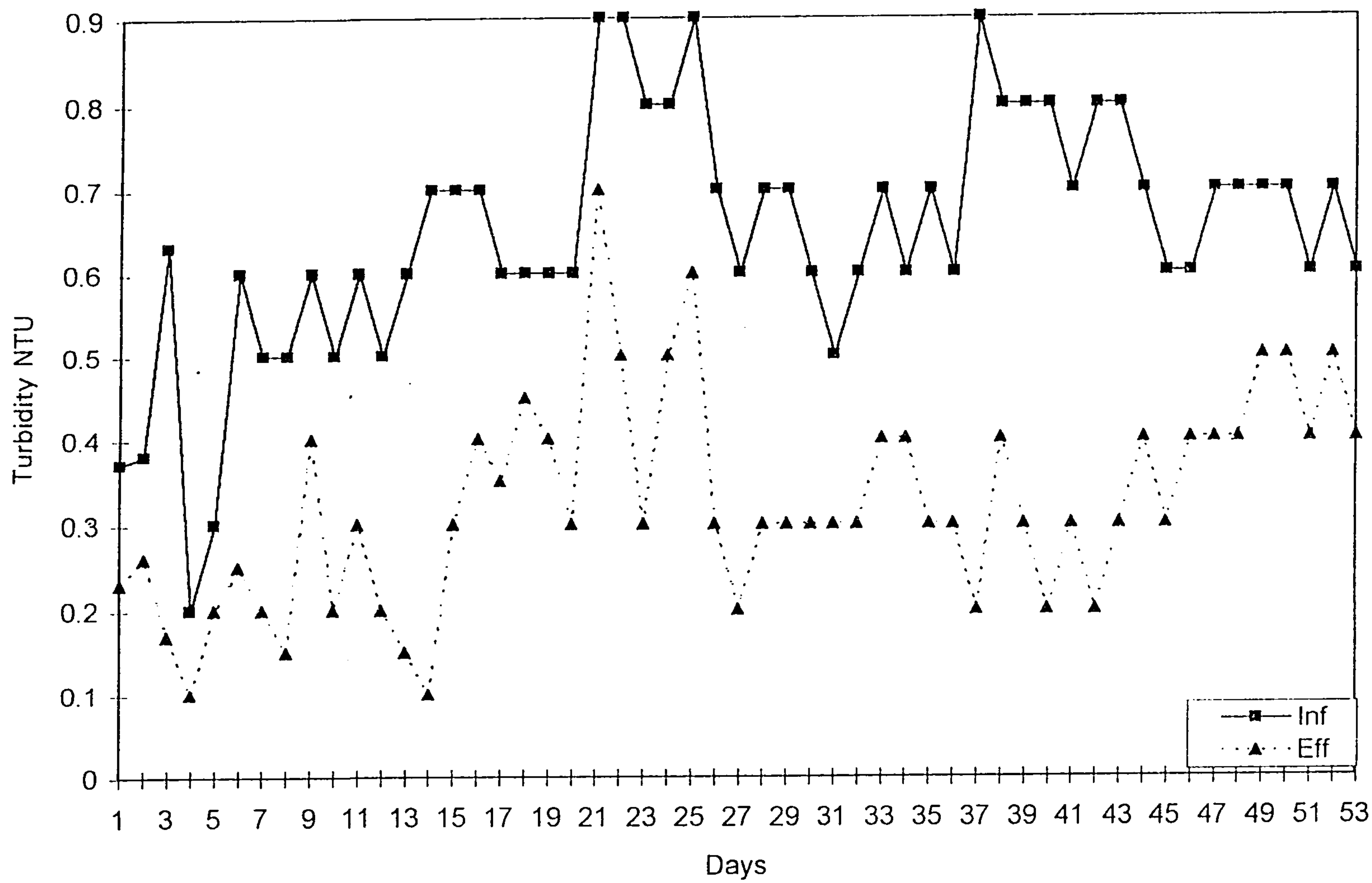


Figure 5.4: Variation of Turbidity in Condition 5

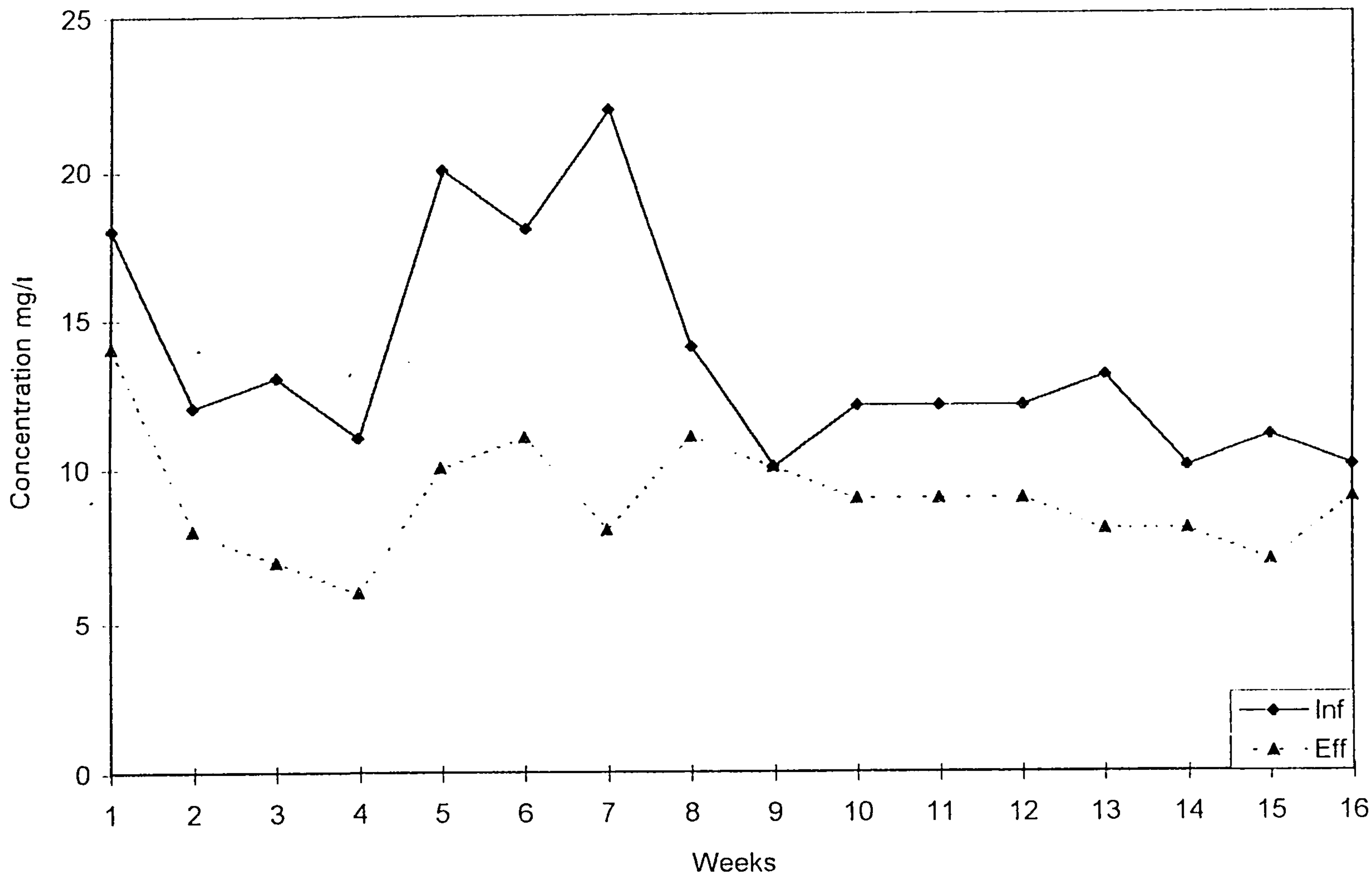


Figure 5.5: Variation of SS in Condition 10

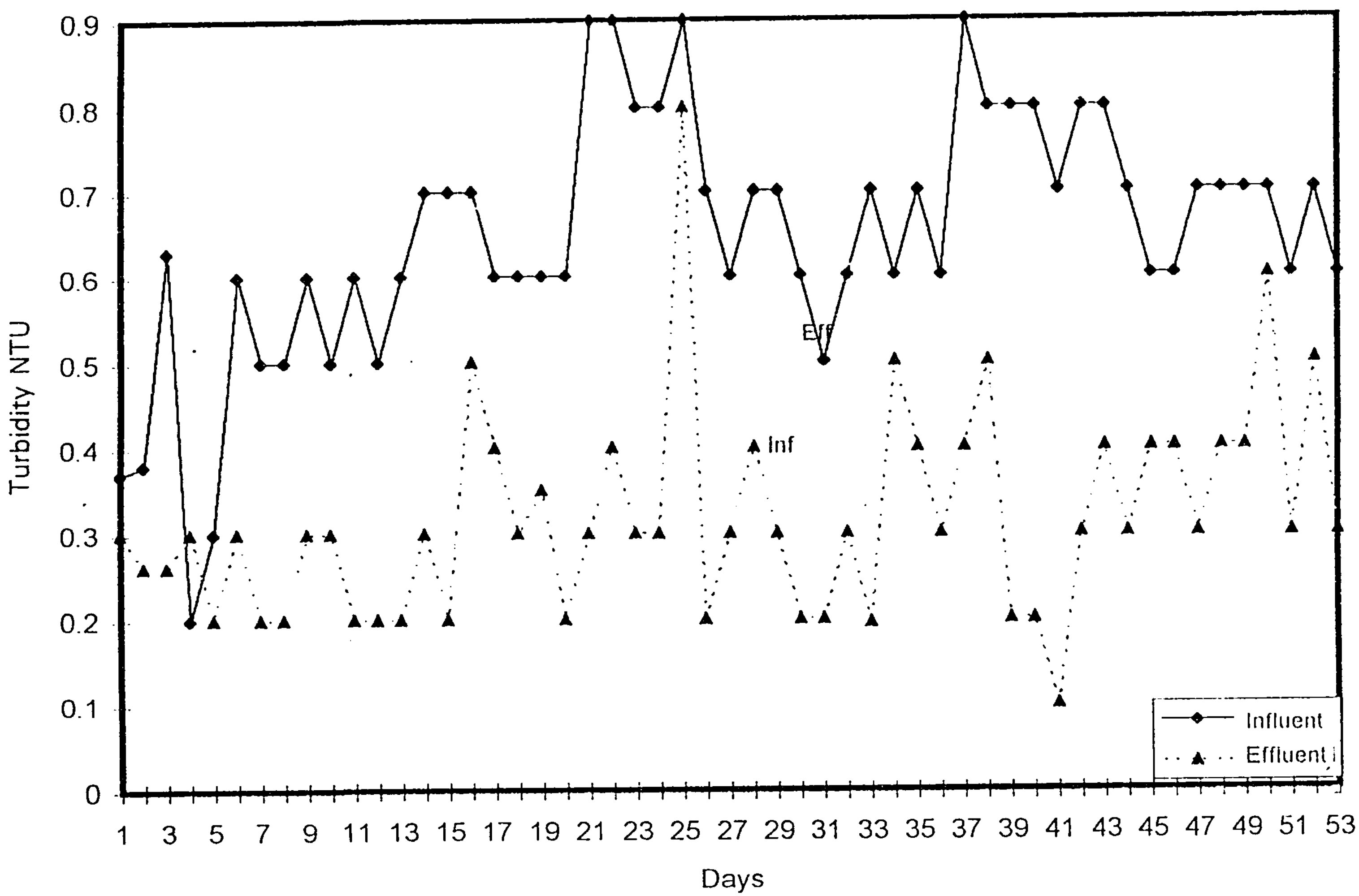


Figure 5.6: Variation of Turbidity in Condition 10

Fig 5.2, 5.4 & 5.6 in case of turbidity exhibited a substantial scatter in all the filters. This could be due to some experimental errors and also due to very low influent concentrations.

Therefore from the above discussion it is observed that the removal efficiency of SS in F1 and F2 is higher than F3, while the turbidity is almost the same in the three filters. This could be due to the influent concentration being extremely low ranging from 0.3 to 0.9NTU. From the above it can be inferred that both filtration rate and sand size have an impact on the removal rate of SS than that of turbidity.

During the next condition of operation the flow rates in F1, F2 and F3 (C2, C6 & C11) were increased by 25% to 10l/min in F1 and 20l/min in F2 and F3. The variations of SS and turbidity are illustrated in Fig 5.7 to 5.12 respectively. From Fig 5.7 and 5.8 in F1 (C2) the influent and effluent concentration of SS and turbidity varied from 10 to 12mg/l and 7 to 9mg/l , 0.4 to 0.95NTU and 0.1 to 0.6NTU respectively. The average removal efficiency of suspended solids and turbidity was found to be 28.45% (3.2mg/l) and 39.7% (0.28 NTU). The maximum and minimum removal of SS and turbidity ranged from 41.7 to 10% and 88.9 to 0% respectively. From the figures 5.7 and 5.8 it can be observed that the effluent concentration of SS was not consistent during the initial period but with increase in filter run the effluent concentration of SS exhibited a consistent trend indicating the maturation of the filter bed. The same was not observed in case of turbidity (Fig 5.8) as the data exhibited a substantial scatter.

Similarly in Fig 5.9 and 5.10 of F2 (C6) the influent and effluent concentration of suspended solids and turbidity ranged from 10 to 12mg/l and 3 to 6mg/l , 0.3 to 0.95NTU and 0.1 to 0.5NTU respectively. The average percent removal of suspended solids and

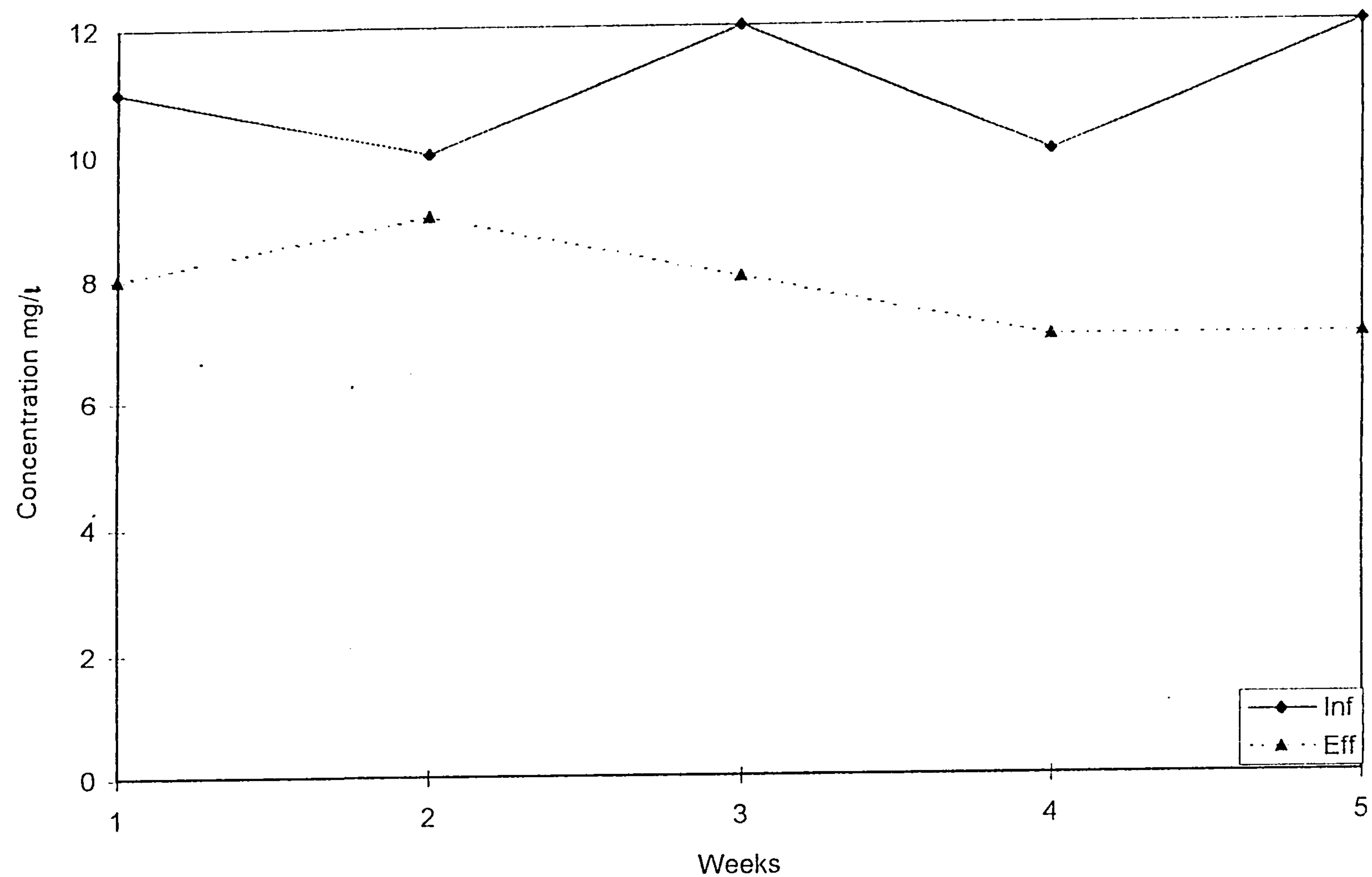


Figure 5.7: Variation of SS in Condition 2

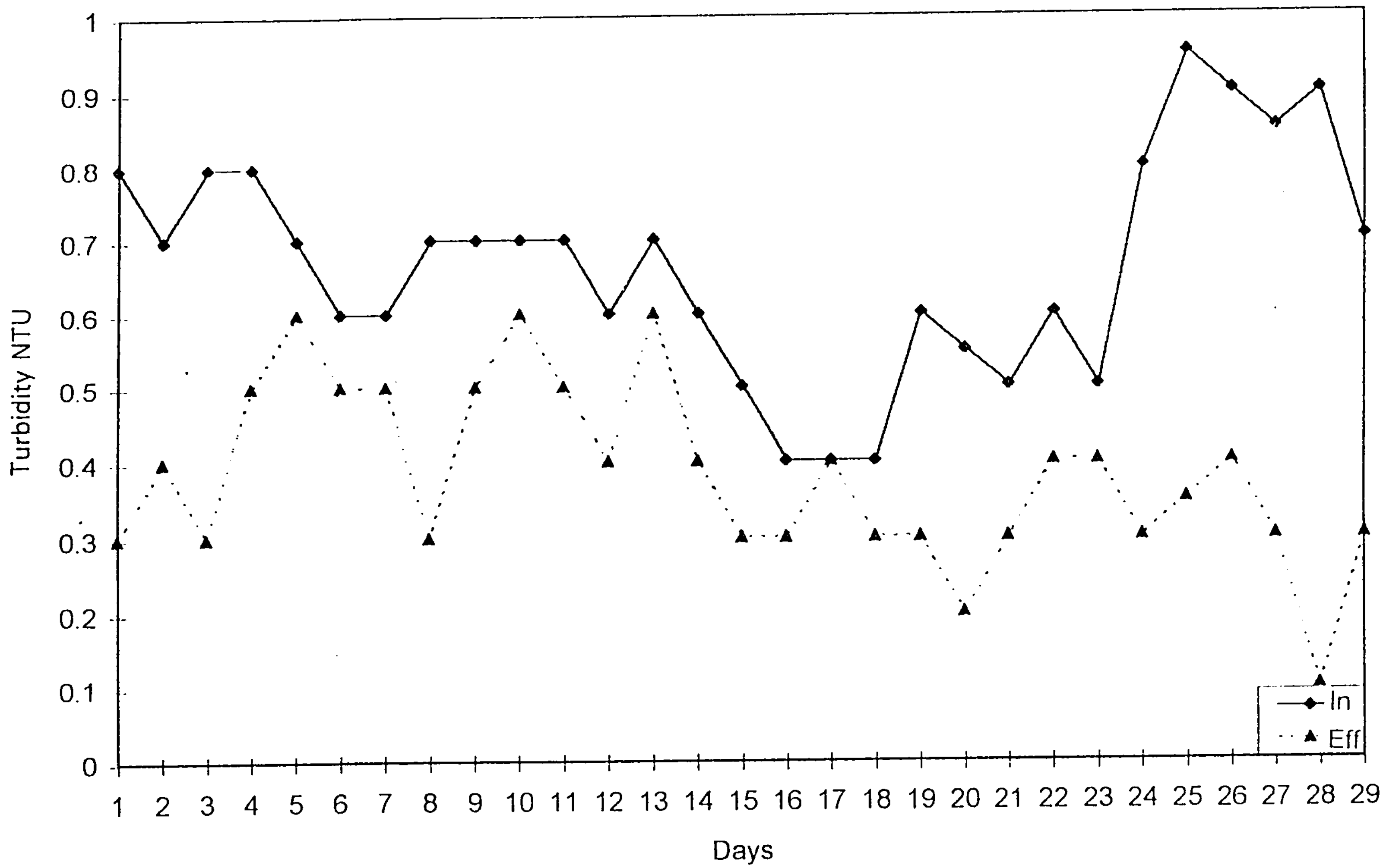


Figure 5.8: Variation of Turbidity in Condition 2

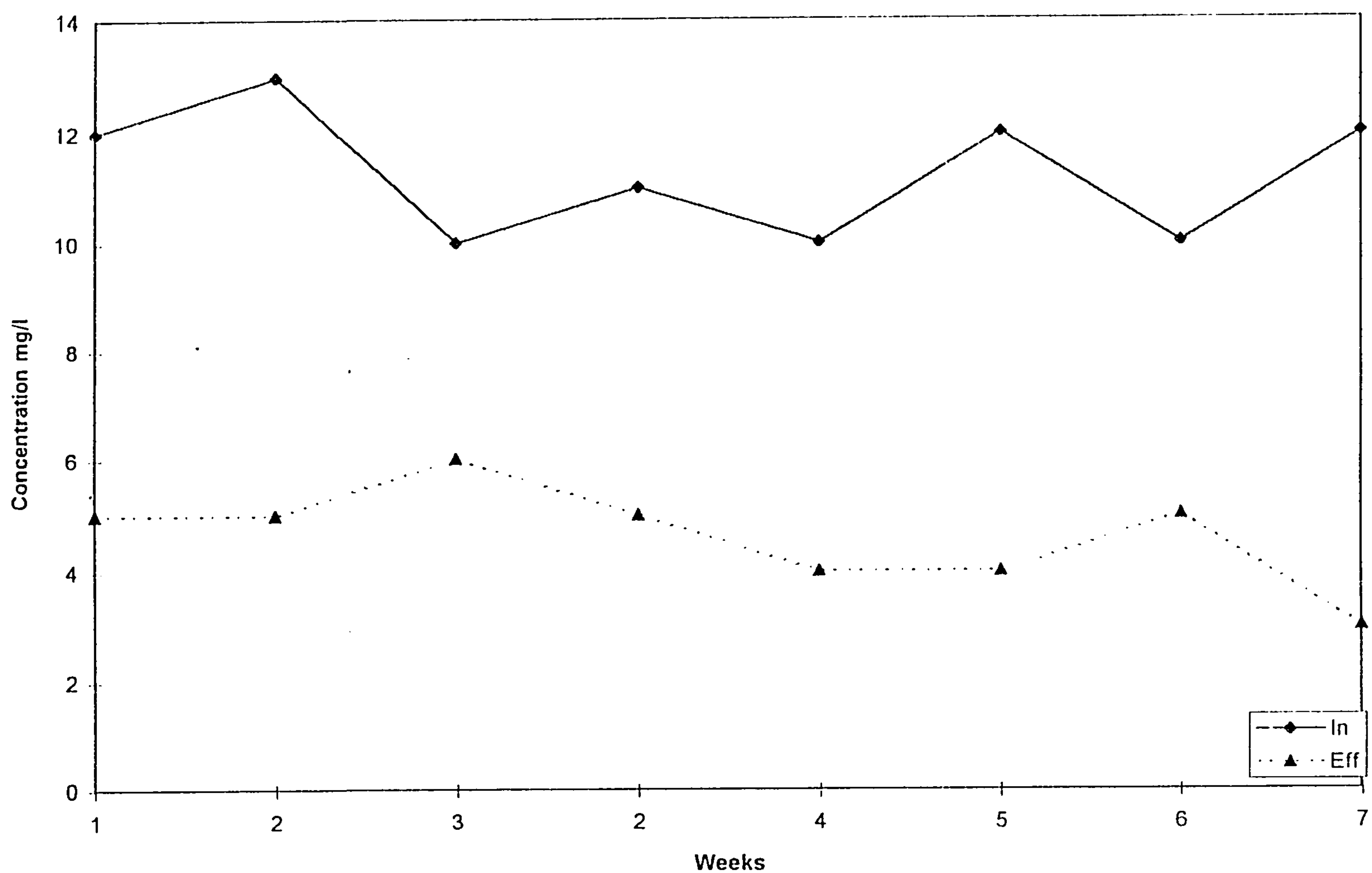


Figure 5.9: Variation of SS Condition 6

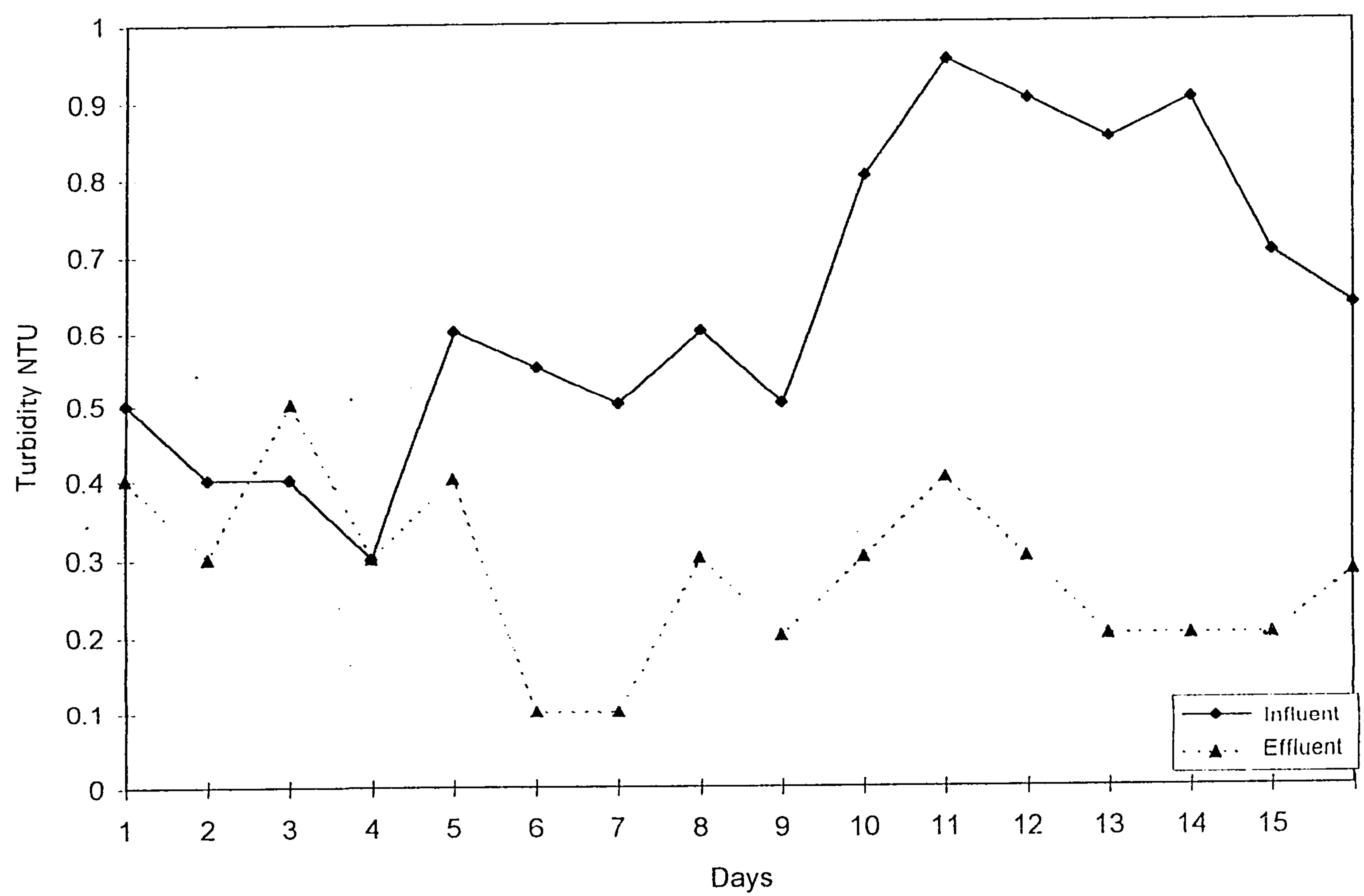


Figure 5.10: Variation of Turbidity in Condition 6

turbidity was found to be 63.9 % (7.3 mg/l) and 50.8% (0.35 NTU) and the maximum and minimum removals were 75% and 40%, 77.8% and 0% respectively. From Fig 5.9 and 5.10 it can be observed that the SS data showed a more consistent trend than the turbidity data. The influent and effluent concentrations of SS exhibited a uniform variation with a discernable trend. In case of F3 (C11) the influent and effluent concentration of suspended solids and turbidity are illustrated in Fig 5.11 and 5.12, with the concentrations ranging from 9 to 12mg/l and 7 to 9mg/l , 0.3 to 0.95NTU and 0.1 to 0.5NTU respectively. The average percent removal of suspended solids and turbidity was found to be 21.6% (2.3mg/l) and 57.7 % (0.42 NTU) and the corresponding maximum and minimum removal ranged between 36 to 0% and 85.7 to 0% respectively.

From the figures it can be observed that the SS concentration decreased with the filter run, while the turbidity data showed substantial scatter with the absence of a discernable trend between the influent and effluent. Hence it can be inferred that removal efficiency of SS in all the three filters dropped with the increase in flow rate, but no change was observed in the removal efficiency of turbidity. Upon comparing the removal rates it can be depicted that the flow rate and sand size has an influence on the removal efficiency at 150cms, of sand depth.

(b) Filter operation at flowrates of 10l/min and 20l/min at sand depth of 80cms:

During C3, C7 and C12 of operation the depth of sand bed was reduced to 80cms in all the three filters while the filtration rate was kept constant. The variation of influent and effluent concentration of SS in F1 is shown in Fig 5.13 and 5.14. The concentrations varied from 9 to 11mg/l and 5 to 8mg/l , 0.5 to 0.9NTU and 0.2 to 0.6NTU respectively.

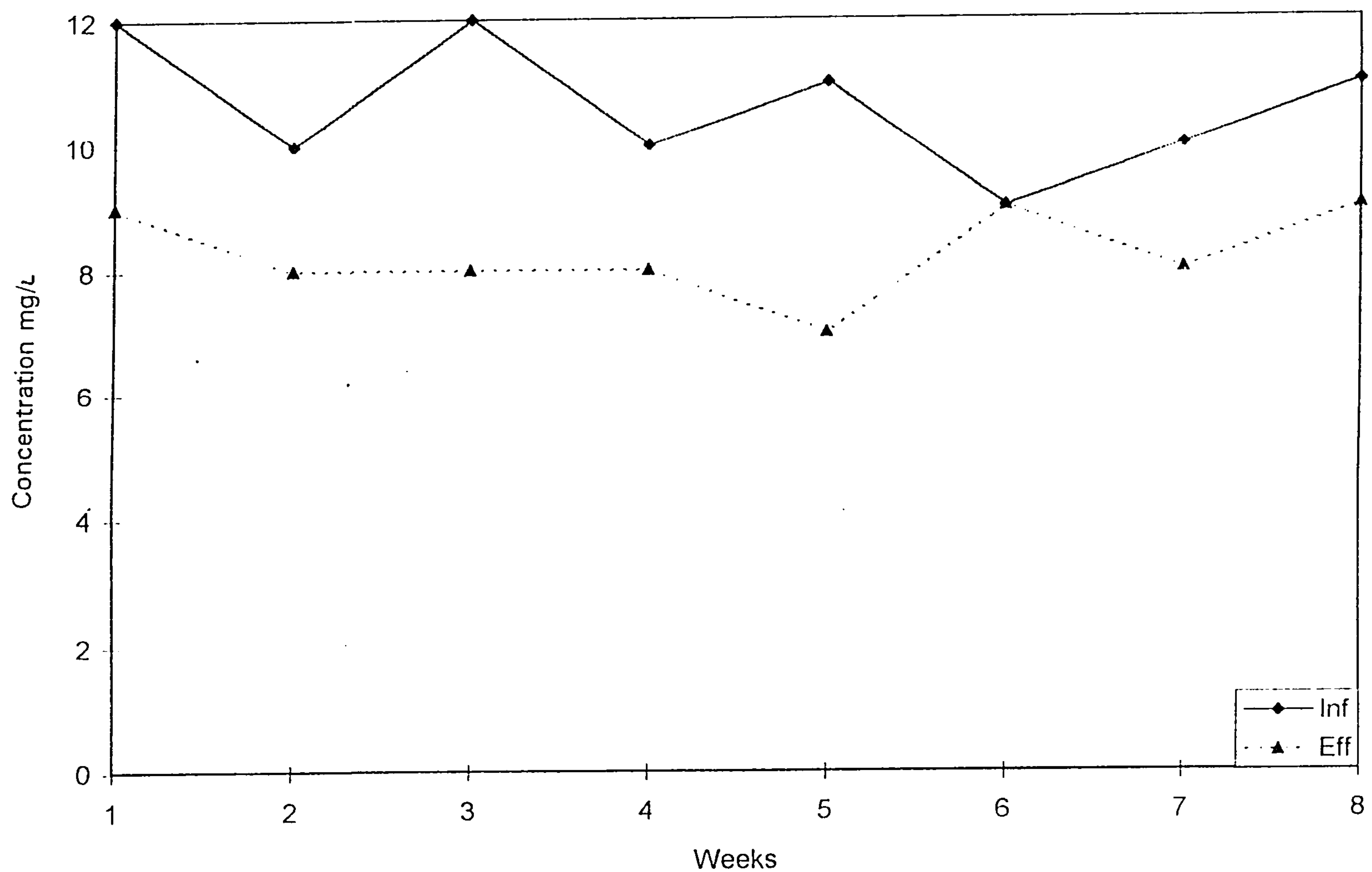


Figure 5.11: Variation of SS in Condition 11

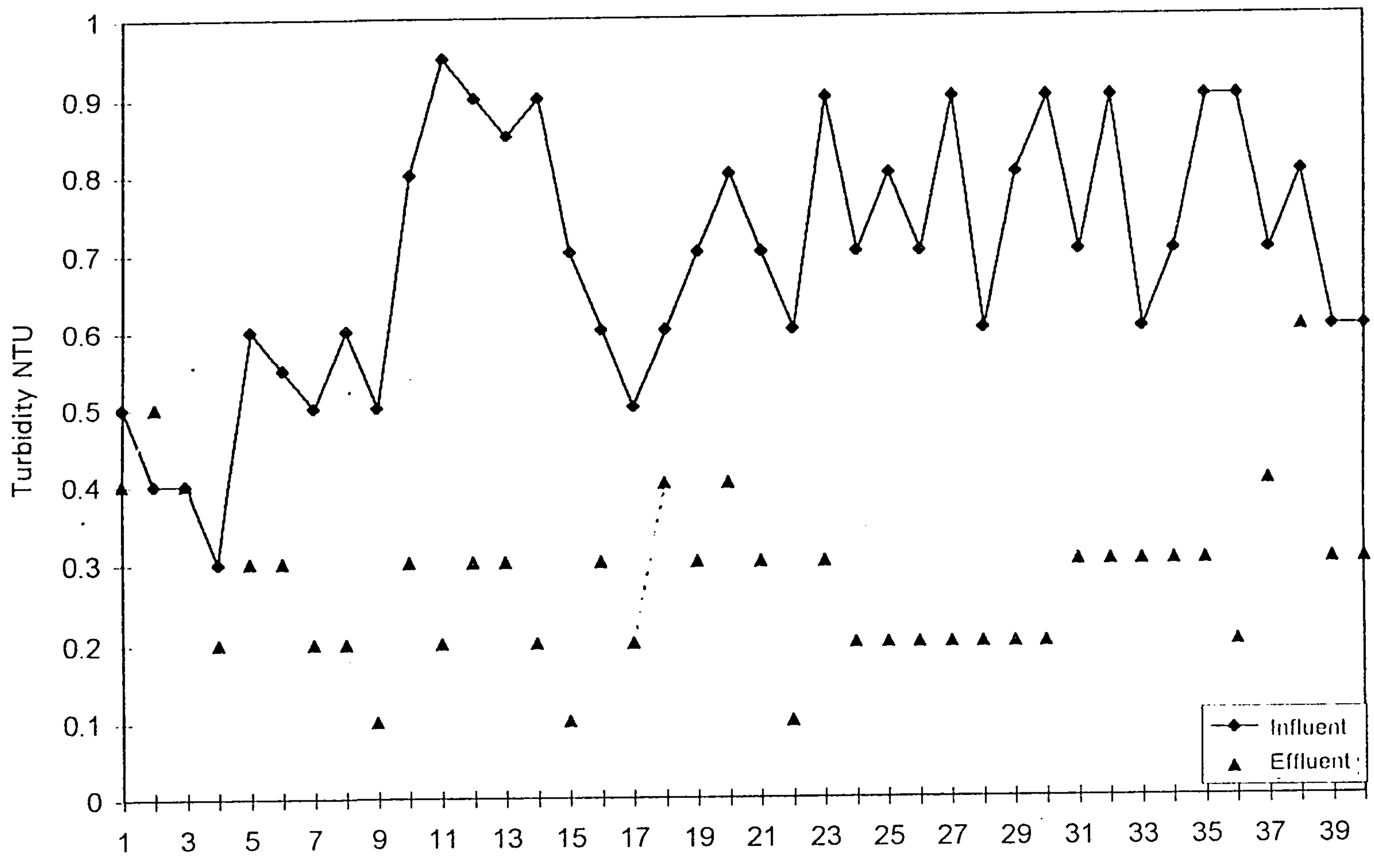


Figure 5.12: Variation of Turbidity in Condition 11

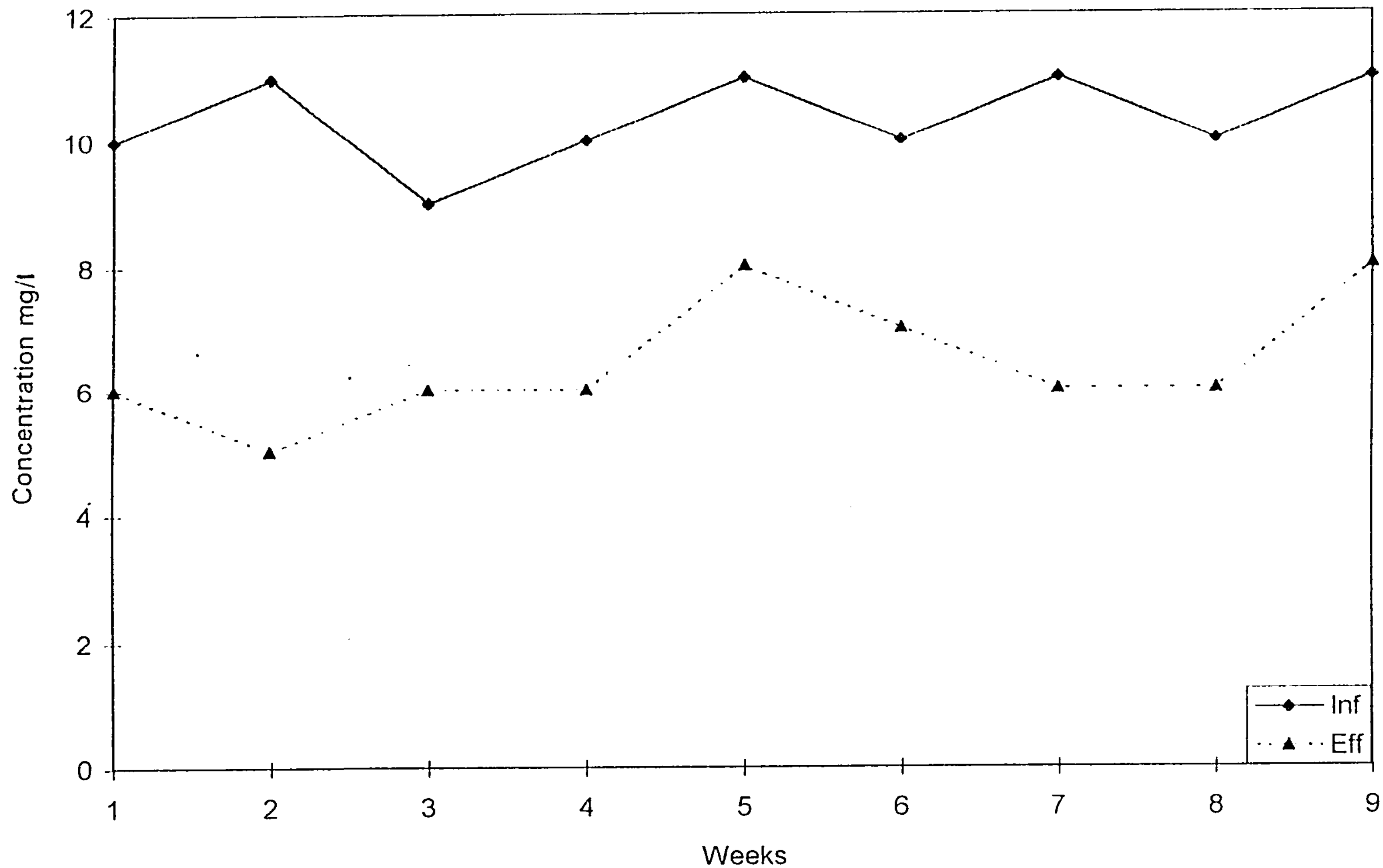


Figure 5.13: Variation of SS in Condition 3

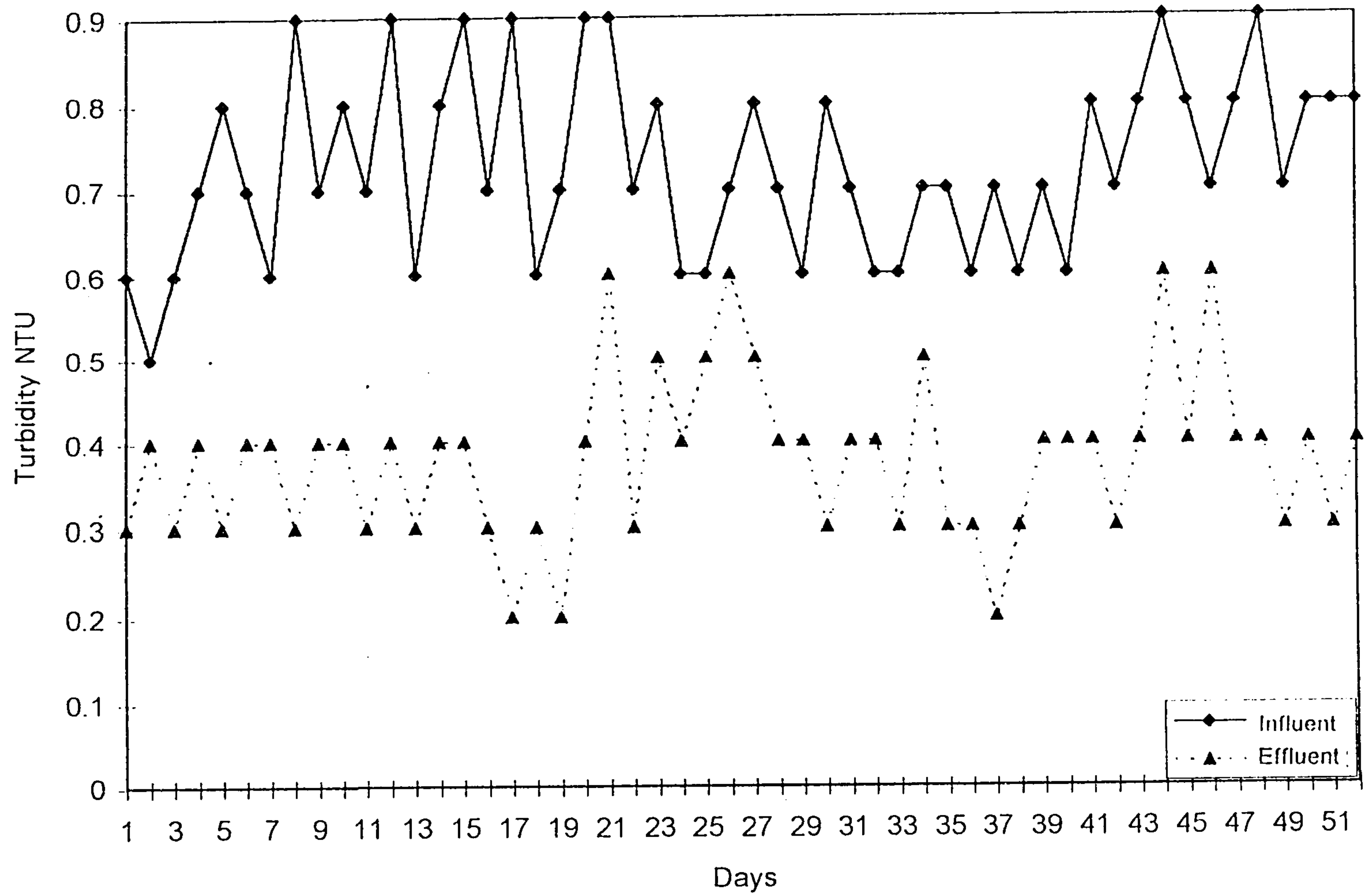


Figure 5.14 : Variation of Turbidity in Condition 3

The average percent removal was found to be 37.5% (4.0mg/l) and 47.1 % (0.35NTU). The maximum and minimum removal of SS and turbidity varied from 54.5 to 27.3% and 77.8 to 20% respectively. It can be observed from Fig 5.13 and 5.14 that the effluent concentration of SS varied in accordance with the influent concentration exhibiting a discernable trend with the absence of such trend in Fig 5.14. In C7 of F2 the influent and effluent concentration of SS and turbidity are presented in Fig 5.15 and 5.16 with the concentrations ranging from 9 to 11mg/l and 3 to 6mg/l, 0.5 to 0.9NTU and 0.1 to 0.5NTU respectively. The average percent removal of suspended solids and turbidity was 57.6% (6mg/l) and 54.8 % (0.4NTU) and the corresponding maximum and minimum removal varied from 72.7 to 40% and 83.3 to 20% respectively. Similarly Fig 5.17 and 5.18 in C11 of F3 illustrate the variation of influent and effluent concentration of SS and turbidity. The concentrations ranged from 10 to 11mg/l and 6 to 9mg/l , 0.6 to 0.9NTU and 0.1 to 0.5NTU respectively. The average percent removal was found to be 28.2% (3mg/l) and 56.5% (0.4NTU). The maximum and minimum removal of SS and turbidity varied from 45.5 to 10% and 83.3 to 28.6% respectively. From Fig 5.15 and 5.17 it can be observed that the SS data exhibited a discernable trend with the elimination of few odd points indicating that F2 performed much better than F1 and F3 in removal of SS, than removal of turbidity as evident from Fig 5.16 and 5.18 which shows a substantial scatter.

(c) Filter operation at flowrates of 10l/min and 20l/min at sand depth of 50cms:

The results of influent and effluent concentrations of SS and turbidity in C4, C8 and C13 are presented in Fig 5.19 to 5.24 respectively for all the three filters. From Fig 5.19 and 5.20 it can be observed that the variation of influent and effluent concentration of

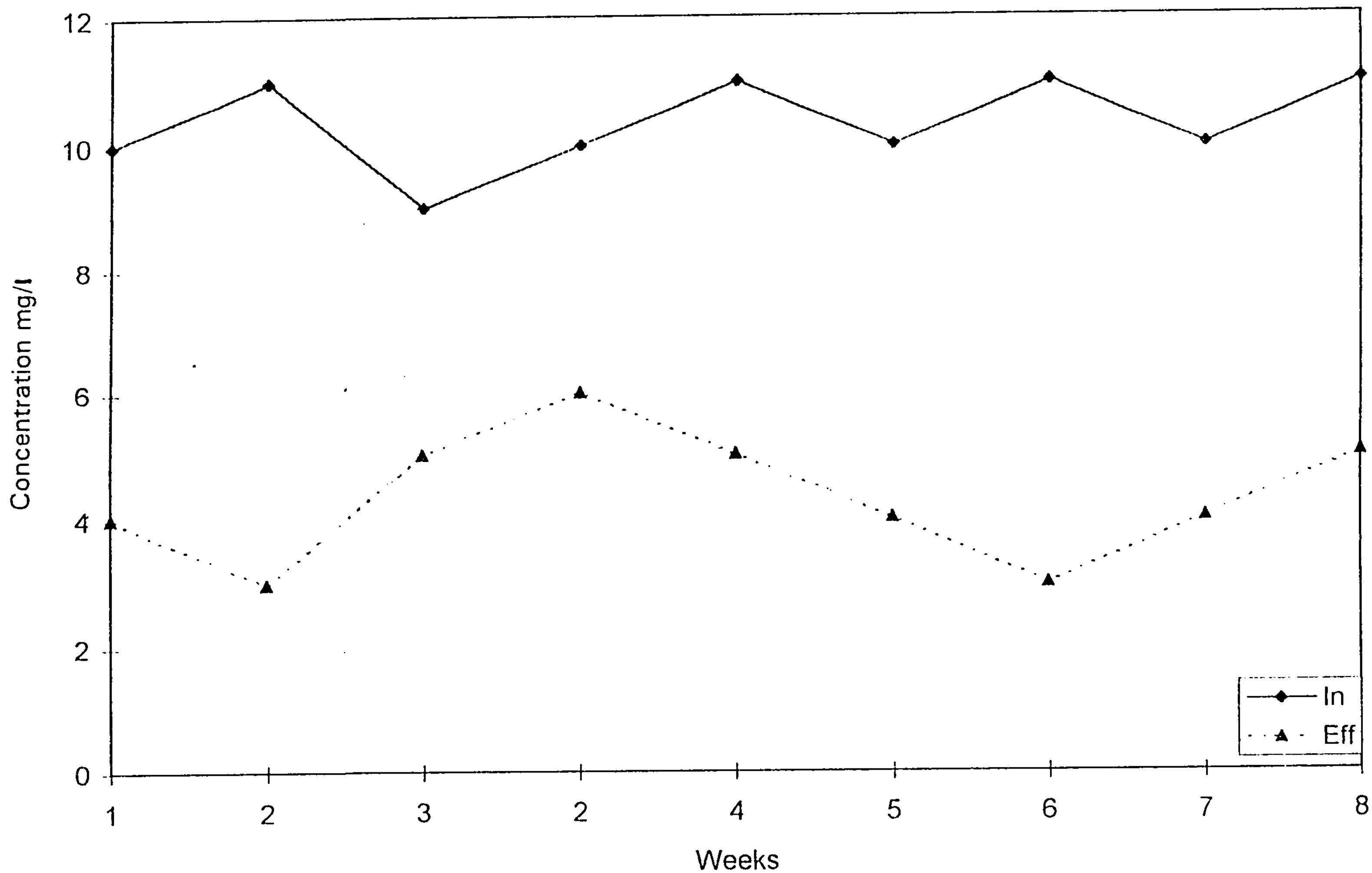


Figure 5.15: Variation of SS in Condition 7

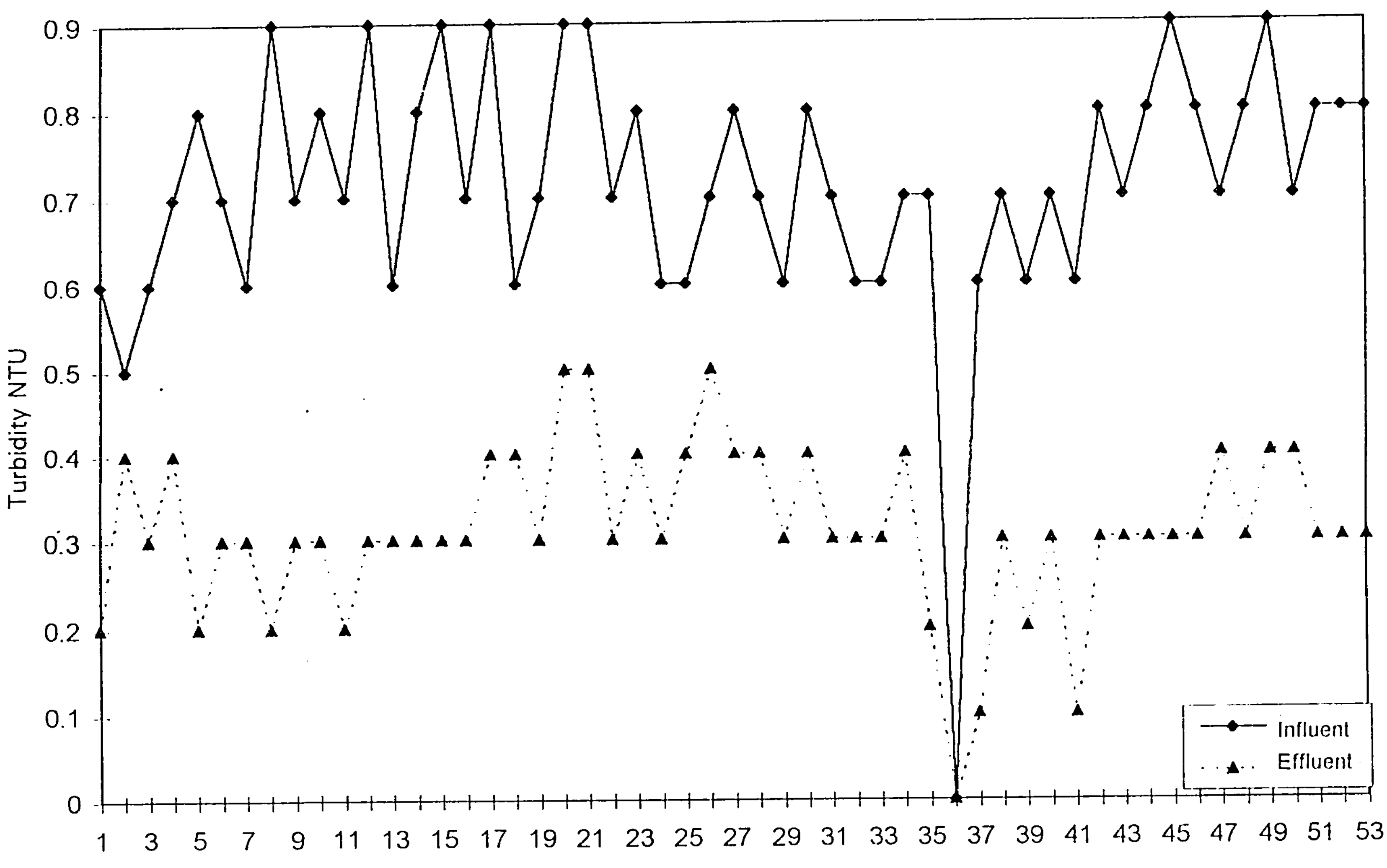


Figure 5.16: Variation of Turbidity in Condition 7

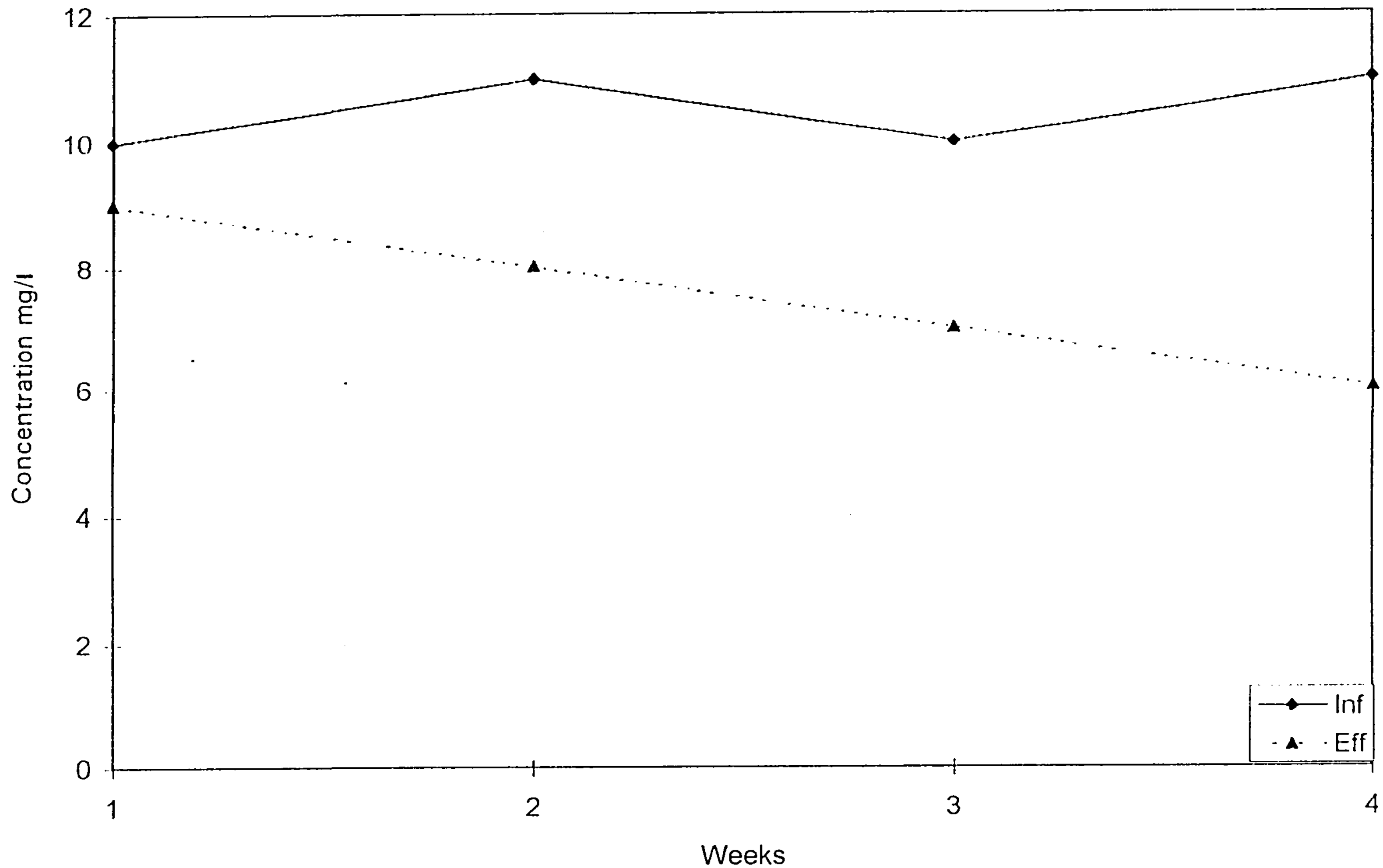


Figure 5.17: Variation of SS in Condition 12

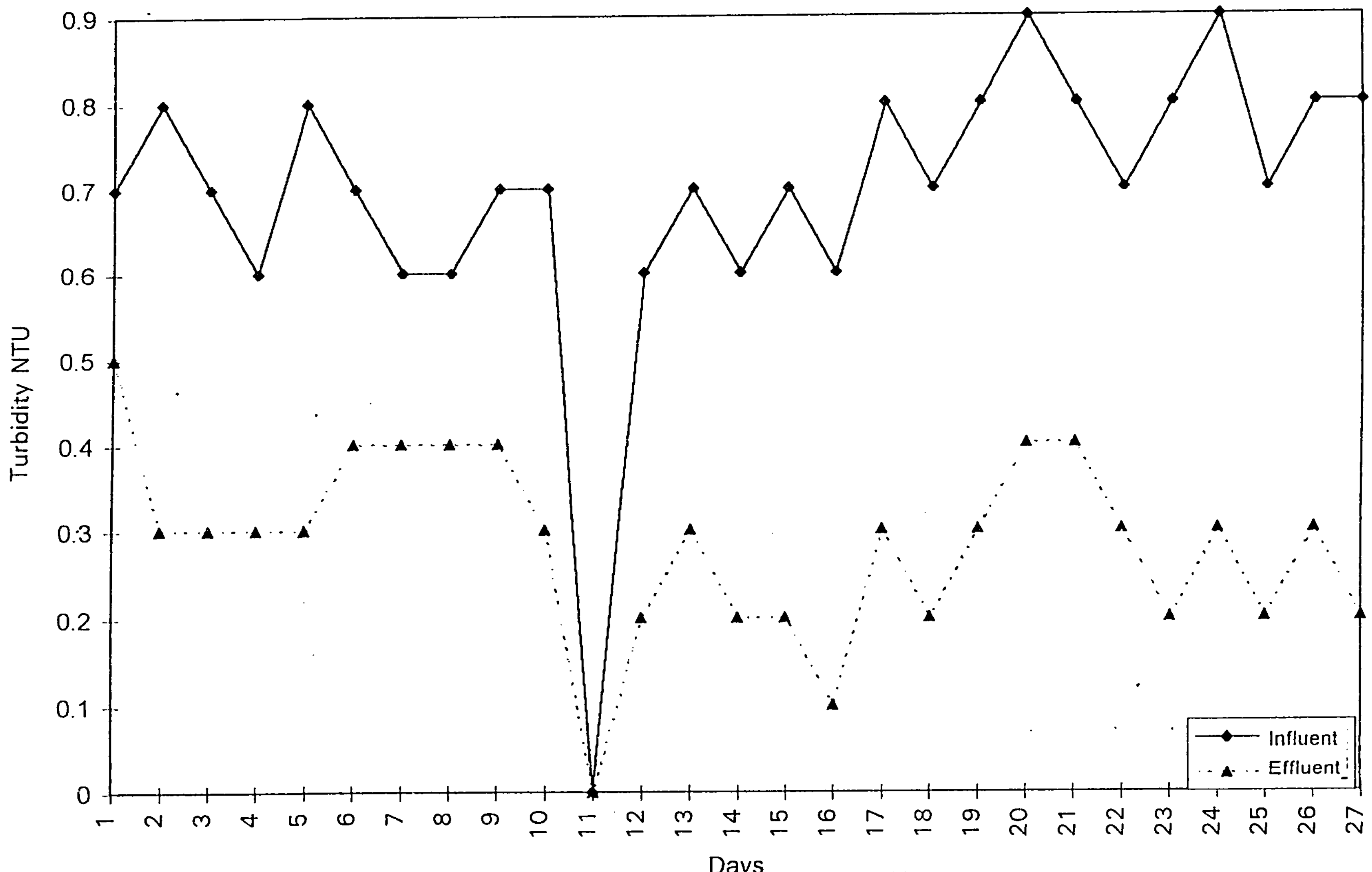


Figure 5.18: Variation of Turbidity in Condition 12

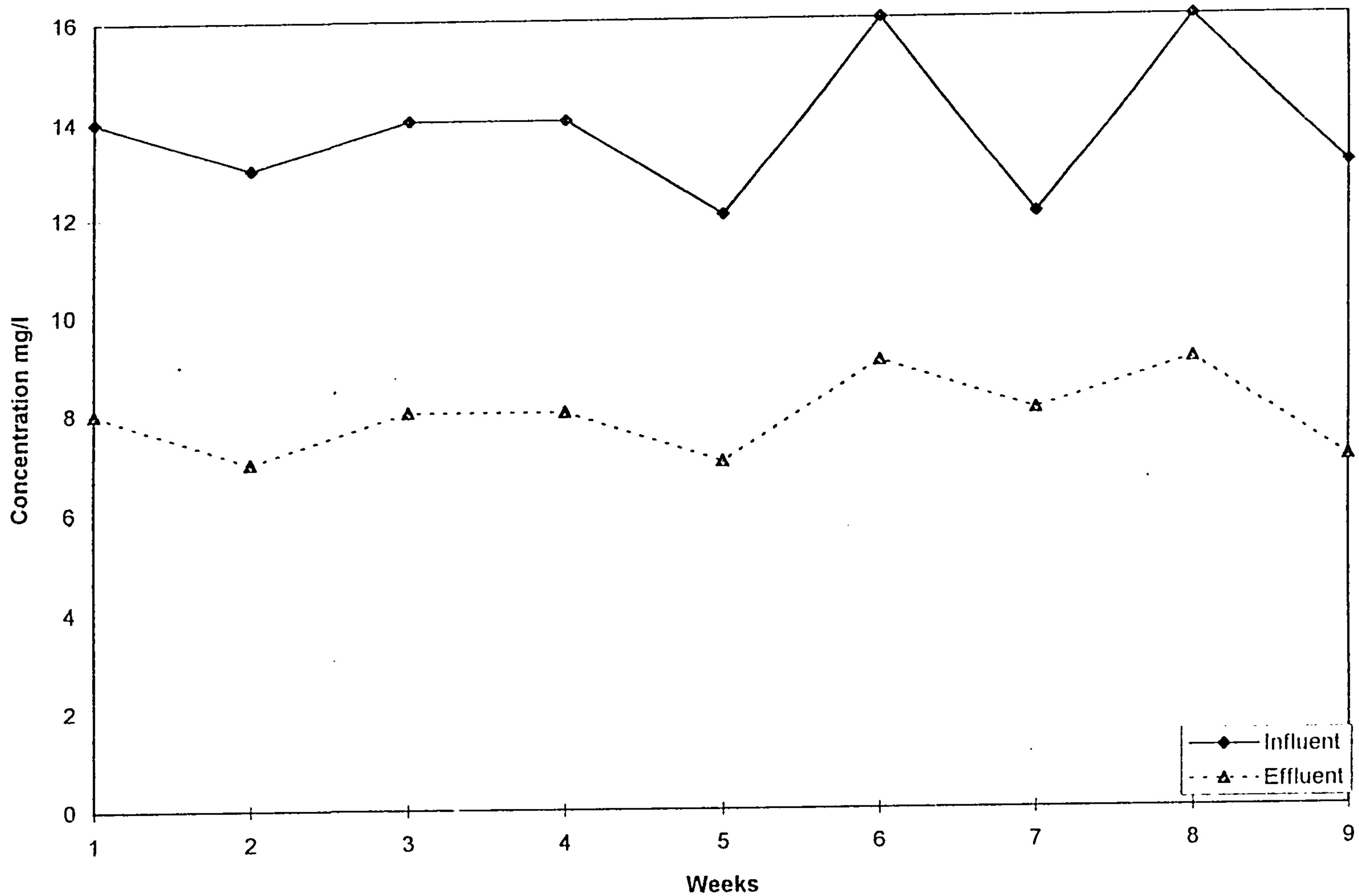


Figure 5.19: Variation of SS in Condition 4

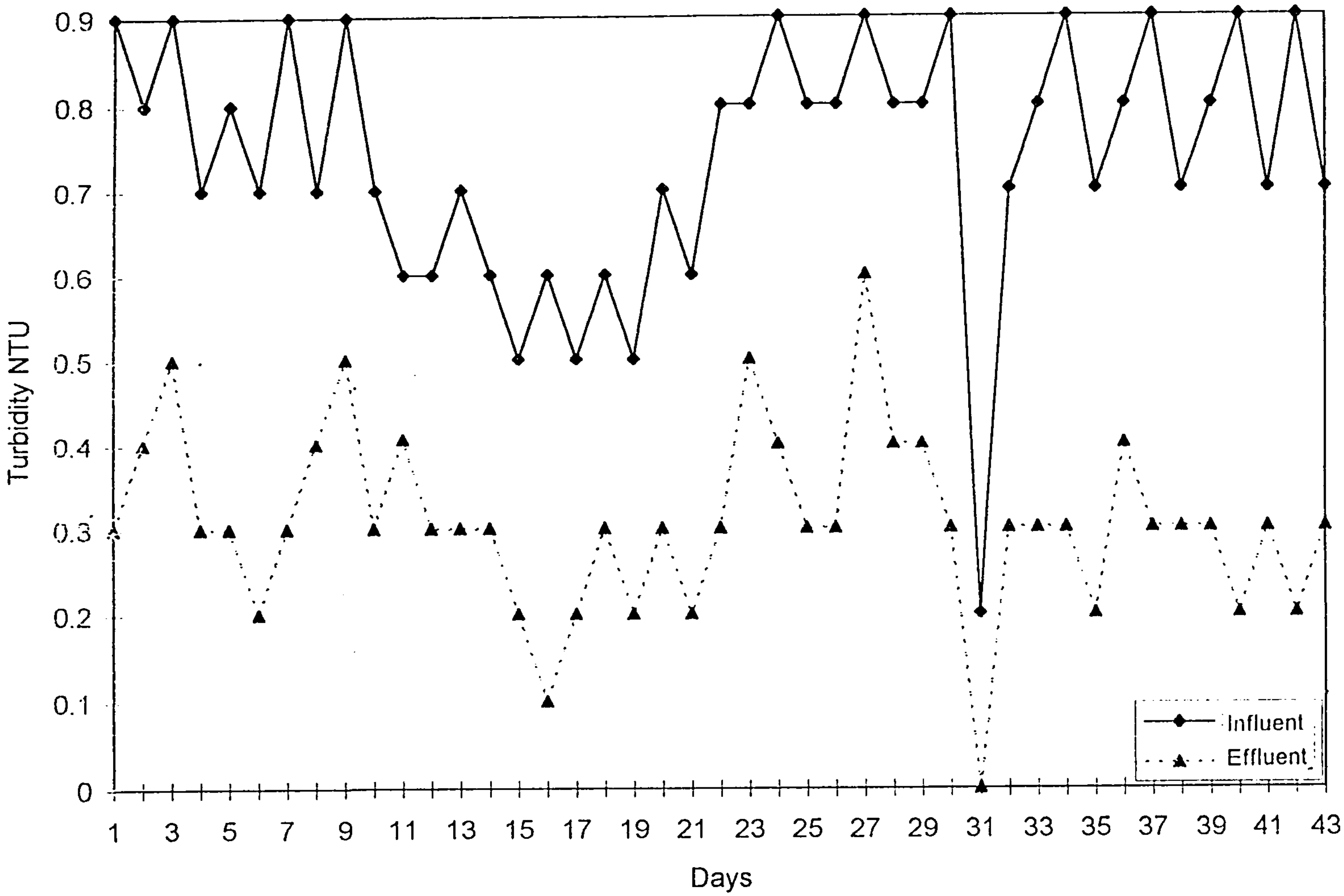


Figure 5.20: Variaiton of Turbidity in Condition 4

SS and turbidity ranged from 12 to 16.0mg/l and 7 to 9mg/l , 0.5 to 0.9 NTU and 0.1 to 0.4NTU with the influent and effluent concentration of the SS exhibiting a consistent trend. It can be seen from the figure that the effluent concentration increased with the increase in influent SS concentration. The average removal efficiency of SS and turbidity was found to be 42.62% (5.9mg/l) and 58.9% (0.44NTU). The maximum and minimum removal was 69% to 55.5% and 77.8% to 32.4% of SS and turbidity.

In C8 of F2 the influent and effluent concentration of suspended solids and turbidity ranged between 12 to 16 mg/l and 4 to 11 mg/l , 0.2 to 0.9NTU and 0 to 0.6NTU as observed from Fig 5.21 and 5.22. The average percent removal of suspended solids and turbidity were 58.5% (8.1mg/l) and 62.4% (0.47NTU). The maximum and minimum removal of SS and turbidity varied from 74.4% to 21.4% and 88.9% to 33.4% respectively. Similarly Fig 5.23 and 5.24 in C13 of F3, presents the influent and effluent concentration of suspended solids and turbidity ranging from 12.0 to 16.0mg/l and 10 to 11mg/l , 0.2 to 0.9 NTU and 0.2 to 0.6 NTU respectively. The average percent removal of SS and turbidity was calculated to be 29.2% (4.1mg/l) and 56.5% (0.42NTU). The maximum and minimum removal was found to be 63.7% and 10% , 77.8% and 33.4% respectively.

(d) Filter operation at sand size of 0.3 and 0.5mm at flowrate of 10l/min and sand depth of 50 cms:

F2 (C9) and F3 (C14) were operated at a reduced filtration rate of 10l/min and a sand depth of 50cms in order to assess the removal efficiency at low hydraulic loading rate. With these operating conditions the filters were run for about 20 days. Fig 5.25 and

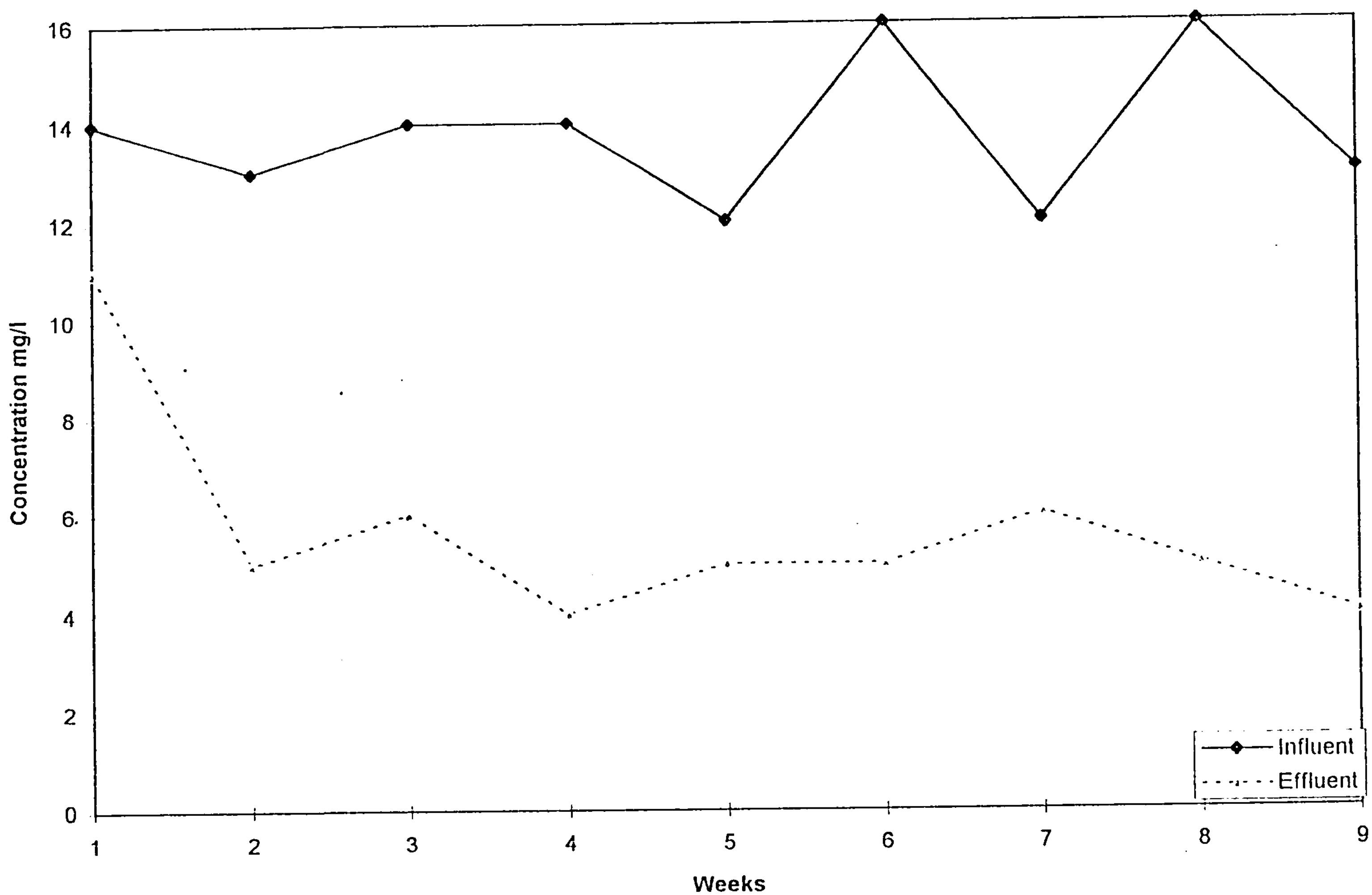


Figure 5.21: Variation of SSin Condition 8

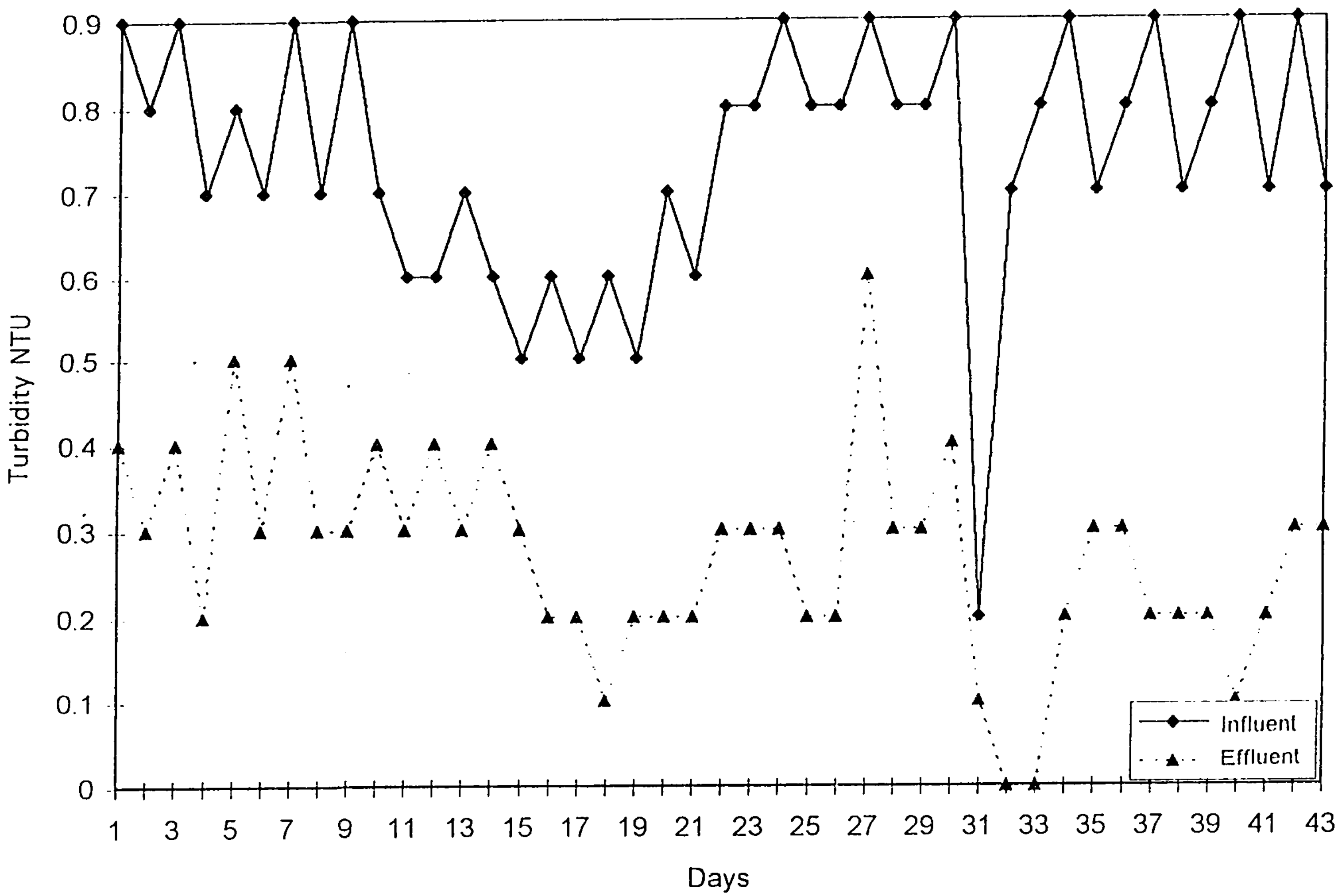


Figure 5.22: Variation of Turbidity in Condition 8

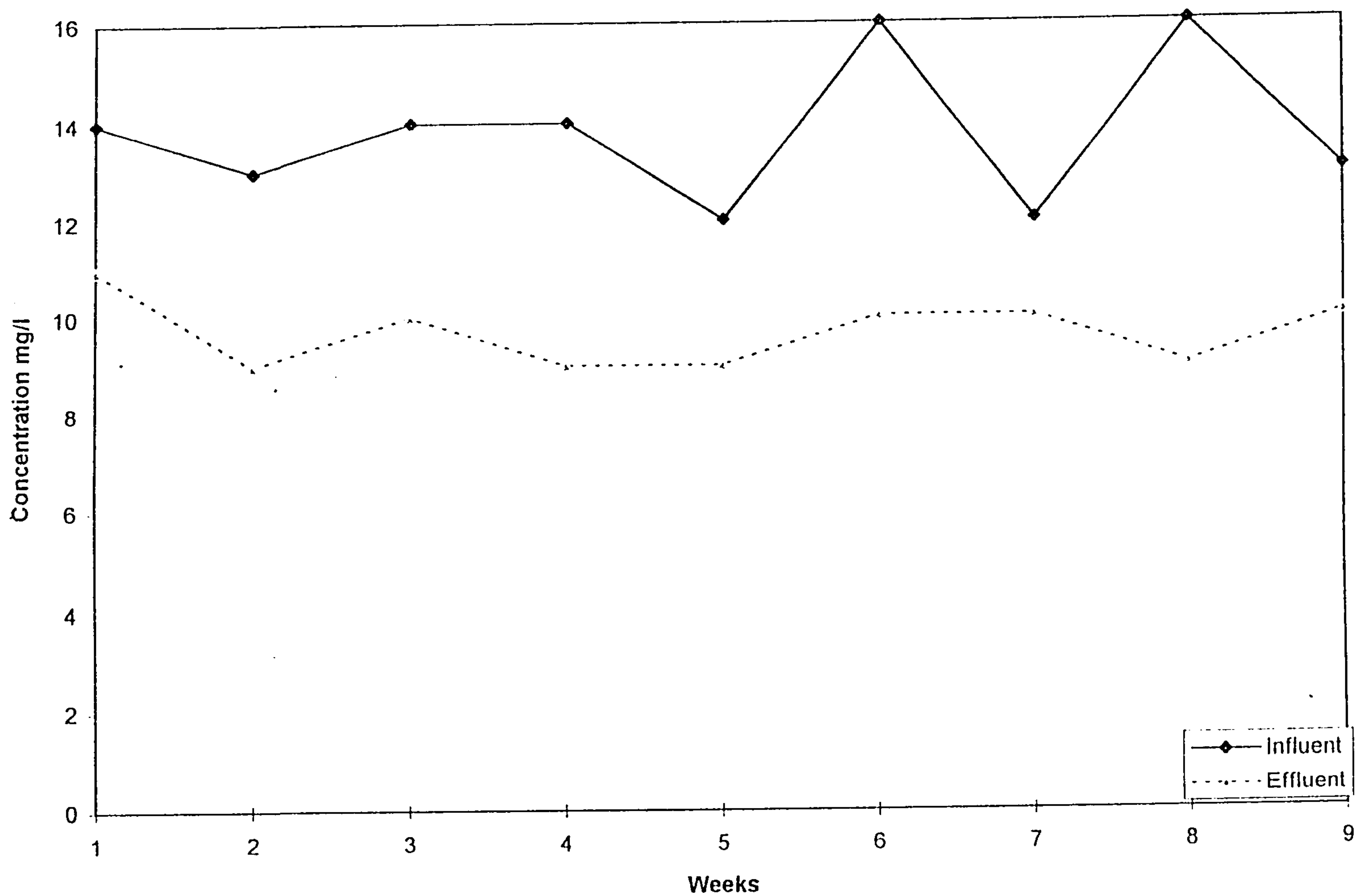


Figure 5.23: Variation of SS in Condition 13

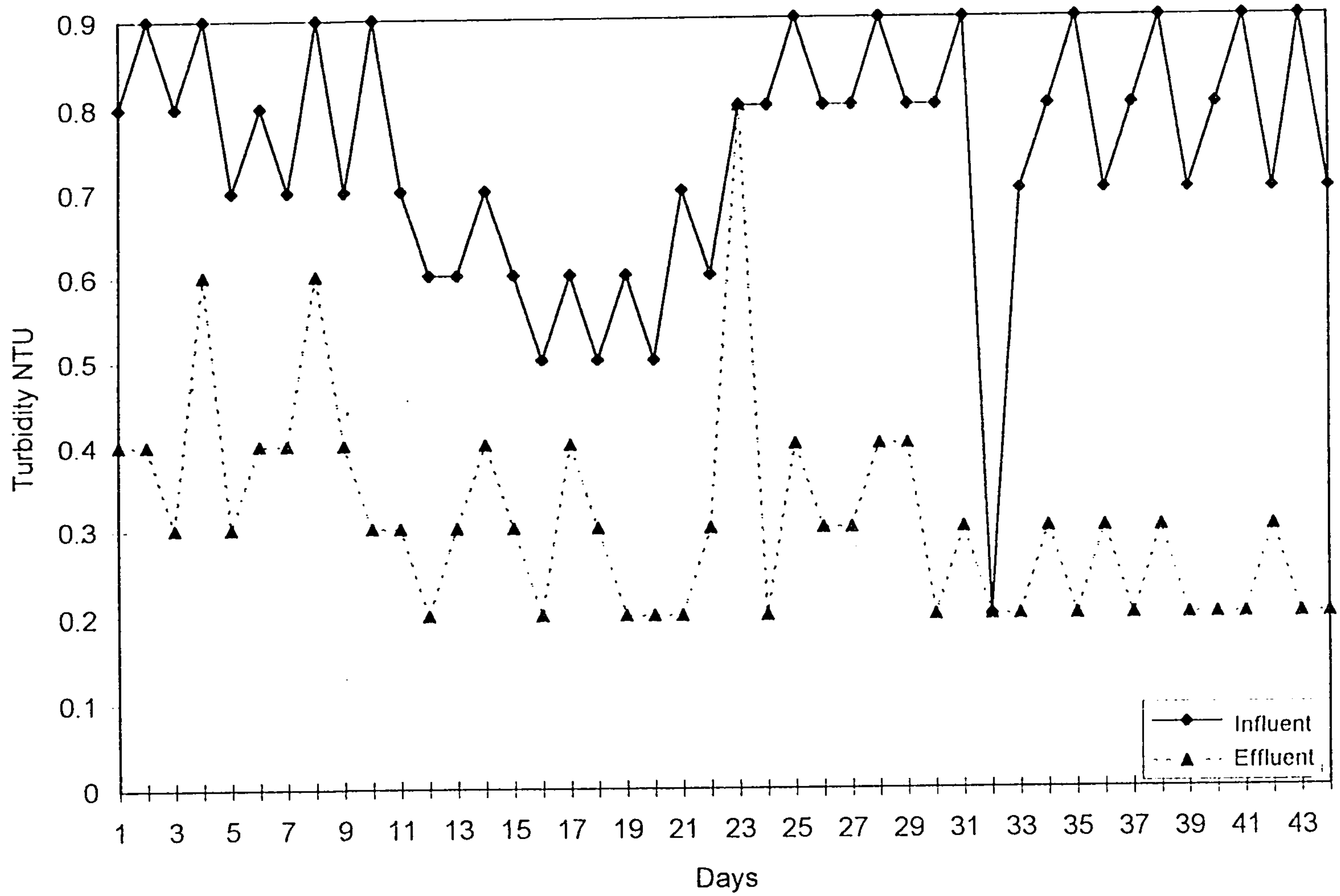


Figure 5.24: Variation of Turbidity in Condition 13

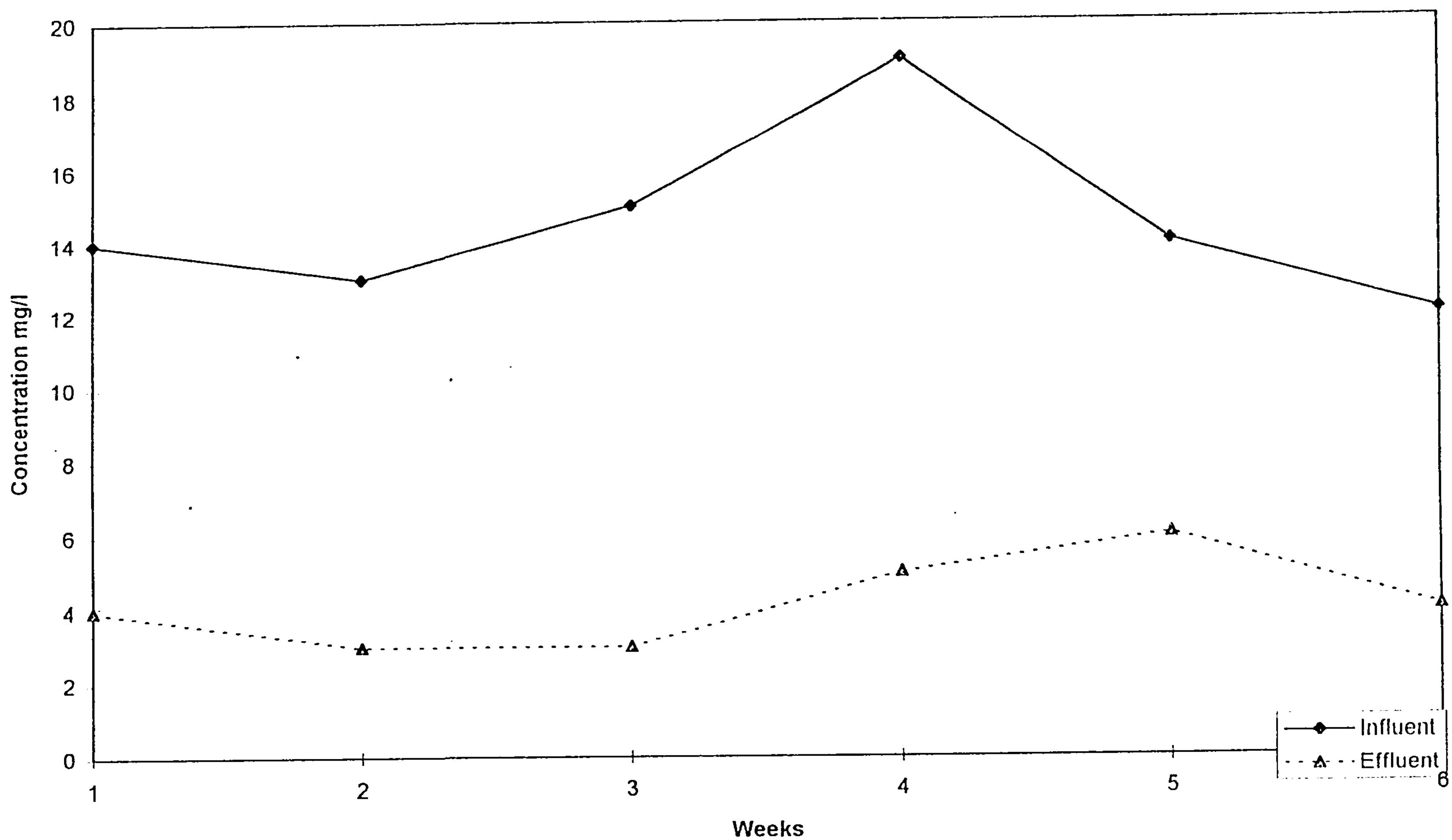


Figure 5.25: Variation of SS in Condition 9

5.26 of F2 illustrates the influent and effluent concentration of suspended solids and turbidity ranging from 12 to 19 mg/l and 3 to 6 mg/l , 0.6 to 0.9 NTU and 0.1 to 0.4 NTU respectively. The average percent removal of suspended solids and turbidity was calculated to be 80.0% (10.3mg/l) and 61.7% (0.47NTU) and the maximum and minimum removals were 80.0% & 57%, 89% & 50% respectively. Similarly in F3, Fig 5.27 and 5.28 shows the influent and effluent concentration of suspended solids and turbidity. The concentrations ranged from 12 to 19mg/l and 5 to 8mg/l , 0.6 to 0.9NTU and 0.2 to 0.4NTU respectively. The average percent removal of SS and turbidity was calculated to be 51.2% (7.5mg/l) and 62.8% (0.5 NTU). The maximum and minimum removal was found to be 63% and 42.8% , 77.8% and 42.8% respectively. It can be observed from Fig 5.25 and 5.27 that there was a discernable tread in the SS data while Fig 5.26 and 5.28 of turbidity exhibited a substantial scatter.

Therefore from the above discussion of various filter operations, operating under varying flow rate, different sand depth and sand size, it can be postulated that on the whole sand size and filtration rate have a strong impact on the performance except for that in case of F2 during C5 and C6. At this stage one might be tempted to think that the filter is not performing well since the removal efficiency of SS and turbidity of slow sand filters did not exceed 90%. This may be within the limits of experimental errors which are likely in the determination of SS and turbidity at such low concentrations. The low turbidity in the filtered effluent of thls study is attributed in part to the high quality of the biologically treated secondary effluent from Al - Khobar WasteWater Treatment Plant.

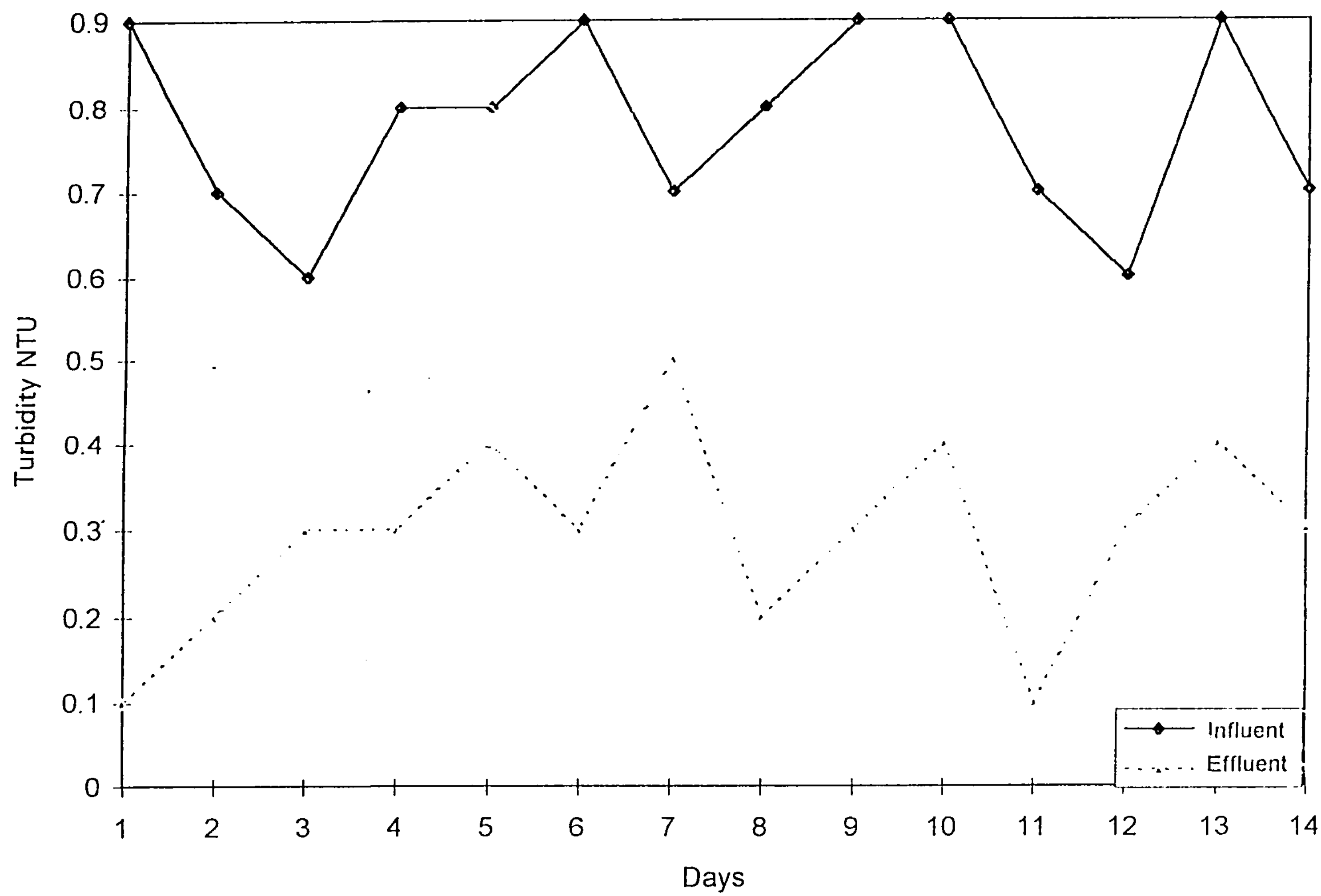


Figure 5.26: Variation of Turbidity in Condition 9

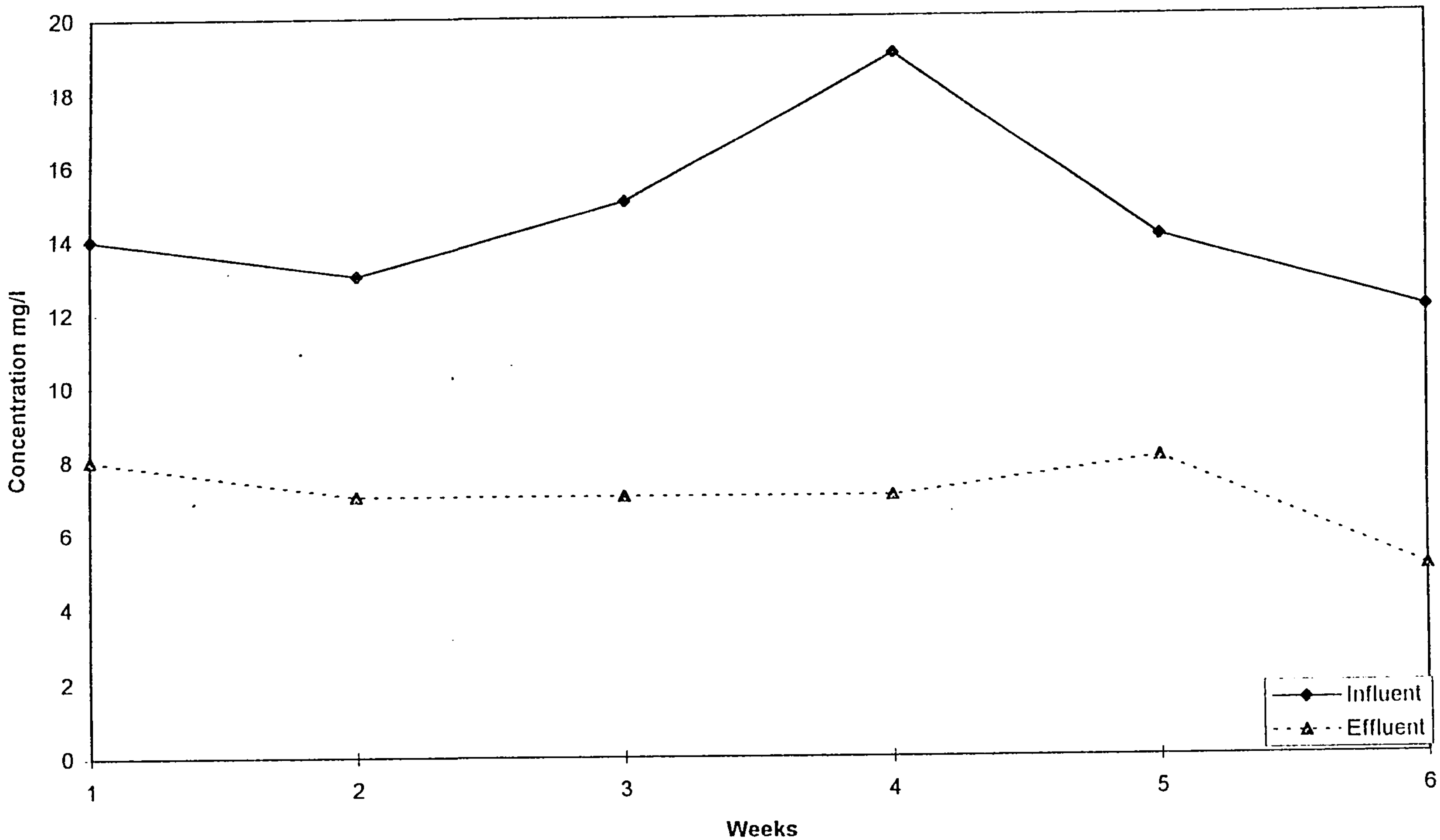


Figure 5.27: Variation of SS in Condition 14

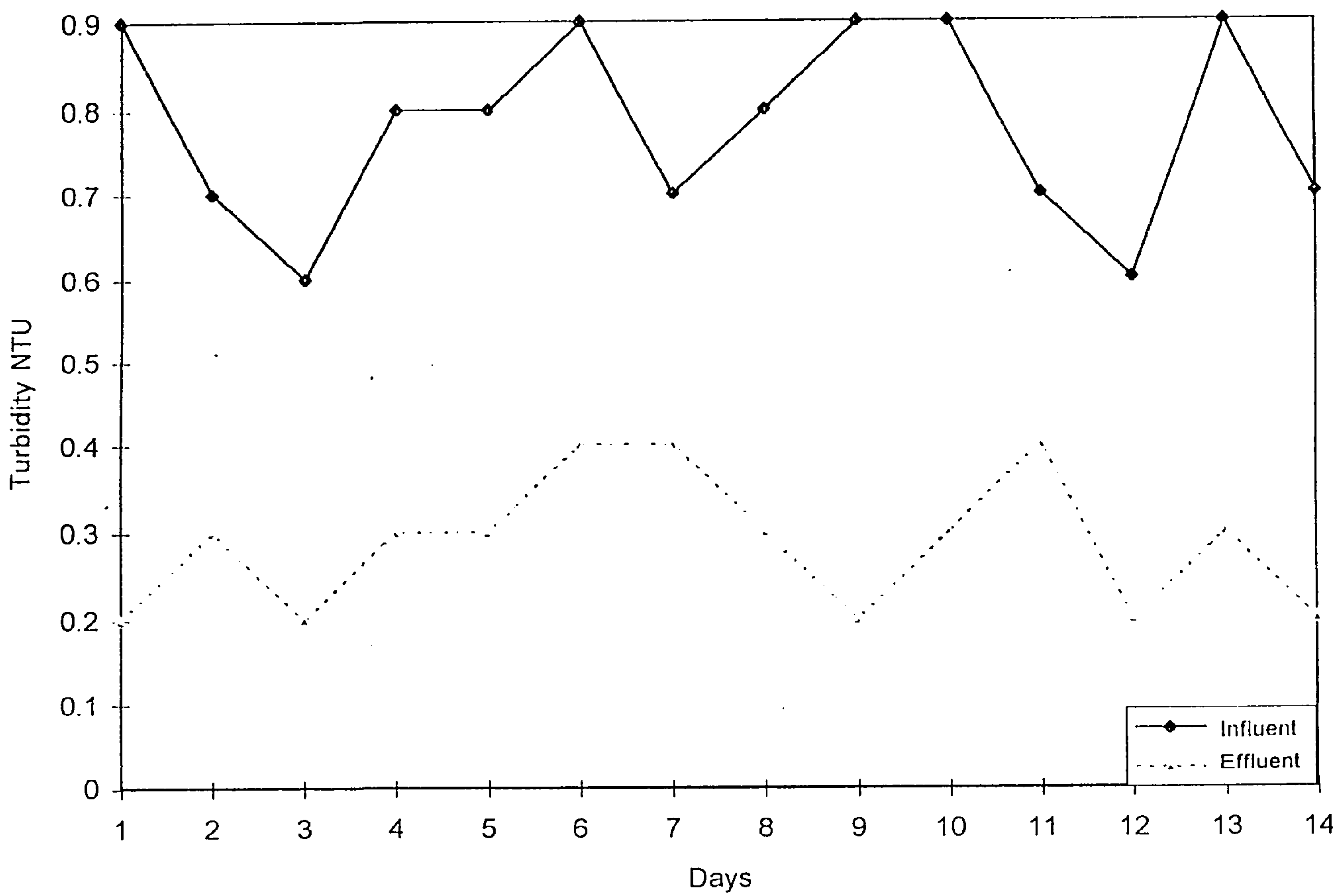


Figure 5.28: Variation of Turbidity in Condition 14

5.1.4 Organic Matter

During operation of the filter, samples of the influent and effluent have been monitored routinely on weekly basis for the analysis of parameters such as BOD and COD.

(a) Filter operation at flowrates of 8l/min, 10l/min, 16l/min and 20l/min at sand depth of 150cms:

The percent variation of BOD and COD data in C1 of F1 is depicted in Fig 5.29. From the figure it can be observed that there is no fixed trend which is attributed to the initial operational problems during the filter run. The influent concentration levels of BOD and COD have ranged from 2.8 to 6 mg/l and 33 to 48 mg/l averaging around 4.65 mg/l and 42.0mg/l respectively. The effluent concentrations of BOD and COD varied from 0.2 to 2.6 mg/l and 29 to 38 mg/l, with an average of 1.3 mg/l and 32.5mg/l. The maximum and minimum percent removal are found to be between 94 to 57% and 33.4 to 11.2% respectively. The average BOD and COD percent removals were 72% (3.35mg/l) and 22.1% (9.5mg/l).

Fig 5.30 presents the percent variation of BOD and COD data in C5 of F2. Due to the initial operational problems there is a wide fluctuation during the beginning of the filter run. The variability decreased as the filter bed matured with the length of the run. The influent and effluent concentration of BOD and COD have ranged from 3 to 3.5 mg/l and 0.6 to 1.1 mg/l , 36 to 48mg/l and 20 to 30mg/l respectively. Their corresponding averages were 4.5mg/l and 0.95mg/l, 41.5mg/l and 25.1 mg/l respectively. The maximum

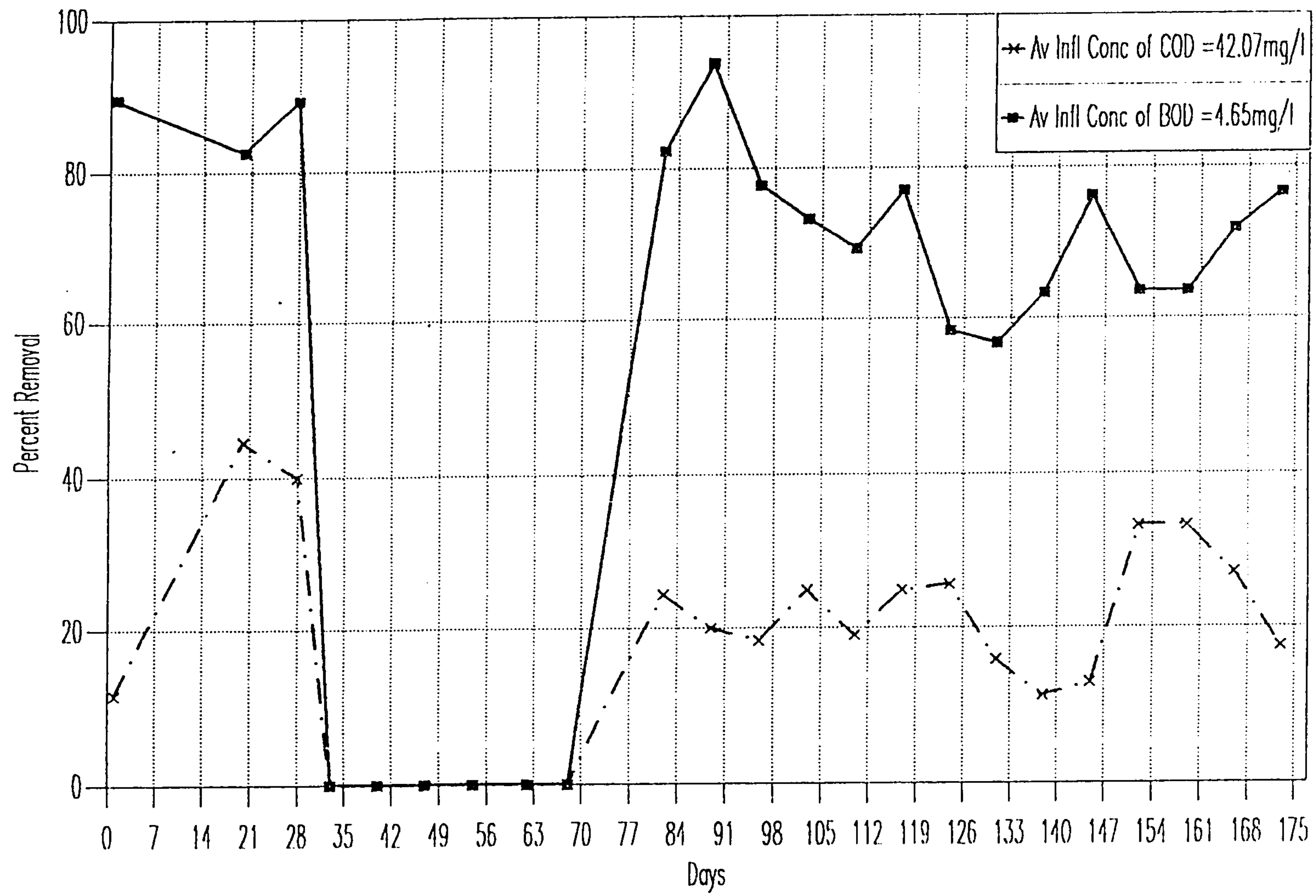


Figure 5.29: Removal Efficiencies of Organics in Condition 1

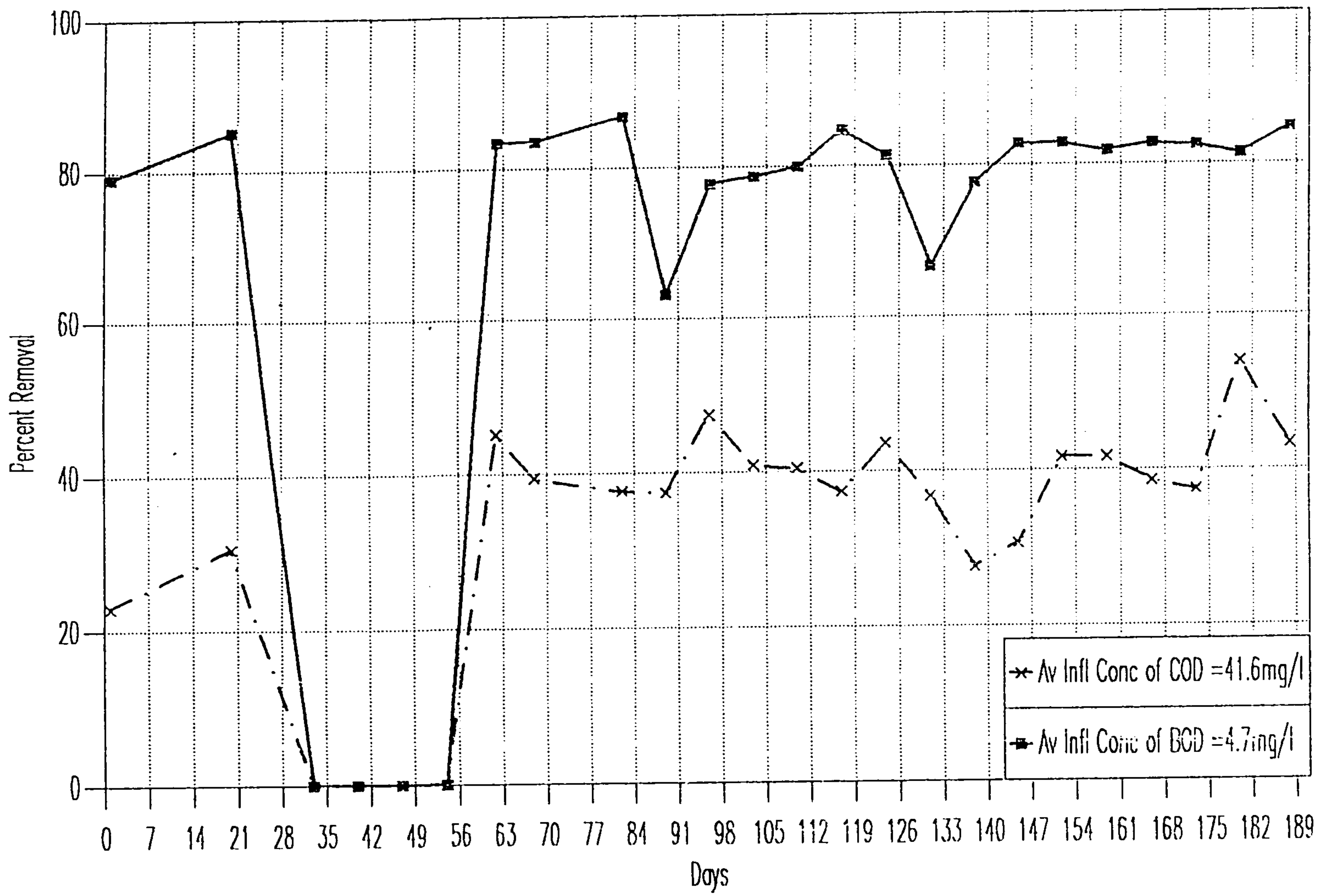


Figure 5.30: Removal Efficiencies of Organics in Condition 5

and minimum percent removal of BOD and COD are 87 to 63.1% and 47.4 to 27.7%. The average removal are 78.5% (3.55mg/l) and 39.6% (16.4mg/l). Similarly in C10 of F3 percent variation of BOD and COD data is illustrated in Fig 5.31. The figure depicts the same trend as in Fig 5.29 and 5.30 with almost the same variability as that in F1 and F2. The influent and effluent concentration levels of BOD and COD have ranged from 3.25 to 6 mg/l and 0.7 to 2.7 mg/l, 36 to 52mg/l and 28 to 38mg/l respectively. The average influent and effluent concentrations are 4.7mg/l and 1.8 mg/l, 42.8mg/l and 34mg/l respectively. The maximum and minimum percent removal of BOD and COD were calculated to be 81 to 46% and 38.5 to 5% with an average removal of 62.2% (2.9mg/l) and 20.3% (8.8mg/l) respectively.

Comparing F1(C1) and F3 (C10) it is found that the removal rate of BOD and COD in F1 with low flow rate is greater than F3 having high flow rate. Also the removal in F2 (C5) consisting of fine sand is greater is than F3 having coarse sand. Upon assessment of the removal efficiencies it is noteworthy that although removals were low the removals in F1, F2 and F3 were according to the expectations. These low removals are attributed to the low influent concentrations of BOD and COD. The Al-Khobar Wastewater Treatment Plant maintained a low influent BOD conspicuously manifesting the excellent BOD removal by the carrousel system of the treatment plant. The removals in F1 and F2 is better than F3 indicating that filtration rate and sand size are inversely related to the removal efficiencies. Farooq (16) has reported that the percent removal of BOD and COD in case of coarse filter having sand size of 0.5mm, sand depth of 110cms and a hydraulic loading of 0.16m/hr was 84.7% and 43.9% respectively. From the above it can

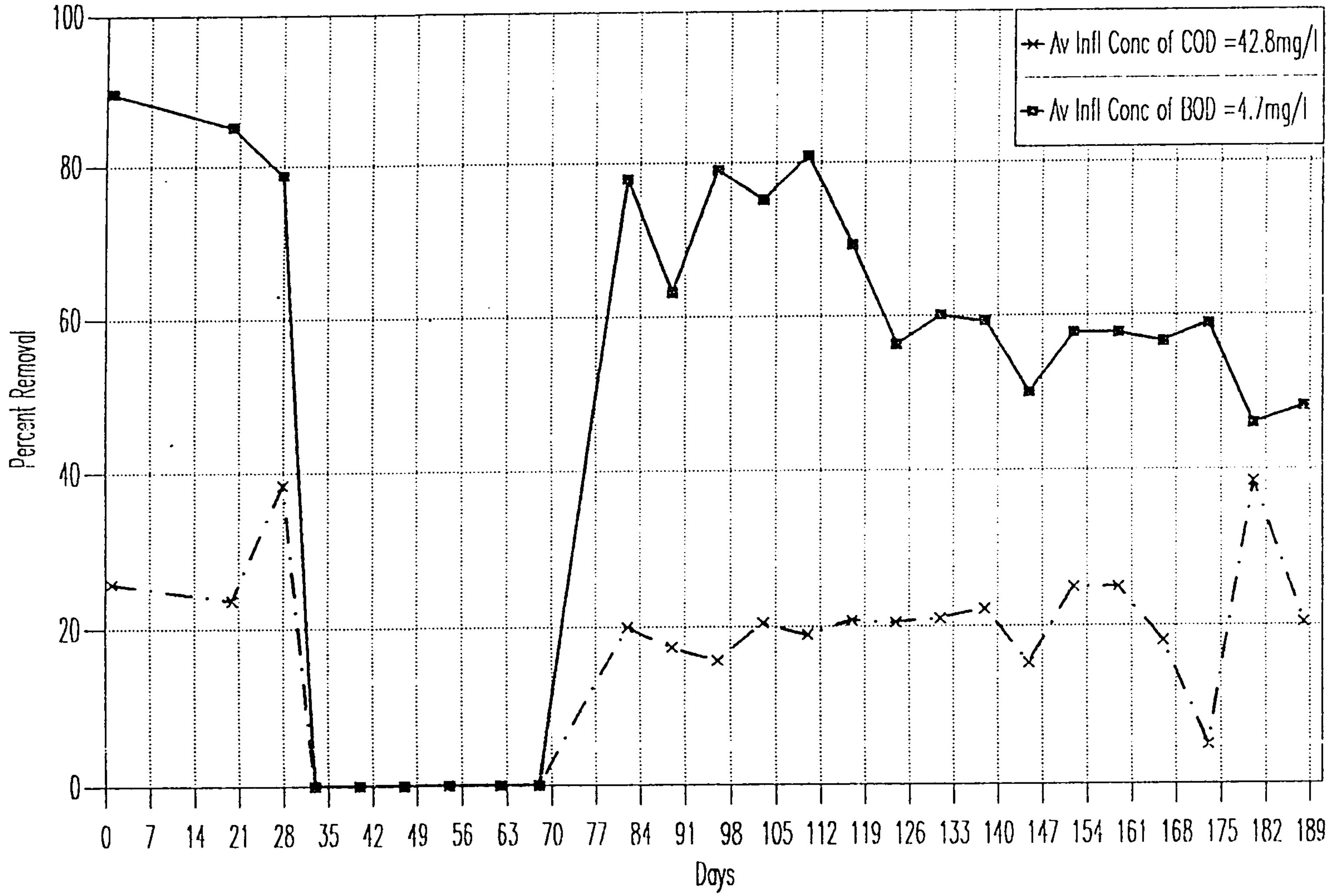


Figure 5.31: Removal Efficiencies of Organics in Condition 10

be observed that the removal efficiencies of BOD and COD in F1 and F3 were 78.5% and 39.6%, 62.6% and 20.3%, respectively.

The percent variation of BOD and COD data in C2 is shown in Fig 5.32. It can be seen from the figure that the BOD gradually increased with decrease in the COD removal rate. The influent and effluent concentration range from 4.8 to 5.6 mg/l and 1.2 to 2 mg/l of BOD and 41.2 to 52 mg/l and 27 to 30 mg/l of COD. The average influent and effluent concentrations of BOD and COD were found to be 5.1 mg/l and 1.7 mg/l , 44.2 mg/l and 28.2 mg/l respectively. The maximum and minimum removals of BOD and COD were 78.5% and 58.4%, 46.2% and 16.6% and the average 65.4% (5.2mg/l) and 34.9% (16mg/l), respectively.

Fig 5.33 depicts the percent variation of BOD and COD data in C6. Both the BOD and COD data followed a consistent pattern. The BOD removal rate gradually increased indicating that biodegradation was more in F2 having fine sand. The influent and effluent concentration in C6 ranged from 5.0 to 5.2 mg/l and 0.8 to 0.9 mg/l of BOD, 36 to 48 mg/l and 23 to 26 mg/l of COD. Their corresponding averages were 5.23 mg/l and 0.86 mg/l, 41.7 mg/l and 24.33 mg/l respectively. The maximum and minimum removals were 84.3% and 82%, 52.1% and 27.8%. The average removals were found to be 83.4% (4.4mg/l) and 40.4% (17.3mg/l) of BOD and COD respectively. Al - Adham (1), has reported a removal of 73% and 38% of BOD and COD at hydraulic loading of 0.16m/hr, sand size of 0.16mm and at a sand depth of 90cms. The percent removal rates obtained above are comparable to the values reported by Al - Adham (1) with the filter operating at higher hydraulic loading of 0.38m/hr.

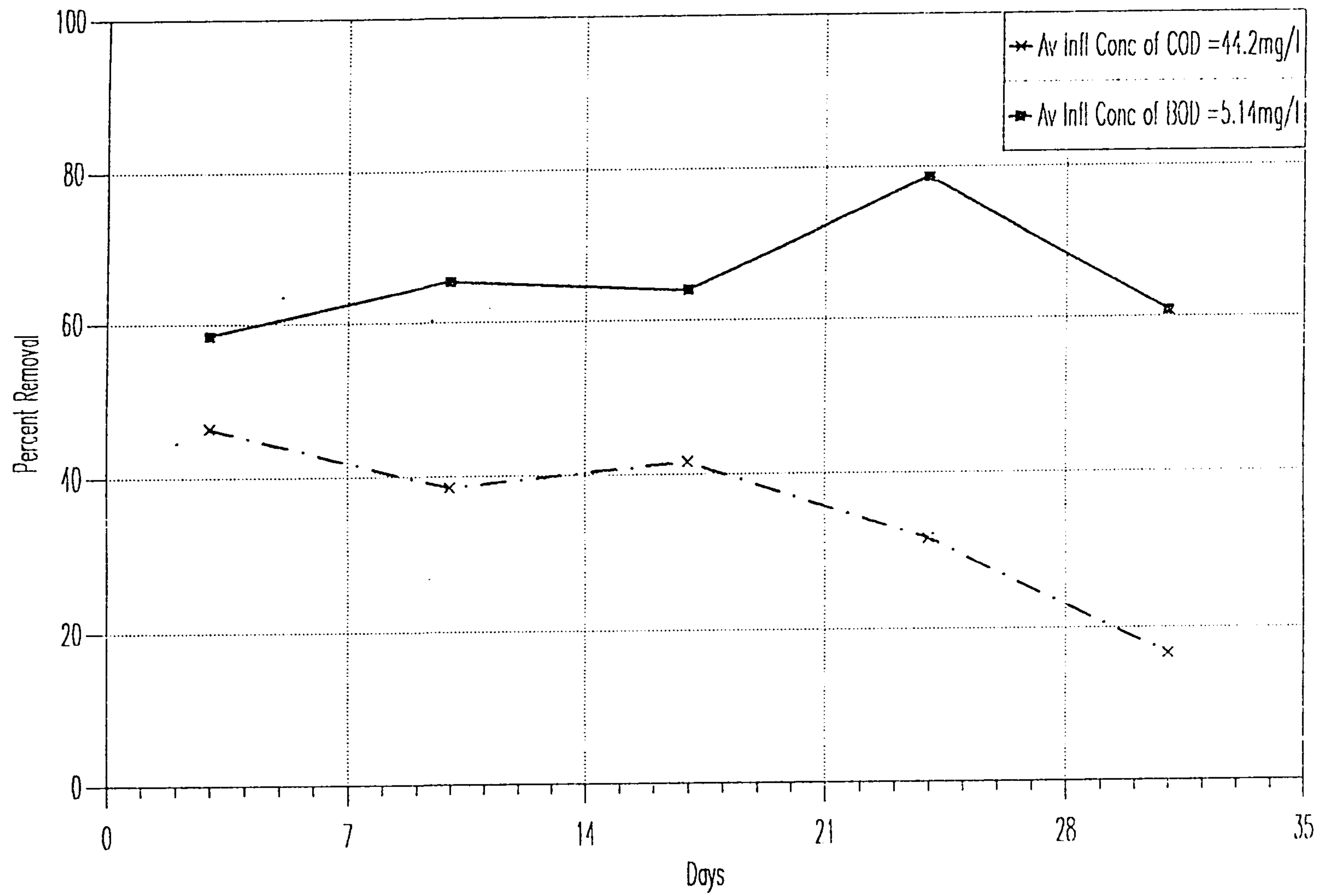


Figure 5.32: Removal Efficiencies of Organics in Condition 2

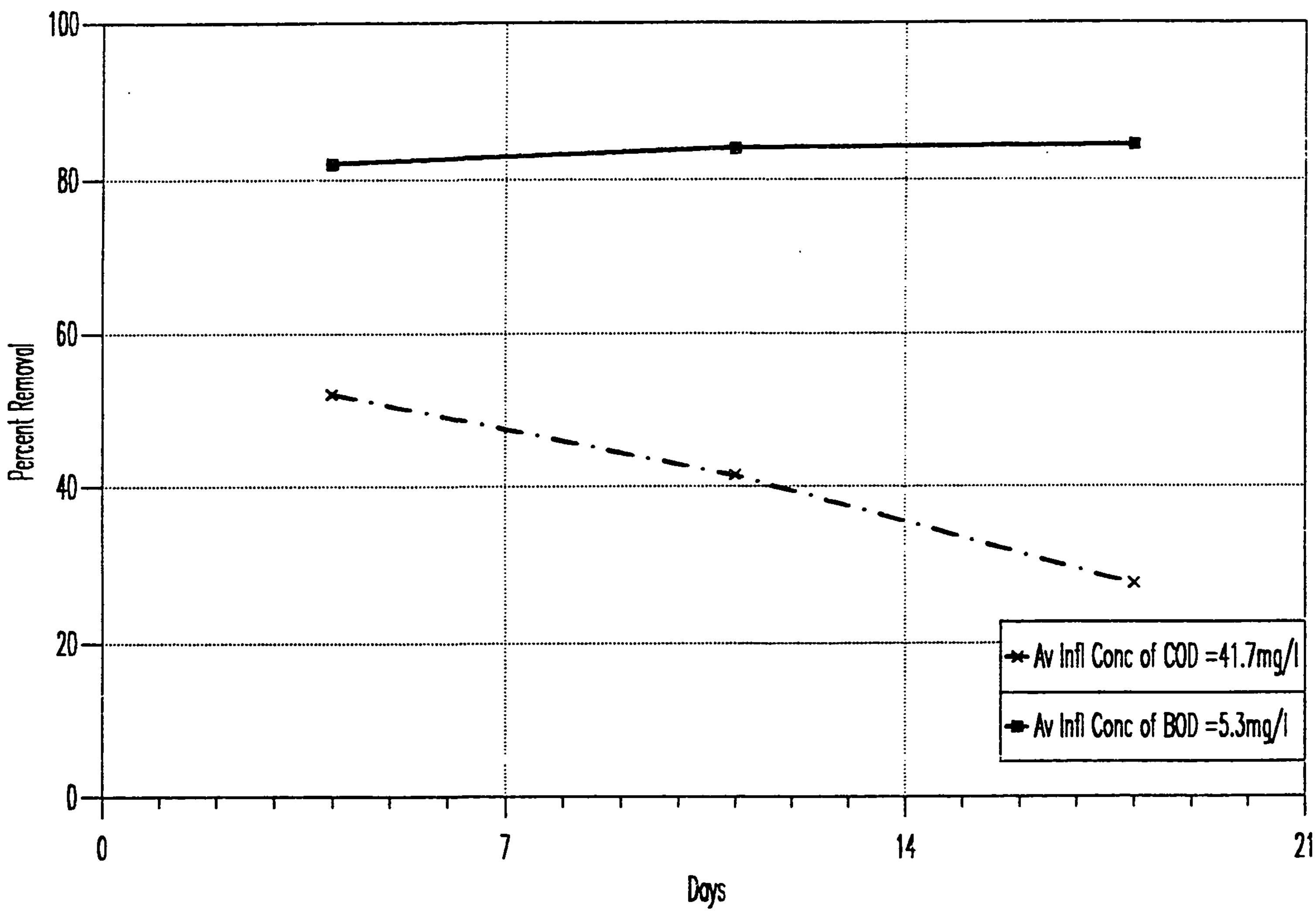


Figure 5.33: Removal Efficiencies of Organics in Condition 6

The percent variation of BOD and COD data during C11 is illustrated in Fig 5.34. The BOD and COD showed no clear consistent trend although the COD data followed the same trend as in Fig 5.32 and 5.33 with the elimination of few odd points. The variation of influent and effluent concentration of BOD and COD ranged from 4.25 to 6.1 mg/l and 1.6 to 3.6mg/l, 36 to 48 mg/l and 30 to 34 mg/l respectively. The average influent and effluent concentrations were found to be 5.0 mg/l and 2.3mg/l, 39.25mg/l and 32.43mg/l respectively. The maximum and minimum removals were 71.4% and 26.5% in case of BOD and 37.5%, 2.8% in COD, corresponding to average removals of 54.1% (2.7mg/l) and 16.4% (6.75mg/l) respectively.

Therefore from the above it can be depicted that the removals have dropped in C2 and C11 compared to Cl and C10 owing to the increase in the filtration rate. It is noteworthy that although removals in C2 and C11 were according to expectations, the removal of BOD and COD in C6 is higher at higher flow rate. This is rather unexpected since the hydraulic retention time has been decreased by 25%, which could be attributed to the operational problems coupled with experimental error.

(b) Filter operation at flowrates of 10l/min and 20l/min at sand depth of 80cms:

With these operating conditions the filters were cleaned and re-operated by reducing the sand depth to 80cms with the filtration rate being constant. Fig 5.35 illustrates the percent variation of BOD and COD data in C3. It can be observed from the figure that initially there was an increase in the removal rate, but as the run length increased the BOD data exhibited a decreasing trend while the COD data showed a scatter although the efficiency decreased. The influent and effluent concentrations ranged from

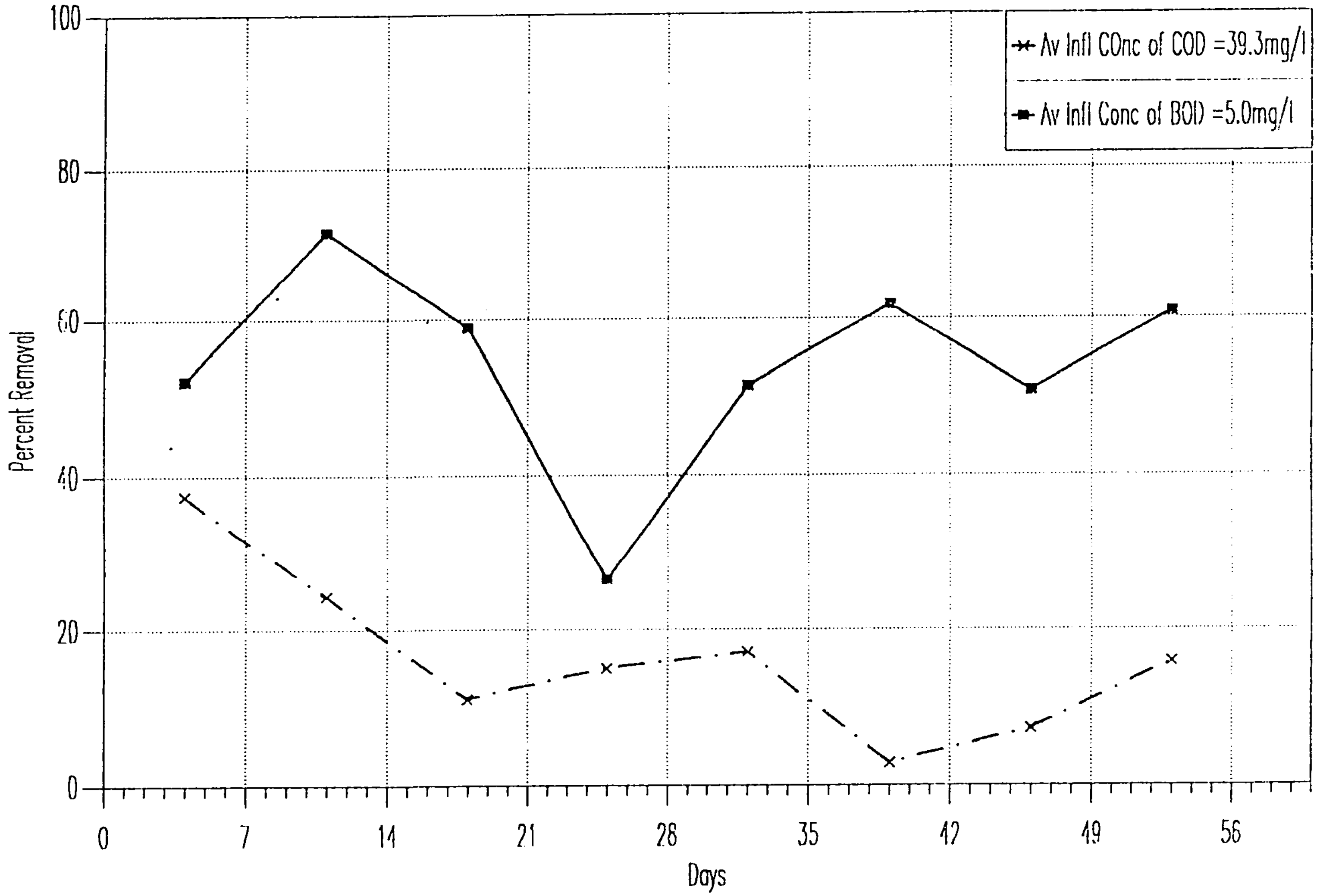


Figure 5.34: Removal Efficiencies of Organics in Condition 11

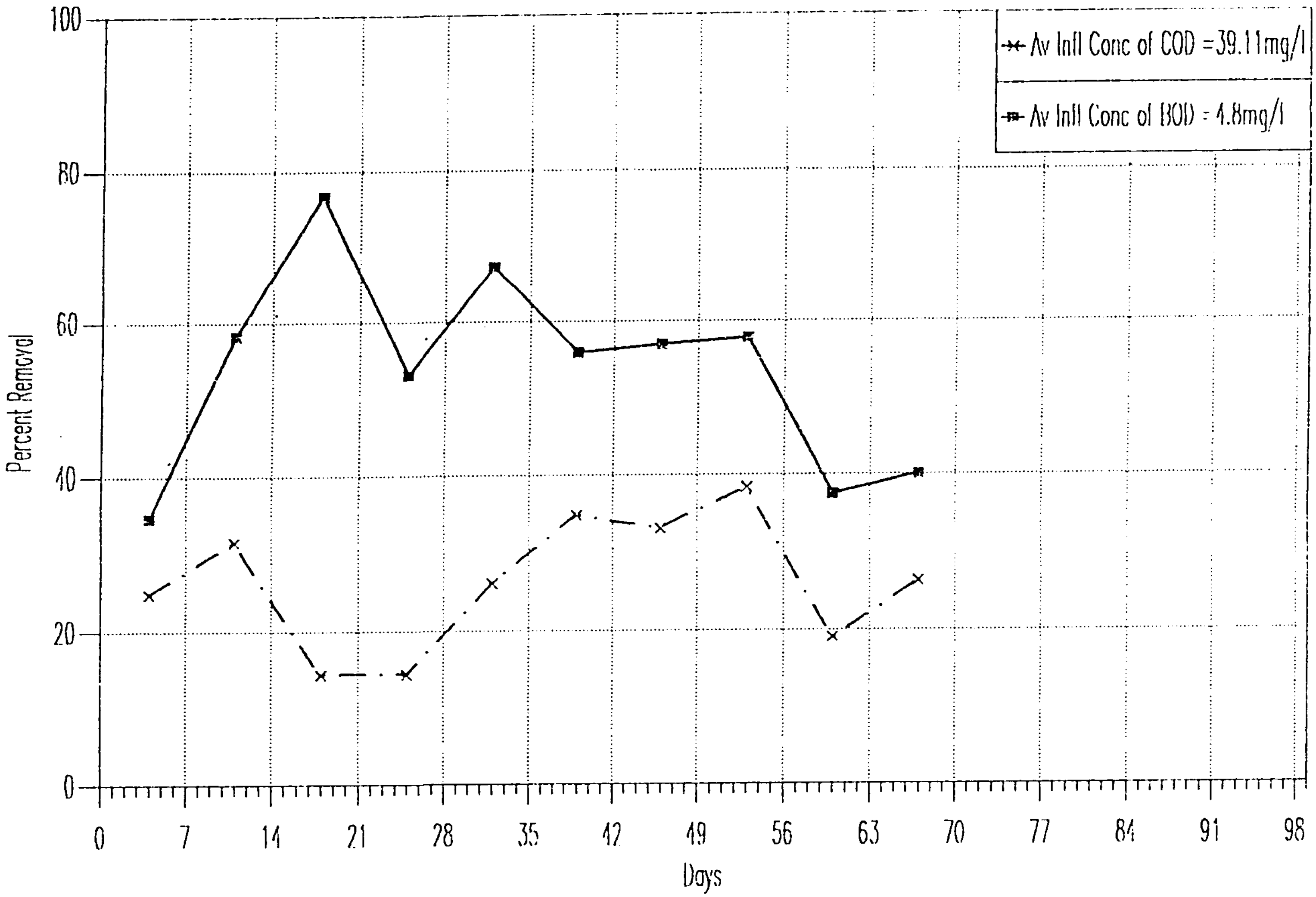


Figure 5.35: Removal Efficiencies of Organics in Condition 3

4.25 to 6.1 mg/l and 1.1 to 3.2 mg/l of BOD and 42-35 mg/l and 24 to 34 mg/l of COD, averaging around 4.77 mg/l and 2.11 mg/l, 39.11 mg/l and 28.6 mg/l respectively. The maximum and minimum removals of BOD and COD varied between 76.6% to 37.5% and 35.0% to 14.3% respectively. The average removals were found to be 55.3% (2.76mg/l) and 26.4% (10.5mg/l)of BOD and COD respectively.

In C7 the percent variation of BOD and COD removal is illustrated in Fig 5.36. From the figure it can be depicted that the BOD exhibits a more discernable trend than the COD data. The influent concentrations of BOD and COD in C7 are same as C3. The effluent concentrations ranged from 0.6 to 2.1 mg/l and 22 to 31 mg/l respectively. The maximum and minimum removals were 86 to 56.3% and 43.6% to 22.9% of BOD and COD. Their corresponding average removals were 76.77% (3.66mg/l) and 35.75% (14.11mg/l) respectively.

The percent variation of BOD and COD data during C12 is presented in Fig 5.37. The BOD and COD data exhibited a consistent trend although there were fewer data points during this condition. Also the profiles were similar to those observed in Fig 5.35 and 5.36 indicating the reliability of the filter run. The influent and effluent concentrations ranged from 4.3 to 5.2mg/l and 3.1 to 2.0mg/l, 39 to 42 and 28 to 34mg/l of BOD and COD, while the corresponding averages being 4.6 and 2.42mg/l, and 40.75 and 31.5 respectively. The maximum and minimum removals of BOD and COD were 54.5 to 35.4% and 28.2 to 19.04%. The average removals were found to be 48.3% (2.25mg/l) and 22.8% (9.25mg/l) respectively.

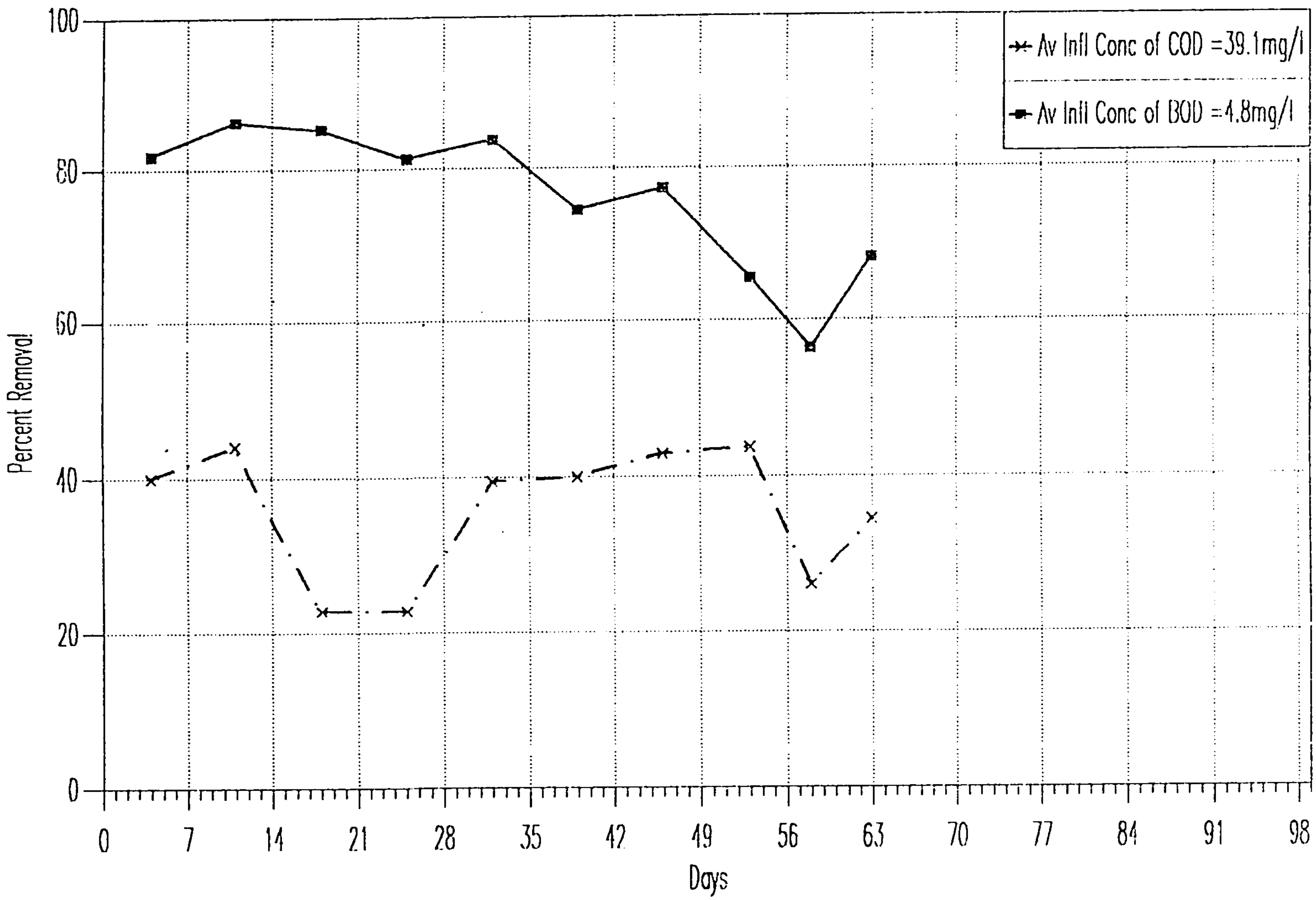


Figure 5.36: Removal Efficiencies of Organic in Condition 7

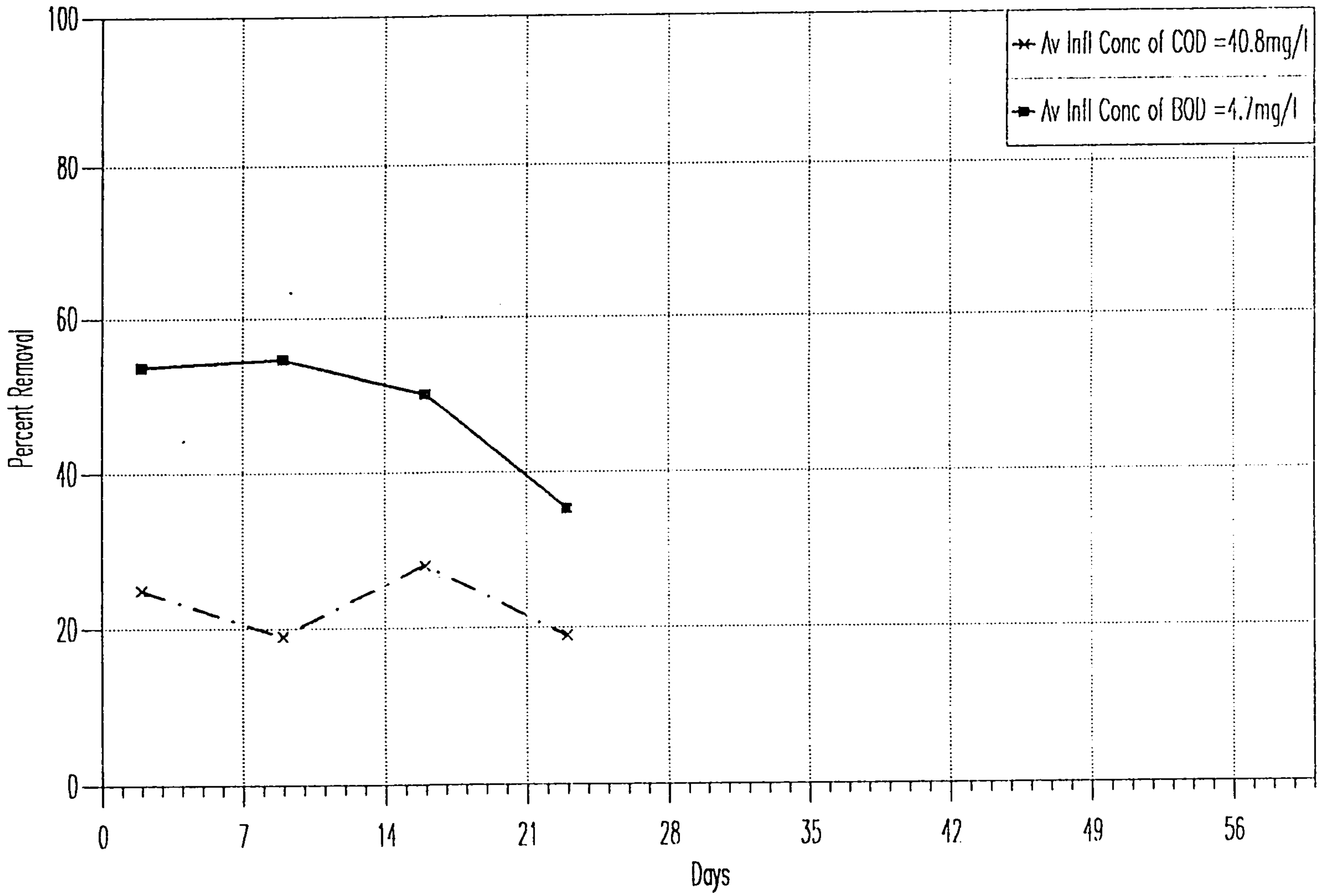


Figure 5.37: Removal Efficiencies of Organics in Condition 12

Comparing the results of C3, C10 (F1, F3) and C7, C12 (F2, F3) is observed that the percent removal has dropped due to the reduction in the sand depth. Thus indicating that sand depth concomitant with flow rate and sand size had a strong influence on the removal efficiency.

(c) Filter operation at flowrates of 10l/min and 20l/min at sand depth of 50cms:

During this condition of operation the filter sand depth was further reduced to 50cms while the filtration rate was kept constant in the respective filters. The percent variation of BOD and COD data is presented in Fig 5.38 - 5.40 in F1 - F3 (C4, C8 & C13) respectively. With the elimination of a few odd points, Fig 5.38 depicts a consistent trend of BOD and COD data. The trend being of decrease in percent removals with increasing days of filters operations. The same trend was observed in the previous Fig 5.35. A sudden drop in the removal rate was observed at the initial stage, this could be due to the prematuration of the filter bed. In Fig 5.39 a similar trend as in Fig 5.38 was observed except for some sudden increase in the COD data during the end of the filter run. Also from Fig 5.40 it can be observed that both the BOD and COD data exhibited a discernable trend although there was some fluctuation during initial and end of the filter run. In Fig 5.38 the influent concentrations of BOD and COD ranged between 5.2 to 4.0 mg/l and 32 to 42 mg/l averaging around 4.5 mg/l and 36.44 mg/l respectively in C4, C8 and C13. The effluent BOD and COD of C4 varies from 2.1 to 2.6 mg/l and 28 to 36 mg/l and averaged around 2.32 mg/l and 31.22 mg/l respectively.

In C8 of F2 (Fig 5.39) the effluent concentration ranged between 0.9 to 1.3 mg/l and 20 to 28 mg/l averaging around 1.06 mg/l and 24.22 mg/l BOD and COD

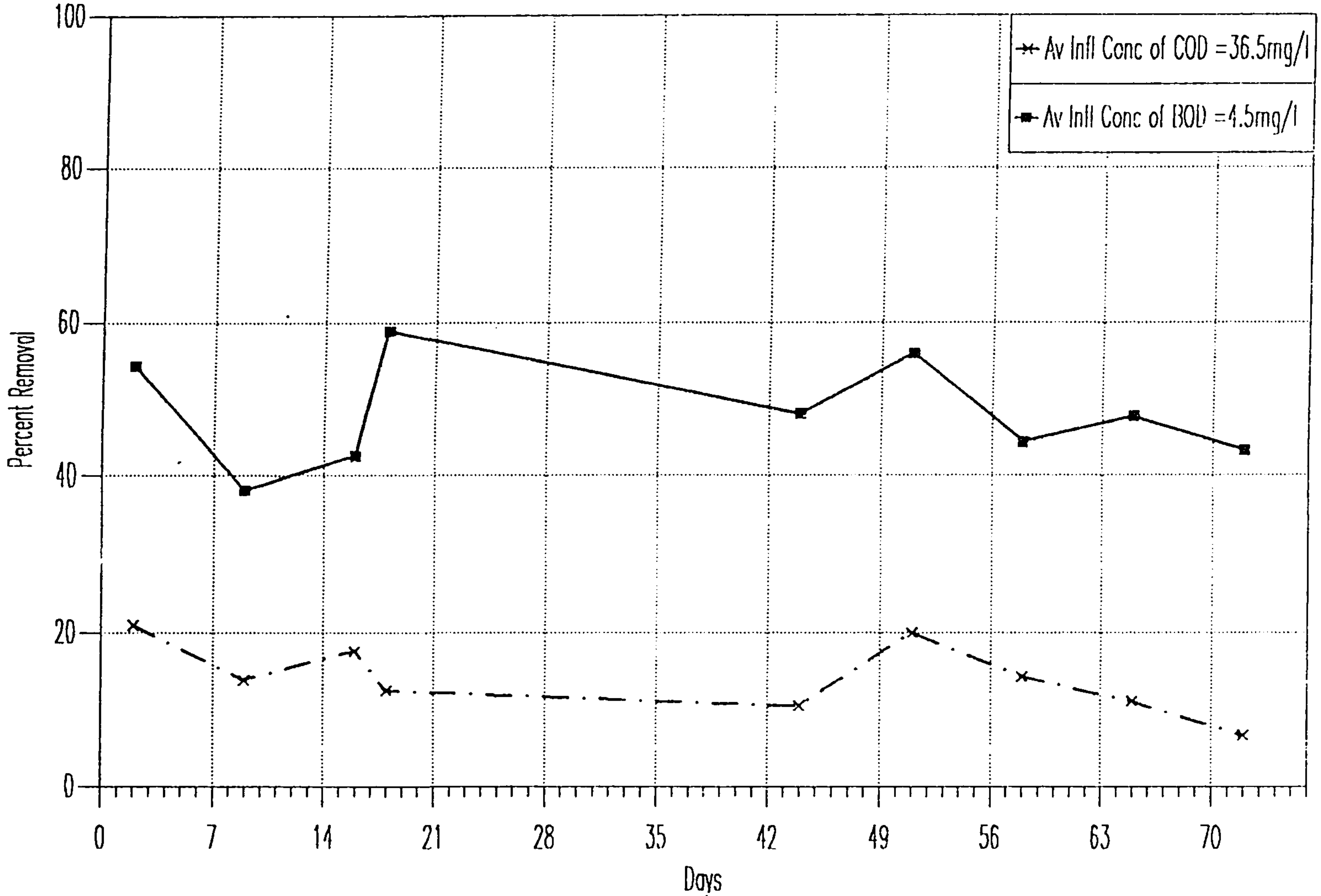


Figure 5.38: Removal Efficiencies of Organics in Condition 4

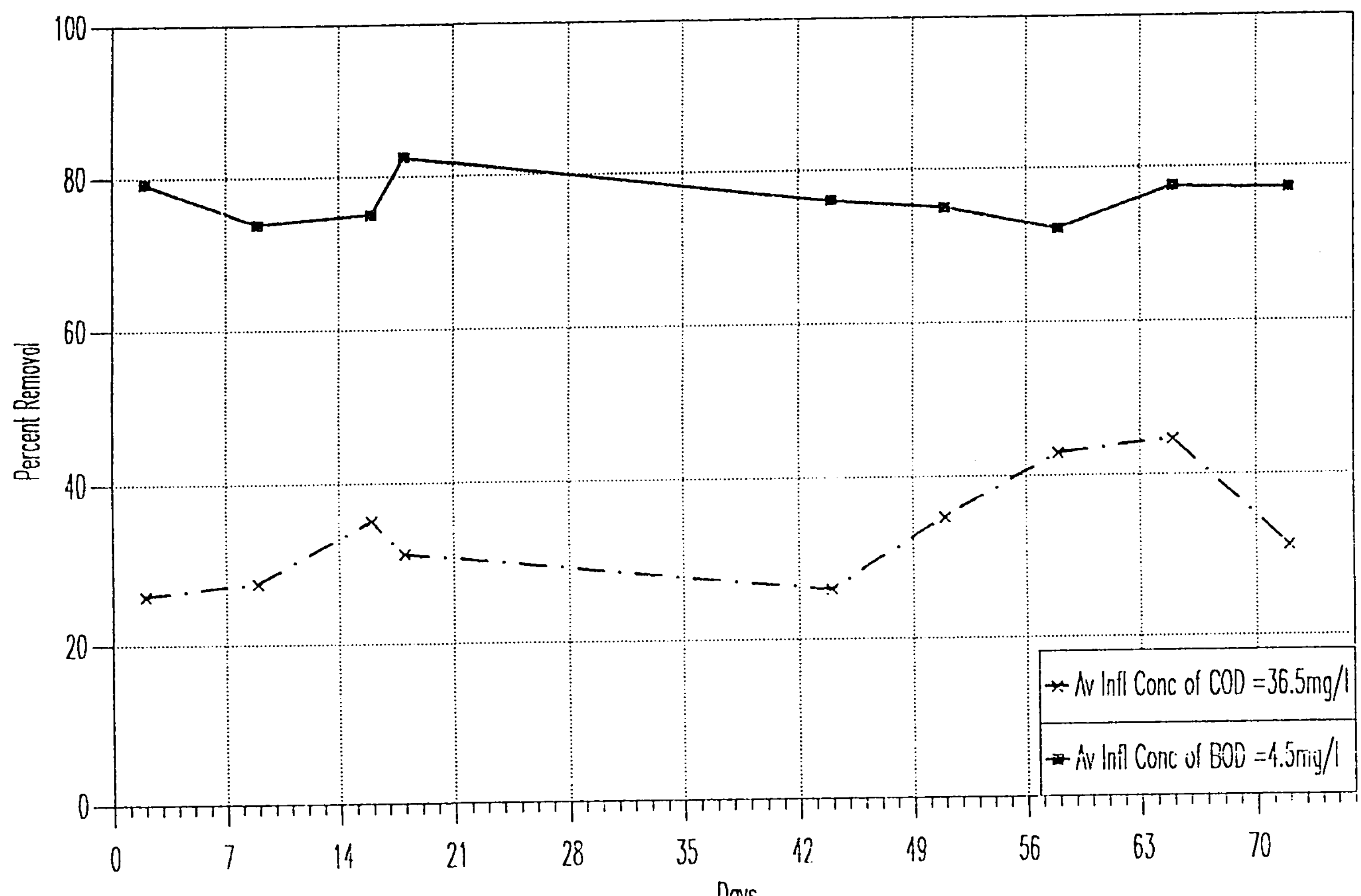


Figure 5.39: Removal Efficiencies of Organics in Condition 8

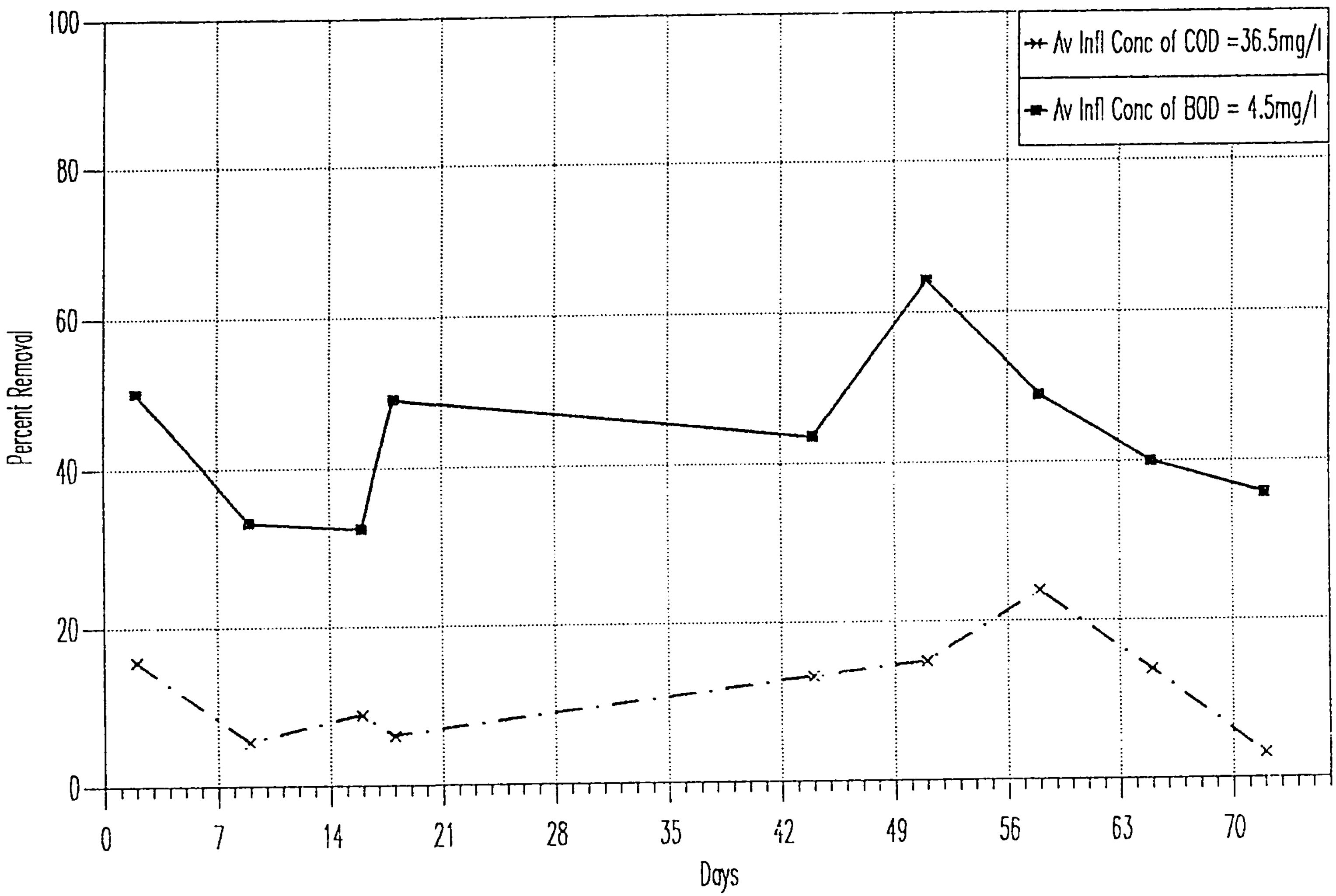


Figure 5.40: Removal Efficiencies of Organics in Condition 13

respectively. Similarly in C13 of F3 (Fig 5.40) the effluent concentrations of BOD and COD were between 2.2 and 2.8 mg/l, and 30 to 34 mg/l averaging around 2.6 mg/l and 32 mg/l, respectively. The maximum and minimum removal efficiencies of BOD and COD in C4 ranged from 58.8% to 38% and 21.1% to 6.7% averaging around 48% (2.18mg/l) and 14.2% (5.22mg/l) respectively. Similarly the maximum and minimum removal efficiencies of BOD and COD in C8 and C13 was found to be 82.4 to 72% and 44.4 to 26.3%, 64.2 to 32.5% and 15.8 to 3.12 respectively. The average removals were 76.47% (3.46mg/l) and 33.4% (12.22mg/l), 33.4% (2.0mg/l) and 11.7% (4.44mg/l) in C8 and C13 respectively. The variation in BOD and COD data is presented in Fig 5.39 and Fig 5.40. From the above it can be observed that, with the decrease in the sand depth the removal efficiencies have further dropped in C4 and C13 but this is not so in C8, the change was negligible. This could be attributed because, the filter may have sustained enough biomass to stabilize BOD at the shorter hydraulic retention time.

(d) Filter operation at sand size of 0.3 and 0.5mm at flowrate of 10 l/min and sand depth of 50 cms:

In F2 (C9) and F3 (C14) the percent variation of BOD and COD is presented in Fig 5.41 and 5.42 respectively. It can be observed from the Fig 5.41 that the BOD data showed no change for half of the filter run and latter dropped suddenly with a slight increase at the end of the filter run.

From Fig 5.42 it can be observed that both the BOD and COD data exhibited a discernable trend with the elimination of few outliers. It can be noticed that the removal rate increased with the decrease in flow rate. The same trend seemed to be absent in C9

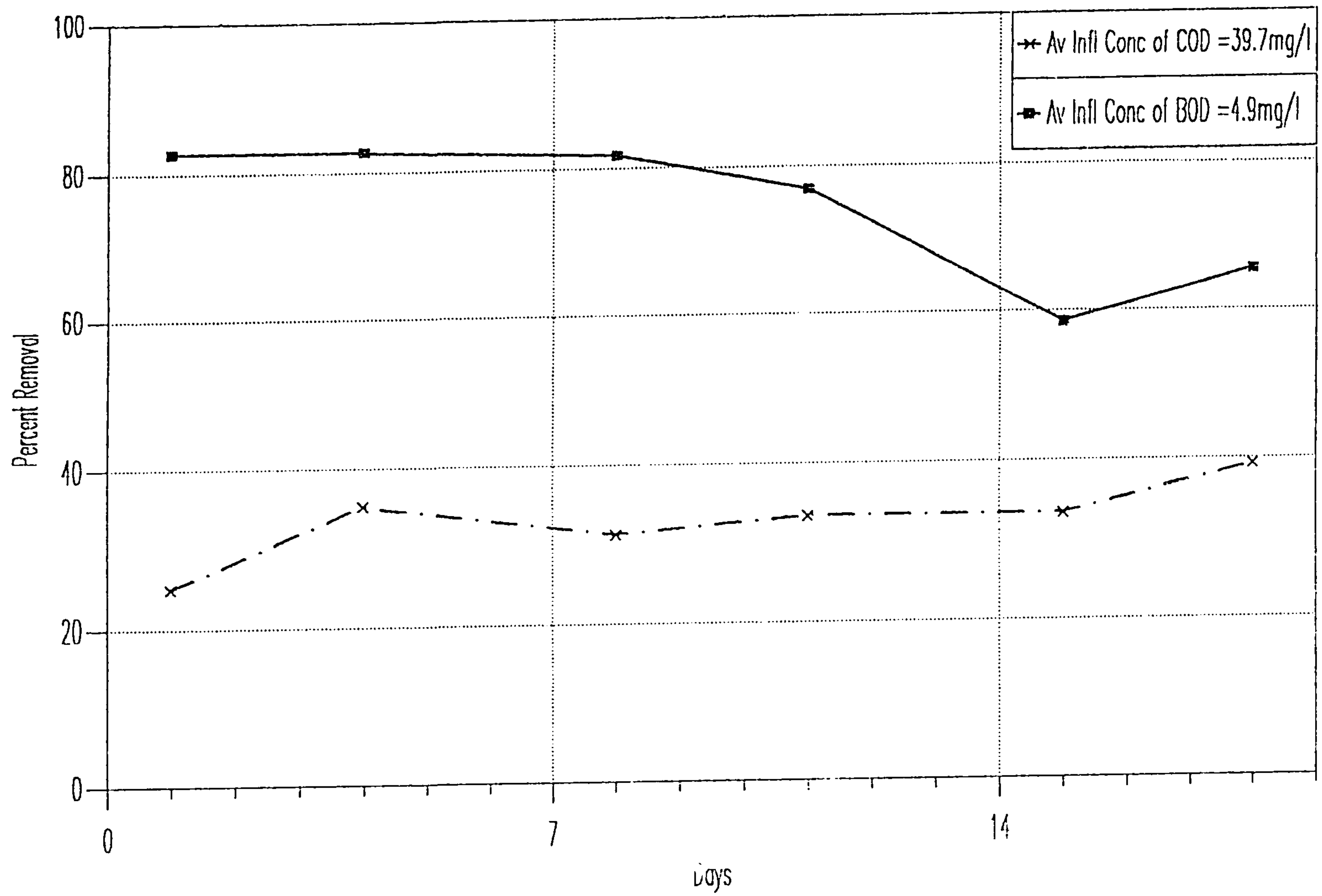


Figure 5.41: Removal Efficiencies of Organics in Condition 9

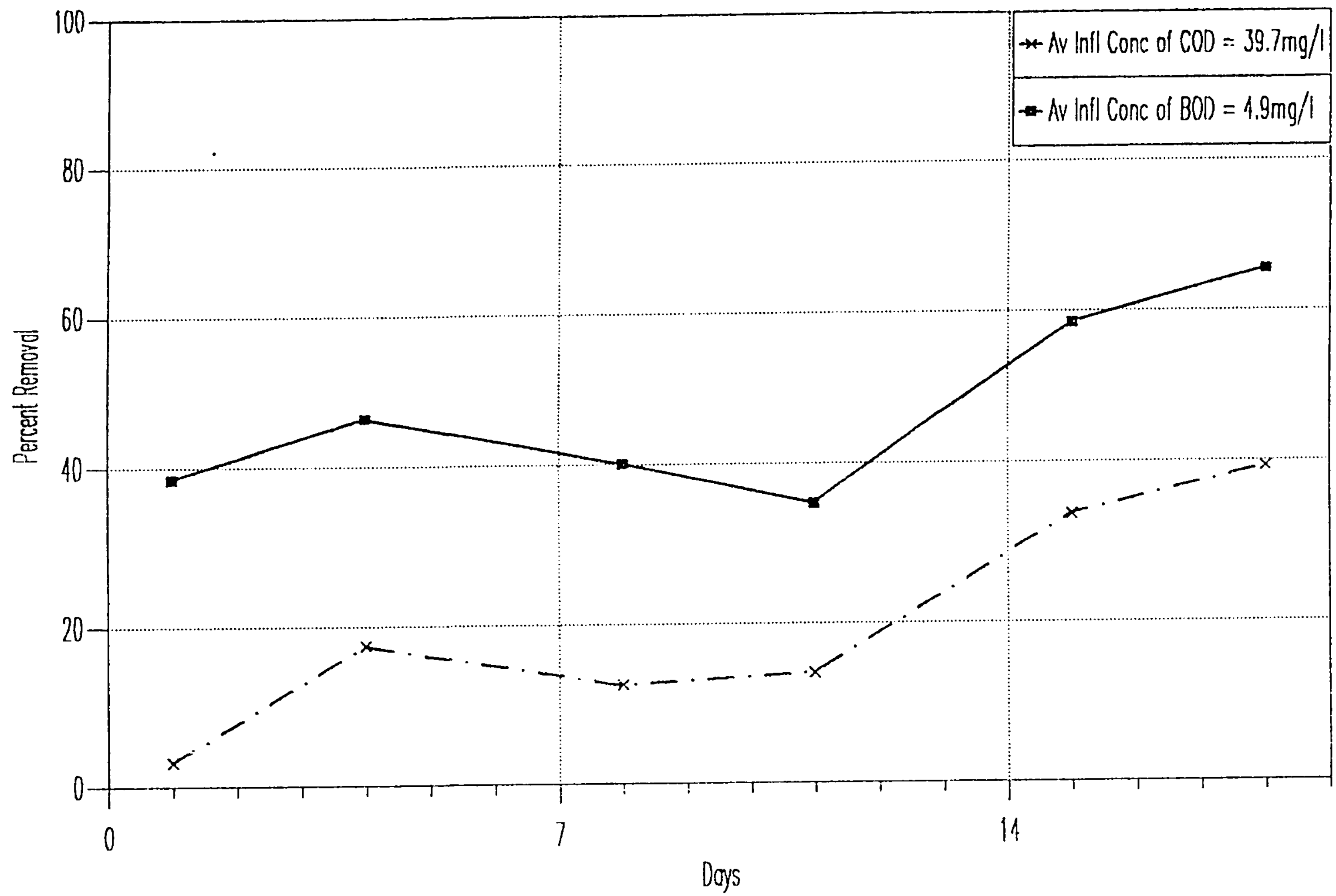


Figure 5.42: Removal Efficiencies of Organics in Condition 14

(Fig 5.41) which is rather unexpected. The influent concentration of BOD and COD ranged from 4.3 to 5.2mg/l and 32 to 56mg/l with an average of 4.85mg/l and 39.7mg/l in both C9 and C14. The effluent BOD and COD ranged from 0.9 to 2mg/l and 22 to 34mg/l with an average of 1.23 mg/l and 26.4mg/l in C9 and 1 to 3.2mg/l and 28 to 36mg/l averaging around 2.4mg/l and 31mg/l in C14 respectively. The maximum and minimum percent removal varied from 82.7% to 58.4% and 39.3% to 25% of BOD and COD in C9 (Fig 5.41) with the corresponding average being 74.7 and 33.0%. Similarly the maximum and minimum percent removals varied from 65.4% to 34.8% and 39.2 to 3.2% in case of C14 (Fig 5.41) with an average of 47.4% and 19.9% of BOD and COD respectively. Al-Youseef (2) has reported that the percent removal of BOD and COD in case of coarse sand with and effective size of 0.56mm, sand depth of 55cm and at hydraulic loading rate of 0.16m/hr was 82.6% and 38.6%. These are superior to the removal attained in C14 at hydraulic loading rate of 0.19m/hr with sand size of 0.5mm and sand depth of 50cms.

Therefore from the above it can be attributed that the removal efficiency of BOD and COD has increased with the decrease in the flow rate, since the hydraulic retention time is double during this condition of operation than that of the previous condition.

Thus summarizing the above discussion it is observed that the percent removal has dropped in all the three filters owing to the reduction in the sand depth. The filters seemed quite effective and performed better at low filtration rate, smaller grain size and higher sand depth.

5.1.5 Statistical Analysis Of Organics

a) Statistical Analysis Using 't' Test

Much of the research in engineering and science make use of statistical analysis. Statistical methods can greatly increase the efficiency of the experiment and strengthen the combinations of data sets for the purpose of interpretation. By statistical analysis we refer to the process of, planning various combinations in order to know whether observed difference in the data have any significant statistical differences or not.

Statistical analysis was performed on the data of BOD using "t test" at different combination of hydraulic loading and sand depth for coarse sand (F1 & F3) and fine sand (F2 & F3). The "t test" was chosen as a tool for comparing the means of each condition to find out whether observed differences were statistically significant. "F - test" was not used as it is used for comparing the variances and any how for a single factor anova $t^2 =$ F, so they are practically equal in our case. The "Z - test" is another test used for comparing the means and it was not used in our case as the population variance should be known for this or the number of samples should be greater than 30, so that the sample variance can be considered equivalent to the population variance. For large sample sizes the t test converges into a Z test. In our case the sample sizes were less than 30 hence t test was used.

The null and alternate hypothesis that was formulated for this purpose, states as follows.

$Ho = \mu 1 = \mu 2$ (Mean of 1 = Mean of 2)

$H1 = \mu 1 \neq \mu 2$ (Mean of 1 ≠ Mean of 2)

To test the above hypothesis studentized t- test was applied. The 't' test value is calculated using the following formula.

$$t_{calculated} = \frac{\overline{Y_1} - \overline{Y_2}}{\sqrt{\frac{S_1^2}{n_1} - \frac{S_2^2}{n_2}}}$$

S_1 = Standard deviation of 1

S_2 = Standard deviation of 2

$\mu 1$ = Mean of 1

$\mu 2$ = Mean of 2

S_1^2 = Variance of 1

S_2^2 = Variance of 2

n_1 & n_2 = Sample size

$$\gamma = \text{Degree of Freedom} = \frac{\left(\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2\right)}{\frac{\left(\frac{S_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{S_2^2}{n_2}\right)^2}{n_2 - 1}}$$

The mean , sample size and variance of F1, F2 and F3 for BOD are shown in the Table 5.1.

The t statistics value (t_{cal}) is compared with t_{table} value (Montegomry, 37) at degrees of freedom = γ and at a confidence interval of 95%.

Table 5.1: Statistical Comparison of Weekly BOD Removal EfficienciesThrough Different Filters @ 95% Confidence Interval

Effect of Flow Rate								Results of ' t test '				
Condition	Sand Size (mm)	Sample Size (n_1)	Mean (Y_1)	Variance S_1^2	Sample Size (n_2)	Mean (Y_2)	Variance S_2^2	t_{cal}	t_{table}	D.F	Null Hypothesis	Inference
C1 vs C2	0.5	14	71.61	101.96	5	65.4	61.68	1.402	2.262	9	Cannot Reject Ho	C1 =C2
C1 vs C10	0.5	14	71.61	101.96	16	62.2	122.2	2.436	2.04	30	Reject Ho	C1 ≠ C10
C1 vs C11	0.5	14	71.61	101.96	8	54.1	172.7	3.259	2.179	12	Reject Ho	C1 ≠ C11
C2 vs C11	0.5	5	65.42	61.68	8	54.1	172.7	1.944	1.796	11	Reject Ho	C2 ≠ C11
C2 vs C10	0.5	5	65.42	61.68	8	54.1	172.7	0.76	1.796	11	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	9	55.3	169.85	4	48.4	78.3	1.097	2.26	9	Cannot Reject Ho	C3 = C12
C4 vs C13	0.5	9	48	47.7	9	41.7	45.4	1.959	2.12	16	Cannot Reject Ho	C4 = C13
C10vs C11	0.5	16	62.2	122.2	8	54.1	172.7	1.5	2.179	12	Cannot Reject Ho	C10 = C11
C13vs C14	0.5	9	41.7	45.4	6	47.36	144.6	-1.05	2.365	7	Cannot Reject Ho	C13 = C14
C5 vs C6	0.3	17	79	37.6	3	83.4	1.5	-2.67	2.110	17	Reject Ho	C5 ≠ C6
C8 vs C9	0.3	9	76.46	9.28	6	74.61	107.1	0.426	2.447	6	Cannot Reject Ho	C8 = C9
Effect of Sand Depth												
C2 vs C14	0.5	5	65.42	61.68	9	47.36	144.64	3.514	2.179	12	Reject Ho	C2 ≠ C14
C2 vs C3	0.5	5	65.42	61.68	9	55.3	169.85	1.812	2.179	12	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	9	55.3	169.85	9	48	47.7	1.485	2.179	12	Cannot Reject Ho	C3 = C4
C3 vs C14.	0.5	9	55.3	169.85	6	47.36	144.6	1.211	1.796	11	Cannot Reject Ho	C3 = C14.
C11vs C13	0.5	8	54.1	172.7	9	41.7	45.4	2.403	2.228	10	Reject Ho	C11 ≠ C13
C11vs C12	0.5	8	54.1	172.7	4	48.4	78.3	0.888	2.262	9	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	4	48.4	78.3	9	41.7	45.4	1.35	2.571	5	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	3	83.4	1.5	9	76.7	100.2	1.943	2.306	8	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	3	83.4	1.5	9	76.46	9.28	5.602	2.262	9	Reject Ho	C6 ≠ C8
C7 vs C8	0.3	9	76.77	100.2	9	76.46	9.28	0.089	2.262	9	Cannot Reject Ho	C7 = C8
Effect of Sand Size												
C4 vs C9	0.5 vs 0.3	9	48	47.7	6	74.61	107.11	-5.53	2.306	8	Reject Ho	C4 ≠ C9
C5 vs C10	0.3 vs 0.5	17	79	37.6	16	62.2	122.2	5.353	2.069	23	Reject Ho	C5 ≠ C10
C6 vs C11	0.3 vs 0.5	3	83.4	1.5	8	54.1	172.7	6.234	2.365	7	Reject Ho	C6 ≠ C11
C7 vs C12	0.3 vs 0.5	9	76.77	100.2	4	48.4	78.3	5.127	2.365	7	Reject Ho	C7 ≠ C12
C8 vs C13	0.3 vs 0.5	9	76.46	9.28	9	41.7	45.4	14.1	1.796	11	Reject Ho	C8 ≠ C13

If t statistics (t_{cal}) value is greater than the t table value the null hypothesis Ho is rejected, which implies that there exists a significant statistical difference between the means else cannot be rejected as there is no significant statistical difference between the means. To assess the effect of flow, sand depth and sand size within the filter and combination with another, the t_{cal} and t_{table} value for BOD are illustrated in Tables 5.1 along with the remarks indicating whether to reject or not reject the hypothesis.

Table 5.1 shows the 't' test results for the BOD data with various filter combinations to assess the effect of flow rate, sand size and sand depth. It can be observed that for the effect of flow rate statistically significant difference were observed between F1 and F3 only at flow rates of 8l/min and 16l/min (C1 vs C10) , 8l/min and 20l/min (C1 vs C11), 10l/min and 20l/min (C1 vs C11) at 150cms of sand depth and at flow rates of 16l/min and 20l/min (C5 vs C6) at 150cms of sand depth within F2. As can be observed from the table no statistically significant differences were observed at other combinations of flow rates and sand depths in F1, F2 and F3 for reasons such as large variance and due to marginal difference between the t_{cal} and t_{table} values. In order to assess the effect of sand depth the filter operations were compared at different depths. It was observed that there existed significant statistical difference between sand depths of 150cms and 50cms within F2 (C6 vs C8) and F3 (C11 vs C13) respectively. No significant difference was observed at other combinations of sand depths in F1, F2 and F3 as presented in Table 5.1. Similarly the effect of sand size was assessed by comparing the conditions or F2 with those of F1 and F3. From the table it can be observed that statistically significant

differences were present in almost all the conditions of F1 and F3 with F2 operating at constant sand depth and flow rate.

A detailed summary table of statistical analysis for the effect of flow rate, sand depth and sand size on BOD efficiency and other parameters such as nitrification efficiency, denitrification efficiency and nitrogen removal efficiency showing the t test results of each comparisons with their actual averages is presented in section 5.2.4.

b) Statistical Model For The Effect Of Flows on BOD Efficiency between F1 and F3

In order to establish and assess the possibility of any relationship that exists at varying flow rates and its effects on removal efficiency of BOD in Filter 1 and Filter 3 consisting of same sand size and constant sand depth. A correlation between flow rate and removal efficiency was established using SAS for a sand depth of 150cms. A Linear Regression model was performed on the data, which gave a good fit. The effect of flow is shown in Fig 5.43 with the coefficient of determination (R^2) equals to 0.922 which accounts for the variability of the data with coefficient of correlation (R) = 0.96 indicating the strength of the model. The higher the value of R, greater is the dependence between the independent and dependent variables. It is worth mentioning that the points correspond to the experimentally obtained data, each point being the mean of the phase of operation (Conditions).

The linear model that was developed between F1 and F3 in order to assess the effect of flow rate on the removal efficiency of BOD is as follows.

BOD Efficiency = -1.27 x Flow + 80.47

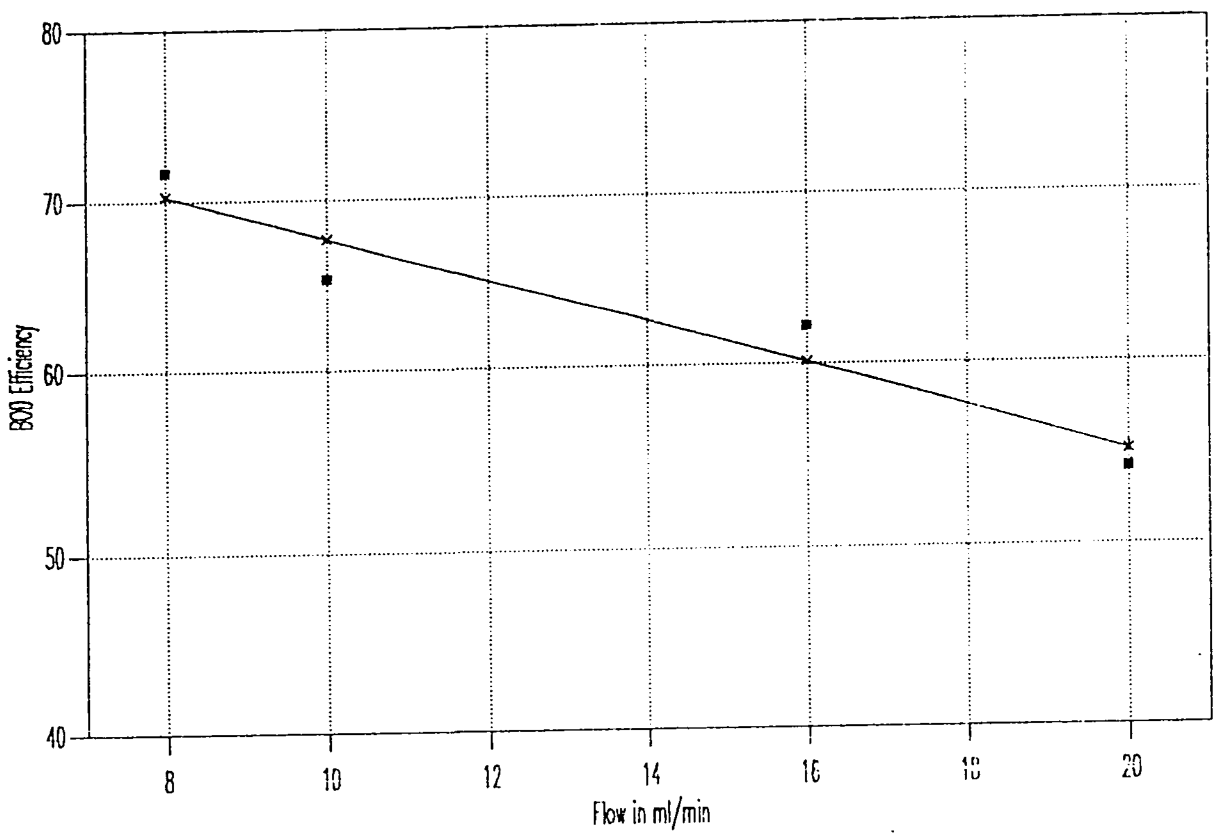


Figure 5.43: Effect of Flow at 150cms Depth on BOD Removal Efficiency between F1 & F3

It is worth mentioning that the correlation between flow rate and removal efficiency at other sand depths could not be performed as the filters were operated at only two flow rates at sand depths of 80cms and 50cms as compared to four at 150cms. Similarly this relationship could not be developed for fine sand operated at only two flow rates.

c) Statistical Model For The Effect Of Sand Size on BOD Efficiency between F2 and F3

To assess the effect of sand size on the removal rate of BOD in F2 and F3. A linear model similar to that of section 5.1.5 (b) was developed. The model gave a good fit to the obtained data with the coefficient of determination $R^2 = 0.906$ and the corresponding coefficient of correlation (R) was 0.95, thus implying that sand size also has strong impact on the BOD removal rate. Figure 5.44 shows the fit obtained by the model. The model that was established was as follows.

BOD Efficiency = -114.5 x Sand Size + 115.4

d) Statistical Model For The Effect Of Sand Depth on BOD Efficiency between F2 & F3

To assess the effect of sand depth on the removal rate of BOD in F1 and F3. A linear model similar to that of section 5.1.5 (b) was developed. The model gave a good fit to the obtained data with the coefficient of determination $R^2 = 0.63$ and the corresponding coefficient of correlation (R) was 0.80, thus implying that sand depth has strong impact on the BOD removal rate. Figure 5.45 shows the fit obtained by the model. The model that was established was as follows.

BOD Efficiency = -0.129 x Sand Depth + 67.66

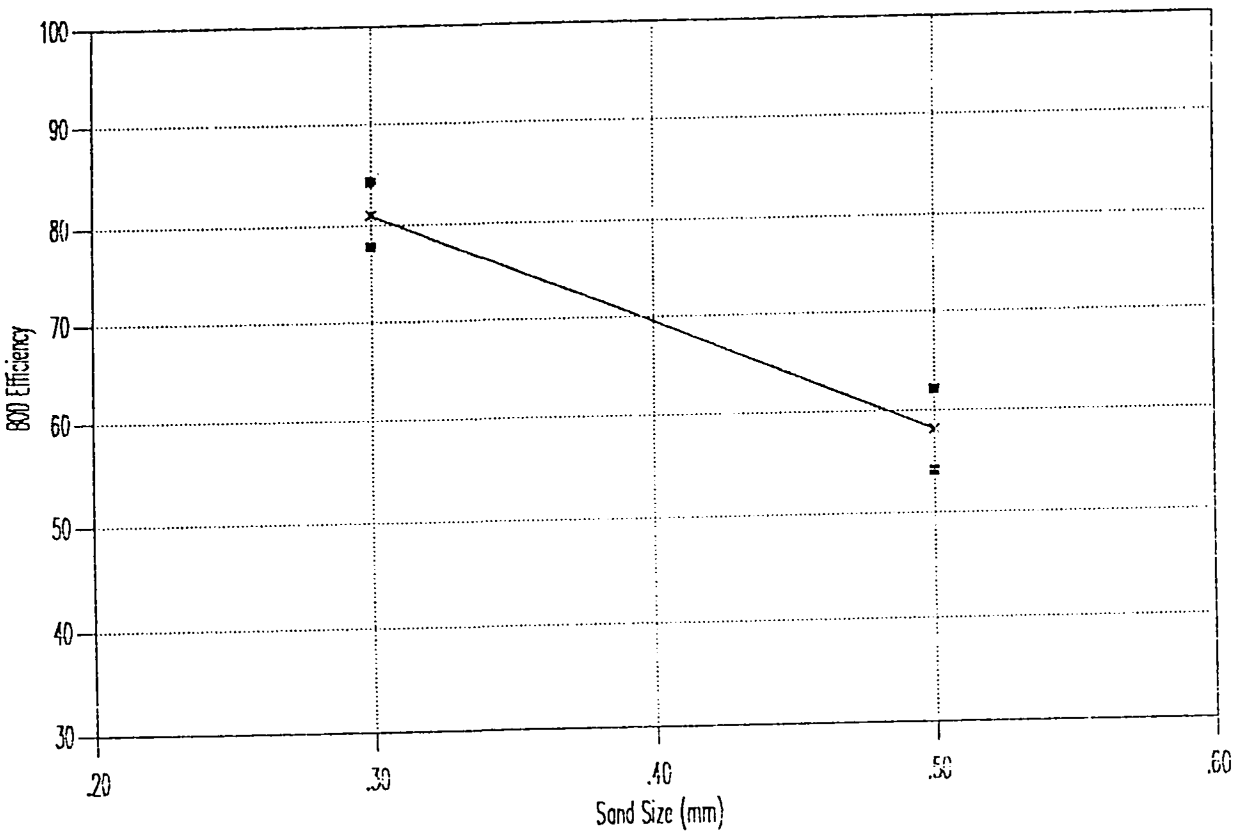


Figure 5.44: Effect of Sand Size at 150cms Depth on BOD Removal Efficiency between F2 & F3

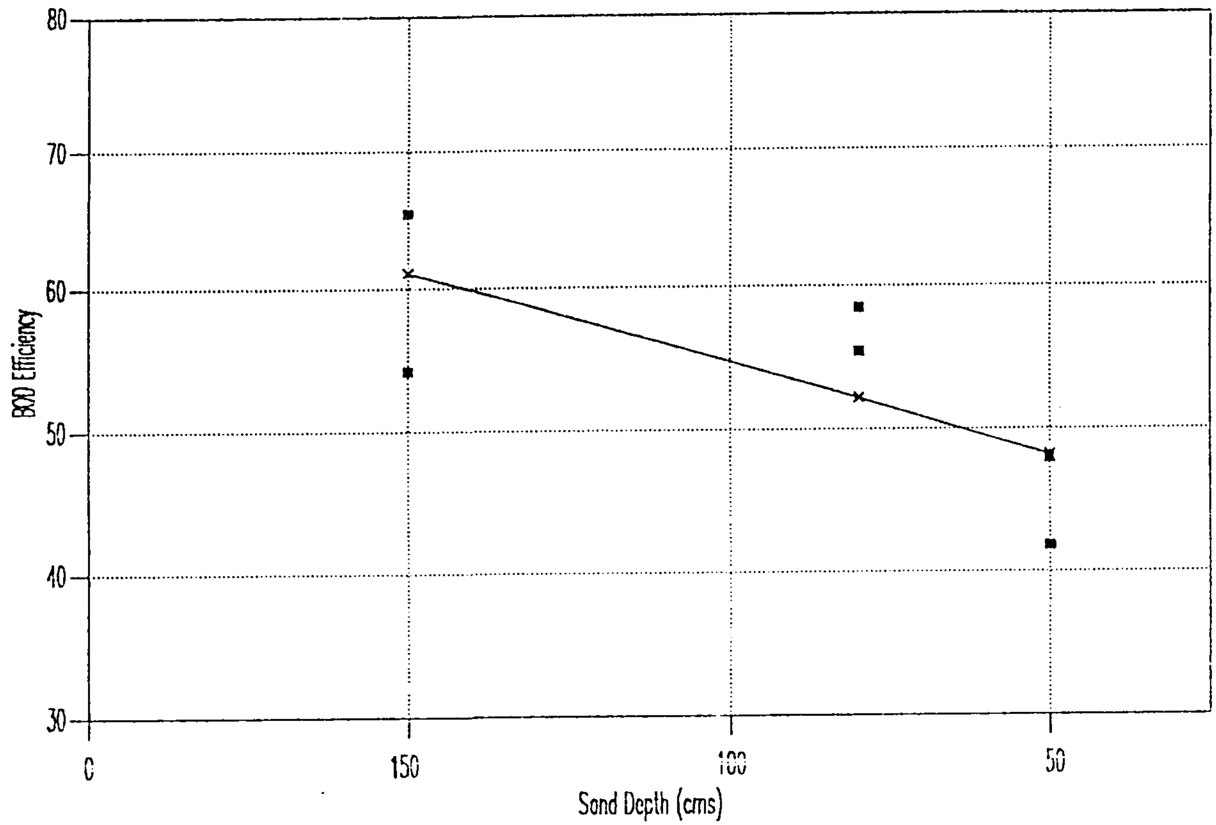


Figure 5.45: Effect of Sand Depth on BOD Efficiency between F1 & F3

Comparing the effect of flow, sand size and sand depth on the removal rate it can be seen that the coefficient of determination in case of flow (F1& F3), sand size (F2 & F3) is greater than that of sand depth (F1 & F3). Thus it can be concluded that flow rate and sand size has a greater impact on the removal efficiency than sand depth does.

5.2 NUTRIENT REMOVAL

5.2.1 Results of Nitrogen Balance:

In order to get an overall view, a nitrogen balance was performed to know the nitrification efficiency in the respective filters. Nitrification efficiency is the removal expressed as a percentage of the initial concentration of Total Kjeldahl Nitrogen, which is written as follows:

$$\text{Nitrification Efficiency} = \frac{(TKN)_{in} - (TKN)_{out}}{(TKN)_{in}}$$

Nitrified nitrogen is computed as the difference between the total influent TKN and the total effluent TKN. Denitrification refers to the difference between mass of nitrified nitrogen and effluent total nitrates as a percentage of the sum of nitrified load and influent nitrites and nitrates given by the following equation

$$\text{Denitrification Efficiency} = \frac{(TKN + NO_3 + NO_2)_{in} - (TKN + NO_3 + NO_2)_{out}}{(TKN + NO_3 + NO_2)_{in} - (TKN)_{out}}$$

Nitrogen Removal is computed as the difference between the influent and effluent total concentrations of nitrogen.

$$\text{Nitrogen Removal Efficiency} = \frac{(TKN + NO_3 + NO_2)_{in} - (TKN + NO_3 + NO_2)_{out}}{(TKN + NO_3 + NO_2)_{in}}$$

The removal efficiencies of nitrification (NE) and denitrification (DE) nitrogen removal (NRE) and nitrate and nitrite reduction (NNRE) during the respective operating conditions of F1, F2 and F3 are illustrated in Fig 5.46 - 5.59.

During condition 1 NE, DE NRE and NNRE calculated over the period of operation are illustrated in Fig 5.46. It can be observed from the figure that the data exhibits substantial scatter with no consistent trend between the parameters. This is attributed to the operation problems during the filter run. The removal efficiencies ranged from 0 to 100%, 23 to 91% & 3 to 53.8% respectively. The corresponding averages were found to be 78.2%, 82.06%, & 25.48% and the average initial concentrations were 3.91mg/l, 4.83mg/l, 0.92mg/l.

The percent variation of NE, DE, NRE and NNRE during C2 is shown in Fig 5.47. From the figure it can be observed that denitrification efficiency is more predominant and is found to vary between 83.62 to 68.1%. NE, DE, NRE and NNRE were found to vary between 41.7 to 80%, 40 to 66.8% and 0 to 39% respectively. It is observed from the figure that NE, DE and NRE efficiencies are found to exhibit a discernable trend with substantially less scatter than nitrate and nitrite removal. The average percent removal of NE, DE NRE and NNRE are calculated to be 65.9%, 77.9%, 55.1% and 20.3% corresponding to an average initial concentration of 3.4mg/l, 4.23mg/l and 0.83mg/l.

The percent variations of NE, DE, NRE and NNRE in C3 are shown in Fig 5.48. The NE, DE, NRE and NNRE exhibited substantial scatter, while the DE showed a

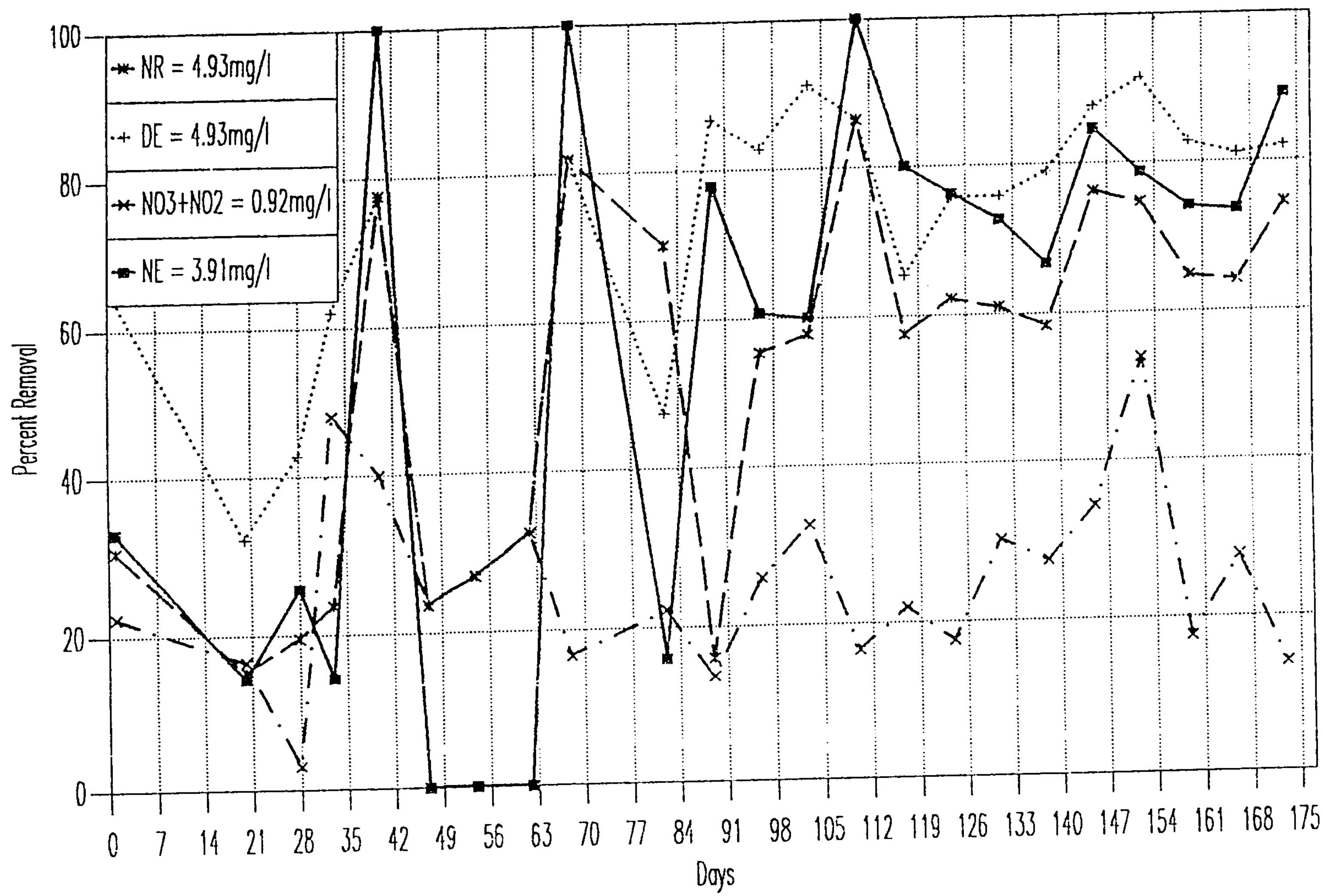


Figure 5.46: Removal Efficiencies of Various Forms of Nitrogen in Condition 1

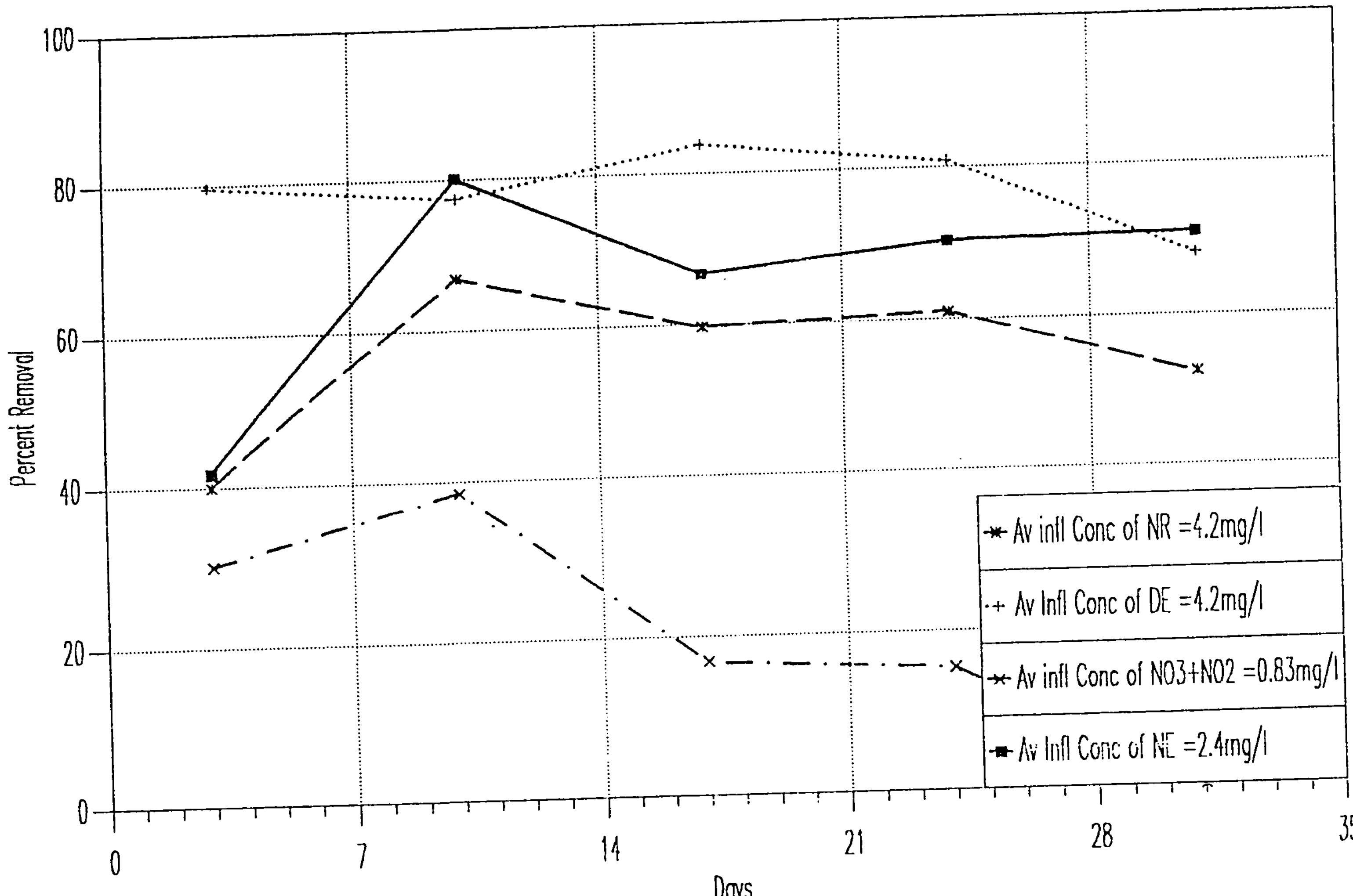


Figure 5.47: Removal Efficiencies of Various Froms of Nitrogen in Condition 2

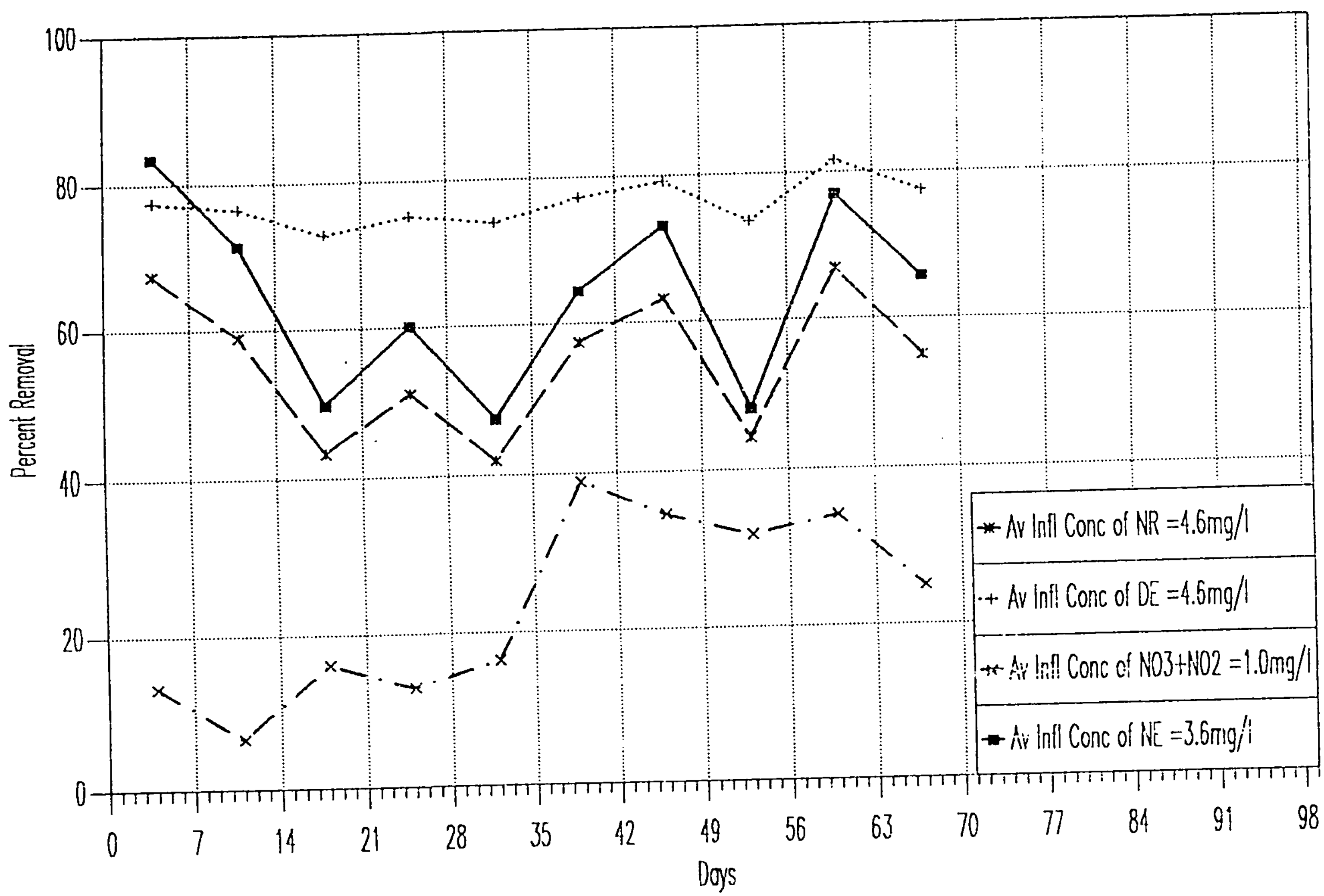


Figure 5.48 : Removal Efficiencies of Various Forms of Nitrogen in Condition 3

consistent trend with the efficiency ranging from 72.9% to 81.5%. NE, NRE and NNRE, varied between 47.2% to 83.4%, 41.8% to 67.5% and 66% to 39% respectively. The average removal efficiency of nitrification, denitrification, nitrogen removal and nitrate and nitrite efficiencies are found to be 63.8%, 76.4%, 54.9% and 23.4% corresponding to an average initial concentration of 3.6mg/l, 4.6mg/l and 1mg/l respectively. With the elimination of few odd points it can be seen from Fig 5.48 that the nitrification efficiency followed denitrification efficiency. Furthermore NRE is dependent on NE and DE as it varied in accordance with the variation in NE and DE.

Fig 5.49 illustrates the percent variation of NE, DE, NRE and NNRE in C4 ranging between 50 to 70% , 62 to 80.9%, 45.5 to 59.2% and 39 to 37.8%. The corresponding averages were found to be 61.4%, 73.7%, 52.01% and 22.5% for average initial concentrations of 3.3 mg/l, 4.3 mg/l and 1.01 mg/l respectively. The nitrate and nitrite exhibits substantial scatter while the NE, DE and NRE are quite stable during the period of operation as can be seen from Figure.

Comparing C1 with C2 both having the same sand depth but different filtration rate, it was found that the rate of nitrification, denitrification, nitrogen removal and nitrate and nitrite was higher in C1 compared to C2 indicating that the flow rate has an impact on the removal rate as the greater the flow rate the lower is the detention time and vice versa.

In order to assess the effect of sand depth on removal rate, C2 was compared with C3. It was found that the removal rate of nitrification, denitrification, nitrogen removal and NO_3+NO_2 at 150 cms of sand depth were higher than that in C3 (80 cms of sand

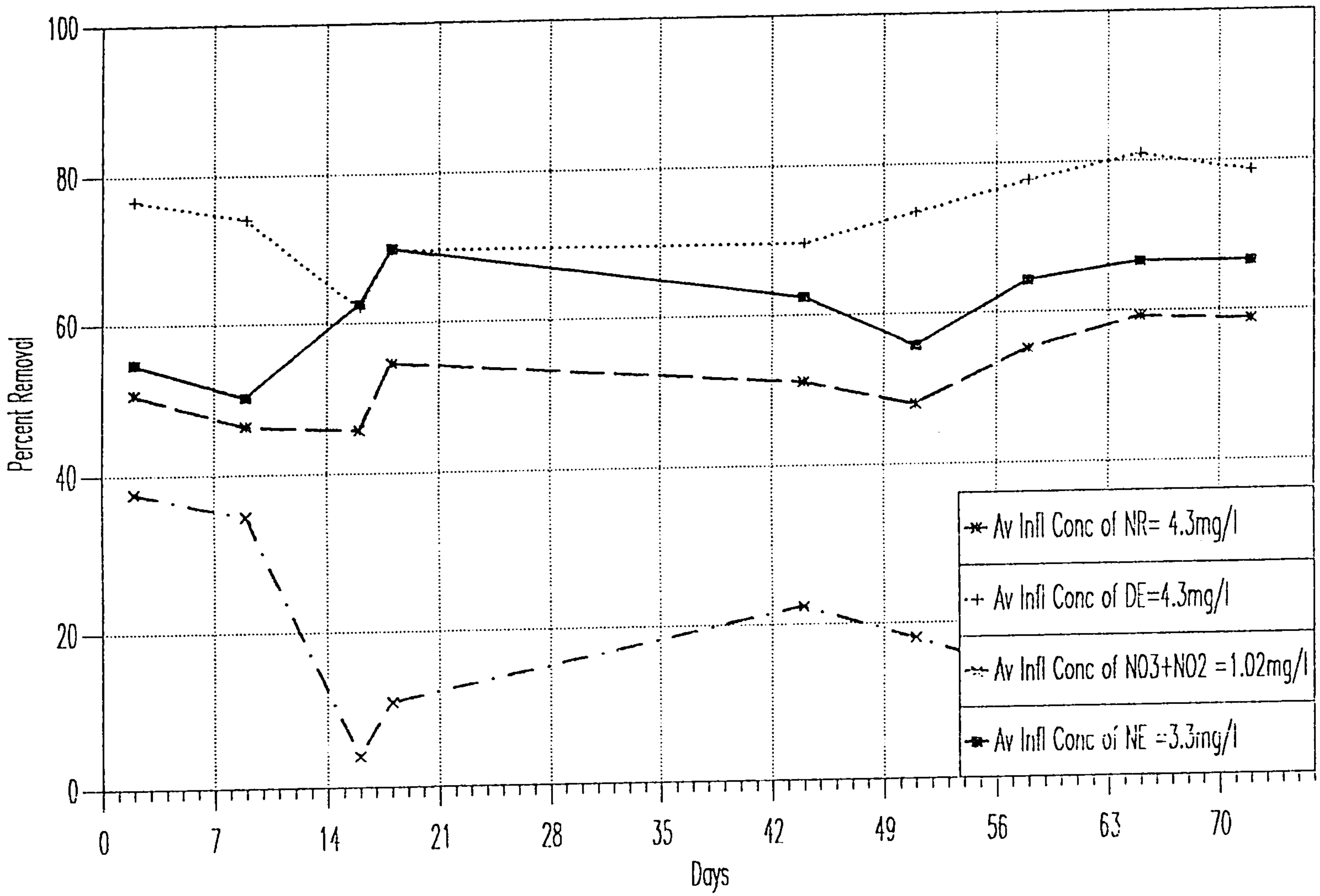


Figure 5.49: Removal Efficiencies of Various Forms of Nitrogen in Condition 4

depth) indicating that sand depth, as flow rate, has an impact on the removal rate, higher the sand depth higher is the removal rate and vice-versa.

Similarly C3 and C4 were compared in order to assess the effect of depth. It was observed that the removal rate at 80 cms of sand depth was found to be higher than that at 50cms, thus it can be inferred that both the flow rate and sand depth have a strong influence on nitrification, denitrification, nitrogen removal and nitrate and nitrite efficiencies.

The percent variation of NE, DE, NRE and NNRE in C5 is illustrated in Fig 5.50. Under this operational condition the filter ran for a period of 191 days with 32 days of suspension for the purpose of cleaning and due to some operational problems. As can be seen from the figure the data of NE, DE, NRE and NNRE exhibited a substantial scatter during the filter operation. The scattering of the removal efficiencies can be attributed to some of the operational problems. The NE, DE, NRE and NNRE ranged from 0 to 100 %, 22.4 to 94.6%, 16.4 to 89.1 % and 0 to 69.9 % averaging around 65.4 %, 73.4 %, 60.2 % and 30.75 respectively. The corresponding average initial concentration are 3.2 mg/l, 4.09 mg/l and 0.89 mg/l respectively. From the graph it can be observed that NRE is dependent more on nitrification efficiency than on denitrification efficiency,

The variation of NE, DE, NRE and NNRE in C6 over a period of 21 days is presented in Fig 5.51. The removal rates were quite uniform except for NO_3+NO_2 . The NE, DE, NRE and NNRE ranged from 69.2% to 78.2%, 75.85% to 85.4% 60.4 to 67 % and 0.85% to 18.4% averaging around 74.2%, 80.8%, 63.4% and 12.3% respectively. The corresponding influent concentration were found to be 3.6 mg/l, 4.4 mg/l and 0.8 mg/l.

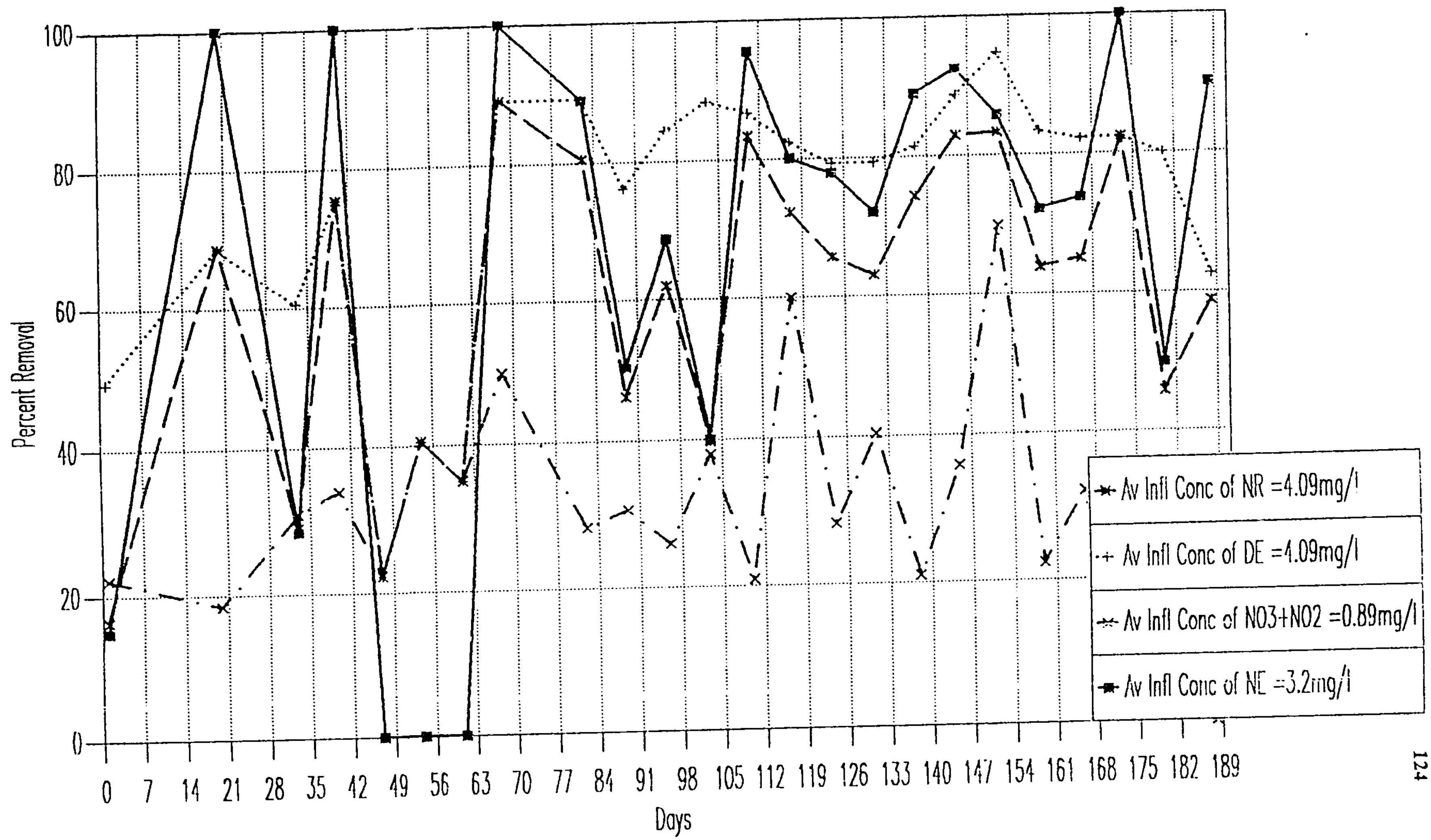


Figure 5.50: Removal Efficiencies of Various Forms of Nitrogen in Condition 5

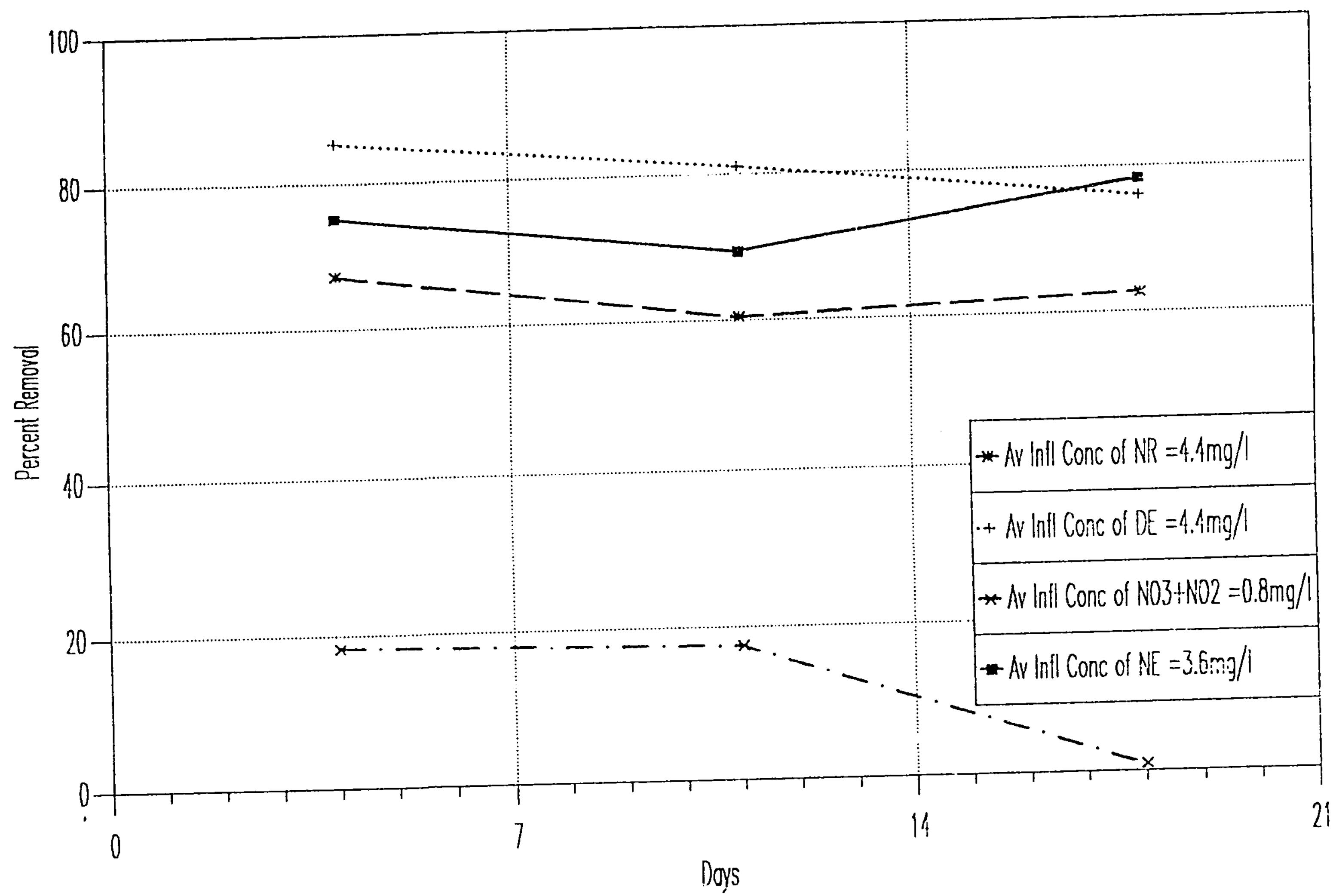


Figure 5.51: Removal Efficiencies of Various Forms of Nitrogen in Condition 6

From Fig 5.51 it is depicted that the rate of denitrifiction is greater than the rate of nitrification and that the nitrogen removal efficiency corresponds to nitrification efficiency.

The percent variation of NE, DE, NRE and NNRE in C7 is shown in Fig 5.52. From the figure it can be observed that nitrification, denitrification, nitrogen removal and nitrate and nitrite efficiencies exhibited substantial scatter with the absence of a discernable profile during the period of operation. The removal rate of nitrification, denitrification, nitrogen removal and NO_3+NO_2 efficiencies ranged from 53.4 to 84.6%, 62.3 to 82.5%, 37 to 69.5% and 0 to 35.9 % averaging around 70.2%, 73%, 56% and 17.6% respectively. The corresponding average initial concentrations were found to be 3.6 mg/l, 4.6 mg/l and 1.0 mg/l.

In order to assess the removal efficiencies at reduced sand depth, the sand depth was reduced to 50 cms in C8. Under this operating conditions the filter was operated for 79 days with 3 days of suspension. The percent variation of NE, DE, NRE and NNRE is shown in Fig 5.53. The NE, DE, NRE and NNRE ranged from 50 to 71.4 %, 57 to 81.3 %, 36.8 to 62.3 % and 4.4 to 27.5 % averaging around 58.03 %, 70.8 %, 48.5 % and 18.4 % respectively. Their corresponding averages initial concentrations were found to be 3.3 mg/l, 4.32 mg/l and 1.02 mg/l. It can be observed from the graph that rate of denitrification is substantially higher than the rate of nitrification. It is also observed that the rate of nitrogen removal is dependent more on the rate of nitrification than the rate of denitrification.

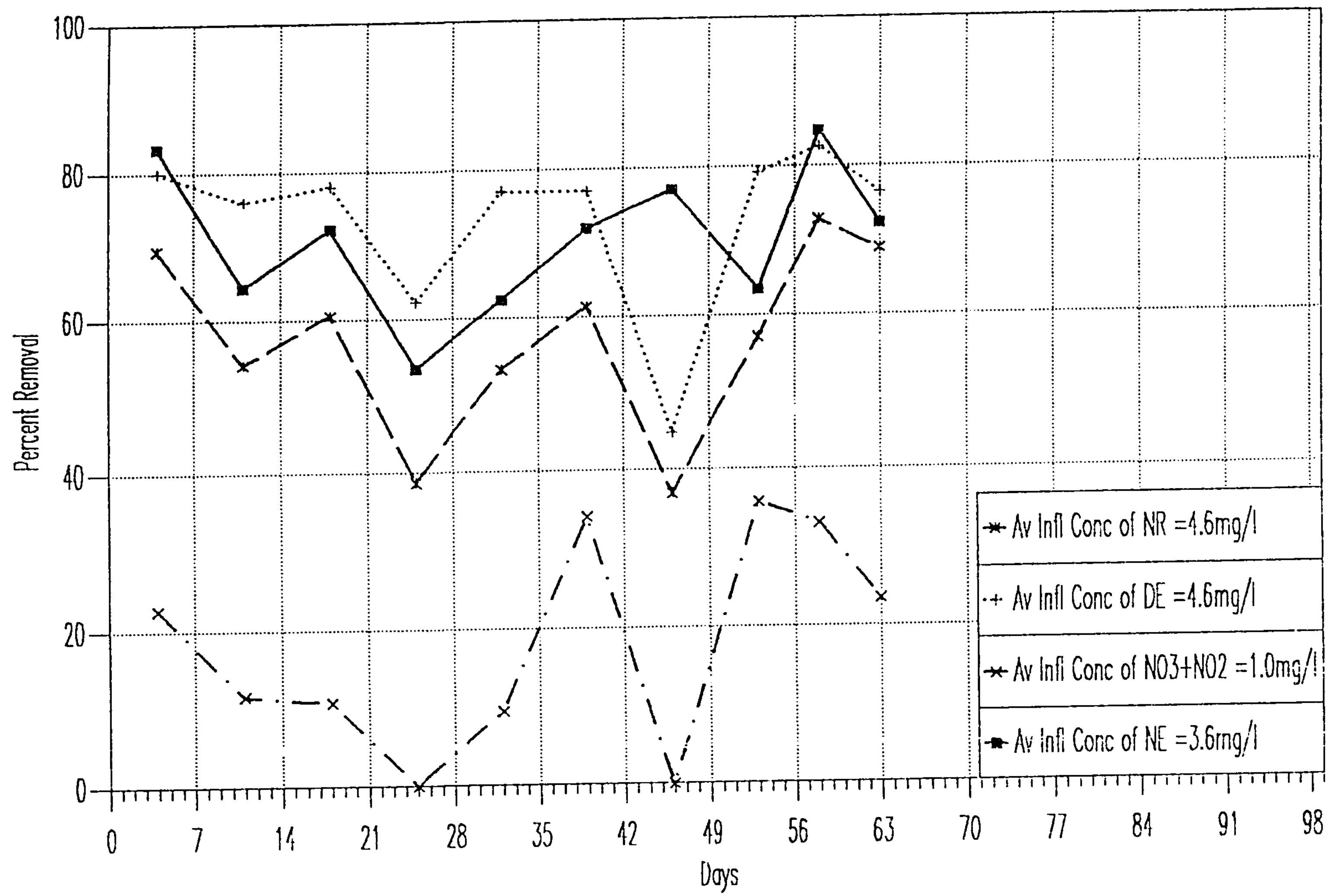


Figure 5.52: Removal Efficiencies of Various Forms of Nitrogen in Condition 7

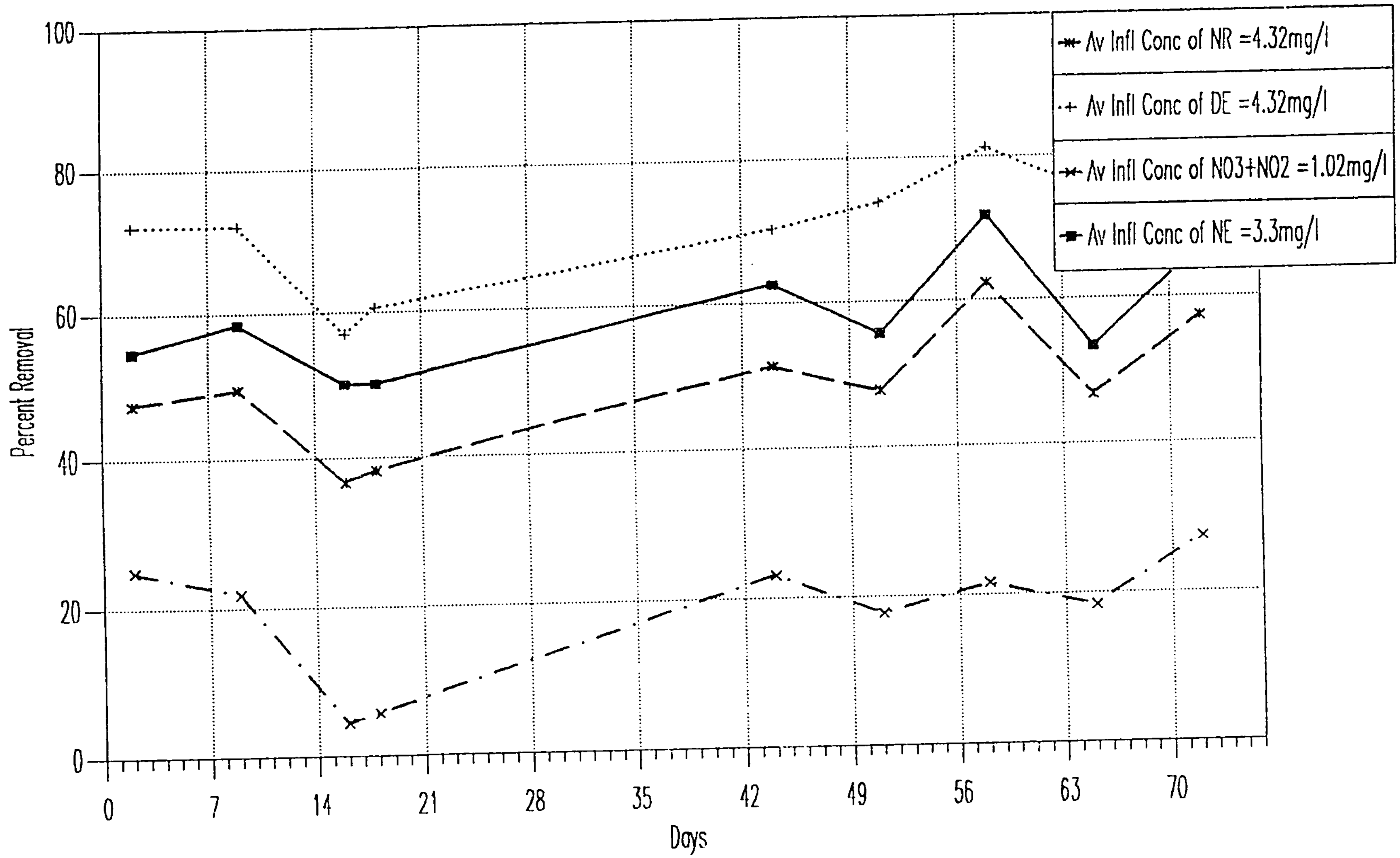


Figure 5.53: Removal Efficiencies of Various Froms of Nitrogen in Condition 8

The percent variation of NE, DE, NRE and NNRE in C9 is illustrated in Fig 5.54. The removal rate of NE, DE, NRE and NNRE ranged from 59.8 to 72.7 %, 67.6 to 80.9 %, 50.4 to 58.5 % and 10.7 to 37.7 % respectively. The average removal rate of nitrification, denitrification, nitrogen removal and NO_3+NO_2 were found to be 64.7 %, 74.0 %, 54.8 % and 26.2 % corresponding to the average initial concentration of 3.2 mg/l, 4.29 mg/l, and 1.1 mg/l respectively.

Comparing C5 and C6 having same sand depth but different flow rate it is observed that the removal rate was unexpectedly high during condition 6 having higher flow rate. This could be attributed to the operational problems during the initial operation of the filters. In order to assess the effect of sand depth, conditions 6 and 7 corresponding to different sand depths were compared. It was found that higher the sand depth the higher was the removal. Thus indicating that the depth of sand has an influence on the removal rate which was also true in case of F1. Similarly when C7 and C8 were compared it was observed that the removal rate was higher in C7 than C8 confirming that sand depth has a strong impact on the removal rate. C8 and C9 were compared to assess the effect of flow rate on the removal rate. It was observed that the removal rates were higher at lower flow rate (C9) than at higher flow rate, thus indicating that both flow rate and sand depth have an impact on the removal rate.

In order to assess the effect of sand size C4 of filter 1 was compared with C9 of filter 2 both having constant flow rate and sand depth with different size of sand. It was observed that C9 of F2 consisting of fine sand showed greater removal than C4 of filter 1

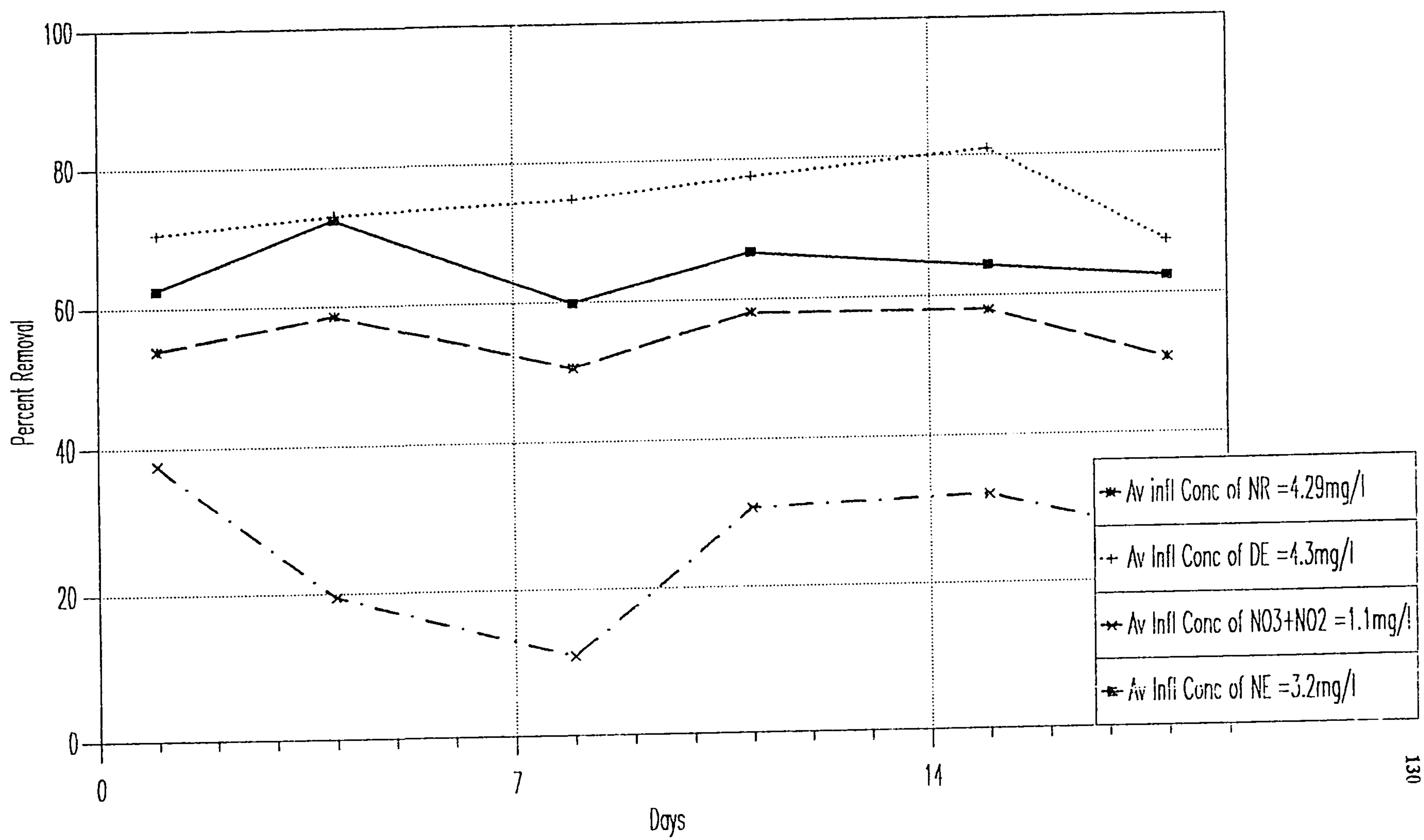


Figure 5.54: Removal Efficiencies of Various Forms of Nitrogen in Condition 9

with coarse sand. This is also confirmed and supported by the results of the 't' test in the following section.

The percent variation of NE, DE, NRE and NNRE in C10 are illustrated in Fig 5.55. During the course of operation the filter was operated for a period of 191 days with 55 days of suspension for the purpose of cleaning the filter bed, and also to overcome some of the operational problems. As can be seen from the figure the data for nitrification, denitrification, nitrogen removal and NO_3+NO_2 exhibited a substantial scatter during the filter operation. It is interesting to note that inconsistent trends with no discernable profile was observed in F1 and F2 during condition 1 and 5. The NE, DE, NRE and NNRE ranged from 0 to 100 %, 1.0 to 91.4 %, 9.3 to 69.4 % and 1.0 to 58.2 % averaging around 54.2 %, 65.5 %, 48.3 % and 25.5 % respectively. The corresponding average initial concentration were 2.98 mg/l, 3.92 mg/l, 3.92 mg/l and 0.95 mg/l. From the graph it can be depicted that the efficiency of nitrogen removal is more dependent on nitrification than denitrification, as observed in case of F1.

The percent variation of NE, DE, NRE and NNRE in C11 are shown in Fig 5.56. With these operating conditions the filter was operated for a period of 60 days. The variation of NE, DE, and NRE exhibited less scatter than NNRE. As can be seen from Fig 5.56 the nitrogen removal efficiency depended largely on nitrification rather than denitrification. The NE, DE, NRE and NNRE ranged between 46.2 to 66.9 %, 67.1 to 78.52 %, 38.2 to 57 % and 0.1 to 13.6 % respectively. The average removals were calculated to be 54.9 %, 72.7%, 45.9 % and 7.9 % corresponding to an average influent concentration of 3.8 mg/l, 4.7 mg/l and 0.87 mg/l.

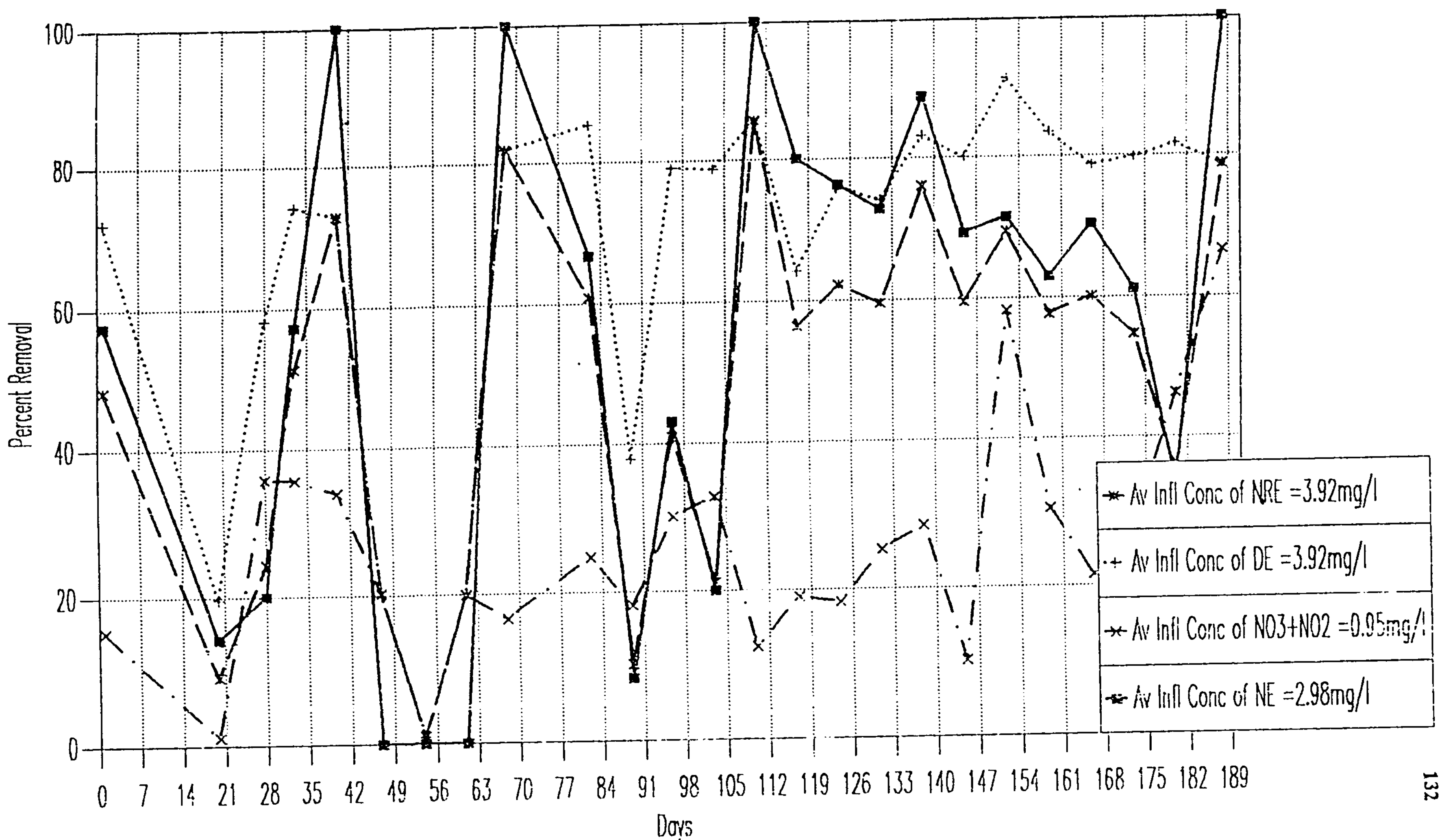


Figure 5.55: Removal Efficiencies of Various Forms of Nitrogen in Condition 10

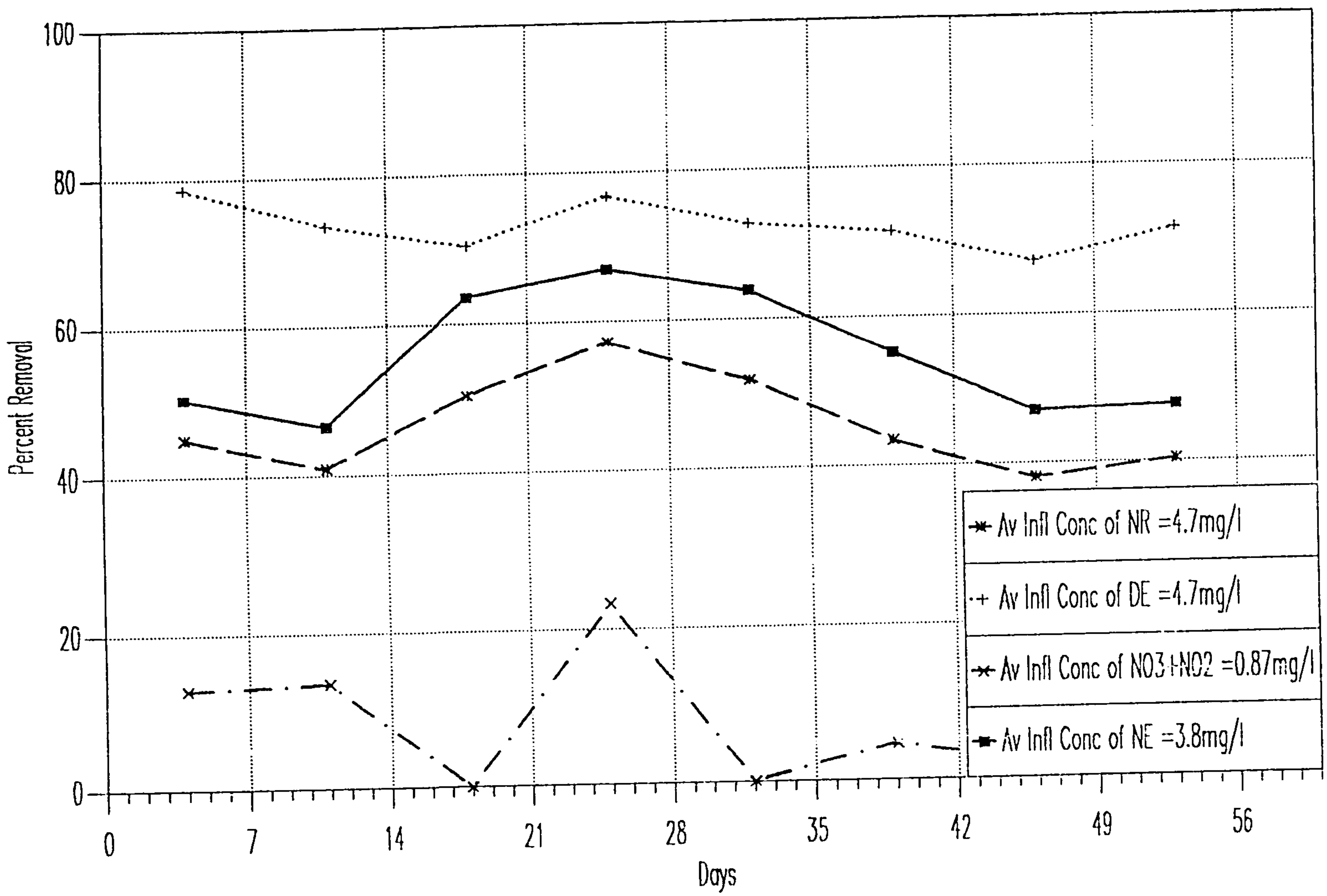


Figure 5.56: Removal Efficiencies of Various Forms of Nitrogen in Condition 11

The filter was operated for a period of 60 days in C12 as can be seen from the Fig 5.57. During the process of operation heavy rain was experienced and though the filter was in operation samples could not be collected due to inaccessibility to the treatment plant. The percent variation of NE, DE, NRE and NNRE is illustrated in Fig 5.57. From the fig it is observed that the rate of denitrification is more than the rate of nitrification and also it can be observed that the rate of nitrogen removal is dependent almost equally on nitrification and denitrification. The nitrification, denitrification, nitrogen removal and NO_3+NO_2 efficiencies varied between 41.7 to 73.6 %, 61.9 to 79 %, 34.2 to 62.9 % and 9.4 to 33.8 % averaging around 59.4 %, 72.6 %, 51.0 % and 27.2 % respectively. The corresponding average initial concentrations were found to be 3.2 mg/l, 4.25 mg/l and 1.05 mg/l.

The percent variation of NE, DE, NRE and NNRE in C13 is shown in Fig 5.58. The efficiency of nitrification, denitrification, nitrogen removal and NO_3+NO_2 ranged from 12.5 to 58.4 %, 23.9 to 74.3 %, 13.6 to 49 % and 2.6 to 22.2 % averaging around 42.4 %, 58.1 %, 34.7 % and 10.5 % respectively. Their corresponding average initial concentrations were found to be 3.09 mg/l, 4.1 mg/l and 1.02 mg/l. It can be observed from the figure that rate of denitrification is substantially higher than the rate of nitrification. It is also observed that the rate of nitrogen removal is dependent more on the rate of nitrification than the rate of denitrification.

The percent variation of NE, DE, NRE and NNRE in C14 is shown in Fig 5.59. The removal rates ranged from 50 to 64.3 %, 69.4 to 77.5 %, 43.2 to 55.4 % and 0.6 to 43.4 % respectively. The average removal rate of NE, DE, NRE and NNRE were found to

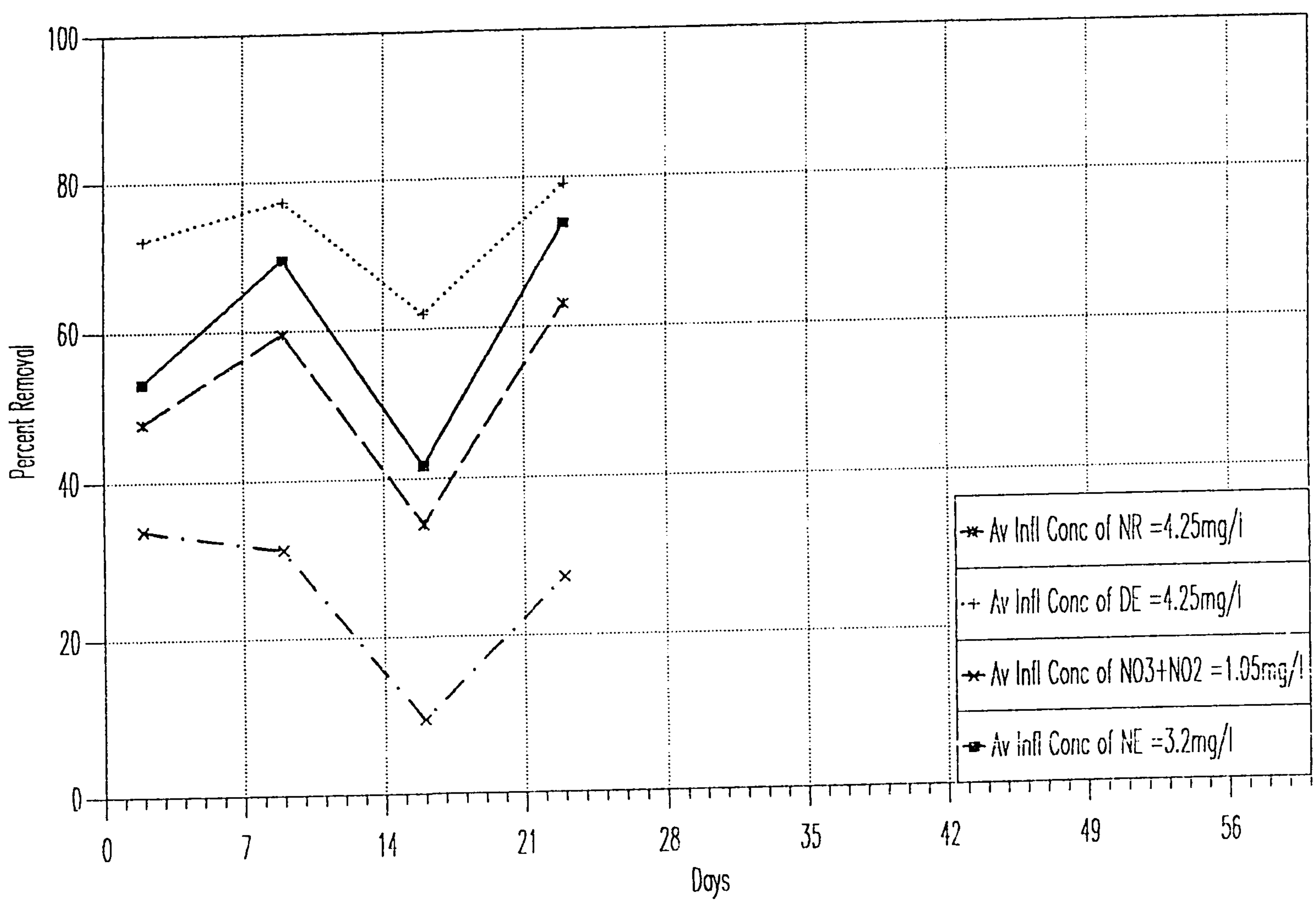


Figure 5.57: Removal Efficiencies of Various Forms of Nitrogen in Condition 12

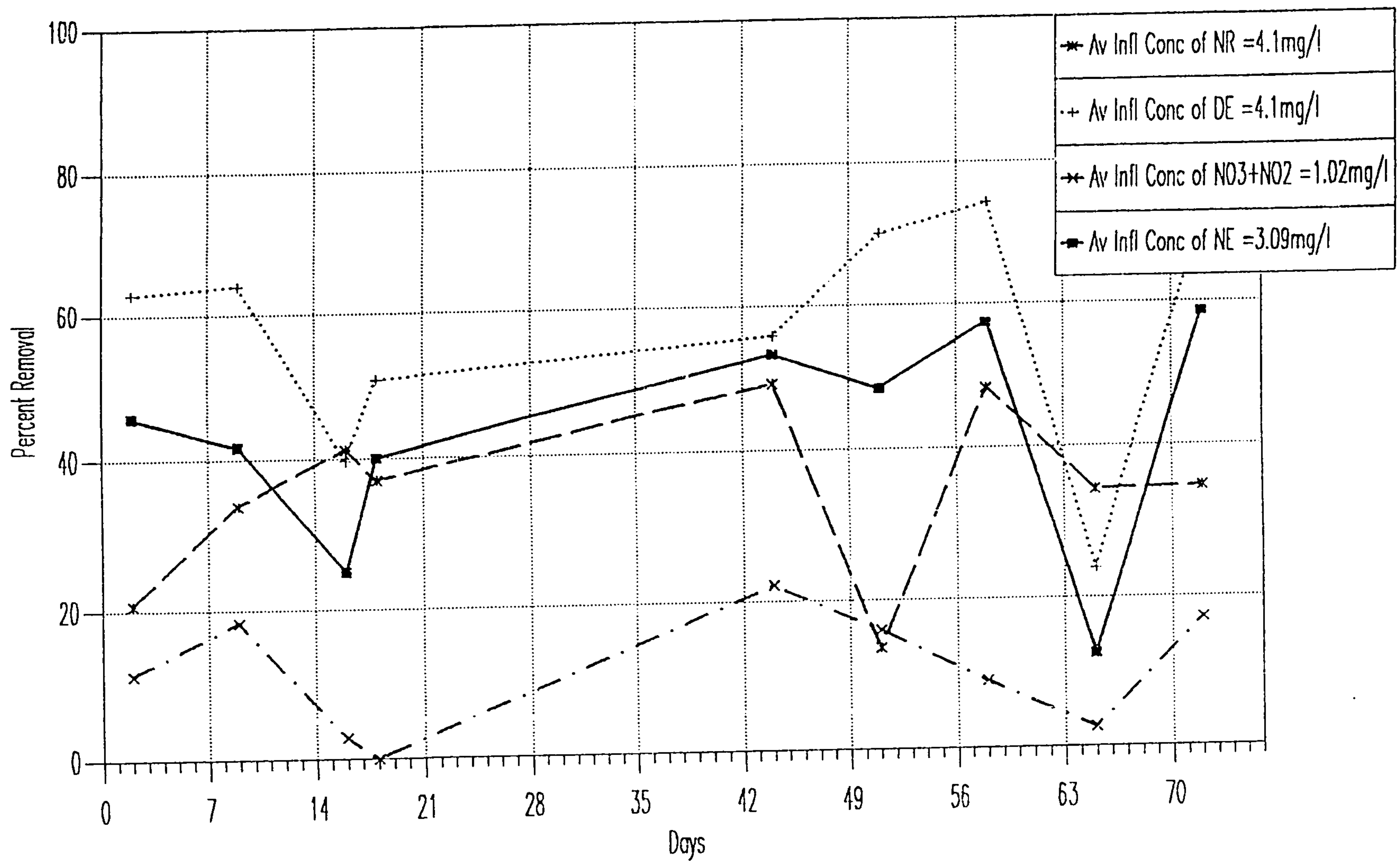


Figure 5.58: Removal Efficiencies of Various Forms of Nitrogen in Condition 13

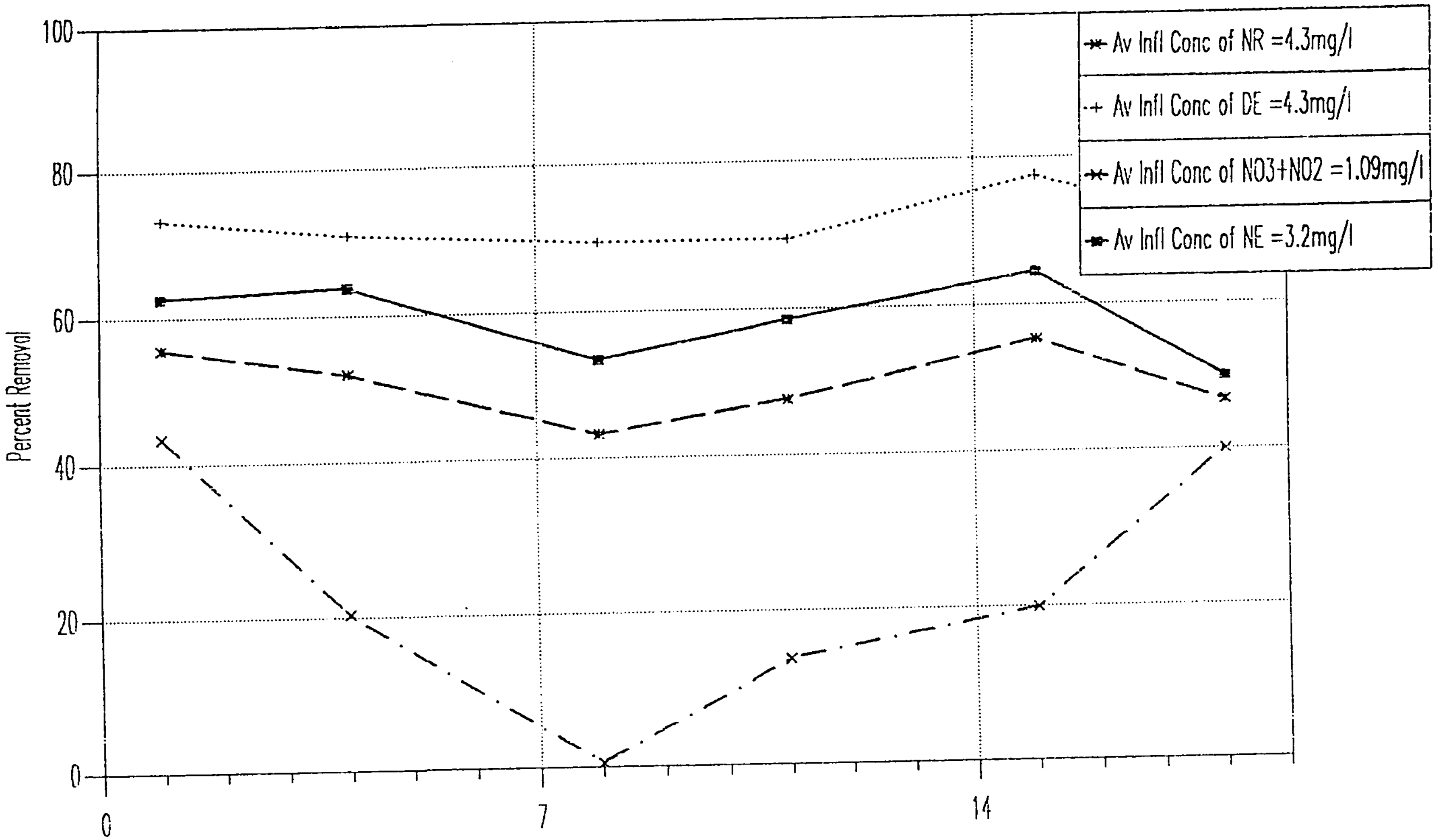


Figure 5.59: Removal Efficiencies of Various Forms of Nitrogen in Condition 14

be 58.7 %, 71.8 %, 50.1% and 23.0 % corresponding to the average initial concentration of 3.2 mg/l, 4.29 mg/l, and 1.1 mg/l respectively.

Comparing C4 and C14 having same sand depth, sand size and flow rate it is observed that the ramoval rates of NE, DE and NRE during C4 were 61.4%, 73.8% and 52% as compared to 58%, 71.8% and 50.1% in case of C14. Thereby confirming that the removal rates are in close proximity indicating that the removal rates of F1 and F3 are consistent under similar operating conditions.

Comparing C10 and C11 having same sand depth but different flow rate it is observed that the removal rates are not consistent in both conditions. This could be attributed to the operational problems coupled with some experimental error. In order to assess the effect of sand depth C11 and C12 having different sand depths were compared. It was found that the there was no significant difference in the removal rate of C11 and C12. Upon comparing C12 and C13 it was observed that the removal rate was higher in C12 than in C13 confirming that sand depth has a strong impact on the removal rate. Furthermore when C13 and C14 were compared to assess the effect of flow rate it was observed that the removal rates were higher at lower flow rate (C14) than at higher flow rate. Thus indicating that flow rate along with sand depth have a strong influence on the removal efficiency. In order to assess the effect of sand size C9 of filter 2 consisting of fine sand and C14 of filter 3 having coarse sand were compared, both operating under constant flow rate and sand depth. It was found that C9 had higher removal than C14. Thus from the above discussion it can be inferred that the flow rate concomitant with sand size and sand depth has an impact on the removal rate.

5.2.2 Nitrification And Denitrification:

The objective of this research was to assess nitrogen removal, nitrification and denitrification taking place in a filter bed and their response to different operating conditions such as varying flow rates, sand size and sand depth. The theoretical background of nitrification and denitrification has been described in chapter #2.

The analysis for NO_2^- and NO_3^- have been conducted routinely on the influent and effluent samples collected from the bottom of the filter throughout the filter operations. The nitrate and nitrite concentrations of the influent and effluent for all the conditions in each filter are shown in Table 5.2 - 5.4.

From Table 5.2 it can be seen that at 150 cms depth the average concentration of nitrate in the effluent has increased with decrease in nitrite effluent concentration. It was observed that there was 5% increase and 49% decrease in applied nitrate and nitrite at hydraulic loading of 0.15m/hr (8 l/min). It is worth mentioning that in the following discussion average influent concentrations of temperature, pH and DO will be presented. As can be seen from the table the DO level dropped by more than 55% in the effluent during most of the conditions (C1 - C14), also it has been noted during the study that pH dropped slightly in the filtration process, indicating the presence of the biological activity which produces CO_2 as a result of the oxidation of the organic matter. This generation of CO_2 depressed the pH of the effluent, substantiating the findings of Farooq (16). Even though the temperature and DO concentration are quite sufficient there is no increase in the effluent concentrations of nitrate and nitrite. The decrease of nitrate and nitrite in the effluent agrees with the findings of Ellis (13). From the nitrogen balance it is found that

Table 5.2: Variation of Influent and Effluent in Filter # 1 for all the Conditions

PARAMETERS	INFLUENT				EFFLUENT			
	C1	C2	C3	C4	C1	C2	C3	C4
Temperature C	34 - 25 (30.0)	29 - 10 (23.9)	28 - 21 (25.6)	40 - 29 (34.8)	33 - 25 (29.6)	28 - 10 (23.2)	28 - 20 (24.7)	38 - 27 (34.0)
D O mg/l	6.8 - 5.2 (6.10)	6.3 - 5.9 (6.2)	6.2 - 5.2 (5.9)	6.8 - 3.0 (5.99)	3.6 - 1.1 (2.7)	4.2 - 1.4 (3.12)	3.8 - 1.1 (2.9)	3.0 - 0.6 (2.08)
Turbidity NTU	0.9 - 0.2 (0.63)	0.9 - 0.4 (0.67)	0.9 - 0.5 (0.73)	0.9 - 0.2 (0.73)	0.7 - 0.1 (0.73)	0.6 - 0.1 (0.381)	0.6 - 0.2 (0.38)	0.6 - 0 (0.30)
Alkalinity mg/l	160 - 130 (140.7)	150 - 115 (138.4)	140 - 95 (118.0)	120 - 105 (116.05)	135 - 120 (126.0)	140 - 105 (132.5)	135 - 80 (109.3)	120 - 100 (111.8)
pH	7.6 - 7.3 (7.4)	7.6 - 7.4 (7.5)	7.6 - 7.3 (7.5)	7.6 - 7.4 (7.54)	7.5 - 7 (7.3)	7.3 - 7.1 (7.3)	7.5 - 7.1 (7.2)	7.4 - 7.1 (7.2)
TKN mg/l	6.2 - 1.4 (3.9)	3.84 - 2.8 (3.4)	4.2 - 2.4 (3.6)	3.92 - 2.8 (3.3)	2.12 - 0 (0.85)	1.96 - 0.56 (1.2)	2.1 - 0.56 (1.28)	1.68 - 0.84 (1.3)
NO_3^- mg/l	1 - 0.15 (0.42)	0.65 - 0.12 (0.259)	0.559 - 0.12 (0.224)	0.5 - 0.16 (0.326)	0.75 - 0.3 (0.434)	0.4 - 0.045 (0.208)	0.138 - 0.03 (0.107)	0.375 - 0.12 (0.242)
NO_2^- mg/l	1.15 - 0 (0.506)	0.74 - 0.38 (0.570)	0.89 - 0.55 (0.764)	0.89 - 0.5 (0.691)	0.675 - 0 (0.262)	0.936 - 0.36 (0.486)	0.82 - 0.36 (0.65)	0.7 - 0.2 (0.541)

Table 5.3: Variation of Influent and Effluent in Filter # 2 for all the Conditions

PARAMETERS	INFLUENT					EFFLUENT				
	C5	C6	C7	C8	C9	C5	C6	C7	C8	C9
Temperature C	34 - 10 (28.35)	27 - 20 (24.2)	29 - 21 (25.7)	40 - 29 (34.81)	39 - 33 (35.94)	33 - 10 (27..83)	27 - 20 (23.7)	28 - 20 (24.3)	39 - 28 (34.0)	38 - 32 (34.9)
D O mg/l	6.8 - 5.4 (6.10)	6.3 - 5.9 (6.2)	6.3 - 5.0 (5.8)	6.8 - 3.8 (5.99)	6.5 -5.9 (6.15)	3.8 -.8 (2.6)	3.8 - 2 (3.0)	3.6 - .6 (1.8)	3.4 -0. 6 (2.23)	3.2 - 2.4 (2.8)
Turbidity NTU	0.9 - 0.2 (0.65)	0.95 -. 3 (0.63)	0.9 - 0.6 (0.72)	0.9-0.5 (0.73)	0.9 - 0.6 (0.78)	0.7 - 0.1 (0.32)	0.5 -0.1 (0.3)	0.5 - 0.1 (0.3)	0.5 - 0.1 (0.27)	0.5 - 0.1 (0.29)
Alkalinity mg/l	160 - 130 (140.7)	150 - 115 (138.7)	140 - 95 (117.9)	120 - 105 (116.05)	120 - 100 (115.4	140 - 110 (124.7)	140 - 100 (129)	120 - 95 (107.7)	120 - 85 (110.5)	110 - 105 (108.9)
pH	7.6 - 7.3 (7.4)	7.6 - 7.3 (7.5)	7.6 - 7.3 (7.4)	7.6 -7.4 (7.54)	7.7 - 7.4 (7.54)	7.5 - 7.1 (7.3)	7.4 - 7.1 (7.3)	7.5 - 7.1 (7.1)	7.4 - 7.1 (6.7)	7.2 - 7.1 (7.154)
TKN mg/l	6.2 - 1.4 (3.8)	3.84 - 3.36 (3.6)	4.2 - 2.4 (3.56)	4.2 - 2.24 (3.3)	4.2 - 2.24 (3.2)	1.7 - 0 (0.81)	1.12 - 0.84 (0.94)	1.96 - 0.84 (1.07)	1.96 - 1.12 (1.37)	1.4 - 0.84 (1.12)
NO_3^- mg/l	1.0 - 0.15 (0.45)	0.23 - 0.15 (0.181	0.63 - 0.14 (0.23)	0.51 - 0.16 (0.33)	0.46 - 0.22 (0.37)	0.83 - 0.1 (0.39)	0.2 - 0.05 (0.105)	0.59 - 0.04 (0.32)	0.36 - 0.12 (0.24)	0.42 - 0.2 (0.31)
NO_2^- mg/l	1.15 - 0 (0.49)	0.74 - 0.4 (0.58)	0.85 - 0.56 (0.76)	0.89 - 0.5 (0.69)	0.89 - 0.53 (0.72)	0.74 - 0 (0.28)	0.88 - 0 (0.57)	0.75 - 0.35 (0.64)	0.68 - 0.4 (0.59)	0.7 - 0.32 (0.42)

Table 5.4: Variation of Influent and Effluent in Filter # 3 for all the Conditions

PARAMETERS	INFLUENT					EFFLUENT				
	C10	C11	C12	C13	C14	C10	C11	C12	C13	C14
Temperature C	33 - 10 (28.35)	29 - 20 (25.3)	29 - 21 (24.3)	40 - 29 (34.8)	39 - 33 (35.94)	33 - 10 (27.8)	27 - 20 (24.5)	27 - 20 (23.44)	39 - 28 (33.18)	38 - 32 (34.9)
D O	6.8 - 5.4 (6.10)	6.3 - 5.4 (6.1)	6.3 - 5.4 (5.80)	6.8 - 3.0 (5.99)	6.5 - 5.9 (6.15)	4.1 - 0.8 (2.59)	3.5 - 0.9 (2.27)	4.8 - 0.8 (2.64)	3.8 - 0.6 (1.96)	3.4 - 2.4 (2.97)
Turbidity NTU	0.9 - 0.2 (0.65)	0.9 - 0.4 (0.69)	0.9 - 0.6 (0.7)	0.9 - 0.5 (0.73)	0.9 - 0.6 (0.78)	0.6 - 0.2 (0.31)	0.5 - 0.1 (0.28)	0.5 - 0.2 (0.29)	0.6 - 0.2 (0.31)	0.4 - 0.2 (0.28)
Alkalinity mg/l	160 - 130 (140.7)	150 - 105 (125)	130 - 95 (116.8)	120 - 105 (116.05)	120 - 100 (115.4)	145 - 110 (117.3)	145 - 95 (117.3)	120 - 95 (107.5)	120 - 95 (108.08)	110 - 95 (103.0)
pH	7.6 - 7.3 (7.44)	7.6 -7.3 (7.47)	7.7 - 7.3 (7.22)	7.8 - 7.4 (7.54)	7.7 - 7.4 (7.54)	7.4 - 7.1 (7.26)	7.5 - 7.1 (7.16)	7.4 - 7.1 (6.95)	7.3 - 7.1 (7.18)	7.3 - 7.0 (7.15)
TKN mg/l	6.16 - 0.84 (3.94)	4.2 - 3.36 (3.8)	3.64 - 2.4 (3.2)	4.2 - 2.24 (3.3)	4.2 - 2.24 (3.2)	1.86 - 0 (1.13)	2.24 - 1.12 (1.71)	1.4 - 0.96 (1.22)	1.96 - 1.4 (1.7)	1.96 - 0.84 (1.3)
NO_3^-	0.69 - 0.05 (0.45)	0.22 - 0.14 (0.16)	0.56 - 0.17 (0.32)	0.51 - 0.16 (0.33)	0.46 - 0.22 (0.37)	0.95 - 0.03 (0.46)	0.32 - 0.06 (0.15)	0.19 - 0.09 (0.15)	0.47 - 0.08 (0.27)	0.49 - 0.18 (0.34)
NO_2^-	0.95 - 0 (0.59)	0.85 - 0.38 (0.708)	0.89 - 0.56 (0.74)	0.89 - 0.5 (0.69)	0.89 - 0.53 (0.72)	0.76 - 0 (0.28)	0.88 - 0.37 (0.66)	0.7 - 0.47 (0.62)	0.76 - 0.42 (0.63)	0.72 - 0.36 (0.49)

the NE and DE were 78.2% and 82.1% respectively. Thus it can be inferred that the rate of denitrification is more compared to the rate of nitrification.

During the C2 it was observed that there was 19.7 % and 14.8% reduction in nitrate and nitrite effluent concentration. The temperature, dissolved oxygen and pH recorded was 23.9°C, 6.12 mg/l and 7.5. Borchardt (9) has reported that no sharp optimum temperature can be defined and that there is a plateau of maximum activity between 15 °C and 35 °C. However below 15 °C nitrification rate drops sharply and is reduced to 50% at 12 °C. In spite of the favorable conditions which were adequate for nitrification it was found that NE was 65.9% and DE was 77.9% respectively. In C3 it was observed that there was a 52% and 14.9% reduction in average applied nitrate and nitrite concentration. During this period the average temperature, dissolved oxygen and pH was found to be 25.6 °C, 5.9 mg/l and 7.5. It can be observed that there is an increase in temperature with 50% drop in dissolved oxygen level when compared to the previous condition indicating greater activity than the previous condition. Viessman and Hammer (56) have reported that increased temperatures have significant effect in establishing and maintaining healthy nitrifier populations. In spite of increase in temperature, it was found from the nitrogen balance that the NE and DE were 63.8% and 76.4% respectively indicating that denitrification is more affected by temperature than nitrification contradicting to what has been documented in the literature.

Similarly in C4 the percent removal of nitrate and nitrite in the effluent decreased by 25.7% and 2.17%. From the nitrogen balance it was found that the NE and DE were 61.4% and 73.7% respectively. While the temperature, dissolved oxygen and pH was 34.8

°C, 5.9 mg/l and 7.3. From the table 5.2 it is interesting to note that the DO level dropped by about 65% in the effluent as the depth of sand is reduced. This is rather unexpected as the DO level in the effluent should have been more than the previous condition (C3). The DO level in the effluent increases with the reduction in the sand depth, as at lower depth the concentration of biomass is lower than at higher sand depths. Furthermore the results obtained are contradicting to that reported by Ellis (13) that no nitrification was observed during the filtration process even when the DO content of the secondary effluent was artificially enhanced from 1.5 to 8 mg/l by positioning air diffusers inside the column above the sand.

In C5 the influent and effluent concentrations of nitrate and nitrite are illustrated in Table 5.3. It is observed that the nitrate and nitrite average effluent concentrations are lower than the influent. The average percent reduction of nitrate and nitrite were 13.2% and 43.4% respectively. The average temperature, dissolved oxygen and pH was recorded to be 28.35°C, 6.2 mg/l and 7.4. Nazih (38) has reported that the nitrification rate is a function of temperature within the range of 5 °C to 35 °C with the maximum rate occurring approximately at 30°C. Veissman and Hammer (56) reported that 90% of maximum nitrification occurs at pH of 7.8 and 8.9. Hofman and Lees (26) have reported that the optimum pH for nitrite oxidation was 7.7. Based on the above literature, though the conditions are quite favorable for nitrification to take place it was found from the nitrogen balance that NE was 77.9% and DE was 82.9% respectively. Thus it can be inferred that degree of nitrification is lower compared to degree of denitrification.

During C6 the flow rate was increased by 25% to 20 l/min keeping the sand depth constant. The average percent reduction of nitrate was 41.9% with 1.7% reduction in nitrite concentration. Furthermore from the Table 5.3 it can be seen that the D O level dropped by 50% with a slight drop in temperature. The NE and DE obtained from the nitrogen balance was found to be 74.5% and 80.8% respectively. Therefore from the above it can be concluded that with the increase in filtration rate both NE and DE have dropped compared to the previous condition.

In C7 the average influent and effluent concentrations of nitrate and nitrite are illustrated in Table 5.3. The average temperature, D O and pH were 25.7°C, 5.8 mg/l and 7.4 respectively. Viessman and Hammer (56) have reported that laboratory studies have shown that there is no detectable inhibition of nitrification at D O levels exceeding 1.0 mg/l. The D O in the effluent is greater than 1.0 mg/l, which is quite adequate for nitrification to take place. The average concentration of nitrate and nitrite in the effluent was lower than the influent. However with the reduction in sand depth the NE and DE were calculated to be 70.2% and 73.0% respectively. Thus it can be observed that the efficiencies have dropped with the decrease in the sand depth, with the rate of nitrification being less than the rate of denitrification.

During C8 the average influent and effluent concentration of NO_3^- , NO_2^- are shown in Table 5.3. The average temperature, D O and pH recorded are 34.8 °C, 5.99 mg/l and 7.54. It can be observed that the effluent concentrations of D O has dropped by 50% compared to influent in all the conditions. The NE and DE were calculated to be 58.03% and 70.9% respectively with the efficiencies dropping with the decrease in the

sand depth. When the flow rate was reduced to 10l/min (C9) it can be observed from the table that the effluent concentration of DO increased to 2.8mg/l. Comparing the effluent concentrations of DO in F2 (C9) and F3 (C14) it is noticed that the concentration of DO in F3 is higher than F2 as the DO level in case of fine sand is less due to reduced permeability and high biomass concentration in the filter bed. The average concentration of nitrate and nitrite in the influent is higher than that in the effluent. Furthermore the NE and DE from the nitrogen balance were 64.8% and 74.0% respectively. Thus indicating that denitrification is more predominant than nitrification in the filter bed. This is also ascertained along the spatial variation in the following section.

The average concentration of influent and effluent NO_3^- and NO_2^- in F3 consisting of coarse sand during each condition of the operation are presented in the Table 5.4. During C10 it is observed that the percent reduction in NO_2^- was around 50% while that in NO_3^- was negligible compared to the applied NO_2^- and NO_3^-. The average temperature, DO and pH are 27.8°C, 2.59 mg/l and 7.26. From the previous documentation it can be recalled that though the conditions are favorable for the nitrification to take place it is observed it from the nitrogen balance that NE and DE were 65.5% and 68.4% respectively. This confirms that denitrification is higher compared to nitrification as was observed in F1 and F2.

During C11 the influent and effluent concentrations of NO_3^- and NO_2^- are shown in Table 5.4. It was found that the percent reduction in NO_3^- was 12.7% and that of NO_2^- was 5.7%. The temperature, DO and pH recorded are 25.3°C, 5.95 mg/l and 7.47 respectively. It is interesting to note that with the increase in flow rate the effluent

concentration of DO has reduced compared to the previous condition, which is unusual and contradicts to that observed in F1 and F2. This increase in DO level could be attributed to experimental error. Furthermore with the increase in flow the rate of NE reduced to 54.9%, while rate of DE peaked to 72.7% contradicting to that stated earlier in F1 and F2.

In C12 the sand depth was reduced to 80cms while the flow rate of 20 l/min was kept constant. From the Table 5.4 it is observed that the percent reduction in NO_3^- was 56.2% and that of NO_2^- was 15.6%. The temperature, DO and pH recorded are 24.3°C, 5.8 mg/l, and 7.22 respectively. Furthermore it can be observed that the effluent concentration of DO has increased when compared to the previous condition due to less biomass concentration in the filter bed. With the NE and DE were found to be 59.4% and 72.6% respectively showing an increase in NE with no change in DE.

During C13 the influent and effluent concentration of. NO_3^- and NO_2^- are shown in Table 5.4. The percent reduction of NO_3^- and NO_2^- were 16.3% and 8.38% respectively. The NE and DE dipped to 42.1% and 58.1% with the reduction in sand depth. The temperature, D O and pH recorded are 34.8°C, 5.99 mg/l and 7.54. It is interesting to note that the D O level of the effluent dropped with the decrease in sand depth, the same observation was made in case of F1, contradicting those reported by Adham (1) and Farooq (16).

When the flow rate was reduced to 10l/min in the last condition of F2 (C9) it was observed the influent concentration of NO_3^- and NO_2^- was higher than the effluent

concentration. The percent reduction of NO_3^- and NO_2^- were 8% and 31.9%. It is important to note that the effluent D O level increased with the decrease in flow rate. This sort of wide fluctuation in the DO content in the filtrate could be attributed to experimental error and due to operational problems. The influent concentration of NO_3^- and NO_2^- higher than that in the effluent, confirming the occurrence of denitrification. The efficiencies of nitrification and denitrification were found to be 58.7% and 71.8% respectively. Ellis (13) has reported significant occurrence of denitrification in the filter bed, which was contrary to the expectation that continuing nitrification would be a feature of the slow sand filtration.

From the above discussion it is observed that there was decrease in the effluent concentrations of NO_3^- and NO_2^- during all operation in F1 - F3. The decrease of NO_3^- and NO_2^- in the effluent and the predominance of denitrification agrees with the findings of Ellis(13). He reported that this effect was indicative of the intensity of biological activity on and within the sand bed. The point that nitrification is taking place within a filter bed was investigated and has been discussed in the following section while assessing the spatial variation. Furthermore the occurrence of nitrification and denitrification in succession within the filter bed was observed by AL - Adham (1).

5.2.3 Spatial Variation of Total Kjeldahl Nitrogen, Organic-nitrogen, Nitrate and Nitrite nitrogen :

To investigate the attenuation of various nitrogen species along the sand depth of the filter at different operating conditions, samples were collected from the ports of the three filters. The details of sampling ports are discussed in chapter # 4. Samples of

supernatant and interstitial water were collected in drop wise through flexible tubes connected to the ports of each filter.

a) Variation along 150 cms of sand depth:

Samples were collected from F1 in C2. The samples were analysed and nitrogen balance was conducted at each point to assess nitrification and denitrification taking place along the sand depth. The segmental and cumulative NE and DE are plotted vs the sand depth (cms) from top as shown in Fig 5.60. It is worth mentioning that the explanation of the graphs is based on the segmental NE and DE as it gives a clear picture that which section of the sand bed is active.

It can be observed from Fig 5.60 that nitrification and denitrification is taking place simultaneously in the filter bed. As can be seen from the figure that NE and DE fluctuated from 0 to 40% and 3.65 to 56.8% through out the entire bed. In the top 25cms of sand bed the NE and DE were 21.5% and 46.5%. In the next 25cms of the sand depth i.e. between 25cms and 50cms the NE and DE dropped to 9.1% and 23.1%, and later increased to 40% and 56.8% between sand depths of 50cms and 75cms. From sand depth of 75cms onwards the NE and DE gradually decreased to 0 and 3.65% at sand depth of 150cms

From the graph it can be inferred that the first 75cms depth of sand bed is more effective for nitrification and denitrification than the other sections of sand depth. Thus indicating that the nitrification and denitrification activity is more concentrated between sand depth of 0cms and 75cms.

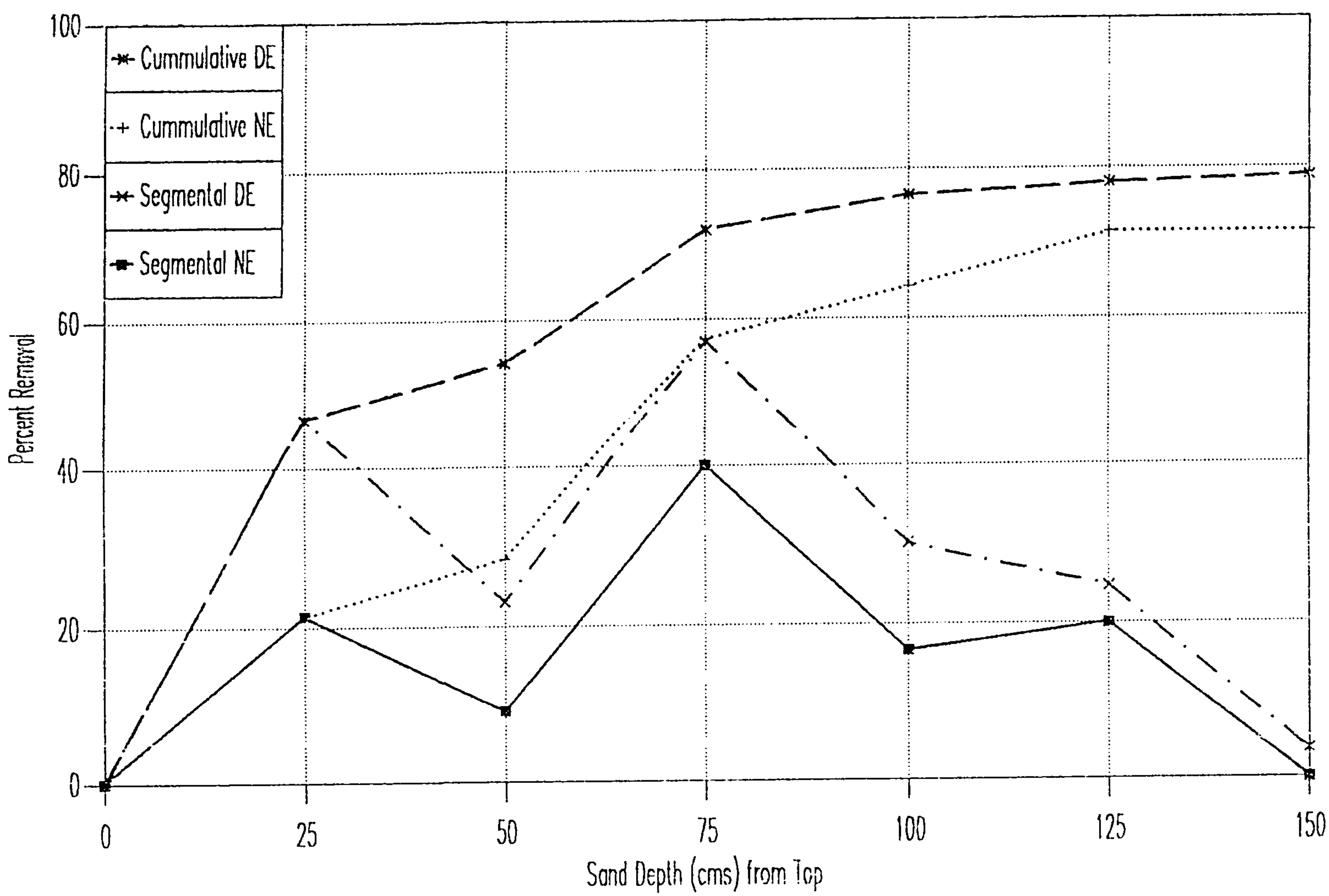


Figure 5.60: Variation of NE & DE along 150cms of Sand Depth in Condition 2

Similarly in C6 of F2 and C11 of F3 the variation of NE and DE are shown in Fig 5.61 and 5.62. From the former it is found that the NE and DE ranged from 0 to 36.4% and 4 to 53.4% in 150cms of the bed. During first 25cms of sand bed the NE and DE was 21.5% and 48.2%, in the subsequent layer they increased to 36.4% and 53.4% respectively. In the following bed that is between 50cms and 75cms it suddenly dropped to 0% and 9.5% respectively. Between 75cms and 100cms they again showed an increase of 17.4% and 31.0% respectively, but then on showed a steady decrease to 0% and 4.0% of NE and DE respectively. Thus it can be concluded that the nitrification and denitrification activity was higher between 0 and 75cms respectively. This matches with the observation made in the previous figure.

Fig 5.62 depicts the percent variation of NE and DE in C11. They varied in the entire bed from 0 to 37.5% and 0 to 52.7% respectively. In the first 50cms of sand bed NE and DE steadily increased to 23.8% and 52.1%. Then after dipping down to 12.5 % and 30.9% between 50cms and 75cms it increased to 37.5% and 52.7% in the subsequent 25cms. In the next 25cms they fell down to 0% and 1.7% before becoming 0% and 0% at 150cms of sand depth. Therefore from Fig 5.62 it is can be observed that the maximum nitrification and denitrification and was during 100cms of sand depth. Thus from Fig 5.59 to 5.62 it can be inferred that the nitrification and denitrification varied very closely and were concentrated in the first 100cms of the 150cms sand depth.

b) Variation along 80 cms of sand depth:

The percent variation of NE and DE in C3 is shown in Fig 5.63. From the figure it can be observed that NE and DE ranged from 0 to 46.7% and 0 to 65.8% in the entire

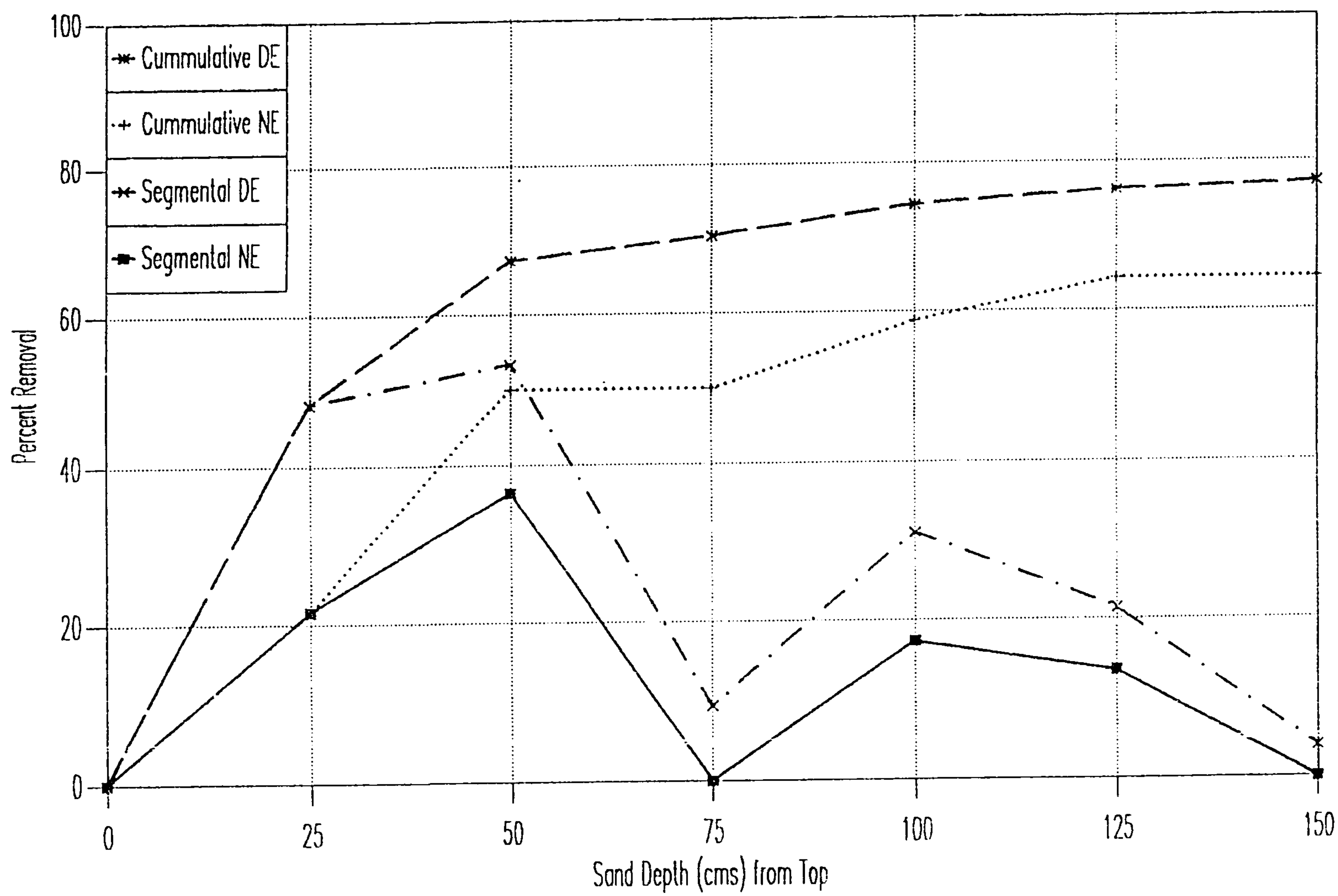


Figure 5.61: Variation of NE & DE along 150cms of Sand Depth in Condition 6

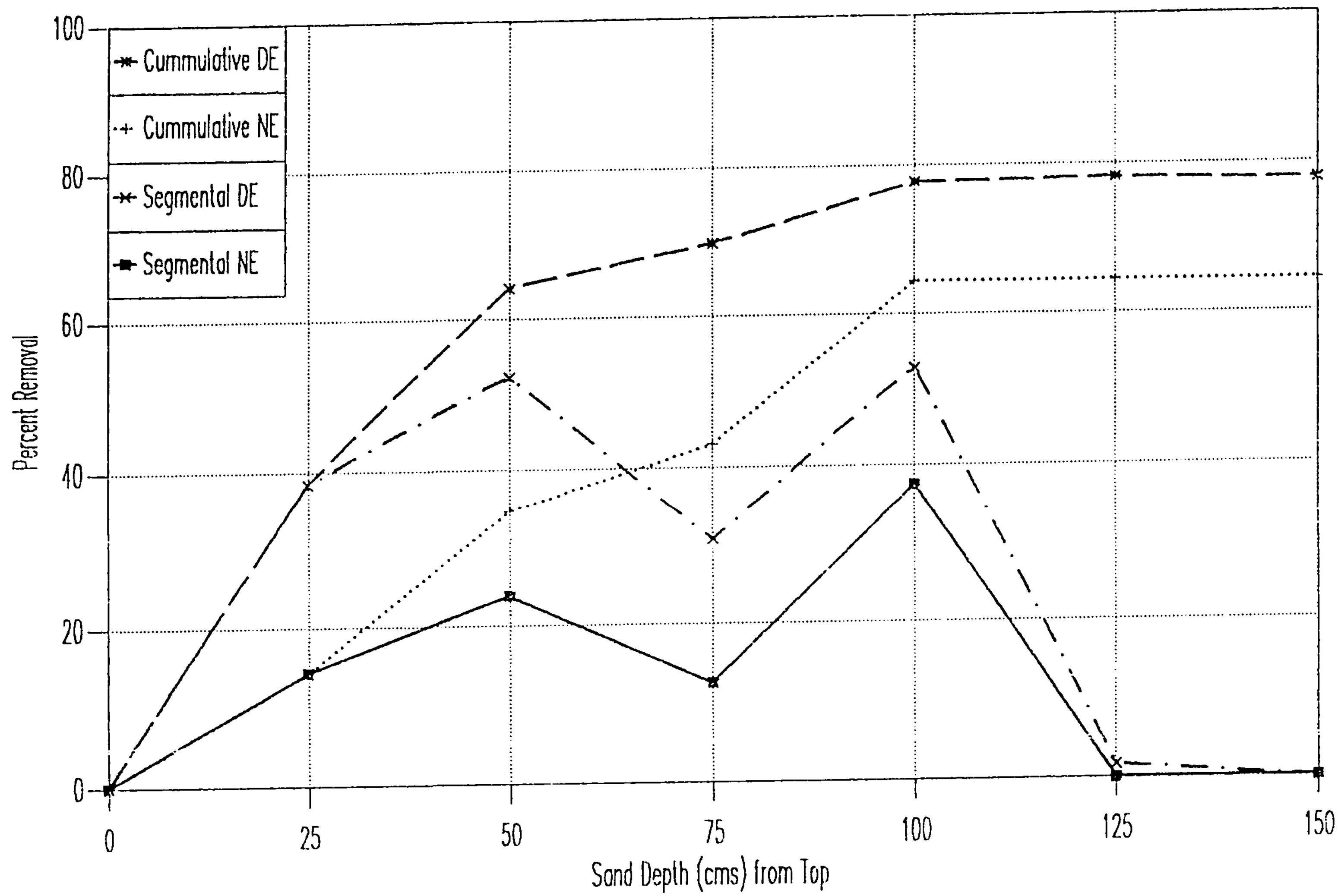


Figure 5.62: Variation of NE & DE along 150cms of Sand Depth in Condition 11

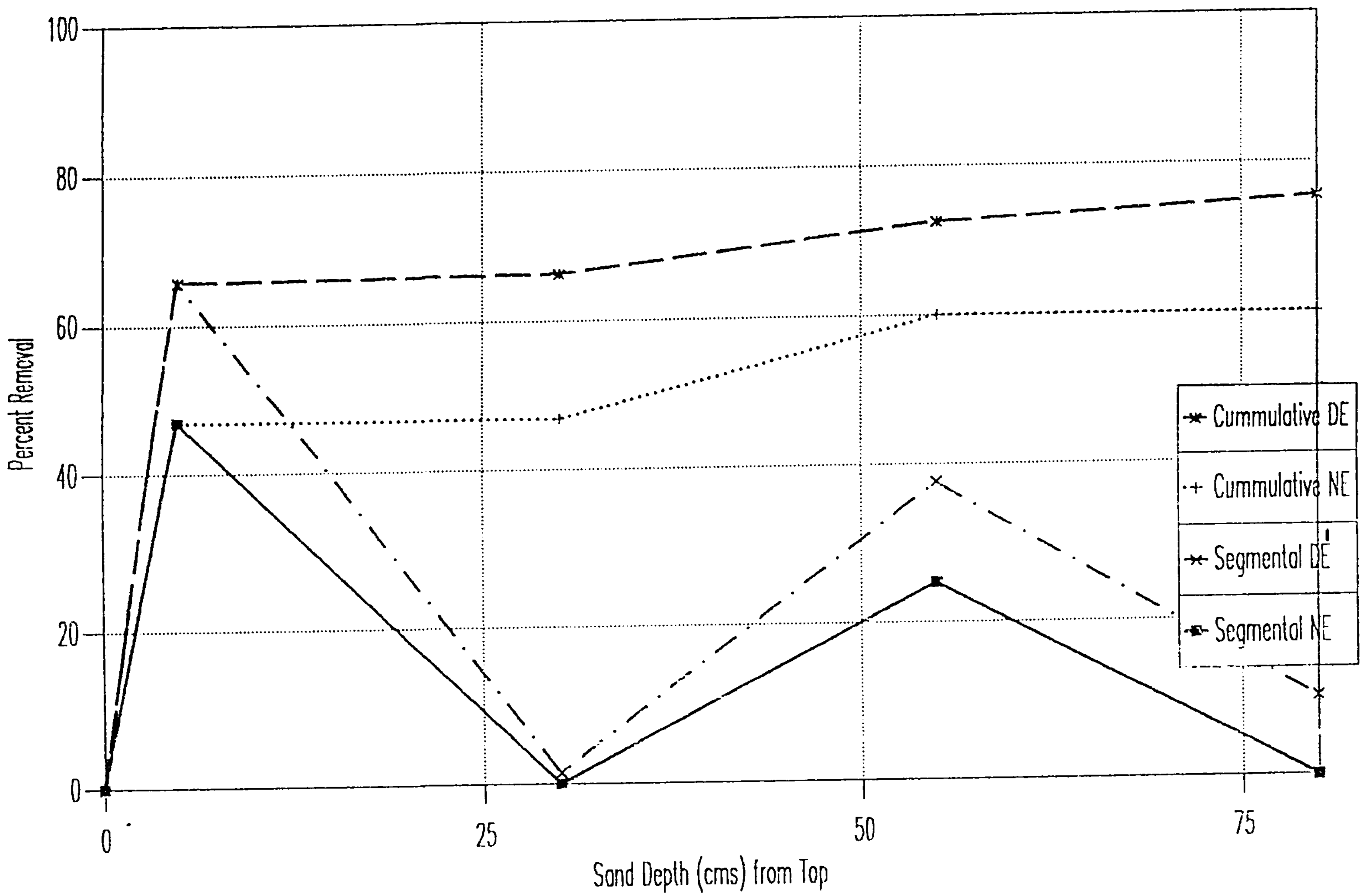


Figure 5.63: Variation of NE & DE along 80cms of Sand Depth in Condtion 3

bed. Both exhibited a very fluctuating trend, peaking in the first 5cms to 46.7% and 65.8% then dropping down to 0% and 1.5% in the next 25cms of the sand bed. They again peaked in the next 25cms to 25% and 37.5% respectively before again dipping down to 0% and 10% in the final 25cms of the sand depth. It is interesting to note that though there was a wide fluctuation still, both NE and DE varied in accordance with one another.

From Fig 5.64 in C7, the NE and DE ranged from 0 to 36.4% and 0 to 52.7% respectively. In the first 5cms of the sand bed DE peaked to 52.7% and then on steadily decreased to 25% in the subsequent 75cms of sand bed. The NE rose to 26.7% in the first 5cms and then went on to 36.36% in the next 25cms. Then it again dipped to 14.3% in the next 25cms before showing a slight rise to 16.7% in the subsequent 25cms. From figure it is clear that denitrification is taking place throughout the bed at a higher level while nitrification too was taking place through out but showed a fluctuating trend.

From Fig 5.65 the NE and DE in C12 varied in the entire bed from 0 to 30% and 0 to 50.8% respectively. It can be observed from the figure both varied very closely exhibiting a similar trend peaking in the first 5cms of sand bed to 26.7% and 50.8% respectively. In the next 25cms both decreased to 9% and 25.6%. They again rose to 30.0% and 46.3%, respectively in the next 25cms before dipping to 0% and 0% in the subsequent layer of the 80cms of sand bed.

From the above figures it is clear that the NE and DE followed the same trend in both the coarse sand filter F1 (C3) and F3 (C11). While in the fine sand filter F2 (C7), DE showed a steady decrease while NE fluctuated in 80cms of the sand bed.

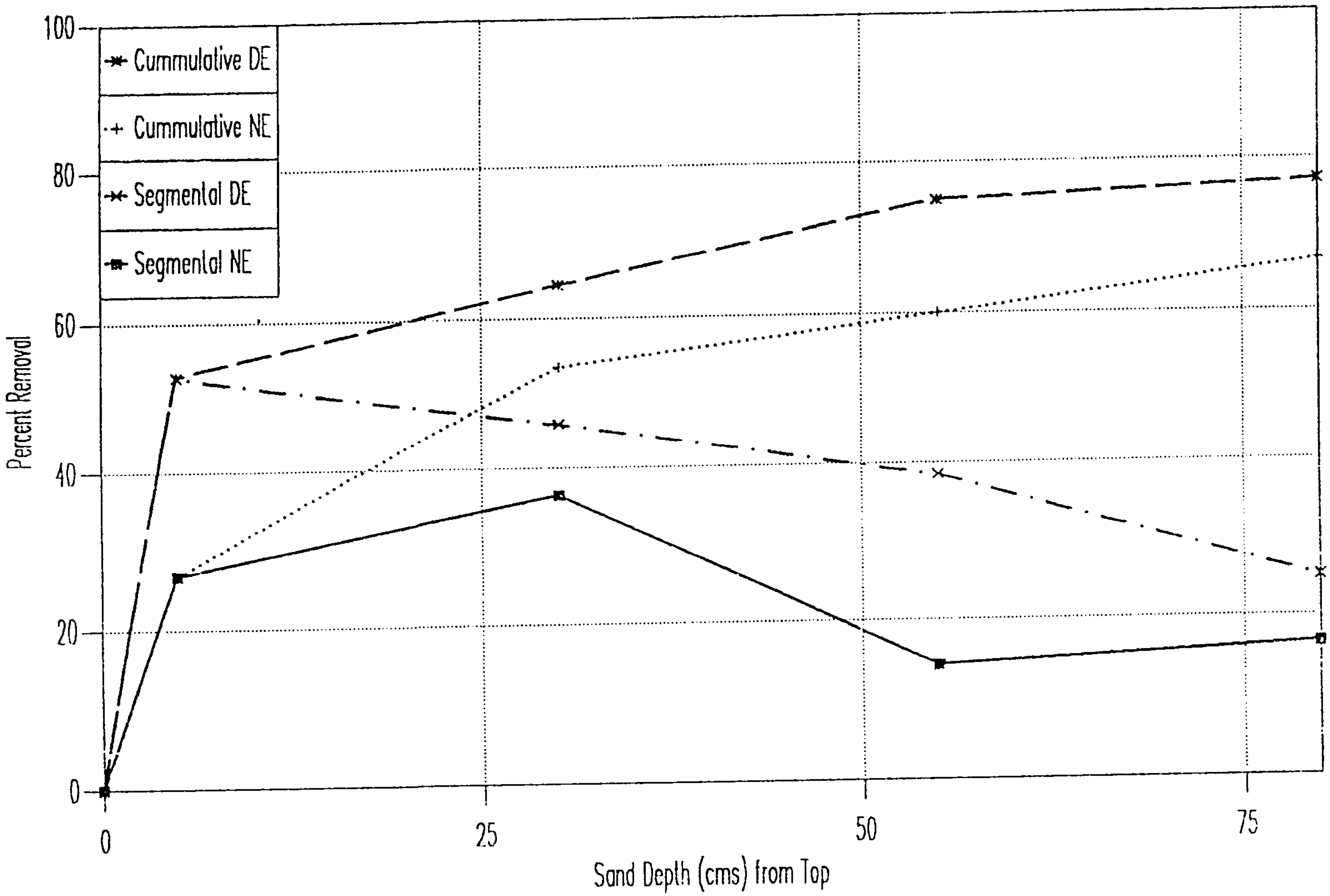


Figure 5.64: Variation of NE & DE along 80cms of Sand Depth in Condition 7

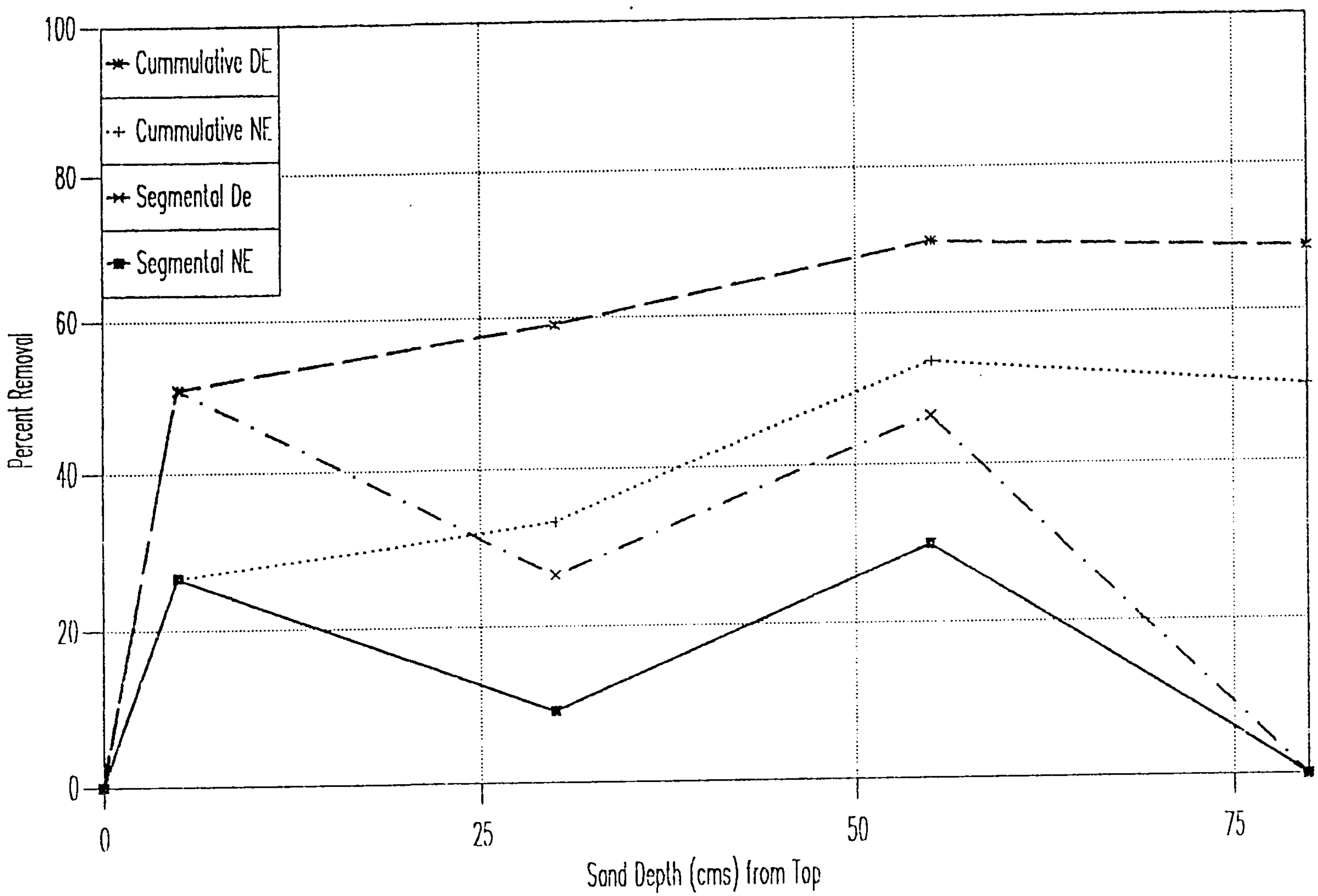


Figure 5.65: Variation of NE & DE along 80cms of Sand Depth in Condition 12

c) Variation along 50 cms of sand depth:

From Fig 5.66 in C4 NE and DE ranged from 8.4 to 42.9% and 28.3 to 67.3% respectively in the entire bed. In the first 25cms NE and DE peaked to 42.9% and 67.3% and then dropped to 8.4% and 28.3% respectively between 25cms and 50cms of sand bed. Similarly the percent variation of NE and DE in C8 are shown in Fig 5.67. It can be observed that both NE and DE ranged from 18.2 to 47.6% and 36.6 to 74.6% respectively during the entire bed. The NE and DE increased to 47.6% and 74.6% between 0 and 25cms and there after dropped to 18.2 % and 36.6% respectively between 25cms and 50cms. In case of C13 the variation of NE and DE are shown in Fig 5.68. From the figure it can be observed that NE and DE ranged from 15.4 to 38.1% and 41.2 to 70.6% respectively in the entire bed. During the first 25cms of sand bed both NE and DE peaked to 38.1% and 70.6% and then on exhibited a decreasing trend with the efficiencies dipping to 15.4% and 41.2% respectively between 25cms and 50cms of the sand bed.

From the above figures it is clear that all the three filters (F1, F2 and F3) showed the similar trend and that the maximum NE and DE for all the three filters occurred between 0 & 25cms of sand bed. Furthermore it is interesting to note that at the three different sand depth (150cms , 80cms and 50cms) it was observed that denitrification was higher than nitrification. Also it can be concluded that NE and DE are directly proportional to each other. Thus from the above discussion it can be inferred that in all the three filters (F1, F2 and F3) the removal rate was significantly higher during the top layer of the sand depth than compared to the subsequent layers. Furthermore it was observed that the removal efficiency of nitrification and denitrification decreased from

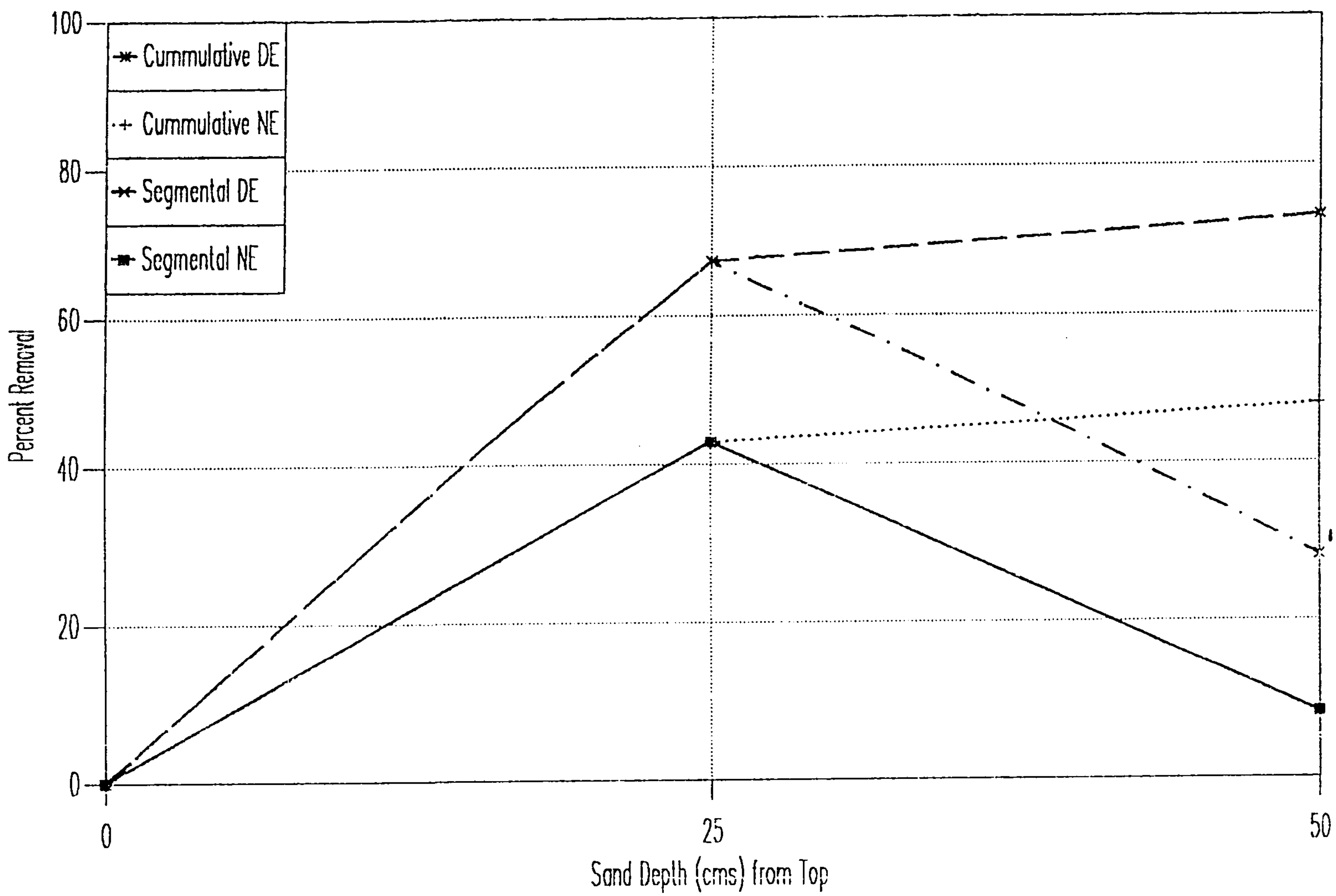


Figure 5.66: Variation of NE & DE along 50cms of Sand Depth in Condition 4

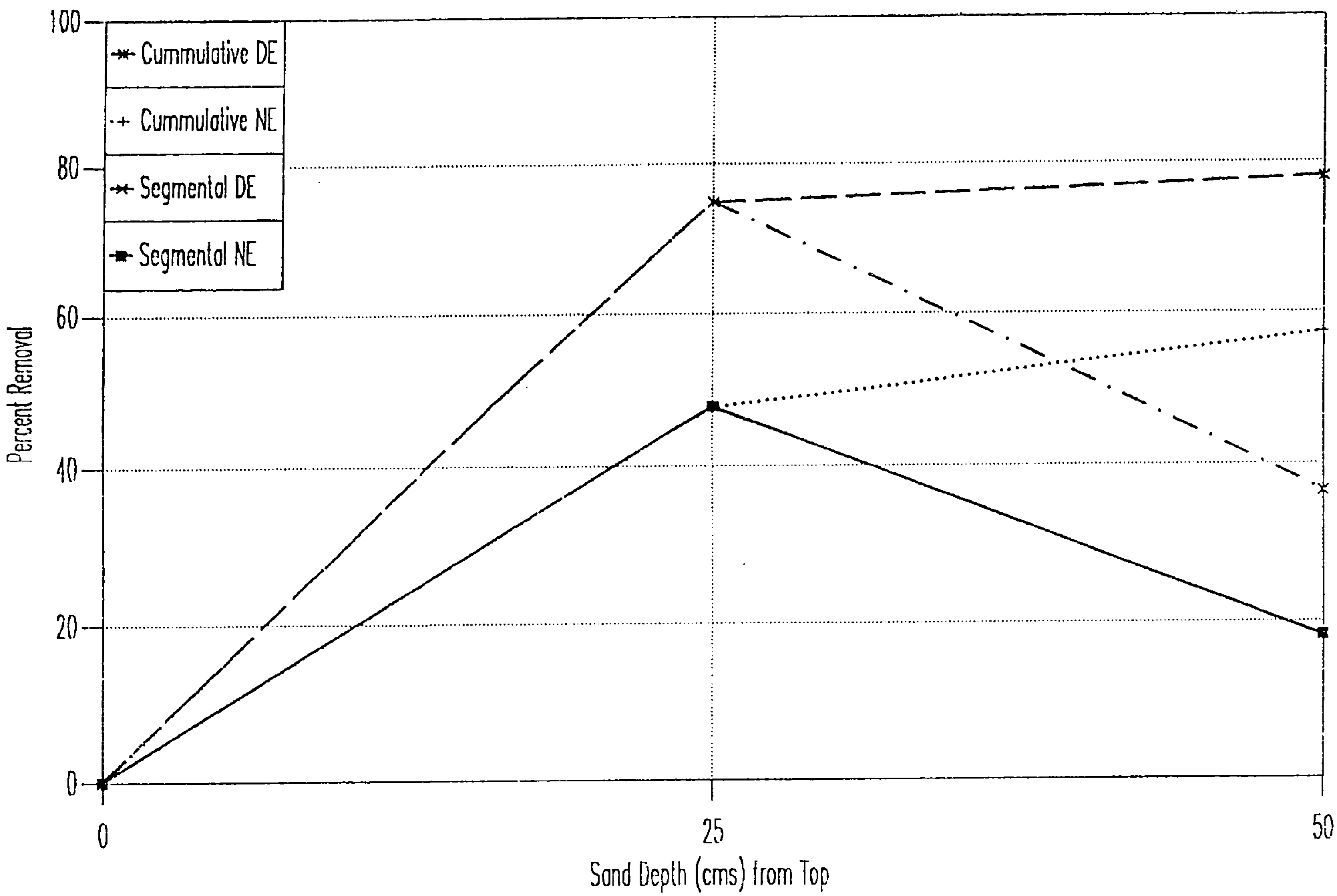


Figure 5.67: Variation of NE & DE along 50cms of Sand Depth in Condition 8

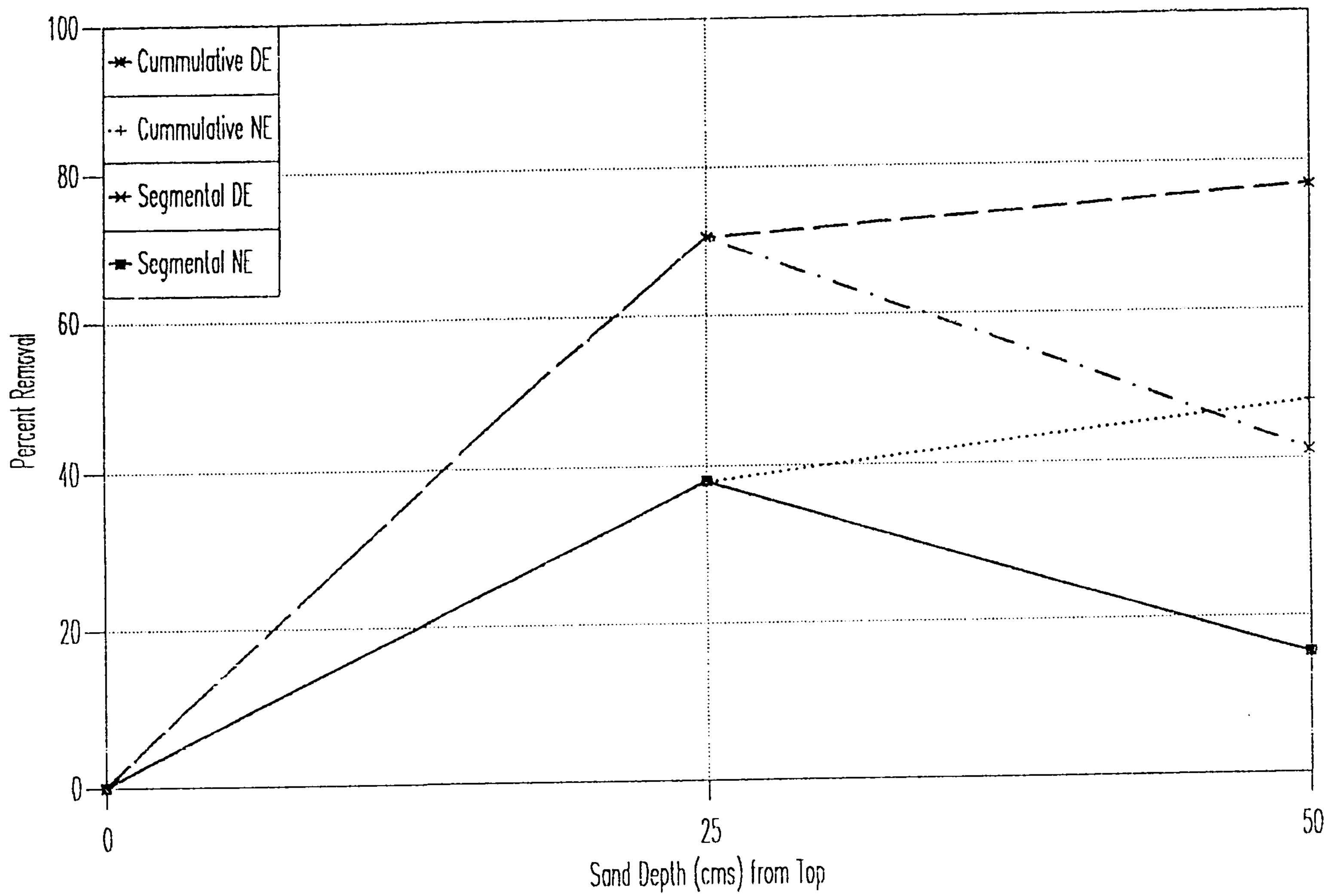


Figure 5.68: Variation of NE & DE along 50cms of Sand Depth in Condition 13

75cms onwards of the sand bed which agrees with the findings of Ellis (11) that the top 55cms of sand bed has high removal rate as the level of biological activity decreases with depth through the sand bed.

5.2.4 Statistical Analysis:

a) *Statistical Analysis Using "t" Test*:

The average removal efficiencies of nitrification, denitrification and nitrogen removal in F1, F2 and F3 were compared with various combinations within and between the filters in order to assess any significant statistical differences that may exist in the removal efficiencies at varying filtration rate, sand depth and sand size. This was performed using 't' test, the details of which have been mentioned in section 5.1.5.

The mean , sample size, variance, t_{cal}, degrees of freedom (d.f) and t_{table} values of the filter combinations nitrification, denitrification and nitrogen removal efficiencies to assess the effect of flow, sand size and sand depth is illustrated in Table 5.5 - 5.7 along the remarks indicating whether to reject or do not reject the hypothesis.

Table 5.5 shows the t test results for nitrification efficiency. It can be observed that significant statistical difference existed between flow rate of 8l/min and 16l/min (C1 vs C10), 8l/min and 20l/min(C1 vs C11) at 150cms of sand depth and 10l/min and 20l/min (C4 vs C13) at 50cms of sand depth in F1&F3. Within F3 there existed significant statistical difference between flow rates of 16l/min and 20l/min (C10 vs C11), 20l/min and 10l/min (C13 vs C14). Similarly within F2 significant statistical difference was found only between 20l/min and 10l/min (C8 vs C9) respectively.

Table 5.5: Statistical Comparison of Nitrification Efficiencies Through Different Filters @ 95% Confidence Interval

Condition	Sand Size (mm)	Sample Size(n_1)	Mean (Y_1)	Variance S_1^2	Sample Size(n_2)	Mean (Y_2)	Variance S_2^2	t_{cal}	t_{table}	D.F	Null Hypothesis	Inference
Effect of Flow Rate								**Results of ' t test '**				
C1 vs C2	0.5	14	78.14	149.77	5	65.9	207.65	1.69	2.447	6	Cannot Reject Ho	C1 = C2
C1 vs C10	0.5	14	78.14	149.97	13	68.4	121.16	2.176	2.06	25	Reject Ho	C1 ≠ C10
C1 vs C11	0.5	14	78.14	149.97	8	54.892	74.802	5.19	2.093	19	Reject Ho	C1 ≠ C11
C2 vs C11	0.5	5	65.9	207.65	8	54.892	74.802	1.543	2.447	6	Cannot Reject Ho	C2 = C11
C2 vs C10	0.5	5	65.9	207.65	13	68.4	121.16	-0.35	2.447	6	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	9	63.77	181.04	4	59.386	218.06	0.507	2.571	5	Cannot Reject Ho	C3 = C12
C4 vs C13	0.5	9	61.404	43.888	9	42.363	228.68	3.46	2.201	11	Reject Ho	C4 ≠ C13
C10vs C11	0.5	13	68.4	121.61	8	54.892	74.802	3.126	2.101	18	Reject Ho	C10 ≠ C11
C13vs C14	0.5	9	42.363	228.68	6	58.681	34.926	-2.92	2.201	11	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	17	77.956	320.98	3	74.119	20.359	0.76	2.131	15	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	9	58.031	55.341	6	64.74	20.506	-2.17	2.160	13	Reject Ho	C8 ≠ C9
Effect of Sand Depth												
C2 vs C14	0.5	5	65.9	207.65	6	58.681	34.926	1.049	2.571	5	Cannot Reject Ho	C2 = C14
C2 vs C3	0.5	5	65.9	207.65	9	63.77	181.04	0.271	2.306	8	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	9	63.77	181.04	9	61.404	43.888	0.473	2.179	12	Cannot Reject Ho	C3 = C4
C3 vs C14	0.5	9	63.77	181.04	6	58.681	34.926	0.999	2.179	12	Cannot Reject Ho	C3 = C14.
C11vs C13	0.5	8	54.892	74.802	9	42.363	228.68	2.125	2.160	13	Cannot Reject Ho	C11 = C13
C11vs C12	0.5	8	54.892	74.802	4	59.386	218.06	-0.56	2.776	4	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	4	59.386	218.06	9	42.363	228.68	1.904	2.447	6	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	3	74.119	20.359	9	70.212	106.95	0.904	2.262	9	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	3	74.119	20.359	9	58.031	55.341	4.473	2.447	6.0	Reject Ho	C6 ≠ C8
C7 vs C8	0.3	9	70.212	106.95	9	58.031	55.341	2.869	2.131	15	Reject Ho	C7 ≠ C8
Effect of Sand Size								**Results of ' t test '**				
C4 vs C9	0.5 vs 0.3	9	61.404	43.888	6	64.74	20.506	-1.160	2.101	13	Cannot Reject Ho	C4 = C9
C5 vs C10	0.3 vs 0.5	17	77.956	320.98	13	68.4	121.61	1.798	2.052	27	Cannot Reject Ho	C5 = C10
C6 vs C11	0.3 vs 0.5	3	74.119	20.359	8	54.892	74.802	4.786	2.365	7	Reject Ho	C6 ≠ C11
C7 vs C12	0.3 vs 0.5	9	70.212	106.95	4	59.386	218.06	1.329	2.776	4	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	9	58.031	55.341	9	42.363	228.68	2.789	2.179	12	Reject Ho	C8 ≠ C13

Table 5.6: Statistical Comparison of Denitrification EfficienciesThrough Different Filters @ 95% Confidence Interval

Condition	Sand Size (mm)	Sample Size(n_1)	Mean (Y_1)	Variance S_1^2	Sample Size(n_2)	Mean (Y_2)	Variance S_2^2	t_{cal}	t_{table}	D.F	Null Hypothesis	Inference
Effect of Flow Rate								**Results of ' t test '**				
C1 vs C2	0.5	14	82.67	46.129	5	77.902	35.12	1.484	2.306	8	Cannot Reject Ho	C1 =C2
C1 vs C10	0.5	14	82.67	46.129	13	79.771	40.753	1.143	2.06	25	Cannot Reject Ho	C1 = C10
C1 vs C11	0.5	14	82.67	46.129	8	72.678	12.842	4.51	2.086	20	Reject Ho	C1 ≠ C11
C2 vs C11	0.5	5	77.902	35.12	8	72.678	12.842	1.778	2.447	6	Cannot Reject Ho	C2 = C11
C2 vs C10	0.5	5	77.902	35.12	13	79.771	40.753	-0.586	2.306	8	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	9	76.405	7.768	4	72.552	58.874	0.976	3.182	3	Cannot Reject Ho	C3 = C12
C4 vs C13	0.5	9	73.688	33.598	9	58.121	283.61	2.622	2.228	10	Reject Ho	C4 ≠ C13
C10vs C11	0.5	13	79.771	40.753	8	72.678	12.842	3.258	2.093	19	Reject Ho	C10 ≠ C11
C13vs C14	0.5	9	58.121	283.61	6	71.755	9.772	-2.37	2.262	9	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	17	82.904	49.3	3	80.773	22.785	0.657	2.776	4	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	9	70.846	58.134	6	74.01	22.836	-0.99	2.160	13	Cannot Reject Ho	C8 = C9
Effect of Sand Depth												
C2 vs C14	0.5	5	77.902	35.12	6	71.755	9.772	2.089	2.447	6	Cannot Reject Ho	C2 = C14
C2 vs C3	0.5	5	77.902	35.12	9	76.405	7.768	0.533	2.571	5	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	9	76.405	7.768	9	73.688	33.598	1.267	2.179	12	Cannot Reject Ho	C3 = C4
C3 vs C14	0.5	9	76.405	7.768	6	71.755	9.772	2.945	2.228	10	Reject Ho	C3 ≠ C14.
C11vs C13	0.5	8	72.678	12.842	9	58.121	283.61	2.529	2.262	9	Reject Ho	C11 ≠ C13
C11vs C12	0.5	8	72.678	12.842	4	72.552	58.874	0.031	2.776	4	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	4	72.552	58.874	9	58.121	283.61	2.122	2.201	11	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	3	80.773	22.785	9	72.964	145.51	1.602	2.262	9	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	3	80.773	22.785	9	70.846	58.134	2.648	2.447	6	Reject Ho	C6 ≠ C8
C7 vs C8	0.3	9	72.964	145.51	9	70.846	58.134	0.445	2.145	14	Cannot Reject Ho	C7 = C8
Effect of Sand Size												
C4 vs C9	0.5 vs 0.3	9	73.688	33.598	6	74.01	22.836	-0.117	2.179	12	Cannot Reject Ho	C4 = C9
C5 vs C10	0.3 vs 0.5	17	82.904	49.3	13	79.771	40.753	1.275	2.052	27	Cannot Reject Ho	C5 = C10
C6 vs C11	0.3 vs 0.5	3	80.773	22.785	8	72.678	12.842	2.669	3.182	3	Cannot Reject Ho	C6 = C11
C7 vs C12	0.3 vs 0.5	9	72.964	145.51	4	72.552	58.874	0.074	2.262	9	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	9	70.846	58.134	9	58.121	283.61	2.065	2.201	11	Cannot Reject Ho	C8 = C13

Table 5.7: Statistical Comparison of Nitrogen Removal Efficiency between F1 F3 and F2 F3 @ 95% Confidence Interval

Condition	Sand Size (mm)	Sample Size(n_1)	Mean (Y_1)	Variance S_1^2	Sample Size(n_2)	Mean (Y_2)	Variance S_2^2	t_{cal}	t_{table}	D.F	Null Hypothesis	Inference
Effect of Flow Rate								**Results of ' t test '**				
C1 vs C2	0.5	14	67.47	98.122	5	55.931	106.58	2.168	2.365	7	Cannot Reject Ho	C1 = C2
C1 vs C10	0.5	14	67.47	98.122	13	59.019	66.497	2.427	2.06	25	Reject Ho	C1 ≠ C10
C1 vs C11	0.5	14	67.47	98.122	8	45.939	41.75	6.157	2.086	20	Reject Ho	C1 ≠ C11
C2 vs C11	0.5	5	55.931	106.58	8	45.939	41.75	1.94	2.447	6	Reject Ho	C2 ≠ C11
C2 vs C10	0.5	5	55.931	106.58	13	59.019	66.497	-0.6	2.447	6	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	9	54.899	105.15	4	51.079	170.01	0.519	2.571	5	Cannot Reject Ho	C3 = C12
C4 vs C13	0.5	9	52.012	25.977	9	34.711	134.36	4.099	2.262	11	Reject Ho	C4 ≠ C13
C10vs C11	0.5	13	59.019	66.497	8	45.939	41.75	4.069	2.101	18	Reject Ho	C10 ≠ C11
C13vs C14	0.5	9	34.711	134.36	6	50.04	25.45	-3.5	2.365	7	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	17	68.124	219.77	3	63.344	11.395	1.168	2.12	16	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	9	48.518	65.319	6	54.78	14.19	-2.02	2.179	12	Cannot Reject Ho	C8 = C9
Effect of Sand Depth												
C2 vs C14	0.5	5	55.931	106.58	6	50.04	25.45	1.165	2.447	6	Cannot Reject Ho	C2 = C14
C2 vs C3	0.5	5	55.931	106.58	9	54.899	105.51	0.18	2.306	8	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	9	54.899	105.15	9	52.012	25.977	0.756	2.179	8	Cannot Reject Ho	C3 = C4
C3 vs C14	0.5	9	54.899	105.15	6	50.04	25.45	1.276	2.179	12	Cannot Reject Ho	C3 = C14.
C11vs C13	0.5	8	45.939	41.75	9	34.741	134.36	2.495	2.160	13	Reject Ho	C11 ≠ C13
C11vs C12	0.5	8	45.939	41.75	4	51.079	170.01	-0.74	2.776	4	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	4	51.079	170.01	9	34.741	134.36	2.15	2.571	5	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	3	63.344	11.395	9	55.988	147.8	1.636	2.228	10	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	3	63.344	11.395	9	48.518	65.319	4.459	2.262	9	Reject Ho	C6 ≠ C8
C7 vs C8	0.3	9	55.988	147.8	9	48.518	65.319	1.535	2.145	14	Cannot Reject Ho	C7 = C8
Effect of Sand Size												
C4 vs C9	0.5 vs 0.3	9	52.012	25.977	6	54.78	14.19	-1.21	2.160	13	Cannot Reject Ho	C4 = C9
C5 vs C10	0.3 vs 0.5	17	68.124	219.77	13	59.019	66.497	2.144	2.056	26	Reject Ho	C5 ≠ C10
C6 vs C11	0.3 vs 0.5	3	63.344	11.395	8	45.939	41.75	5.796	2.365	7	Reject Ho	C6 ≠ C11
C7 vs C12	0.3 vs 0.5	9	55.988	147.8	4	51.079	170.01	0.64	2.571	5	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	9	48.518	65.319	9	34.741	134.36	2.925	2.145	14	Reject Ho	C8 ≠ C13

In order to assess the effect of sand depth the conditions of operations in the filters were compared at different depths within a filter and with another. From the table it can be observed that there was significant difference between sand depth of 150cms and 50cms (C6 vs C8) 80cms and 50cms (C7 vs C8) in F2 with no significant difference at rest of the sand depth combinations in F1, F2 and F3. Similarly the effect of sand size was assessed by comparing the conditions of F2 with that of F1 and F3. From the table it can be observed that significant statistical difference was found between F2 and F3 at a sand depth of 150cms and 50cms and a flow rate of 20l/min in (C6 vs C11) and (C8 vs C13).

Table 5.6 shows the results of statistical comparison for denitrification efficiency that was performed using t test. From the table it can be observed that significant difference was present between flow rates of 8l/min and 20l/min (C1 vs C10), 16l/min and 20l/min (C10 vs C11) at sand depth of 150cms and between 10l/min and 20l/min (C10 vs C11), 20l/min and 10l/min (C13 vs C14) at 50cms of sand depth, while no significant difference was observed in F2.

To obtain the effect of sand depth conditions were compared at different sand depths within a filter and with another. From table 5.6 it can be found that significant difference exists between sand depth of 80cms and 50cms (C3 vs C14), between F1 F3 and 150cms and 50cms (C6 vs C8) in F2, with no effect at other combinations of sand depths. Furthermore the sand size also does not hold any significant difference on the denitrification efficiency.

Table 5.7 shows the results of statistical comparison for nitrogen removal efficiency. The effect of flow rate on the removal rate was assessed and found that

significant difference was present between flow rate of 8l/min and 20l/min (C1 vs C10), 8l/min and 20l/min (C1 vs C11), 10l/min and 16l/min (C2 vs C10), 10l/min and 20l/min (C4 vs C13) at 150cms of sand depth and 10l/min and 20l/min (C4 vs C13), at 50cms of sand depth in F1 & F3. Also there was significant difference in F3 between flow rates of 16l/min and 20l/min (C10 vs C11) and 20l/min and 10l/min (C13 vs C14) at 150cms and 50cms of sand depth. No significant difference was observed with other combination of flow rates in F2.

In order to assess the effect of sand depth, the conditions of operations in the filters were compared at different depths within a filter and with another. From the table it can be observed that there was significant difference between sand depth of 150cms and 50cms (C11 vs C13) in F3 and between 150cms and 50cms (C6 vs C8) in F2 with no significant difference at rest of the sand depth combinations in F1 F2 and F3. Similarly to assess the effect of sand size conditions of F2 were compared with that of F1 and F3. From the table it can be observed that significant statistical difference was found between F1& F2 at a sand depth of 50cms (C4 vs C9) and F2 & F3 at sand depths of 150cms and 50cms (C5 vs C10, C6 vs C11, C8 vs C13) respectively.

The summary of statistical analysis for the effect of flow rate, sand depth and sand size on the removal efficiencies of BOD, nitrification, denitrification and nitrogen removal is presented in Table 5.8 - 5.10 respectively. From Table 5.8 it can be generally observed that half (50%) of the 11 comparisons (of conditions) showed that statistically (according to the t - test) there is no significant difference between the removal efficiencies of conditions operating at low flow rate and high flow rate at 95% confidence interval. Upon

Table 5.8: Summary of Statistical Analysis for the Effect of Flow Rate

Condition Description	Condition Number	BOD Efficiency	Nitrification Efficiency	Denitrification Efficiency	Nitrogen Removal Efficiency
* ** *** * ** ***					
C1 = 8, 150, 0.5 ; C2 = 10, 150, 0.5	C1 vs C2	C1 = C2	C1 = C2	C1 = C2	C1 = C2
Actual Averages	C1 vs C2	C1 > C2	C1 > C2	C1 > C2	C1 > C2
C1 = 8, 150, 0.5 ; C10 = 16, 150, 0.5	C1 vs C10	C1 > C10	C1 > C10	C1 = C10	C1 > C10
Actual Averages	C1 vs C10	C1 > C10	C1 > C10	C1 > C10	C1 > C10
C1 = 8, 150, 0.5 ; C11 = 20, 150, 0.5	C1 vs C11	C1 > C11	C1 > C11	C1 > C11	C1 > C11
Actual Averages	C1 vs C11	C1 > C11	C1 > C11	C1 > C11	C1 > C11
C2 = 10, 150, 0.5 ; C11 = 20, 150, 0.5	C2 vs C11	C2 > C11	C2 = C11	C2 = C11	C2 > C11
Actual Averages	C2 vs C11	C2 > C11	C2 > C11	C2 > C11	C2 > C11
C2 = 10, 150, 0.5 ; C10 = 16, 150, 0.5	C2 vs C10	C2 = C10	C2 = C10	C2 = C10	C2 = C10
Actual Averages	C2 vs C10	C2 > C10	C2 > C10	C2 < C10	C2 < C10
C3 = 10, 80, 0.5 ; C12 = 20, 80, 0.5	C3 vs C12	C3 = C12	C3 = C12	C3 = C12	C3 = C12
Actual Averages	C3 vs C12	C3 > C12	C3 > C12	C3 > C12	C3 > C12
C4 = 10, 50, 0.5 ; C13 = 20, 50, 0.5	C4 vs C13	C4 = C13	C4 > C13	C4 > C13	C4 > C13
Actual Averages	C4 vs C13	C4 > C13	C4 > C13	C4 > C13	C4 > C13
C10 =16, 150, 0.5 ; C11 = 20, 150, 0.5	C10 vs C11	C10 = C11	C10 > C11	C10 >C11	C10 >C11
Actual Averages	C10 vs C11	C10 > C11	C10 > C11	C10 >C11	C10 >C11
C13 = 20, 50, 0.5 ; C14 = 10, 50, 0.5	C13 vs C14	C13 = C14	C13 < C14	C13 < 14	C13 < 14
Actual Averages	C13 vs C14	C13 < C14	C13 < C14	C13 < 14	C13 < 14
C5 = 16, 150, 0.3 ; C6 = 20, 150, 0.3	C5 vs C6	C5 < C6	C5 = C6	C5 = C6	C5 = C6
Actual Averages	C5 vs C6	C5 < C6	C5 > C6	C5 < C6	C5 > C6
C8 = 20, 50, 0.3 ; C9 = 10, 50, 0.3	C8 vs C9	C8 = C9	C8 < C9	C8 = C9	C8 = C9
Actual Averages	C8 vs C9	C8 > C9	C8 < C9	C8 < C9	C8 < C9

Note: * = Flow Rate (l/min) ; ** = Sand Depth (cms) ; *** = Sand Size (mm)

comparing the actual averages of each conditions, it was observed that the conditions operated at lower flow rates showed higher removals than compared to the conditions operating at higher flow rates.

From Table 5.9 it can be observed that, for the effect of sand depth the t - test results showed no significant difference between the removal efficiencies of conditions having higher sand depth and lower sand depth in almost all the 9 comparisons. But upon comparing the actual averages of each condition operating at higher sand depth with that of condition operating at lower sand depth it was observed that conditions operating at higher sand depths showed higher removal as compared to the condition at lower sand depth. Similarly from Table 5.10, it can be observed that for the effect of sand size no significant difference was observed between the removal efficiencies of conditions for nitrification, denitrification and nitrogen removal having finer sand and coarse sand. But based on actual averages conditions operated with finer sand showed higher removal as compared to the conditions operating with coarse sand.

Therefore from the above tables it can be inferred that generally the removal efficiencies at low flow rates in the range of 8 - 10 l/min and high flow rates in the range of 16 - 20 l/min varied from 48 % - 82.7% and 34.7% to 83.4% respectively. The removal efficiencies dropped with the increase in flow rate, decrease in sand depth and increase in sand size and correspondingly increased with decrease in flow rate, increase in sand depth and decrease in sand size. Thus it can be concluded that flow rate concomitant with sand depth and sand size have an influence on the removal efficiencies of BOD, nitrification, denitrification and nitrogen removal.

Table 5.9: Summary of Statistical Analysis for the Effect of Sand Depth

Condition Description	Condition Number	BOD Efficiency	Nitrification Efficiency	Denitrification Efficiency	Nitrogen Removal Efficiency
* ** *** * ** ***					
C2 = 10, 150, 0.5 ; C14 = 10, 50, 0.5	C2 vs C14	C2 > C14	C2 = C14	C2 = C14	C2 = C14
Actual Averages	C2 vs C14	C2 > C14	C2 > C14	C2 > C14	C2 > C14
C2 = 10, 150, 0.5 ; C3 = 10, 80, 0.5	C2 vs C3	C2 = C3	C2 = C3	C2 = C3	C2 = C3
Actual Averages	C2 vs C14	C2 > C3	C2 > C3	C2 > C3	C2 > C3
C3 = 10, 80, 0.5 ; C4 = 10, 50, 0.5	C3 vs C4	C3 = C4	C3 = C4	C3 = C4	C3 = C4
Actual Averages	C3 vs C4	C3 > C4	C3 > C4	C3 > C4	C3 > C4
C3 = 10, 80, 0.5 ; C14 = 10, 50, 0.5	C3 vs C14	C3 = C14	C3 = C14	C3 > C14	C3 = C14
Actual Averages	C3 vs C14	C3 > C14	C3 > C14	C3 > C14	C3 > C14
C11 = 20, 150, 0.5 ; C13 = 20, 50, 0.5	C11 vs C13	C11 > C13	C11 = C13	C11 >C13	C11 > C13
Actual Averages	C11 vs C13	C11 > C13	C11 > C13	C11 > C13	C11 > C13
C11 = 20, 150, 0.5 ; C12 = 20, 80, 0.5	C11 vs C12	C11 = C12	C11 = C12	C11 = C12	C11 = C12
Actual Averages	C11 vs C12	C11 > C12	C11 < C12	C11 > C12	C11 < C12
C12 = 20, 80, 0.5 ; C13 = 20, 50, 0.5	C12 vs C13	C12 = C13	C12 = C13	C12 = C13	C12 = C13
Actual Averages	C12 vs C13	C12 > C13	C12 > C13	C12 > C13	C12 > C13
C6 = 20, 150, 0.3 ; C7 = 20, 80, 0.3	C6 vs C7	C6 = C7	C6 = C7	C6 = C7	C6 = C7
Actual Averages	C6 vs C7	C6 > C7	C6 > C7	C6 > C7	C6 > C7
C6 = 20, 150, 0.3 ; C8 = 20, 50, 0.3	C6 vs C8	C6 > C8	C6 > C8	C6 > C8	C6 < C8
Actual Averages	C6 vs C8	C6 > C8	C6 > C8	C6 > C8	C6 < C8
C7 = 20, 80, 0.3 ; C8 = 20, 50, 0.3	C7 vs C8	C7 = C8	C7 > C8	C7 = C8	C7 < C8
Actual Averages	C7 vs C8	C7 > C8	C7 > C8	C7 > C8	C7 < C8

Note: * = Flow Rate (l/min) ; ** = Sand Depth (cms) ; *** = Sand Size (mm)

Table 5.10: Summary of Statistical Analysis for the Effect of Sand Size

Condition Description	Condition Number	BOD Efficiency	Nitrification Efficiency	Denitrification Efficiency	Nitrogen Removal Efficiency
* ** *** * ** *** C4 = 10, 50, 0.5 ; C9 = 10, 50, 0.3	C4 vs C9	C4 < C9	C4 = C9	C4 = C9	C4 = C9
Actual Averages	C4 vs C9	C4 < C9	C4 < C9	C4 < C9	C4 < C9
C5 = 16, 150, 0.3 ; C10 = 16, 150, 0.5	C5 vs C10	C5 > C10	C5 = C10	C5 = C10	C5 = C10
Actual Averages	C5 vs C10	C5 > C10	C5 < C10	C5 > C10	C5 > C10
C6 = 20, 150, 0.3 ; C11 = 20, 150, 0.5	C6 vs C11	C6 > C11	C6 > C11	C6 = C11	C6 > C11
Actual Averages	C6 vs C11	C6 > C11	C6 > C11	C6 > C11	C6 > C11
C7 = 20, 80, 0.3 ; C12 = 20, 80, 0.5	C7 vs C12	C7 > C12	C7 = C12	C7 = C12	C7 = C12
Actual Averages	C7 vs C12	C7 > C12	C7 > C12	C7 > C12	C7 > C12
C8 = 20, 50, 0.3 ; C13 = 20, 50, 0.5	C8 vs C13	C8 > C13	C8 > C13	C8 = C13	C8 > C13
Actual Averages	C8 vs C13	C8 > C13	C8 > C13	C8 > C13	C8 > C13

Note: * = Flow Rate (l/min) ; ** = Sand Depth (cms) ; *** = Sand Size (mm)

b) Correlation between NE, DE, NRE and Filtration Rate in Filter1 & 3

In order to study the effect of varying flows on nitrification efficiency and denitrification efficiency and nitrogen removal efficiency in Filter 1 and Filter 3, a correlation between removal efficiency and varying filtration rates at constant sand depth and sand size was established using SAS package. Both linear and non-linear models were applied. The nonlinear model gave a good fit to the data with a R^2 value of = 0.72, 0.66 and 0.672 for nitrification efficiency, denitrification efficiency and nitrogen removal efficiency respectively. The corresponding value of coefficient of correlation is 0.845, 0.815, and 0.819 respectively. The value of coefficient of correlation in all three cases is quite high which indicates the strength of the model in establishing the correlation between the independent and dependent variable. The non-linear models that were established are as follows.

Nitrification Efficiency as Percentage = $1007.58 \times \text{Flow}^{0.02} - 22.5 \times \text{Flow}^{0.5} - 911.65$

Denitrification Efficiency as Percentage = $-4.39 \times \text{Flow}^{0.5} + 93.8$

Nitrogen Removal Efficiency as Percentage = $- 9.613 \times \text{Flow}^{0.5} + 91.90$

The graphical representation of the fitted models are shown in Fig 5.69 - 5.71 for NE, DE and NRE respectively. Furthermore variation of error between the actual and the estimated value in case of nitrification efficiency, denitrification efficiency and nitrogen removal efficiency ranged from -5.8 to 5.4, -2.0 to 3.0 and -5.8 to 5.3 respectively. From the above it can be inferred that the variation of error is assumed to be within the limits of

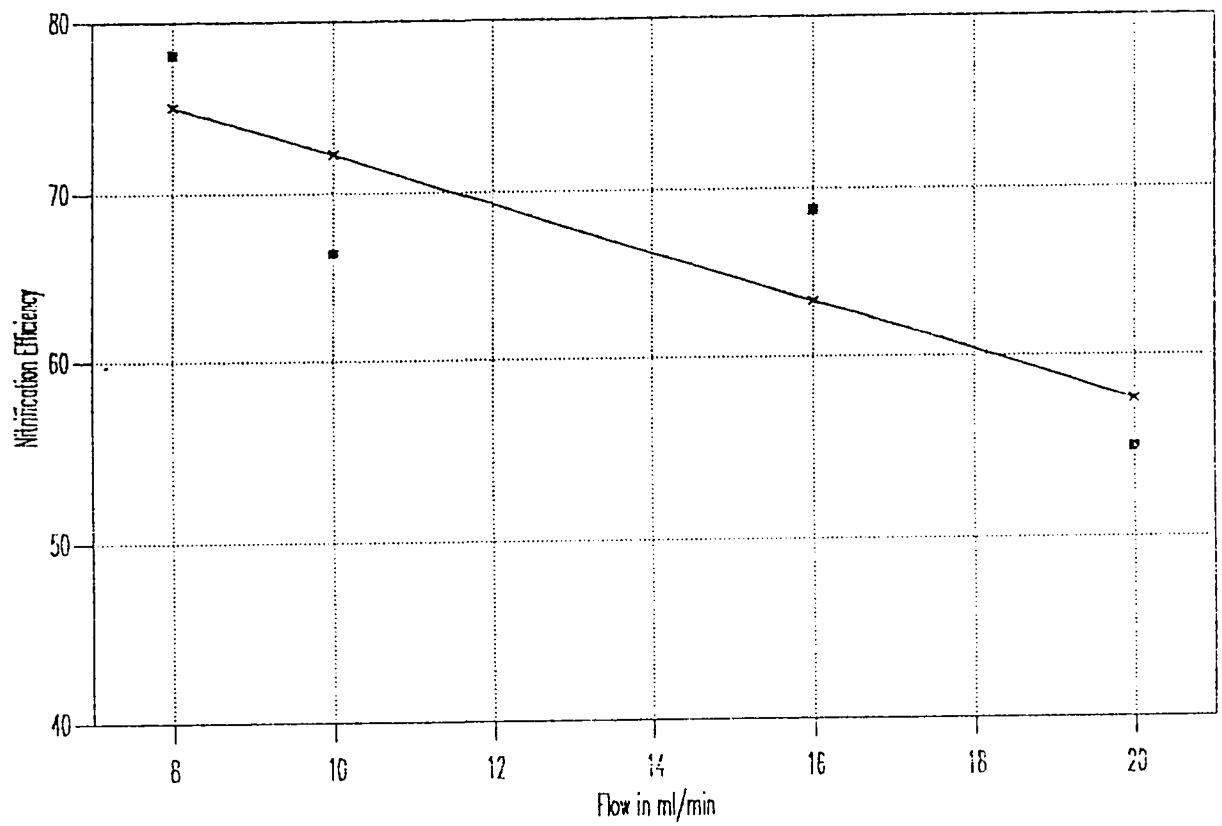


Figure 5.69: Effect of Flow Rate at 150cms Depth on Nitrification Efficiency in F1 & F3

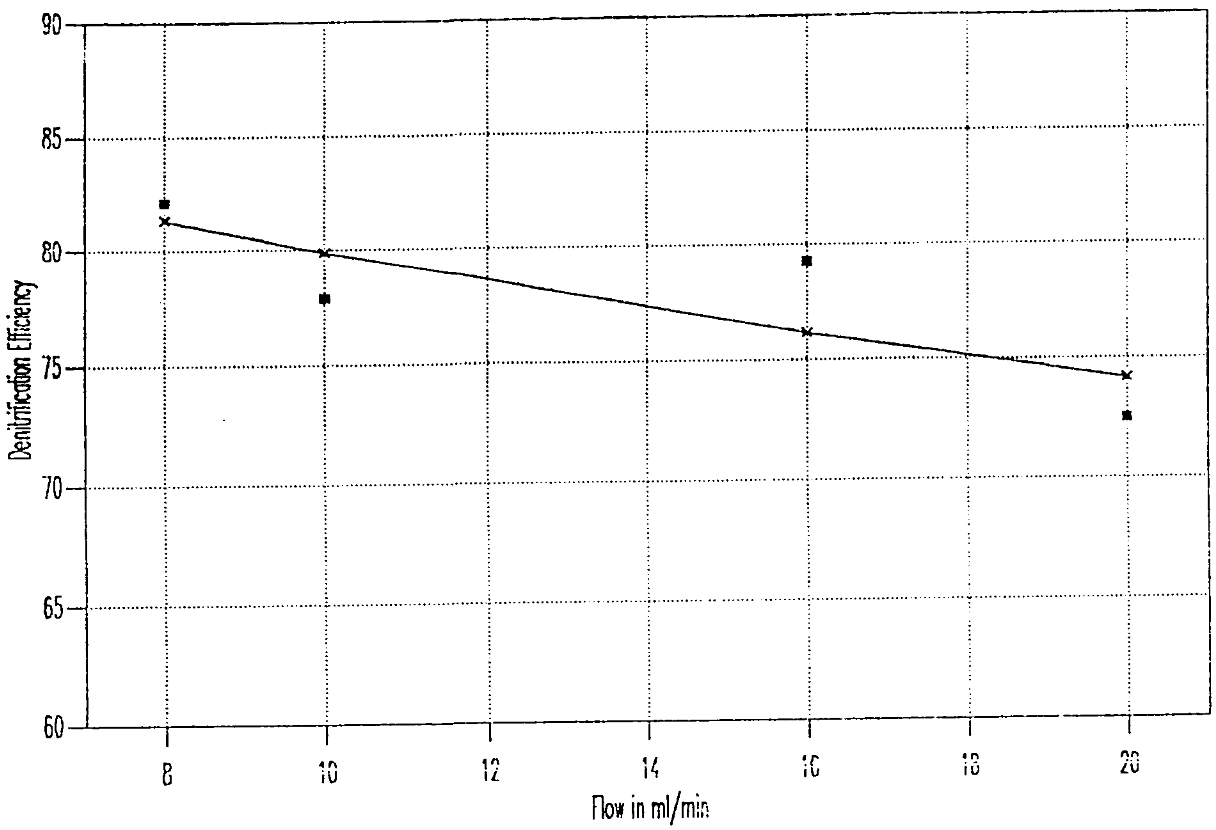


Figure 5.70: Effect of Flow Rate 150cms Depth on Denitrification Efficiency in F1 & F3

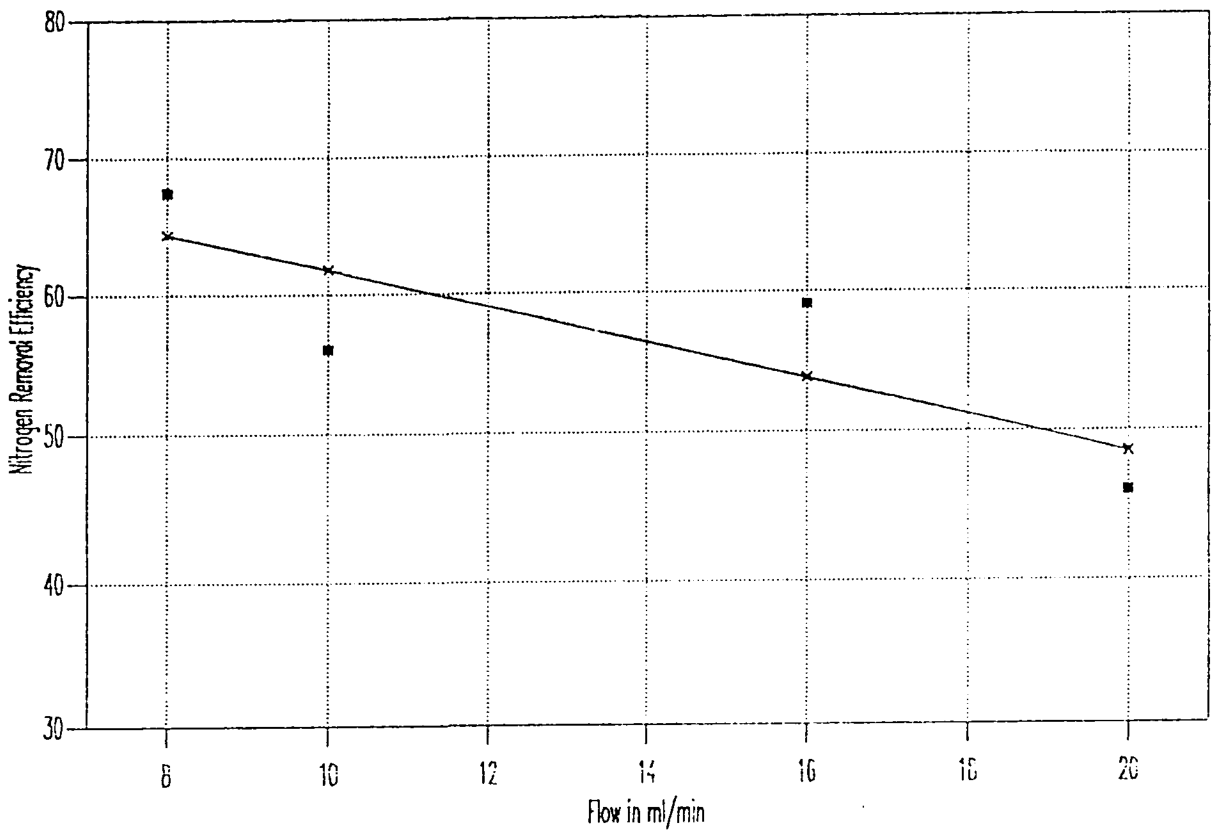


Figure 5.71: Effect of Flow Rate 150cms Depth of Nitrogen Removal Efficiency in F1 & F3

experimental errors. It is worth mentioning that the correlation between flow rate and removal efficiency at other sand depths (80cms and 50cms) could not be performed due to insufficient data as the filters were not operated at varying flow rates at sand depths of 80cms and 50cms as compared to that of 150 cms.

c) Correlation between NE, DE, NRE and Sand Size in Filter1 & 3

In order to obtain the effect of sand size on NE, DE, and NR a correlation between sand size and nitrification efficiency, denitrification efficiency and nitrogen removal efficiency in F2 and F3, a correlation between removal efficiency and sand size at constant filtration rate and sand depth was established. As mentioned earlier both linear and non-linear models were compared and it was found that non-linear model gave a good fit for the data with an R^2 (coefficient of determination) of 0.66, 0.59, and 0.65 in case of nitrification efficiency, denitrification efficiency and nitrogen removal efficiency respectively. The corresponding value of R (coefficient of correlation) is 0.81, 0.77 and 0.8 respectively. These values indicate the strength of the non-linear model in establishing the relation between the dependent and independent variables. The following are the models developed for the removal efficiencies.

$$\text{Nitrification Efficiency} = -89.5 \times \text{Sand Size}^{0.5} + 125.1$$

$$\text{Denitrification Efficiency} = -38.0 \times \text{Sand Size}^{0.5} + 102.7$$

$$\text{Nitrification efficiency} = -82.9 \times \text{Sand Size}^{0.5} + 111.2$$

The graphical representation of the fitted models for NE, DE and NRE are illustrated in Figs 5.72 - 5.74 respectively. Furthermore variation of error between the

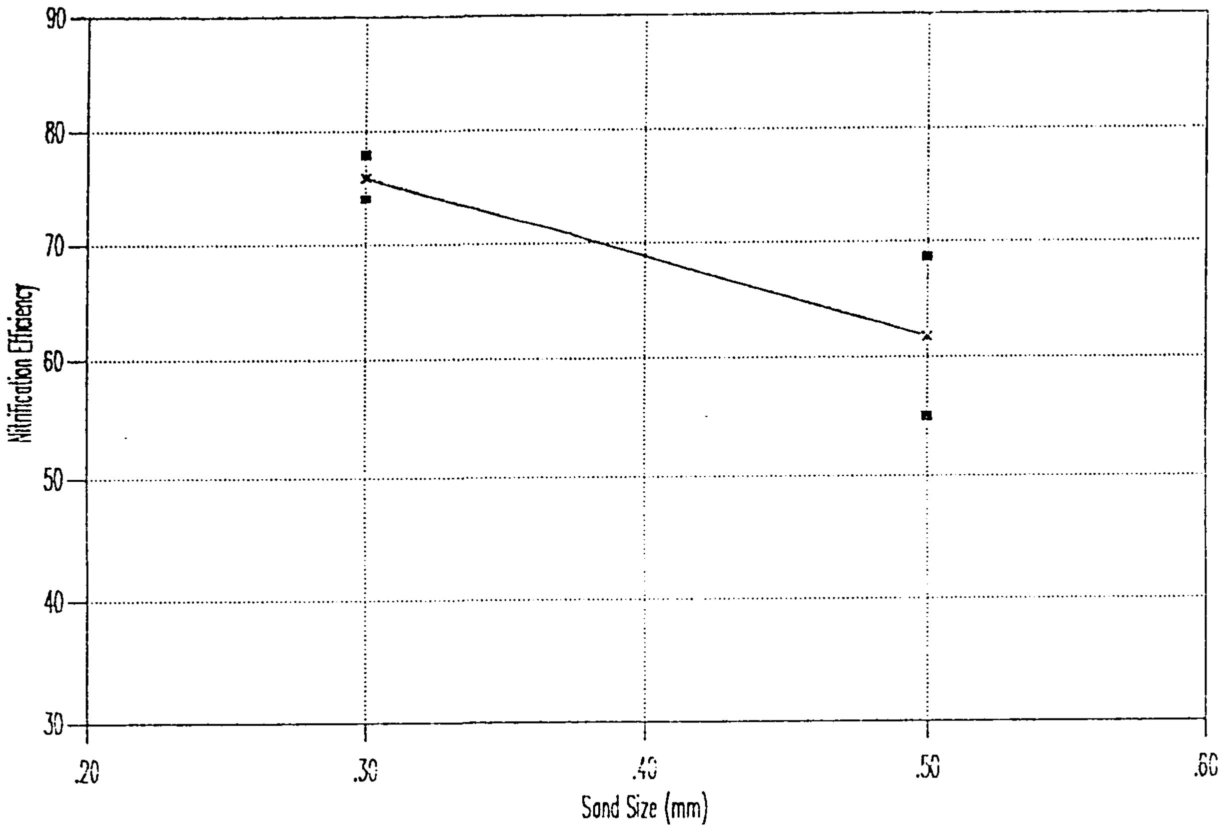


Figure 5.72: Effect of Sand Size at 150cms Depth on Nitrification Efficiency in F2 & F3

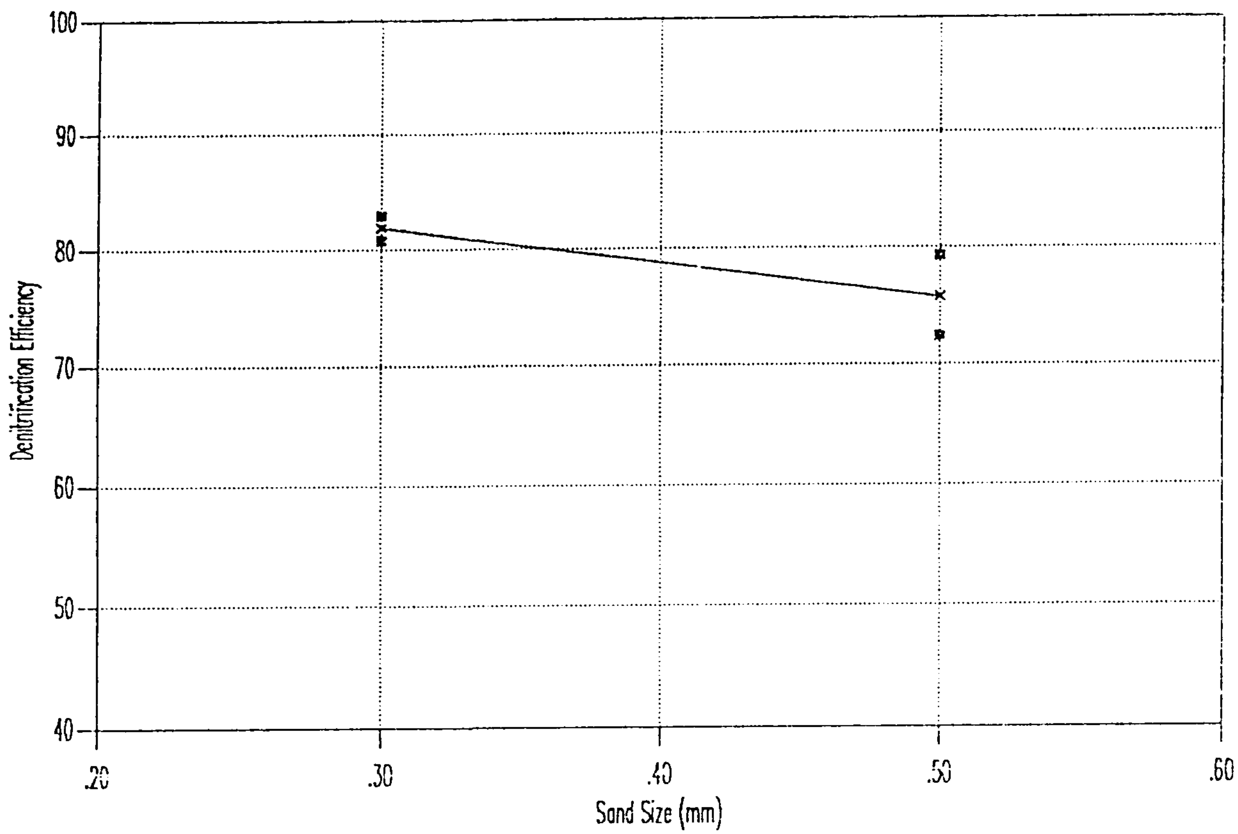


Figure 5.73: Effect of Sand Size at 150cms Depth on Denitrification Efficiency in F2 & F3

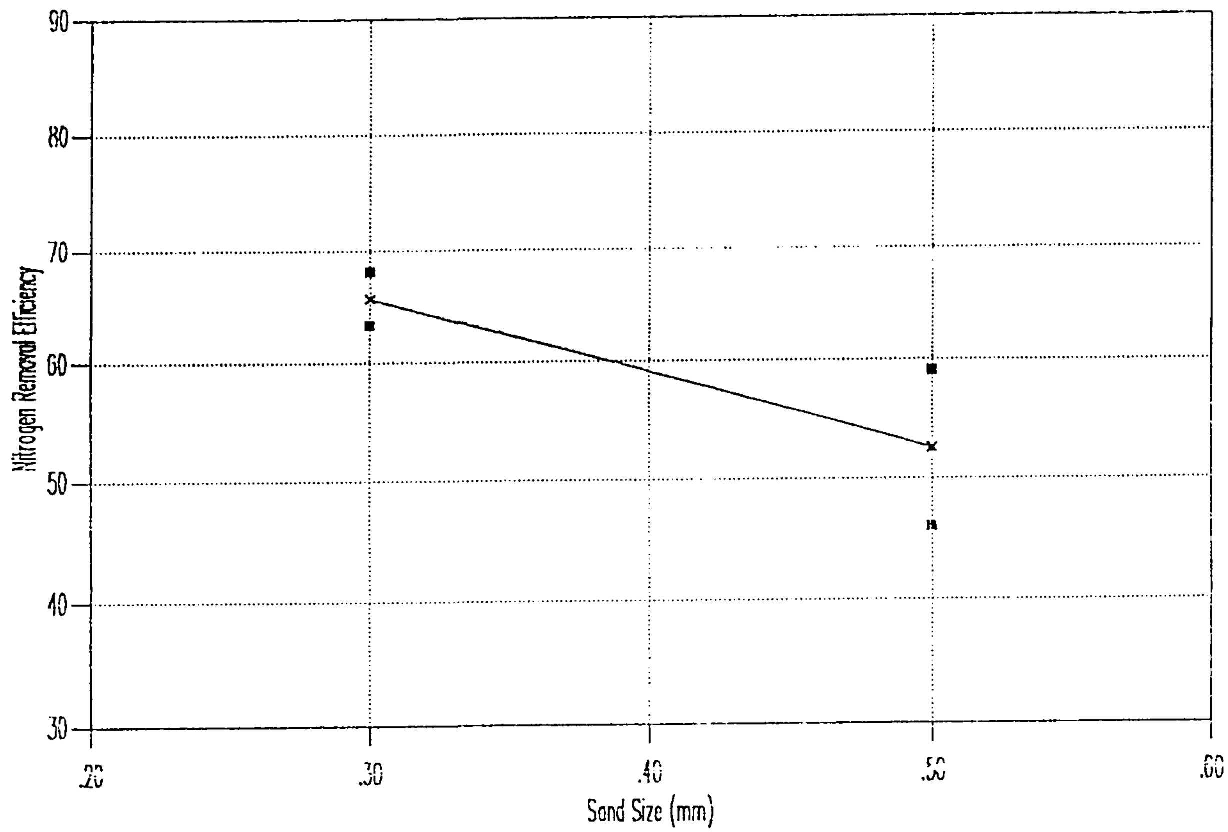


Figure 5.74: Effect of Sand Size at 150cms Depth on Nitrogen Removal Efficiency in F2 & F3

actual and the estimated value in case of nitrification efficiency, denitrification efficiency and nitrogen removal efficiency ranged from -6.9 to 6.9, -3.4 to 3.4 and -6.5 to 6.5 respectively. From the above it can be inferred that the variation of error is well with in the limits of experimental errors.

d) Correlation between Nitrification Efficiency and Sand Depth in Filter1 & 3:

In order to obtain the effect of sand Depth on NE a correlation between sand depth and NE in F1 and F3 was established. Graphical representation of the obtained points and the fitted line from the model is shown in Fig 5.75 with an R^2 (coefficient of determination) of 0.26. The corresponding value of R (coefficient of correlation) is 0.52. The following model is developed for the removal efficiency.

Nitrification Efficiency = - 0.003 x Sand Depth $^{2.0.}$ + 63.035

e) Correlation between Denitrification Efficiency and Sand Depth in Filter1 & 3

In order to obtain the effect of sand depth a correlation between sand depth and DE in F1 and F3 was established. Fig 5.76 depicts the obtained points and the fitted line from the model with an R^2 (coefficient of determination) of 0.34. The corresponding value of R (coefficient of correlation) is 0.6. The following model is developed for the removal efficiency.

Denitrification Efficiency = - 1.44 x Sand Depth $^{0.5}$ + 86.47

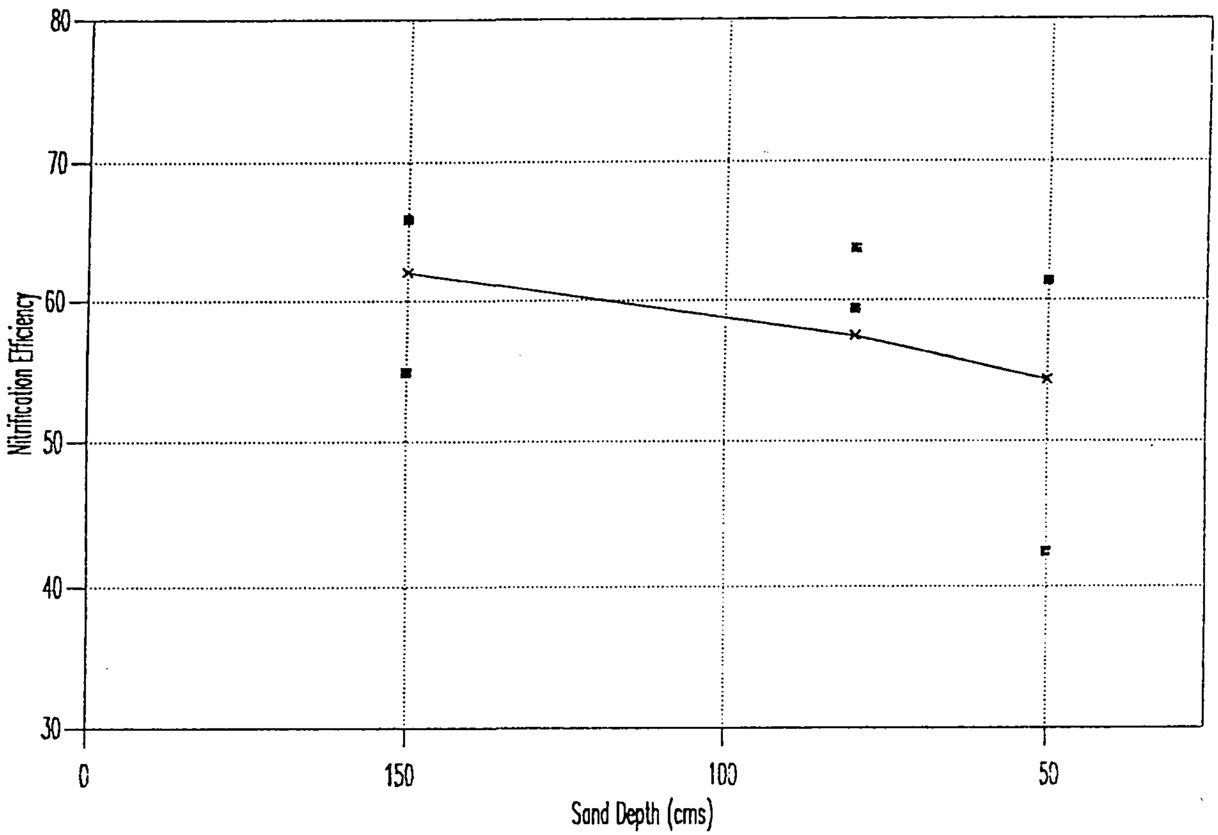


Figure 5.75 : Effect of Sand Depth at 150cms Depth on Nitrification Efficiency in F1 and F3

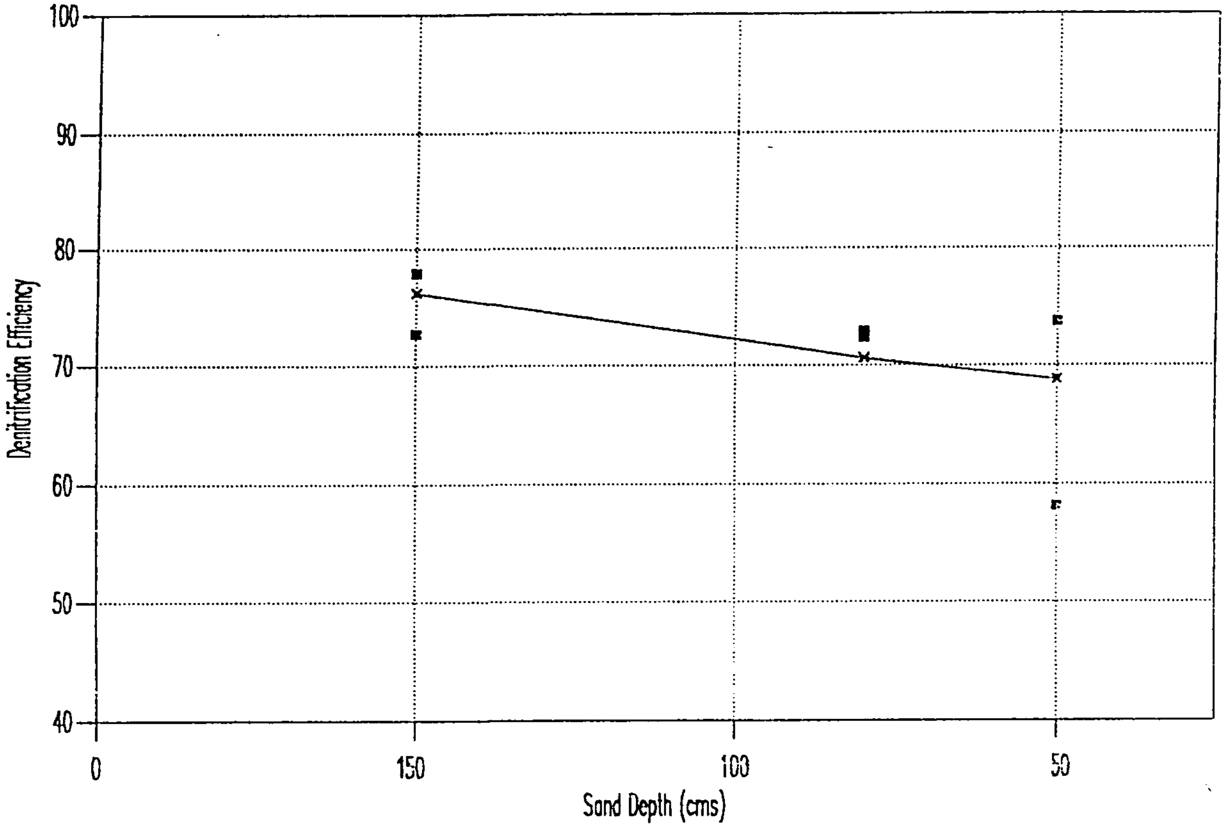


Figure 5.76: Effect of Sand Depth at 150cms Depth on Denitrification Efficiency in F1 & F3

f) Correlation between Nitrogen Removal Efficiency and Sand Depth in Filter1 & 3

In order to obtain the effect of sand depth a correlation between sand depth and nitrogen removal effeiciency in F1 and F3 was established. Fig 5.77 depicts the obtained points and the fitted line from the model with an R^2 (coefficient of determination) of 0.27. The corresponding value of R (coefficient of correlation) is 0.52. The following model is developed for the removal efficiency.

Nitrogen Removal Efficiency = - 0.000003 x Sand Depth $^{3.5}$ + 52.8

From the above correlation's comparing the values of R^2 and R for the effect of filtration rate, sand size and sand depth it can be observed that filtration rate and sand size have a stronger impact on the removal rate than the sand depth. as the values of R^2 and R are higher in the former (flow rate and sand size) than the later case (sand depth).

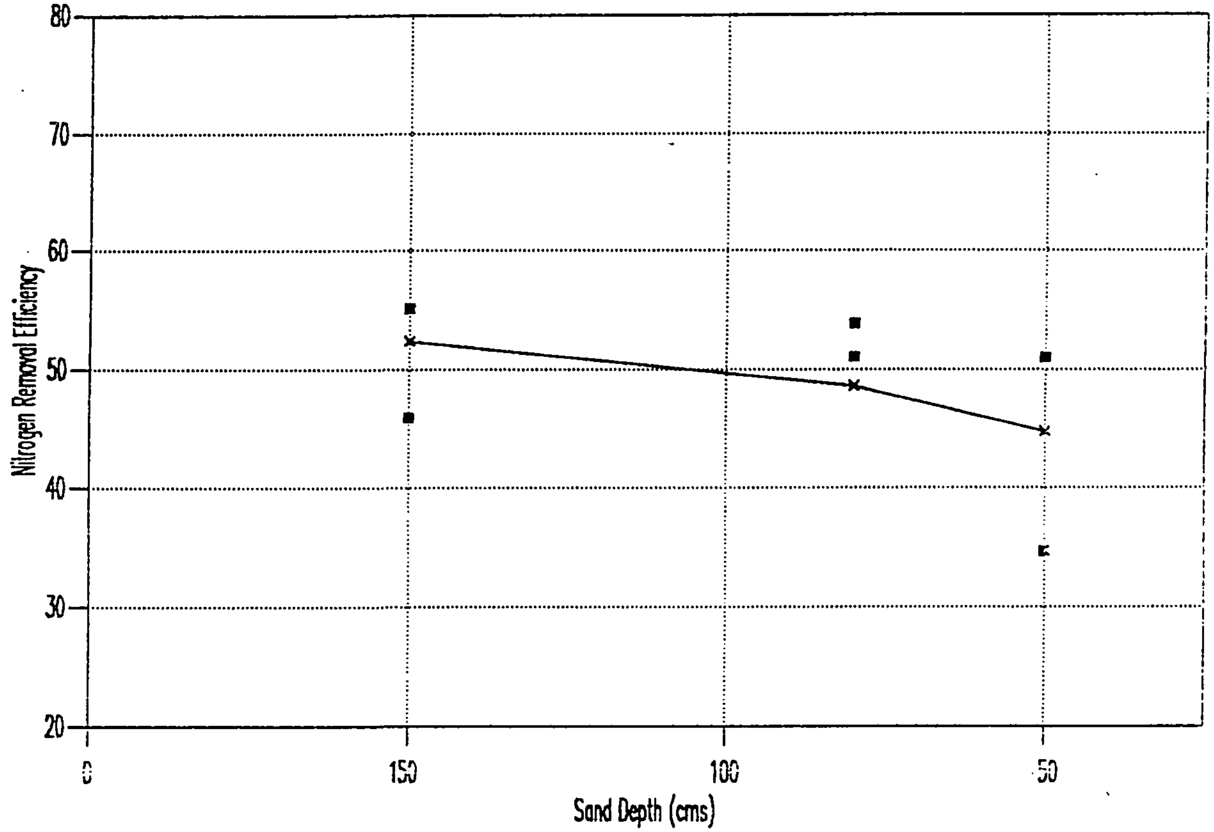


Figure 5.77: Effect of Sand Depth at 150cms on Nitrogen Removal Efficiency in F1 and F3

CHAPTER # 6

6. SUMMARY AND CONCLUSIONS

This study is a field evaluation of slow sand filtration as a tertiary treatment of secondary wastewater effluent at pilot-scale. Three filter units (F1, F2, F3) cylindrical in shape with a diameter of 2m and a height of 3.5m were employed. Two different sizes of media i.e. coarse and fine sand with an effective sand size of 0.5mm and 0.3mm were used in the respective filters. The initial depth of sand bed was 1.5m. All the three filters were operated for about 15 months at three different sand depths (150cm, 80cm and 50cm) and the hydraulic loading range throughout the study was between 0.15m/hr - 0.38 m/hr. The operational mode was constant head, constant rate, the latter was achieved by manual adjustment of the outlet value. The overall filter operation that was performed has been categorized under fourteen conditions (C1 - C14). During these conditions of operations the filters were monitored daily and samples were collected on daily and weekly basis. The specific conclusions that were drawn from the study are as follows.

- Filter 1 consisting of coarse sand has resulted in long duration of runs due to low hydraulic loading rate of 0.15m/hr - 0.19 m/hr compared to Filter 2 and Filter 3 operating at high hydraulic loading rates of 0.3 m/hr - 0.38 m/hr.

- Lot of operational problems were experienced during the filter run and most of it was due to the presence of algae in the filter influent which lead to the clogging of the foot valve and also filter bed which affected in the long filter runs.

- Average removal of SS was higher in F2 consisting of fine sand compared to F1 and F3 with coarse sand indicating that F2 out-performed F1 and F3.

- Average removal of SS in fine sand ranged from 55% to 80% as compared to 21.6% to 51.2% in case of coarse sand.

- It was found that the turbidity data exhibited a substantial scatter due to low influent turbidity values which made the accurate determination of turbidity difficult. The average removal of turbidity in fine sand ranged from 49.5% to 61.7% while in coarse sand they ranged from 37.7% to 62.8%.

- Average removal of BOD and COD in fine sand ranged from 76.5% to 83.4% and 33.4% to 40.4% as compared to coarse sand where the removals were 33.4% to 65.4% and 11.7% to 35% respectively.

- When the flow rates in fine sand and coarse sand were reduced to 10l/min there was no substantial increase in the removals of BOD, NE and DE.

- Average percentage of NE and DE in fine sand ranged from 58.0% to 74.2% and 60.2% to 80.8% when compared to 42.4% to 78.6% and 58.1% to 82.1% in case of coarse sand.
- NE and DE were found to be higher during the top 75cms and 5cms along a sand depth of 150cms and 80cms respectively when compared to the subsequent lower layers of sand bed.
- The effect of flow rate is significant on the percent removal of BOD, NE and DE. It is found that the percent removals dropped with the increase in the flow rate both in case of coarse and fine sand.
- The sand depth also has an effect on the removal rate of BOD, NE and DE. It was found that the removal rate dipped with the decrease in the sand depth.
- Similarly it was observed that the sand size has an significant effect on the removal rate of BODwhile there is no significant effect on NE and DE.
- With increase and/or decrease in the temperature, pH and D O, no correlation with the nitrification and denitrification was observed. Also it was observed that there was no appreciable increase in the D O concentration with the reduction of sand depth and increase in flow rate.
- It is found that the percent removal for all the parameters analyzed are decreasing by decreasing the sand depth and/or by increasing the sand size.

- The filters seemed quite effective and performed better at low filtration rate, smaller grain size and higher sand depth . Thus indicating that sand depth concomitant with flow rates and sand size has strong influence on the removal percentage.

CHAPTER # 7

7. RECOMMENDATIONS

- The nitrate removal efficeincy and other parameters can be studied by adding methanol as carbon source for the removal of nitrate.
- Kinetics of the population of nitrifying and denitrifying bacteria can be studied along the sand depth of the filter.
- Efficiency of nitrogen removal can be studied using dual media having a sand size of 0.3mm and 0.5mm at varying flow rates and sand depths.

CHAPTER # 8

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