Removal of coliphage and bacteria through slow sand filtration

Asad Mohammad Khan

Civil Engineering

December, 1995

Abstract

This study was aimed at evaluating slow sand filtration as a tertiary treatment of secondary wastewater effluents on a pilot scale under field conditions. The wastewater was taken from Al-Khobar Sewage Treatment Plant located in the Eastern Province of Kingdom of Saudi Arabia. Three slow sand filters were constructed at the site of Al-Khobar STP, and these filters were operated in parallel over a period of about one year. Effects of flow rate, sand depth and sand size on percent removal of microorganisms, suspended solids and turbidity were investigated. Four different flow rates of 8, 10, 16 and 20 1/min, three different sand depth of 150, 80 and 50 cm and two different sizes of sand of 0.5 mm and 0.3 mm were used. The data generated over the entire period of operation was grouped under fourteen different operational conditions. Statistical analysis was performed on the entire data using t-test for all the three filters. This statistical analysis was used to find out whether there existed significant satistical difference for the obtained results within the filter and combination with another.

The results of this pilot scale study proved that slow sand filtration is an effective process in the treatment of secondary affluents. The average removal efficiencies of coliphage, coliforms, fecal coliforms, standard plate counts, suspended solids and turbidity ranged from 68-86%, 78-90%, 79-99%, and 82-96%m 22-64%, and 33-62%, respectively, under different filter operational conditions. Statistical analysis concluded that the effect of changing the flow rates between 8 to 22 1/min at constant sand depth and sand size had little or no significant effect on the removal of microorganism, suspended solids and turbidity, except in few cases. The removal of microorganisms were significantly effected when the sand depth was changed from 150 cm to 50 cm. Higher removal efficiencies were obtained at higher sand depths. Little or no significant effect of sand size on the percent removal of all parameters except turbidity were observed. Higher removal of turbidity were achieved when smaller sand size was used.

Removal of Coliphage and Bacteria Through Slow Sand Filtration

by

Asad Mohammad Khan

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

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THESIS ABSTRACT

<u>FULL NAME OF STUDENT</u> ASAD MOHAMMAD KHAN

<u>TITLE OF STUDY</u> REMOVAL OF COLIPHAGE AND BACTERIA THROUGH SLOW SAND FILTRATION

<u>MAJOR FIELD</u> CIVIL ENGINEERING

<u>DATE OF DEGREE</u> DECEMBER, 1995

This study was aimed at evaluating slow sand filtration as a tertiary treatment of secondary wastewater effluents on a pilot scale under field conditions. The wastewater was taken from Al-Khobar Sewage Treatment Plant located in the Eastern Province of Kingdom of Saudi Arabia. Three slow sand filters were constructed at the site of Al-Khobar STP, and these filters were operated in parallel over a period of about one year. Effects of flow rate, sand depth and sand size on percent removal of microorganisms, suspended solids and turbidity were investigated. Four different flow rates of 8, 10, 16 and 20 l/min, three different sand depths of 150, 80 and 50 cm and two different sizes of sand of 0.5 mm and 0.3 mm were used. The data generated over the entire period of operation was grouped under fourteen different operational conditions. Statistical analysis was performed on the entire data using t-test for all the three filters. This statistical analysis was used to find out whether there existed significant statistical difference for the obtained results within the filter and combination with another.

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MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
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Date: December, 1995.

اسم الطالب : أسد محمد خان

عوان الرسالة : ازالة فيروس كوليفيج والبكتيريا بالترشيح الرملى البطى

التخصص : الهدسة المدية

تاريخ : ديسمبر ١٩٩٥م

تهدف هذة الدراسة الى يقتيم الترشيح البطى بالرمل كمعالجة من الدرجة الثالثة للمياة العادمة ذات الرتبة الثاوية على مقياس ارشادى تحت الظروف الميدانية. أخذت المياة العادمة من محطة تفية المياة العادمة بالخبر (المطقة الشرقية – المملكة العربية السعودية). أشئت ثلاث مرشحات رملية بطئية في موقع محطة تفية المياة العادمة بالخبر, وتم تشغيل هذة المرشحات على التوازي في فترة سة تقريبا, حيث بجث تاثير كمية التدفق, وسمك الرمل و حجمه على ازالة الكائات المجهرية و المواد الصلية العالقة و عكورة المياة. كات كميات التدفق المبتعملة هي ٨،١٠،١٦،٢٠ لتر/دقيقة, بيما كان سمك الرمل ١٥٠،٨٠،٥٠ سم, في حين استخدم حجمان لجبيات الرمل هما ٠,٣،٠,٥ مم وقد رتبت المعلومات الاتجة خلال فترة التشغيل الى أربع عشرة مجموعة حسب ظروف التشغيل المختلفة وأجرى تحليل اخصائى على كافة المعلومات الاتجة باستخدام اختبار (t) للثلاثة مرشحات، و ذلك اكتشاف أى اختلاف احصائى له مغزى من التائج المستقاة في المرشح وحدة و بين مرشح و الأخر.

تائج هذة الدراسة على مستوى المقياس الارشادى أثبتت أن الترشيح البطئى بالرمل عملية فعالة فى معالجة المياة العادمة ذات الرتبة الثاوية. وقد كات معدل كفاوة الازالة لفيروس كوليفيج، البكتيريا كوليفورم، البكتيريا البراز، لعدات الطبق المونجية، للمواد العالقة الصلبة و العكورة في مدى ٦٨–٨٦٪،٧٨–٩٩٪،٨٢–٩٦٪، ٢٢–٦٣٪ و ٣٣–٦٢٪ على الترتيب تحت ظروف تشغيل المرشح المختلفة. و يستخلص من التحليل الحصائى أن تغير التدفق بين ٨، ٢٠ لتر/دقيقة مع بقأ سمك الرمل و حجمه ثابتين له تأثير معوى قليل او معدوم على اذالة الكائات المجهرية، والمواد العالقة الصلبة والعكورة – باستثأ حالات المحدودة. ولكن اذالة الكائات المجهرية تأثرت معويا عدما تغير سمك الرمل من ١٥٠سم الى ٥٠سم. تم الحصول على كفالات اذالة أعلى عدما كات سماكات الرمل اكبر. ولم يلأحظ أى تاثير ذا مغزى لتغير حجم حبيبات على سبة اذالة المتغيرات السابقة فيما عدا اذالة العكورة، حيث ازدادت سبة اذالة العكورة عدما استمل رمل ذو حبيبات صغرى.

درجة ماجستير

جامعة الملك فهد للبترول و المعادن

الظهران ، المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

The reuse of wastewater is a valuable economical source of water in arid country such as the Kingdom of Saudi Arabia. In recognition of the importance of conserving its water resources, the Kingdom has planned in its Third Five Year Development Plan to recycle 730 million cubic meters of wastewater per year by the end of year 2000. Major uses of this reclaimed water will be for agriculture and landscape irrigation. The Ministry of Agriculture has set the effluent standard for unrestricted irrigation, stipulating BOD, total suspended solids, and NO_3-N concentrations of less than 10 mg/l, and fecal coliform 7-day average values of 2.2 MPN per 100 ml with no sample above 23 MPN per 100 ml in any 30 days period.

The major concern in wastewater reuse is related to health aspects. Although properly operated wastewater treatment plants employing chlorination as a final disinfection stage can reduce pathogens concentrations by many orders of magnitude, it is till virtually impossible to assume complete elimination of pathogens. Many studies have corroborated the presence of viruses in chlorinated secondary effluents that met the coliform standard. This combined with the infections potency of viruses and their ubiquity in wastewater

necessitates further treatment of wastewater particularly when reuse in under consideration. Since viruses are effectively removed by soils, sand filtration is thus a viable process.

Slow sand filtration is a process widely used in Europe for purification of potable water. Recent evidence has documented the amenability of secondary effluents to tertiary treatment by slow sand filters. In contrast to rapid sand filters which operate 25-150 times faster than slow rate filters, and require extensive pretreatment, slow sand filters can be operated without pretreatment. The major drawback of this process is its excessive land requirement, which is not a critical issue in the Kingdom. It offers the advantages of simplicity of design and operation, performance reliability and inexpensiveness.

A very limited information of evaluation of slow sand filters in arid region like Saudi Arabia is presently available. The previous works investigated the removal of microorganisms and other pollutants at laboratory level in pilot studies. The present study evaluated the slow sand filters at pilot scale under field conditions. The influence of important process variables like flow rate, sand depth and sand size on filtration efficiencies were investigated in the present work.

CHAPTER 2

LITERATURE REVIEW

2.1 SLOW SAND FILTERS

Traditionally slow sand filtration units are used for the treatment of drinking water. Its first application dates back as early as the first half of the 19th century [28]. Their exceptional performance in removing microbial contaminants from raw waters used for public supplies is well documented in the literature [28-33,35]. Most notable Poynter and Slade [22] observed poliovirus 1 and coliform removals over 99.9% and Bellamy *et al.* [3,4] report Giardio cyst and coliform removals of 99.98% and 99.01%, respectively. Unfortunately, published research work regarding application of slow sand filtration to waste water effluents is very limited [35,36].

Earlier work [37-39] on the subject revealed BOD and suspended solids removals of 3- and 60-65%, respectively, and over 95% of coliform bacteria from the settled effluent of an operational trickling filter plant. The minimum BOD and suspended solid removals were slightly inferior when secondary effluent from an operational activated sludge plant was used. Apparently, no results are reported in the literature on the removal of viruses through slow sand filtration of waste water effluents.

Slow sand filtration is basically a passive filtration process which requires very little attention for operation. Its major difference from rapid sand filters is the rate of filtration. The filtration rates in rapid filters are 20-150 times faster than those of slow filters [28]. Hence, the land area requirement of slow sand filters are much larger than rapid filters. However, the large area requirement of the former is partially offset by elimination of the pre-treatment units (e.g. coagulation, flocculation, and sedimentation) required in the latter. More importantly, a slow rate of filtration leads to drastically different filtration behavior than that of faster rate. During regular operation of a slow sand filter biological growth occurs within the filter bed. Also, a layer of solid deposits and biological material forms on the surface of the bed. This layer is referred to as "Schumutzdecke", a German word meaning dirt-layer. Both the Schumutzdecke and the biological growth within the bed play an important role in the performance of slow sand filters. They may require several weeks to develop, a period referred to as the "ripening period" of the filter. The conditions in the filter are unsuitable for the multiplication of intestinal bacteria. They do not live long as the filter does not contain enough organic matter to meet their nutritional requirements. In addition, may types of predatory organisms (such as protozoa) are usually present in the upper parts of the filter. Furthermore, it is suspected that microorganisms in a slow sand filter produce various substances that act as chemical or biological poisons to intestinal

bacteria [28]. This is how substantial removal levels of microbial contaminants are realized. At lower temperatures the activity of bacteria consuming protozoa drop sharply while the metabolism of the intestinal bacterial slow down, thereby increasing their chance of survival [28].

As filtration progresses, naturally, head losses due to clogging builds up in the bed. When the head loss reaches the allowable limit the filter has to be cleaned. The cleaning process of slow sand filters is radically different than that of rapid filters. Rapid sand filters are cleaned by back washing of the bed in the reverse direction, whereas in slow sand filters the cleaning process covers the removal of Schumutzdecke by scrapping 2-4 cm from the surface of the sand bed. Hence, a gradual decrease in the depth of sand takes place in slow filters. When the minimum sand depth is reached (e.g. 50 to 60 cm) the bed has to be resanded. The frequency of cleaning depends mainly on the influent characteristics and the rate of filtration an can be in the order of several months. The scraped sand can be discarded or washed and stored for future use. The amount of water required for washing is around 0.2 to 0.6% of the water filtered which compares very favorably with the corresponding values of 1 to 6% for back washing of rapid sand filters [41]. Incidentally, back washing of rapid sand filters result in a natural gradation of the sand with smaller grains in the upper part of the bed, upon the resumption of normal operation. As a consequence, the upper parts of the bed clog more easily and head losses reach

the allowable limit before an effective use of the whole sand bed is realized. In slow sand filters, however, there is no such adverse stratification as there is no back washing. In summary, the operational requirement of slow sand filters covers two periodic tasks:

1. Removal of Schmutzdecke
2. Replacement of sand

Throughout the years slow sand filters were criticized for their:

1. large land area requirement,
2. low efficiency at low temperatures,
3. unsuitability for highly turbid waters

In spite of the above, many developed countries, with the exception of the USA, have recently constructed (or are under construction) slow sand filters for public water supplies [28]. In London, for example, the area employed by slow sand filters covers 72 hectares [30]. It should be observed that the above criticisms are not valid within the context of this proposed study. This is simply because the first two do not apply to Saudi Arabia, while the third is of no concern by virtue of the characteristics of secondary effluents. Added to this are the following advantages of the slow sand filters:

1. stable and effective suspended solids and microbial removal
2. low cost of construction
3. simplicity in design (i.e. little pipe work and instrumentation)

4. minimal operational problems and skilled labor requirements.

In view of the above discussion and within the framework of the need for, and keen interest directed to, water conservation in Saudi Arabia slow sand filtration offers itself as an appropriate tertiary treatment process. Hence, a study covering its evaluation at pilot scale under the field conditions seems well justified.

2.2 INDIACTOR ORGANISMS

Much concern and studies have been directed towards the survival of enteric viruses during sewage treatment. Disease causing human enteric viruses are usually present in domestic sewage. Due to their small size, enteric viruses have the potential of passing even small pores and contaminate the ground water. Because of difficulty in their isolation and enumeration coliphages have been used as indicator of enteric viruses by many investigators. Detection of levels of bacteriophages (i.e. bacterial viruses) in water and wastewater has been recommended by some investigators as being a sensitive, convenient, economic, and reliable index of water contamination of sewage containing pathogenic enteric bacterial and viruses, and as a useful epidemiological tool in tracing the origins of waterborne microbial diseases.

Coliforms are considered as the indicator organisms of bacterial and viral pollution by many authors. The indicator coliform most often used is a group

of microbes which are organisms normal to the digestive traces of warm blooded animals. It is observed that coliforms are plentiful, hence not difficult to find. They are found to survive longer than most known pathogens. That is why coliforms have become universal indicator organisms.

Many studies have been conducted on routine monitoring of recreational waters for the purpose of detecting the presence of fecal wastes which may, in turn, contain certain pathogenic bacteria, viruses and other microorganisms. Recent American epidemiological investigations [6, 9], which attempted to related public health risk to levels of fecal bacterial indicators such as *Escherichia coli* and *enterococci*, demonstrated a positive correlation between the two. Palmateer *et al.* [24] reported a high degree of correlation between levels of coliphage and fecal coliforms in two highly polluted beaches in Scotland, however, the correlation was low on less polluted beach.

The standard plate test counts attempt to provide a single standardized means of determining the density of aerobic and facultative anaerobic heterotrophic bacteria in water. This measurement can be a valuable criterion for detecting water quality deterioration in supply distribution lines and storage reservoirs and for indicating the magnitude of excessive bacterial populations. The EPA's primary drinking water standard specify that public water supplies provide a potable water with not greater than 500 organisms per ml as determined by the standard plant count.

2.3 COLIPHAGE AS AN INDICATOR OF VIRAL POLLUTION

For public health safety microbiological water analysis has become the prime step. The analysis is mainly done by testing for possible faecal pollution as human and animal feces are the main source of water borne disease. It is experimentally proven that there are some microorganisms which coexist with pathogens. It was suggested that these microorganisms can serve as the indicators of various pathogens. Because the pathogens appear in low concentrations and their detection needs more dependable and broader base, the idea of using microorganisms as indicator for pathogens has become more a fact.

Over many years *E.coli* and faecal *streptococci* were used as indicators for viral pollution. But there have been cases when epidemics have occurred even when these indicators were removed fully from the effluents. In 1974, this idea led some authors to suggest that coliphages might serve as indicators of faecal pollution.

Borrego *et al.* [5] developed a highly specific, sensitive and rapid technique for detection of *E.coli*. The numerical relationship between *E.coli* and its parasitic phages was investigated in three different aqueous ecosystems such as seawater in the vicinity of sea outfalls, river water contaminated by domestic and industrial sewage discharges, and estuarine waters, and fond to be very close. The result of the study have indicated that coliphages are good

indicators of the presence of the pathogenic microorganisms.

Ratto *et al.* [26] conducted a study in Lima, Peru, in which twenty samples were analyzed for coliphage content from five different sources. It was found that in 47% of the samples, coliphage were the only indicator organisms present. The presence of coliphage in these samples suggested that there is a high probability that human pathogenic virus can survive the conventional treatment processes.

It has been experimentally proven that coliphages will spread only wherever *E.coli* bacteria are found and it is because of this fact that coliphages serve as pollution indicators. MS2 and f2 are considered as reference bacteriophages as these two are found to be resistant to adverse environmental conditions and chemicals.

2.4 REMOVAL OF BACTERIA & VIRUSES THROUGH FILTRATION

Work conducted by Robeck *et al.* [27]) confirmed the ability of slow sand filters to reduce titres of poliovirus 1 by 83 - 98 percent. Lower flow rates were found to provide greater efficiencies of poliovirus removal. However, removals were still relatively low (69 per cent) at moderate conventional flow velocities, i.e. 0.15 m/h.

Detailed work was conducted by Poynter and Slade [23] over a period of years using perspex slow sand filter columns of surface area 0.99 m^2. At

flow rates of 0.2 - 0.5 mh^{-1} and water temperatures of 5 - 18°C, reductions in bacteria and viruses were as follows: poliovirus 1 : 98.25 - 99.99 per cent, *Escherichia coli:* > 88.0 - > 98.7 per cent, 37°C colony count: 81.2- 93.7 per cent, and 22°C colony count: 94.5 - 98.4 per cent. The effect of flowrate and sand depth on efficiency suggested that to a certain extent, a reduction in efficiency caused by higher flow rates might be mitigated by increasing sand depth. The observation that reductions in poliovirus 1 titres were consistently similar to or greater than reductions in *Escherichia coli* densities led to the conclusion that the mechanism of removal was essentially similar, and was predominantly biological.

Cleasby *et al.* [7] investigated three parameters of filtrate quality, i.e. turbidity, particle counts, and total coliform counts. Results indicate when raw water quality is good, slow sand filtration performs better than in-line filtration operating with alum or cationic polymer as a coagulant. Also, it was found that to judge the raw water acceptability for slow sand filtration, enumeration of algae is essential. Also, the study included a part on transmission of *Giardia cysts* by public water supplies.

Bellamy *et al.* [3-4] conducted a study in two phases. Phase I investigated the effects of filter biological aging, schmutzdecke development, and hydraulic loading rate. The percentage removal of total coliform bacteria evaluated the effectiveness of filter's response to test conditions. It also

demonstrated that the state of the biological community within the filter significantly influenced filter effectiveness. Percent removals of total coliform bacteria were greatest (e.g. 97.6 - 99.996 per cent) when the filter had a mature biological population. These removals decreased by a factor of 10-100 after removal of the schmutzdecke and replacement of the sand, respectively. In Phase II it was shown that bacterial removal is not overly sensitive to sand bed depths in excess of 1.57 ft (0.48 m). In practice this means that a series of schmutzdecke removals, with the resulting attrition of sand bed from 3.2 to 1.6 ft (1 to 0.5m), will not seriously impair the efficiency of the filtration process. It has also been shown that increase in treatment efficiency occurs with decrease in sand size. Coliform removal improved from 96.0 to 98.6 to 99.4 per cent for effective sand sizes of 0.615, 0.278, and 0.128 mm, respectively. The data reported is the average of 18 test runs for each filter. About removal mechanism, straining and adsorption were considered plausible.

Gross and Mitchell [16] determined the removal of viruses by sand filtration where effluent of septic tank was used. It was found that most of the viruses were retained in the top 25.4 cm layer of coarse sand, and any viruses that pass through the biological layer are adsorbed onto the fine sand or glass sand. The filter effluent was virus-free.

A pilot study was conducted by Farooq *et al.* [15] over a period of one year using the secondary treated effluent from North Aramco Wastewater

Treatment Plant, Dhahran. The study was conducted at a flow rate of 0.16 m/hr to determine the slow sand filtration process efficiency. Samples were collected routinely from influent and effluent of the filter. The influent standard plate count levels throughout the routine runs ranged from 3×10^3 to 2.95×10^4 colonies per ml, whereas the effluent levels ranged from 3×10^2 to 2.6×10^3 colonies per ml giving the removal of 90 to 91.15 percent.

2.5 REMOVAL OF TURBIDITY

Turbidity is one of the most important parameters for monitoring the performance of a filter. It is believed that turbidity serves as a carrier for nutrients that result in biological activity.

Suhail [40] used rapid sand filtration which is also widely investigated as a tertiary treatment for the secondary effluent at bench scale level. The process employed for this study was a conventional filtration system consisting of chemical mixing, flocculation, sedimentation, sand filtration disinfection. He reported that the overall percentage of turbidity removal ranged from 77% to 92%. Sawaf [30] also investigated the treatability of secondary effluent using direct filtration with some chemical mixing dual-media filtration and chlorination. He found that the average turbidity removal ranged from 75% to 90%. He also investigated the removal of turbidity without chemical addition and found the effluent turbidity exceeded 1.0 NTU with percentage removal

averaging between 28% and 39%.

Farooq *et al.* [15] conducted a study for about a year on slow sand filtration of chlorinated secondary effluents at a hydraulic loading of 0.16 m/h and found that the effluent turbidity levels ranged from 0.08 to 0.43 NTU. The percentage removal ranged from 87 to 95%. They also found out that larger depth of sand is better for the removal of turbidity. Al-Adham [1] also reported that the per cent turbidity removal was 88% for sand size of effective size 0.23 mm and depth 84 cms during the treatment of secondary effluent from the North Aramco Wastewater Treatment Plant at a hydraulic loading of 0.16 m/h. Cleasby *et al.* [7] conducted a study on surface water treatment by slow sand filter diameter of 0.76 m, and changed with 0.94-m-deep sand bed (effective size of 0.32 mm). The filters were operated from October 1981 until December 1982. During this period 11 filter runs ranging the length from 9 to 123 days were conducted. The reported average turbidity removal was over and produced water well below 1 NTU in all filter runs even during the first two days of the run. The turbidity of the last seven runs, conducted in May to December 1984, averaged near 0.1 NTU. He noticed that the filter performance gradually improved throughout the series of run, with respect to turbidity particle counts total coliform bacteria and chlorophyll. He also concluded that just using turbidity measurements, to predict filter run length are not adequate. The concentration of algal cells had a strong influence on run

length.

2.6 REMOVAL OF ORGANIC MATTER

For many years there has been concern about the organics in fresh water and sewage effluents. In wastewater the impurities are present in the form of dissolved matter. Sand filtration systems have long being recognized for organics removal. Andredakis [2] conducted a study for the removal of organic matter from wastewater using a system consisting of a upflow gravel filter, and a sand filter (SF) and s soil column (SC). The influent water had BOD_5 and suspended solids (SS) concentration of about 70 and 300 mg/l. It was found that the upflow gravel filter gave BOD_5 removal efficiency between 24 and 69%. The suspended solids removal varied from 23 to 49% with an average value of 39%. The removal efficiency did not depend on the hydraulic loading or the sewage strength. The BOD_5 removal efficiency depended on the permeability of sand.

Ellis [11] conducted a study using grass plots for the tertiary treatment of sewage. In this experiment the secondary effluent was run on top edge of the plot from feed channel or a sprinkler system and slowly percolated through the grass to be collected by a parallel channel at the bottom. He found the grass plots removal between 60% and 70% of the SS from the influent together with 50% and 60% of the BOD. The efficiency of 82% SS removal and 83%

BOD removal was achieved together with 49% reduction of ammonia and 12% nitrates.

Ellis [14] conducted a study treating secondary effluent derived from aerobic biological treatment processes using slow sand filtration with an effective size of sand of 0.3 and 0.6 mm operating at 3.5 m/d and 7.0 m/d at different stages. He observed that the slow sand filtration was capable of removing more than 70% of BOD, 88% of suspended solids, 50% COD and 97% removal of coliforms organisms. He also observed that the removal rate of BOD, COD ad suspended solids dropped when the rate of filtration was doubled but the removal rate of coliforms improved from 96% to 99% in the faster filter.

Al-Adham [1] used slow sand filtration as a tertiary treatment of municipal sewage and found out that with a hydraulic loading of 0.16 m/h a removal of 89% of BOD, 69% of SS, 88% of turbidity and 99% of total coliform bacteria was achieved. Farooq *et al.* [15] conducted a pilot study using slow sand filtration with effective sand sizes of 0.31 mm and 0.56 mm and have found that the fine sand achieved better percentage removal of BOD and COD. They achieved a percentage removal of 79 to 92% in case of BOD and from 50 to 67% of COD. They also found out that the removal efficiency is dependent upon sand depth.

2.7 EFFECT OF PROCESS VARIABLES ON FILTER PERFORMANCE

Generally, the literature published on slow sand filtration is limited. Moreover, most of the literature available is related to filtration of potable water. Studies on experimental and pilot plant models as well as full-scale water treatment plants showed excellent performance, especially in terms of SS and microbial contaminants.

Bellamy *et al.* [3] conducted pilot plant studies to determine the efficiency of slow sand filters in removing Giardia cysts in particular and other substances. They reported that Giardia cyst removal exceeded 98% for all operating conditions tested. Once the sand bed matures biologically will be virtually 100 per cent. Coliform removal exceeded 99 per cent, averaged over all operating conditions. For new sand, coliform removal reached 85 per cent. Removal of standard plate count bacteria and particles ranged from 88 to 91 per cent and 96 to 98 per cent, respectively.

Bellamy *et al.* [4] conducted a research to determine the influences of selected process variables on the treatment efficiency of slow sand filtration. Their findings are summarized below.

Temperature: The slow sand filters removal efficiency decreased with declining the ambient temperature in terms of coliform and standard plate counts bacteria. However, Giardia removal efficiency was insensitive to temperature variations.

Sand Bed Depth: The results showed that the bed depth can be reduced to 48

cm without significant effect on the bacteriological quality of the filtrate.

Sand Size: When the effective sand size of the sand bed was increased, insignificant decrease in removal efficiency was reported on both coliform and standard plate counts. Giardia removal was again insensitive to sand size variation.

Hydraulic Loading Rate: Basically speaking, there was an apparent decrease in removal efficiencies of total coliform, standard plate counts bacteria, and turbidity with an increase in the hydraulic loading. However, it was reported that within the range studied the difference was not substantial.

Filter Medium: The filter bed may employ any inert, granular material as a filtration medium with sand being mostly selected because of its turbidity, inexpensiveness, and wide availability. Sand used in slow sand filtration should be relatively fine with an effective size of 0.15-0.3 mm and a uniformity coefficient below 3. Collins *et al.* [8] reports that the Ten States Standards [42] recommend sand with an effective diameter of 0.3-0.45 mm compared to the 0.15-0.3 mm recommended by International Research Council [20]. Filter media that are sized too large will increase the potential for particle breakthroughs and 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. Ellis [13] indicated that it is better to use deeper beds than to reduce grain size if an additional margin of

safety is required.

Flow Control: Controlling the filtration rate is the key to proper functioning of a slow sand filter. For surface water operation at a rate of 0.1-0.2 m/h which may increase to 0.3 m/h for short periods is usually satisfactory. Research reported by Bellamy *et al.* [4] showed that for a filter having a mature biomass within the bed depth, removal efficiencies exceeded 99.9% for total coliform bacteria and Giardia cysts regardless of the filtration rate in the range of 0.04-0.4 m/h. Visscher [43] reported that in Amsterdam, where slow sand filtration is one of the last treatment steps, excellent product water is produced at a filtration rate of 0.6 m/h.

2.8 MECHANISMS OF SLOW SAND FILTRATION

The purification achieved in a slow sand filter may be considered to be principally the result of straining through the developed filter skin and the top few millimeters of sand, together with biological activity. However, Huisman, [19] suggested mechanical straining, sedimentation, adsorption, and chemical and biological activity as the important process of slow sand filtration, [13].

Sedimentation and Straining:

Sedimentation and straining take place usually during the first few days of operational. The supernatant water above the sand bed is about 100 - 150 cm deep, depending upon the design of filters. The average time that the

sample remains above the sand bed ranges from 3 to 12 hours, depending upon the filtration ate. The heavier particles of suspended matter start to settle while the lighter particles are drawn into the pores between the sand grains and removed by straining on the top few millimeters. During the filtration process, a layer of inert deposits and biological matter forms on the top layer of the sand bed. This layer is refereed to as Schmutzdecke. Moreover, biological growth also occurs within the sand bed and within the gravel support. Both the schmutzdecke and the biological growth have significant effect in the purification mechanism [15].

Chemical and Bacteriological:

On the surface of the sand, there is a thin layer of material, schmutzdecke, which consists of thread like algae and numerous other forms of life including plankton, diatoms, protozoa ratifiers, fungi, bacteria, nd actinomycetes, some of which may also live several centimeters below the sand surface. When the water passes through this layer, nearly all the suspended matter and bacteria are removed. Some of the coloring matter and organic matter are also removed through this layer. The impurities stick to the bacterial slim and are subsequently broken down by biochemical action. The bacteria which were present in the same are caught up in the schmutzdecke, since the amount of organic matter may not be sufficient to support the bacteria that may, in turn, slowly die out or may be eaten up by protozoa. Accordingly, some of

the living organisms feeding upon bacteria are also affected. As a result, some additional organic matter is also available from the dead organisms as a feeding for bacteria at lower depths of sand. This feeding is depleted at lower depths. In other words, the original degradable organic matter present in the same is gradually broken down and discharged with the effluent as inorganic compounds such as nitrates, sulfates, phosphates and carbon dioxide [15].

2.9 EFFECTS OF ALGAE

Some forms of algae have significant effect on the working of a biological filter. These effects may be beneficial or harmful depending on a variety of conditions. The algae may enter the filter along with the influent drawn from the reservoir or develop directly in the filter as a result of certain nutrients, (particularly nitrates and phosphates) and under the influence of sunlight.

The major adverse effects of algae on the operation and efficiency of a slow sand filtration are:

- early blocking of the filter
- increase difficulties associated with filter cleaning
- increase in concentration of soluble and biodegradable organics.

Other changes would also occur as a result of the presence of algae. For example, during the photosynthetic activity of algae, inorganic carbon sources

as dissolved CO_2, bicarbonate and carbonate are used for anabolic processes. This both reduces the natural buffering capacity and produces hydroxyl ions. As a result of this, the pH would increase (up to pH 10, or even higher). As a consequence, magnesium hydroxide and calcium hydroxide are precipitated onto the sand grains. Algae are able to produce oxygen in relatively large quantities as a result of photosynthesis [15].

$$CO_2 + 2H_2O + \text{sunlight........} \ CH_2O + O_2 \ H_2O$$

The dissolved oxygen content would rise to as much as three times the theoretical saturation level during the day time [18]. However, the reverse reaction will occur during the night time. The rate at which algae consume oxygen from the water may only be 10 to 15% of the rate of their production during the day. The presence of high concentration of algae may cause anaerobic biological activity and in turn produces tastes and odors [13].

Algal growth in filters is not totally disadvantageous. At moderate concentrations, they help in building up the filter skin. They also perform a useful service in providing the water with oxygen. The algae themselves, according to some investigations, produce substances harmful to bacteria, thus reducing their chances of survival. At high concentrations, however, they should be controlled by using one or more of a number of possible techniques. Both chemical and physical methods may be employed. Physical controls include harvesting the algal blooms from water surface periodically.

Configuration is the most rapid and simple means of harvesting; however, it is costly. A more realistic approach is autoflocculation, which occurs in shallow ponds when the pH becomes above 9.5. The flocs settle out and can be recovered in the same method used for sludge collection [22]. Covering both the filter and the fed reservoir is another means to control algal blooms. Chemical controls include prechlorination, preozonation, or addition of copper sulfate to the water [13]. Chlorination of the supernatant water has been attempted, usually employing low chlorine concentrations 0.2 to 1.0 mg/l, but studies showed that even prechlorination resulting in total chlorine residuals of 0.8 mg/l, prolonged the filter run without affecting the treatment process. This is probably due to the prevention of algal growth in the supernatant reservoir [21, 44].

2.10 OBJECTIVES OF THE STUDY

The main objective of this study was to evaluate slow sand filtration as tertiary treatment of secondary wastewater effluents at pilot level under field conditions.

The specific objectives can be summarized as follows:

1. *Study the Effects of Flowrates:*

Four different flowrates (i.e. 8, 10, 16, and 20 l/min)were studied regarding removal efficiencies of various microorganisms, and pollution

parameters such as coliphage plaque, total coliforms, fecal coliforms, standard plate counts, suspended solids and turbidity.

2. *Study the Effects of Sand Depth:*

Three different sand depths of 150 cm, 80 cm, and 50 cm were studied to investigate the removal of microorganisms, suspended solids (SS) and turbidity.

3. *Study the Effects of Sand Size:*

Two different sizes of local sand were used to investigate the removal efficiencies of microorganisms along the sand depth by collecting effluent samples at various depths of the sand bed.

4. *Study the Removal of Microorganisms:*

To study the removal of microorganisms along the sand depth.

5. *Statistical Comparison:*

To study statistical comparison of removal efficiencies of microorganisms, SS and turbidity at different flowrates, sand depths and sand sizes.

CHAPTER 3

EXPERIMENTAL WORK

3.1 EXPERIMENTAL SET-UP

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. Al-Khobar Wastewater Treatment Plant is designed as carousel system capable of treating 35 MGD of raw sewage. The effluent from plant is of good quality and thus, can be utilized for tertiary treatment.

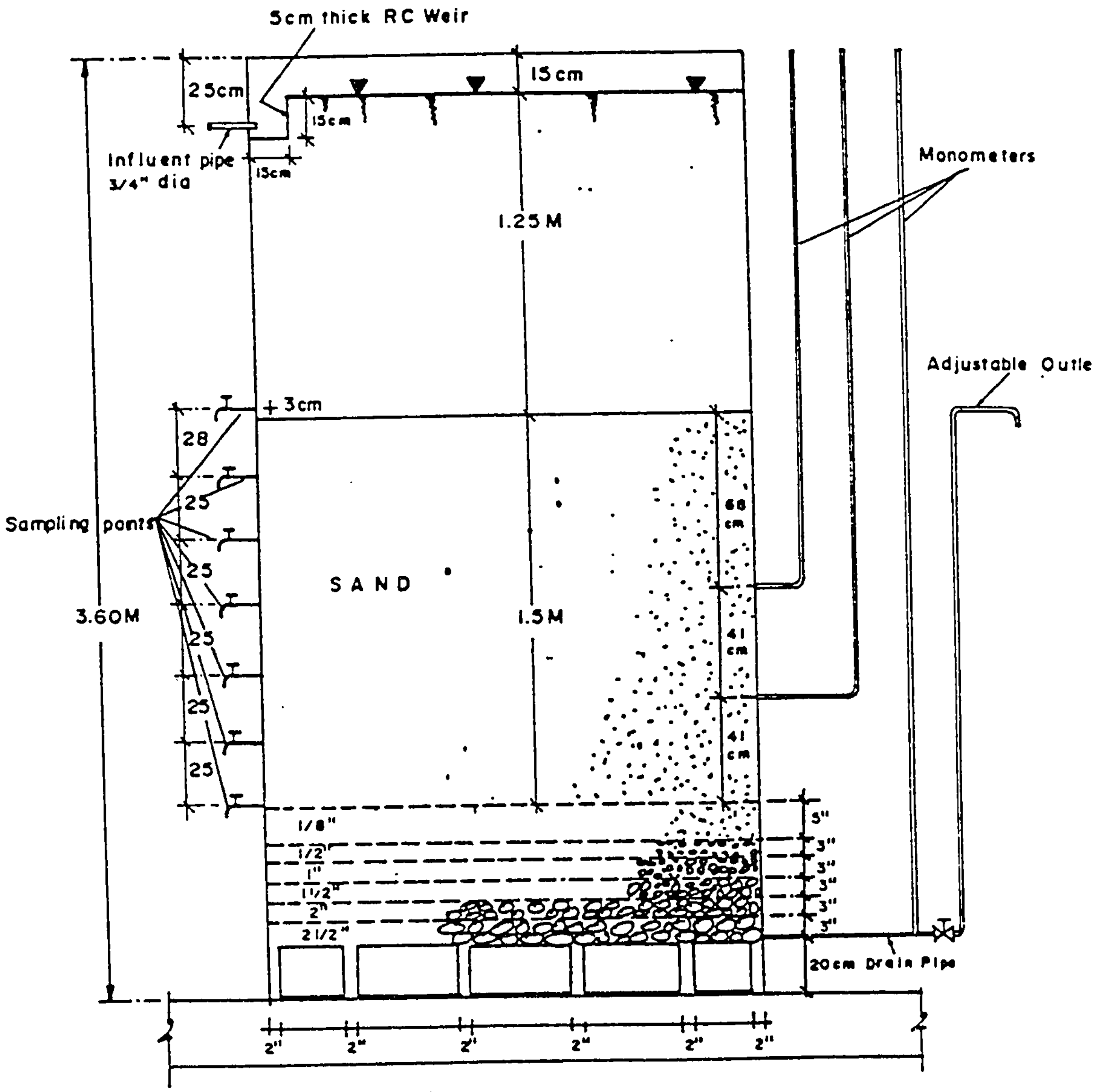
3.1.1 Slow Sand Filter Units

Three units of slow sand filters were constructed at the located site. These filters were operated in parallel. Two of these filters were packed with coarse sand (0.5 mm) and one with fine sand (0.3 mm). This in turn provided flexibility for obtaining sufficient conclusive data under a wide variety of operational conditions. The unchlorinated secondary effluent from the aforementioned plant was received as influent for this study.

3.1.2 Construction of Slow Sand Filters

The three identical filter modules were 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. The 2-m internal diameter, 3.65 m high filter units were constructed of 15 cm thick, 3500 psi reinforced concrete walls with a 1-m 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 minimize disturbance of the supernatant water and subsequent erosion of the sand bed by the feed. Each filter was also fitted with a 1" 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 would be 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 3.56 m. All sampling ports and manometers utilize 1/2" schedule 80 PVC pipes whereas the influent and effluent lines were constructed of 3/4" and 2" schedule 80 PVC pipes respectively. To ensure unimpeded discharge of collected filtrate, the blocks were cemented to the floor 2" apart with the entire pore volume interconnected. To prevent the potential accumulation of particulate mater in the pipe, particularly during breakthrough, the pipe was inverted downwards to a depth of 10 cm below the blocks. To ensure that sand does not clog the underdrain, several layers of supporting reversely graded gravel were provided in sizes ranging from 2½" at the bottom to 1/8" at the bottom of the sand. Figure 3.1 shows the details of the filter bed and supporting gravel.



Plan for Gravel Layers
1:20

Figure 3.1: Details of the Slow Sand Filter.

To preclude the development of negative pressure within the sand bed which could have impeded operation and rendered flawed data, the tip of the 2" outlet pipe from each filter module discharging freely onto the common effluent box was located slightly above the sand surface.

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.

3.2 MATERIALS and METHODS

Sample Collection:

Grab samples were collected in sterilized 300 ml glass bottles both from influent and effluent outlets of the filters. Samples used for microbiological analysis were placed in an ice box with ice packs to maintain the temperature of 4°C. Strict sterilized conditions were maintained throughout collection and transportation of these samples. Separate 100 ml bottles were used to collect the samples for suspended solids and turbidity analysis. Samples for microbiological analysis were collected analyzed on biweekly basis, whereas samples for suspended solids and turbidity analysis were collected on weekly

and daily basis respectively. The samples were immediately brought to the laboratory for analysis.

Sample Analysis:

The analysis of microbiological parameters (i.e. coliphage plaque, total coliforms, fecal coliforms and standard plate counts), suspended solids and turbidity were carried out as prescribed in Standard Methods [38]. *Escherichia coli*, C ATCC No. 13706 was used as host culture for the detection of coliphage (Section 919C) Multiple tube technique (Sections 908A, C) were used for the detection of total coliforms and fecal coliforms. The bacterial density (plate counts) wastewater were determined using Spread Plate (Section 907B) technique. Dilutions of samples were made wherever found necessary, as per the requirement of application of procedures in Standard Methods. Suspended solids were analyzed as prescribed in Section 209C of Standard Methods, while turbidity was recorded using Nephelometric method as described in Section 214A of Standard Methods [38].

CHAPTER 4

RESULTS AND DISCUSSION

4.1 OPERATIONAL SCHEDULE OF THE SLOW SAND FILTERS

Three slow sand filter units were operated in parallel for a period of 15 months to monitor and investigate the removal efficiencies of coliphage, bacteria, suspended solids and turbidity. Filter #1 and Filter #3 were operated with a coarse sand size of 0.5 cm. Filter #2 was operated with a fine sand of 0.3 mm. The provision of two filters, i.e. F1 and F3 with coarse sand size provided a flexibility of collecting the data over a wider range of process variables. All the three filters were operated at four different flow rates, i.e. 8, 10, 16, 20 l/min and three different sand depths of 150, 80 and 50 cm. The entire operation of filters was divided into 14 different operational conditions as given in Table 4.1. Moreover, the different flowrates and sand depths at which filters were operated using coarse sand and fine sand are separately listed in Table 4.2.

During the study the initial flowrates of 8 and 16 l/min were used for the preliminary run to attain bed maturation of the filters. The flowrates of 10 and 20 l/min were used as designed flowrates for the study during the entire period of operation. The objective of the study was to obtain maximum duration of

Table 4.1: Operational Schedule of Slow Sand Filters

Filter Number	Flow l/m	Sand Depth cm	Sand Size mm	Starting Date	Termination Date	Total Days of Operation	Total Days of Suspension	Condition Number
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

Table 4.2 : Grain Size Distribution of Various Process Variables

Sand Size (mm)	Flowrates (l/m) at Sand Depth of 150 cm				Flowrates (l/m) at Sand Depth of 80 cm		Flowrates (l/m) at Sand Depth of 50 cm	
0.5	8	10	16	20	10	20	10	20
0.3	-	-	16	20	-	20	10	20

filter runs without interruption in order to determine maximum flow durations of filter run. Two different sand sizes of 0.3 and 0.5 mm were used. Sand size of 0.3 mm was selected as it is generally recommended in the literature for slow sand filters [4, 8, 13]. Sand size of less than 0.3 mm have indicated frequent filter cloggings effecting the filter runs. Moreover, the larger sand size of 0.5 mm was used as it was locally available. Selection of 0.5 mm was also justified by Farooq and Yousif [15] as it has indicated longer filter runs in the past. The maximum sand depth of 150 cm was used during the study. Sand depths of higher than 150 cm increases the head loss and thus reduces the length of filter runs.

Among fourteen different operational conditions, four conditions (i.e. conditions #1-#4) were operated in Filter #1, five conditions (i.e. conditions #5-#9) were operated in Filter #2 and remaining five (i.e. conditions # 10-#14) were operated in Filter #3.

Condition #1 was operated at 8 l/min of flowrate at an original sand depth of 150 cm using coarse sand of 0.5 mm for 177 days. The flowrate was increased to 10 l/min in condition #2 keeping the other variables constant. Condition #3 was operated at reduced depth of 80 cm at 10 l/min of flowrate and 0.5 mm of sand size. Sand depth was further reduced to 50 cm in condition #4, while the other variables were same as in previous condition (i.e. condition #3).

Condition #5, the first operational stage of Filter #2, was operated at 16 l/min of flowrate and 150 cm sand depth using fine sand size of 0.3 mm. The flowrate was further increased to 20 l/min in condition #6, keeping all other variables constant. Condition #7 was operated at reduced depth of 80 cm, at a flowrate of 20 l/min and using fine sand of 0.3 mm. The sand depth was further reduced to 50 cm in condition #8 with all other variables same as in condition #7. Condition #9 was operated at 10 l/min of flowrate, and sand depth of 50 cm using fine sand of 0.3 mm.

Condition #10, the first operational stage of Filter #3, was operated at 16 l/min of flowrate at 150 cm sand depth and coarse sand size of 0.5 mm. During condition #11 the flowrate was further increased to 20 l/min, with all other variables same as in previous condition. Condition #12 was operated at reduced depth of 80 cm, at a flowrate of 20 l/min using sand size of 0.5 mm. The sand depth was further reduced to 50 cm in condition #13 and flowrate of 20 l/min and sand size of 0.5 mm. Next condition, i.e., condition #14 was operated at low flowrate of 10 l/min at 50 cm sand depth and 0.5 mm of sand size.

The above fourteen operational conditions provided effects of flowrates, sand depths and sand sizes on removal of microorganisms, suspended solids and turbidity. The removal efficiencies of above parameters were studied under wide range of process variables through slow sand filters.

4.1.1 Regulation of the Filtration Rate

The desired filtration rate was achieved by manual adjustment of the effluent valve. As the operation progressed, the resistance to flow or headloss was increasing due to clogging. At this point, the effluent value was open further until the desired flowrate was reached. This operation was continued until the outlet valve was fully open. In this case, the run was terminated by stopping the inflow and cleaning of the filter bed was conducted.

4.1.2 Cleaning the Filter Bed:

The filter was drained to a level of 10 to 20 cm below the sand bed so that the filter skin and the top layer became relatively dry and easy to handle; then the upper 6 to 8 cm layer was removed. Then the inflow pump was resumed again. The desired filtration rate was adjusted by the outlet valve and the filter was restarted.

4.1.3 Changing the Depth of the Filter Bed:

The filter was operated at three different sand depths as mentioned before. The operation was started as follows:

At the start of the experiment, the depth of sand was 150 cm in each of the three filters. When the depth of sand was desired to be decreased to (80 cm or 50 cm) the filters were drained and were left for drying of only filter skin. After that the desired sand depth was removed manually and discarded. A

measuring tape was installed in each of the three filters to indicate the exact sand depths of the filters. At this stage, the filter was ready for the next operation.

4.2 REMOVAL OF COLIPHAGE AND BACTERIA

The removal of four different microorganisms, i.e., coliphage plaque, coliforms, fecal coliforms and standard plate counts were monitored through three different slow sand filters. Samples analyzed for above four microorganisms had been collected from influent and effluent of the filters. The performance of filters during entire period of operation involving various process variables are discussed in the following sections.

4.2.1 Filter Operations at Flowrates of 8, 10, 16 and 20 l/m, and Sand Depth of 150 cm:

There were six different conditions (#1, #2, #5, #6,#10 and #11) which were operated to investigate the effect of flowrates on microorganisms removal efficiencies at constant depth of 150 cm (Table 4.1). During Condition #1, the observed variation of influent and effluent of coliphage, coliforms, fecal coliforms and standard plate counts are shown in Figures 4.1 - 4.4 respectively. The densities of coliphage plaque, coliforms, fecal coliforms and standard plate counts in the influent ranged from 1.4×10^2 to 6.2×10^3/100 ml, 3.1×10^3 to 8.20×10^5 MPN/100 ml, 1.10×10^3 to 6×10^5 MPN/100 ml, and 3.20×10^3

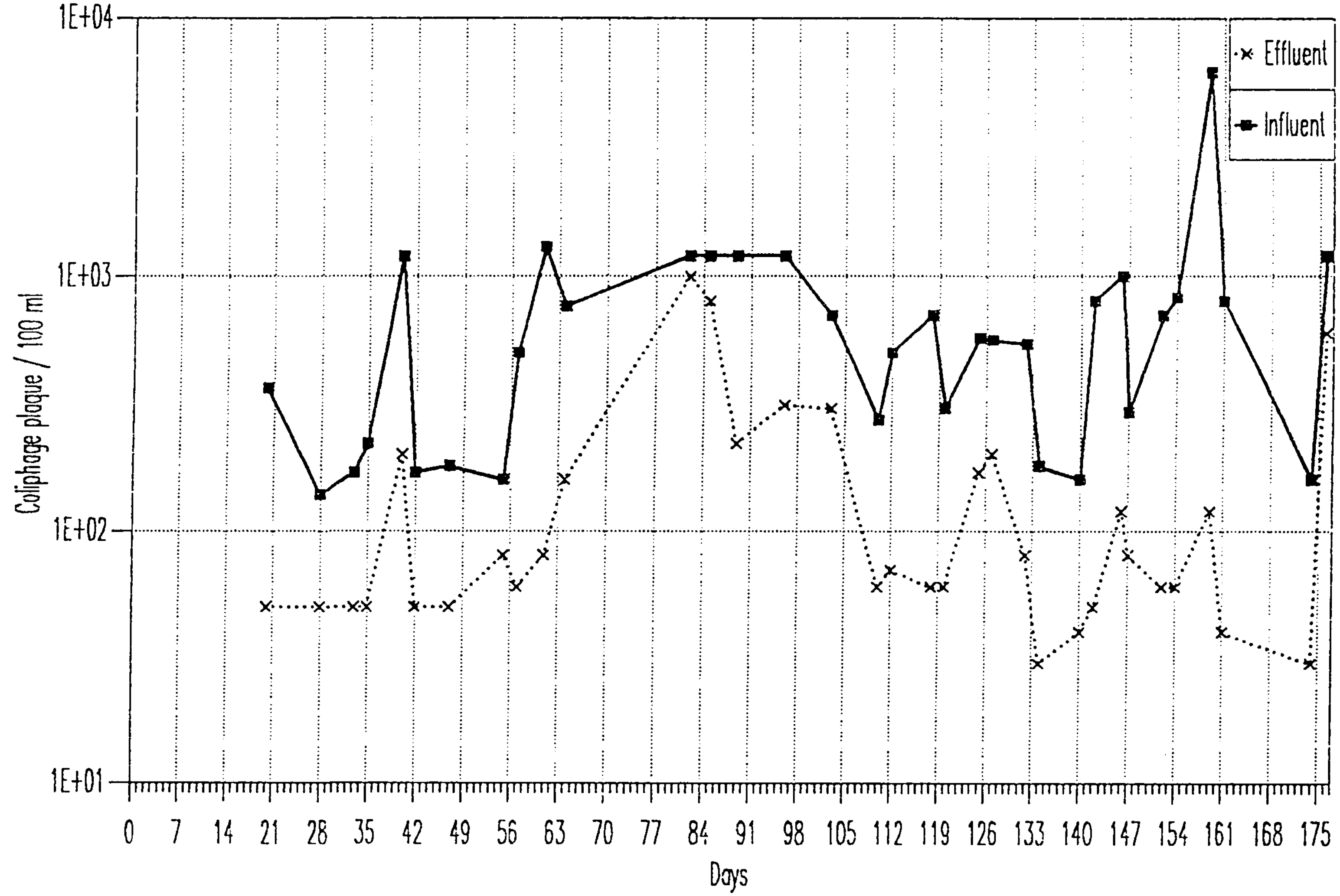


Figure 4.1: Variation of Coliphage plaque in Condition 1

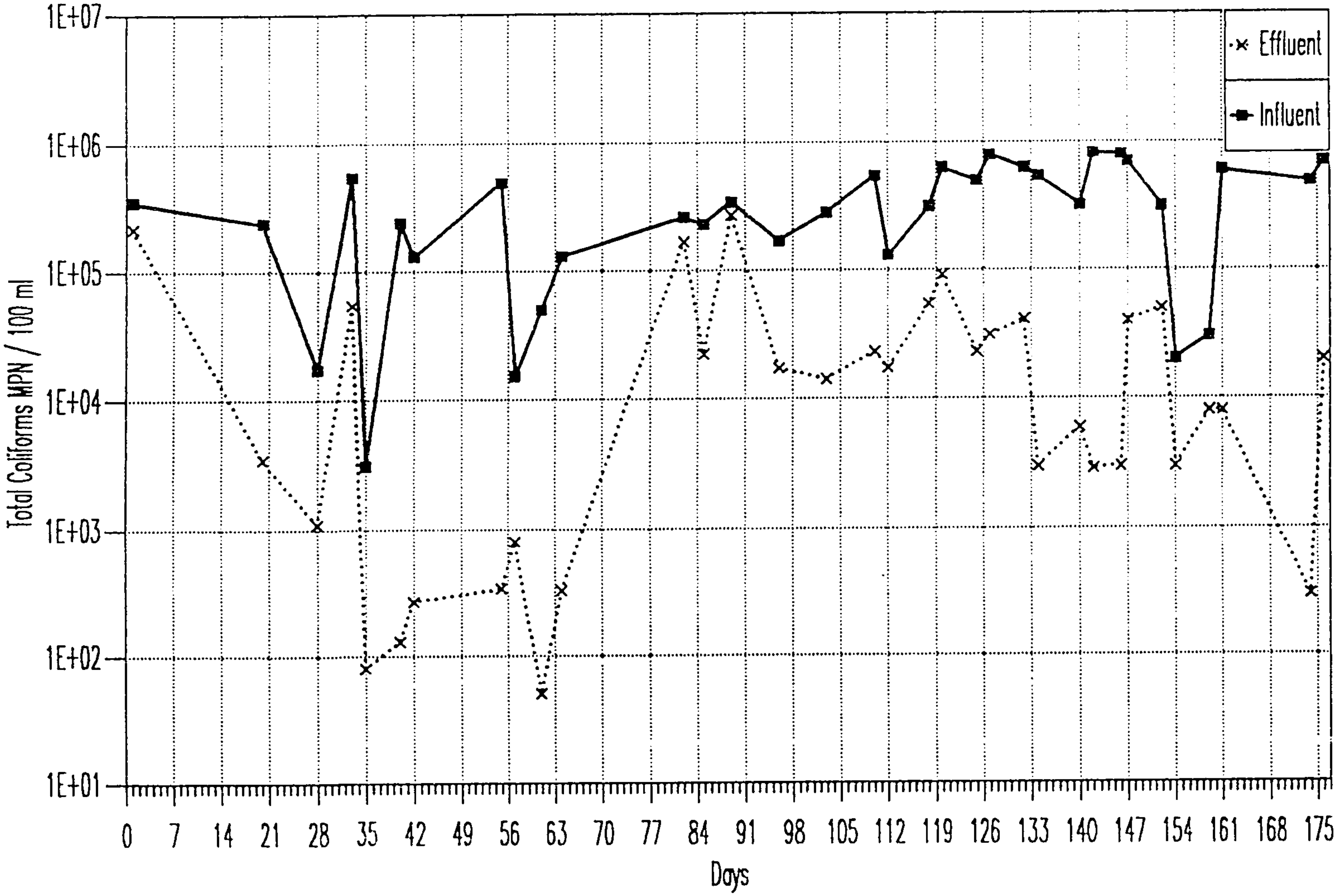


Figure 4.2: Variation of Total Coliforms in Condition 1

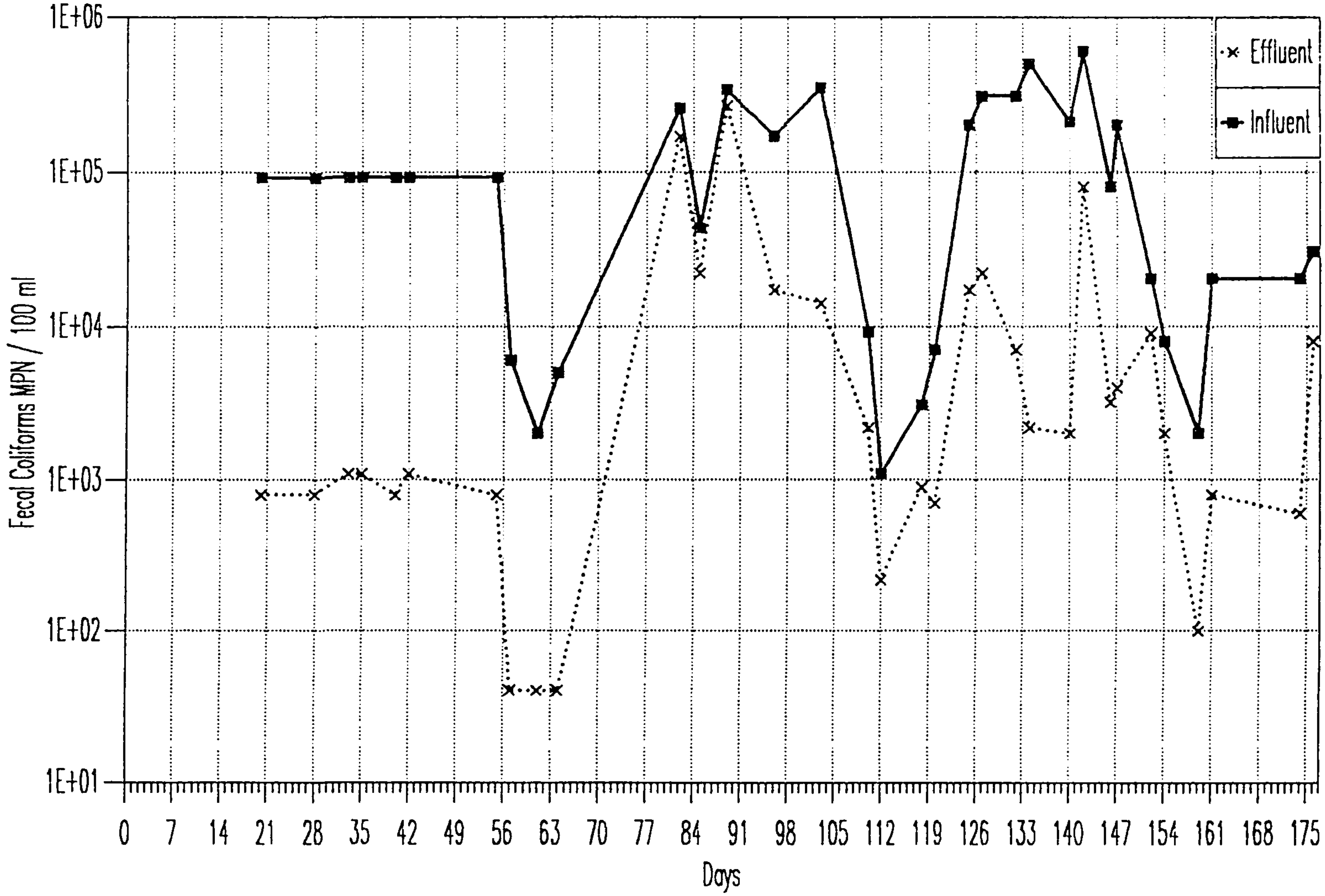


Figure 4.3: Variation of Fecal Coliforms in Condition 1

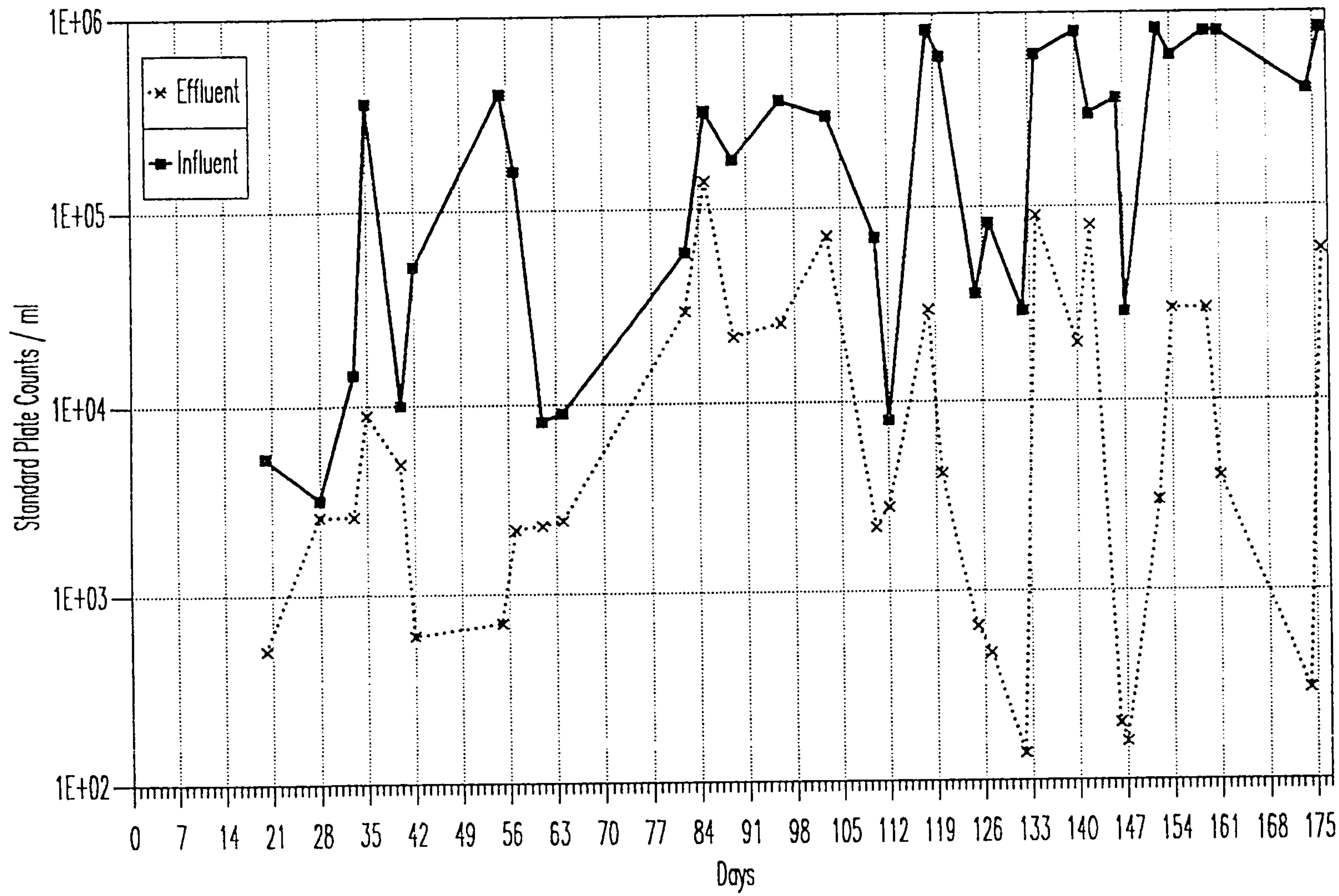


Figure 4.4: Variation of Standard Plate Counts in Condition 1

to 8.20 x 10^5/ml, respectively in Condition #1, whereas in the effluent the densities for the same organisms ranged from 30 to 1000/100 ml, 50 to 2.70 x 10^5 MPN/100 ml, 40 to 2.70 x 10^5 MPN/100 ml, and 4.70 x 10^2 to 1.40 x 10^5/ml, respectively. No regular trend for any of the above microorganisms could be observed. For the same data, average influent densities of coliphage, coliforms, fecal coliforms and plate counts were 7.95 x 10^2/100ml, 3.63 x 10^5 MPN/100 ml and 1.32 x 10^5 MPN/100 ml and 3.10 x 10^5/ml, respectively, and the average effluent densities were 1.56 x 10^2/100 ml, 3.52 x 10^4 MPN/100 ml, 2.0 x 10^4 MPN/100 and 2.04 x 10^4/ml, respectively. The percentage removal variation of each of the four microorganisms are presented in Figure 4.5. The percentage removal data were fluctuating and no regular trend could be observed. The average percentage removal of coliphage, coliforms, fecal coliforms and standard plate counts during condition #1 were 80%, 88%, 86% and 86%, respectively.

Condition #2 was operated at 25% higher flowrate than the previous one. The influent and effluent variations of coliphage, coliforms, fecal coliforms and standard plate counts are shown in Figures 4.6-4.9, respectively. The variation trend of the effluent densities of coliphage, coliforms and plate counts were same as observed in the influents. However, no particular trend could be obtained for both influent and effluent densities. The percentage removal for these microorganisms are shown in Figure 4.10. The average removal

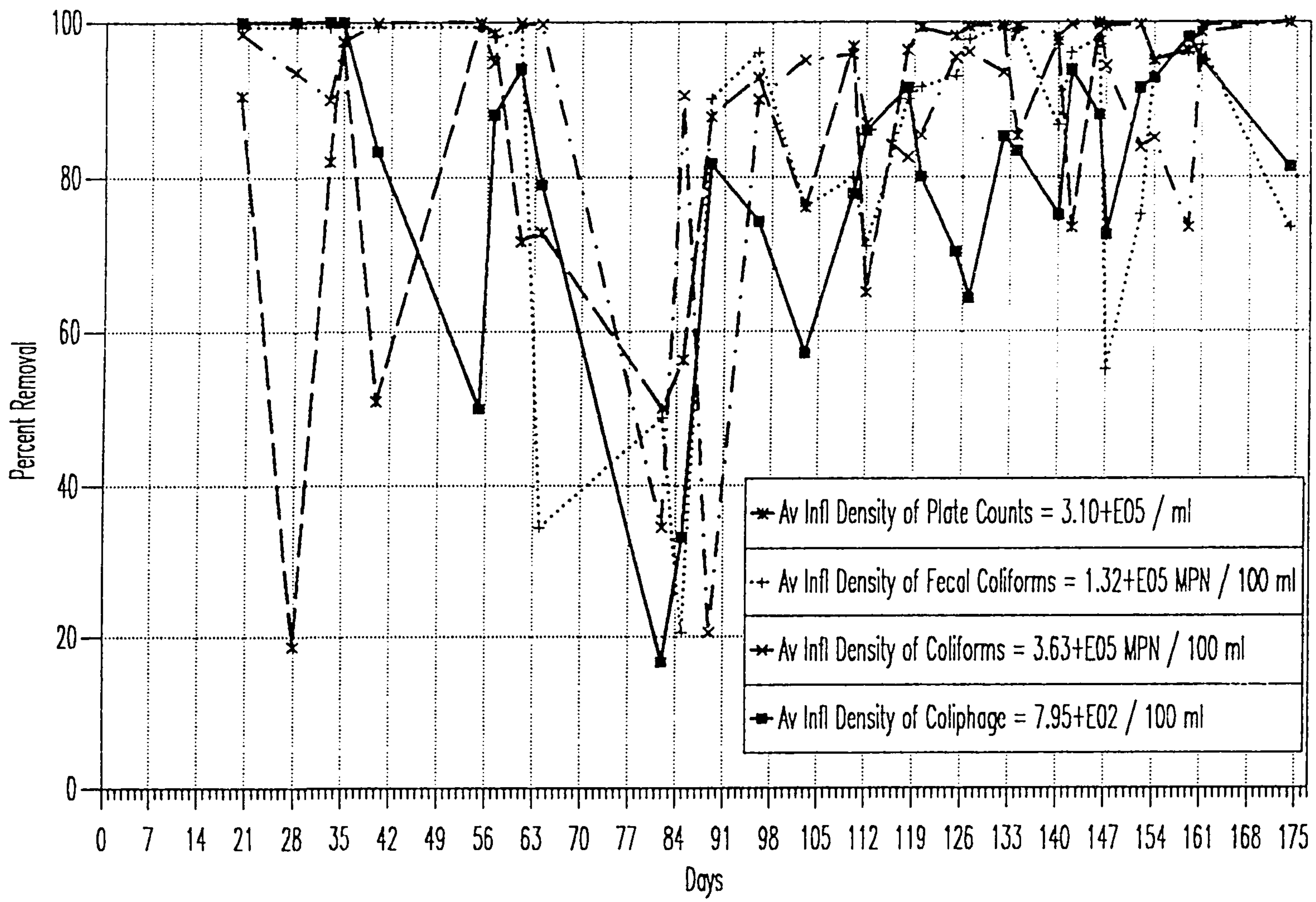


Figure 4.5: **Removal Efficiencies of Various Microorganisms in Condition 1**

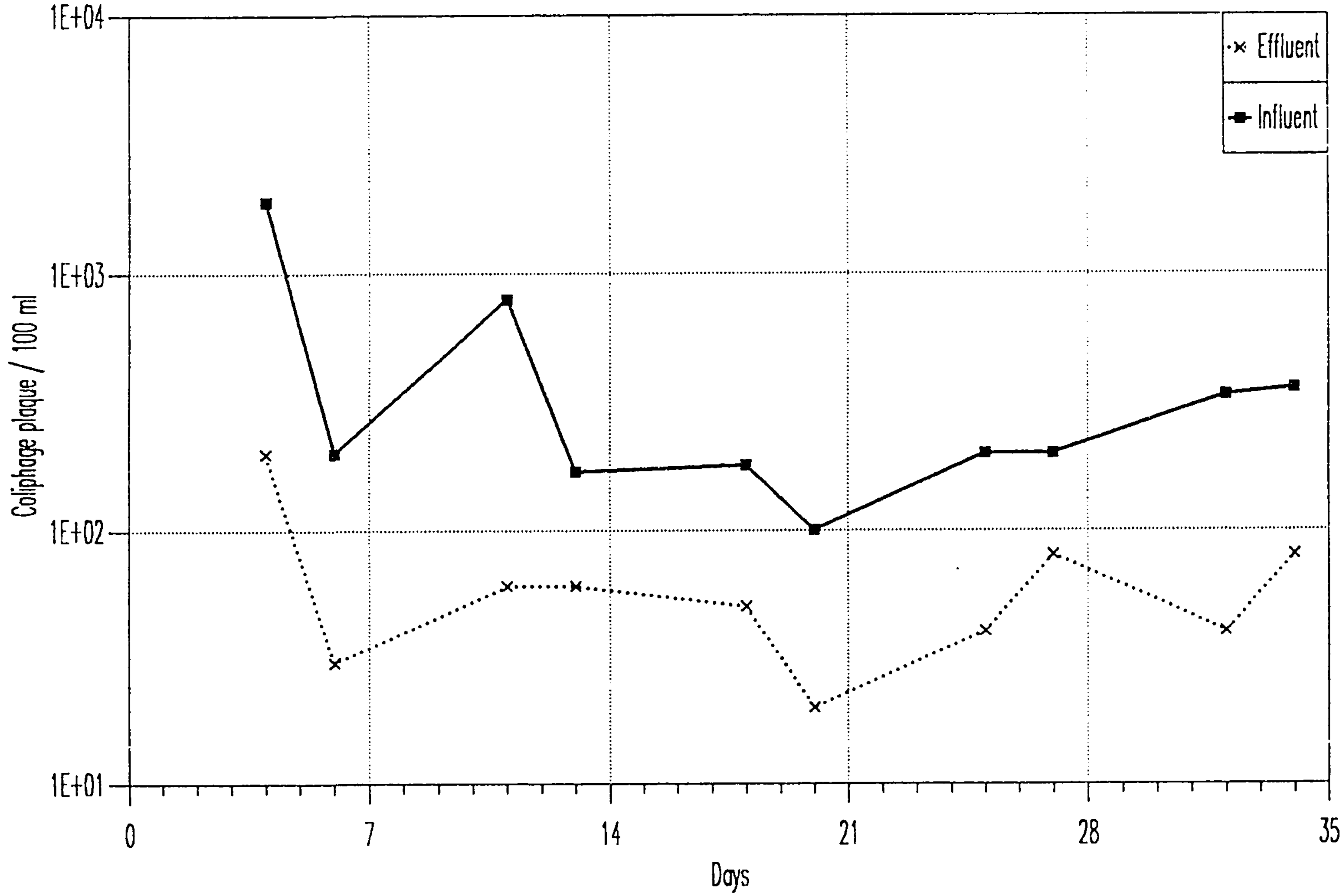


Figure 4.6: Variation of Coliphage plaque in Condition 2

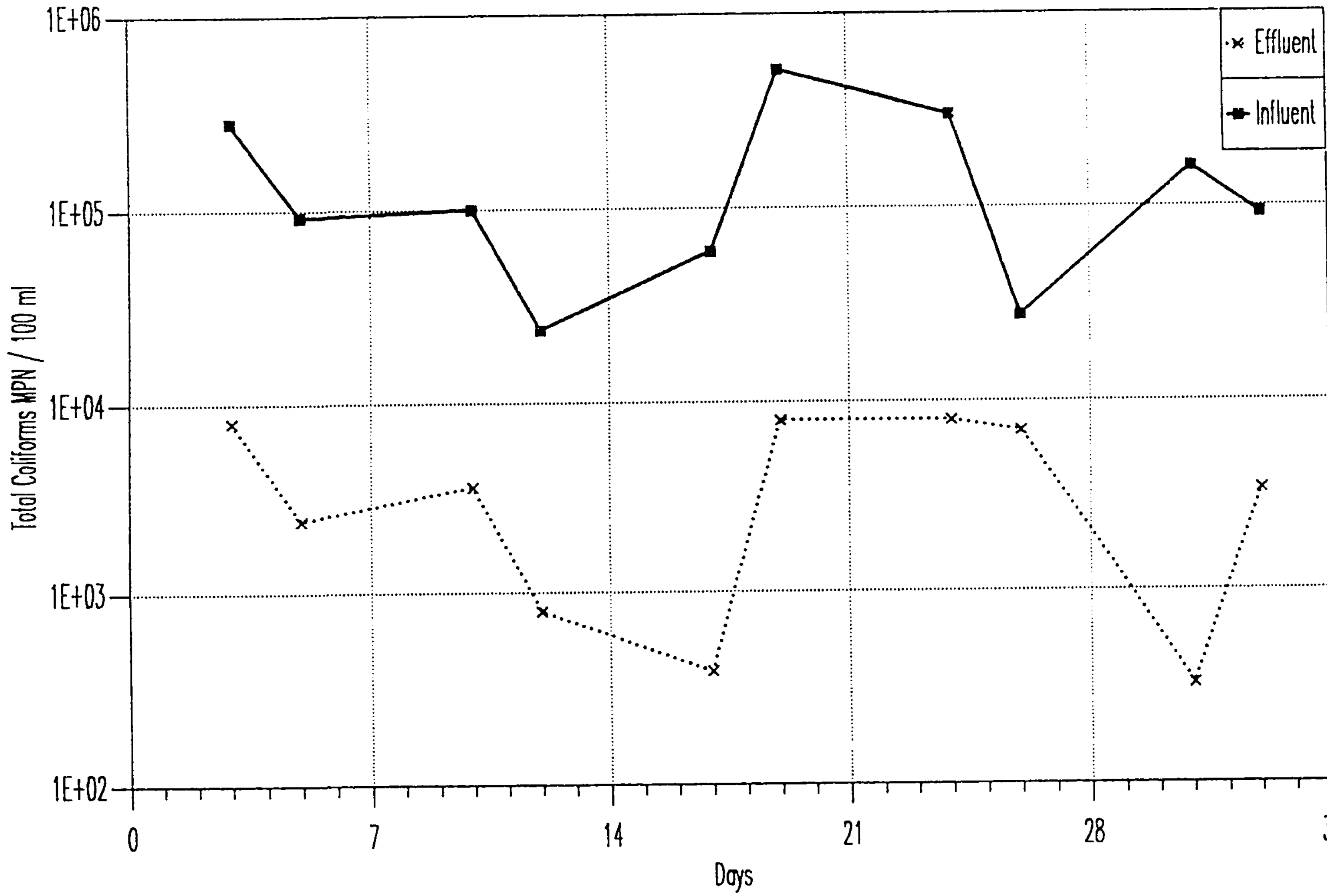


Figure 4.7: **Variation of Total Coliforms in Condition 2**

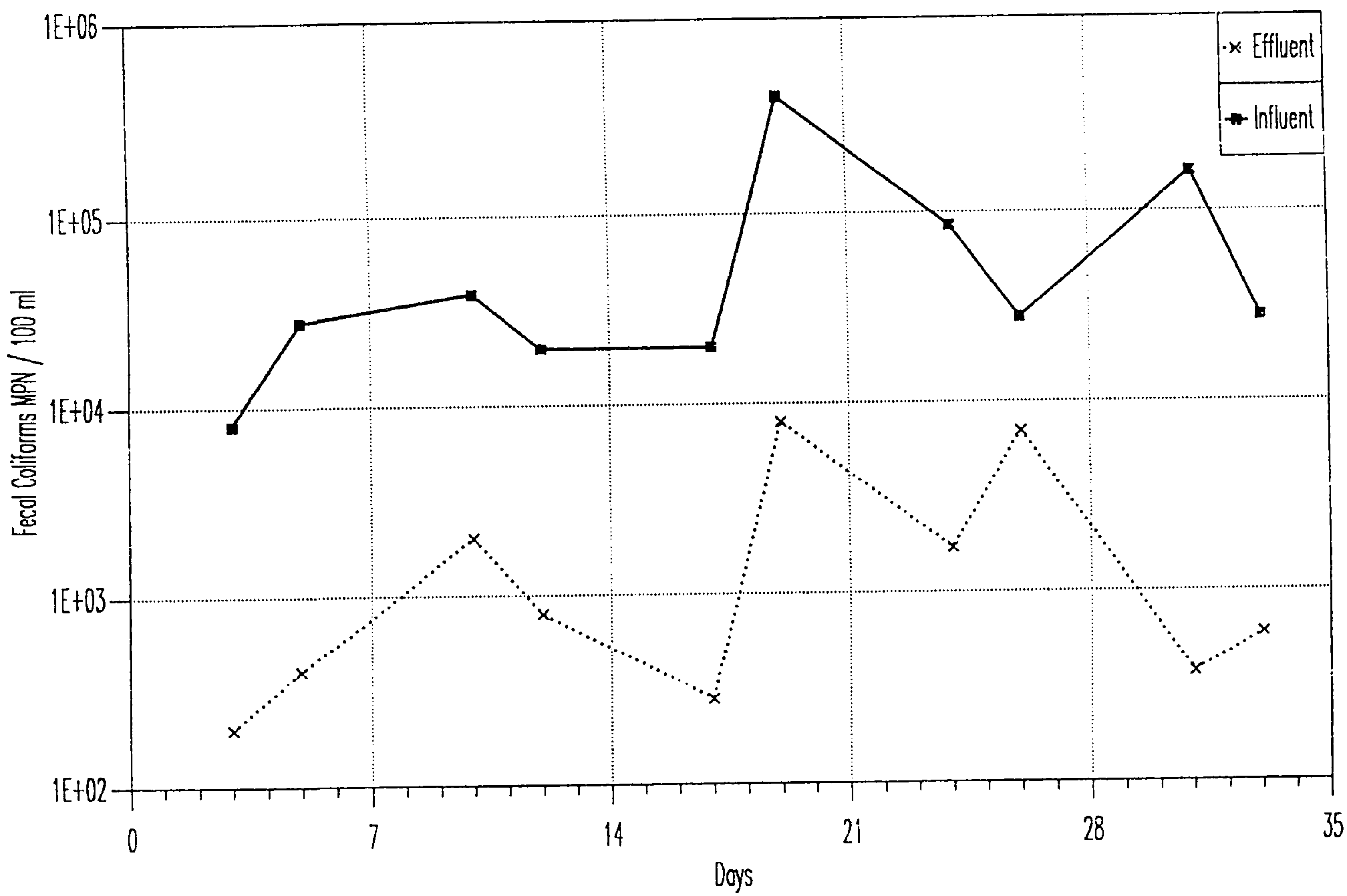


Figure 4.8: Variation of Fecal Coliforms in Condition 2

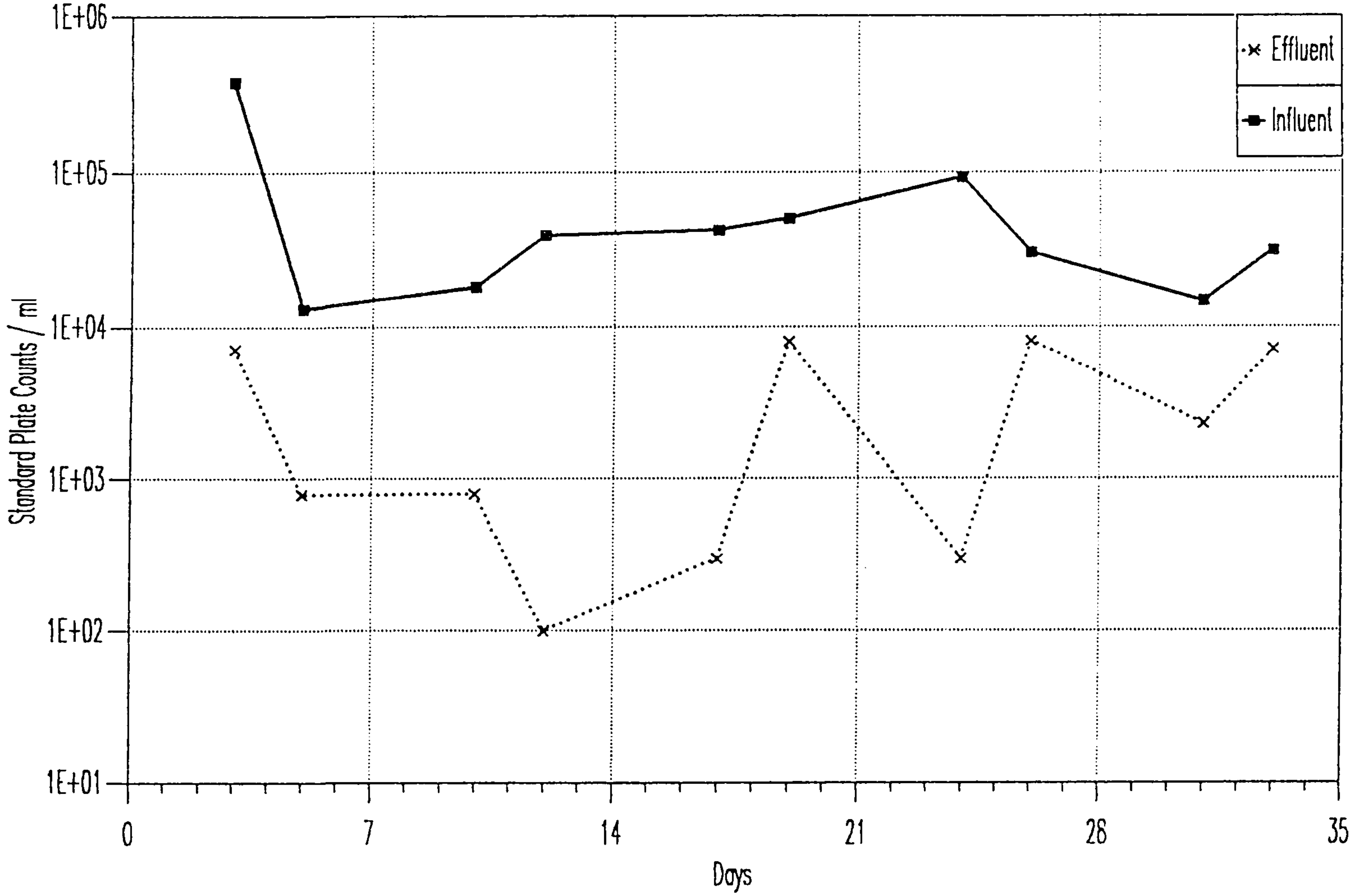


Figure 4.9: Variation of Standard Plate Counts in Condition 2

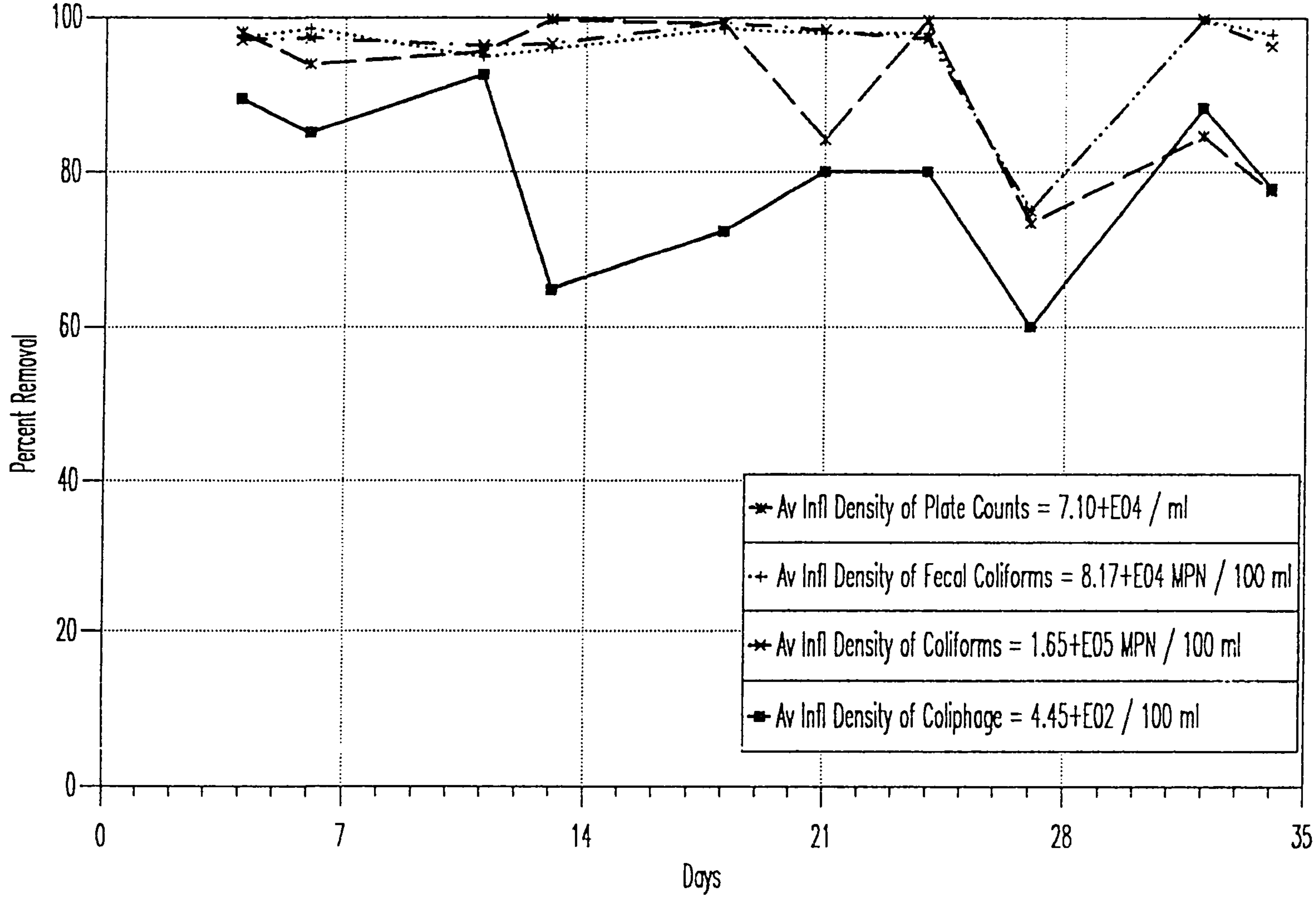


Figure 4.10: **Removal Efficiencies of Various Microorganisms in Condition 2**

efficiencies of coliphage, coliforms, fecal coliforms and standard plate counts were 79%,95%, 95% and 96%, respectively. When compared with the previous results, the percent removals were higher in condition #2. The higher removal in condition #2 was primarily due to smooth operation of the filter as compared to condition #1, where filter was marred with several interuptions due to modification of the operation and inadequate maturation of the filter. Therefore, higher removal efficiencies in condition #2 indicated that the filter bed had fully matured.

Bellamy *et al.*, [3,4] have demonstrated that the state of biological community within the slow sand filter significantly affects the filter effectiveness. They achieved the greatest percentage removals of total coliform bacteria (e.g. 97.6 - 99.96%) when the filter had mature biological population. These removals decreased by a factor of 10 -100 after removal of the schmutzdecke and replacement of the sand respectively.

Most simply, the purification achieved in slow sand filters is considered principally as the result of straining through the developed filter skin. The enhanced straining action, adsorption due to developed biological activity were responsible for higher removal efficiencies in condition #2.

Variations of influent and effluent densities of coliphage, coliforms, fecal coliforms and standard plate counts in condition #5 (Filter #2)are presented in Figures 4.11-4.14, and the average influent densities were 7.93 x 10^2/100 ml,

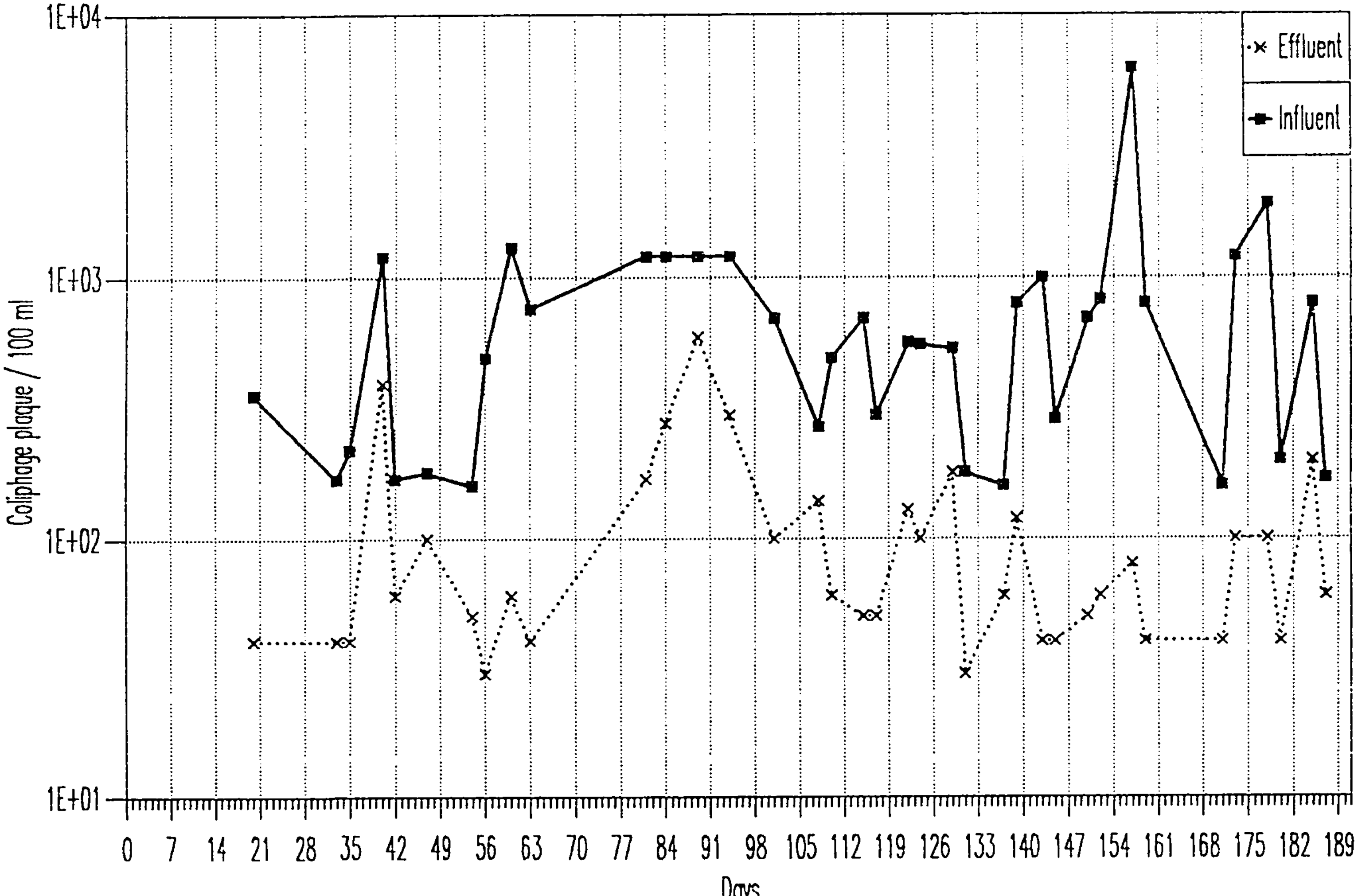


Figure 4.11: Variation of Coliphage plaque in Condition 5

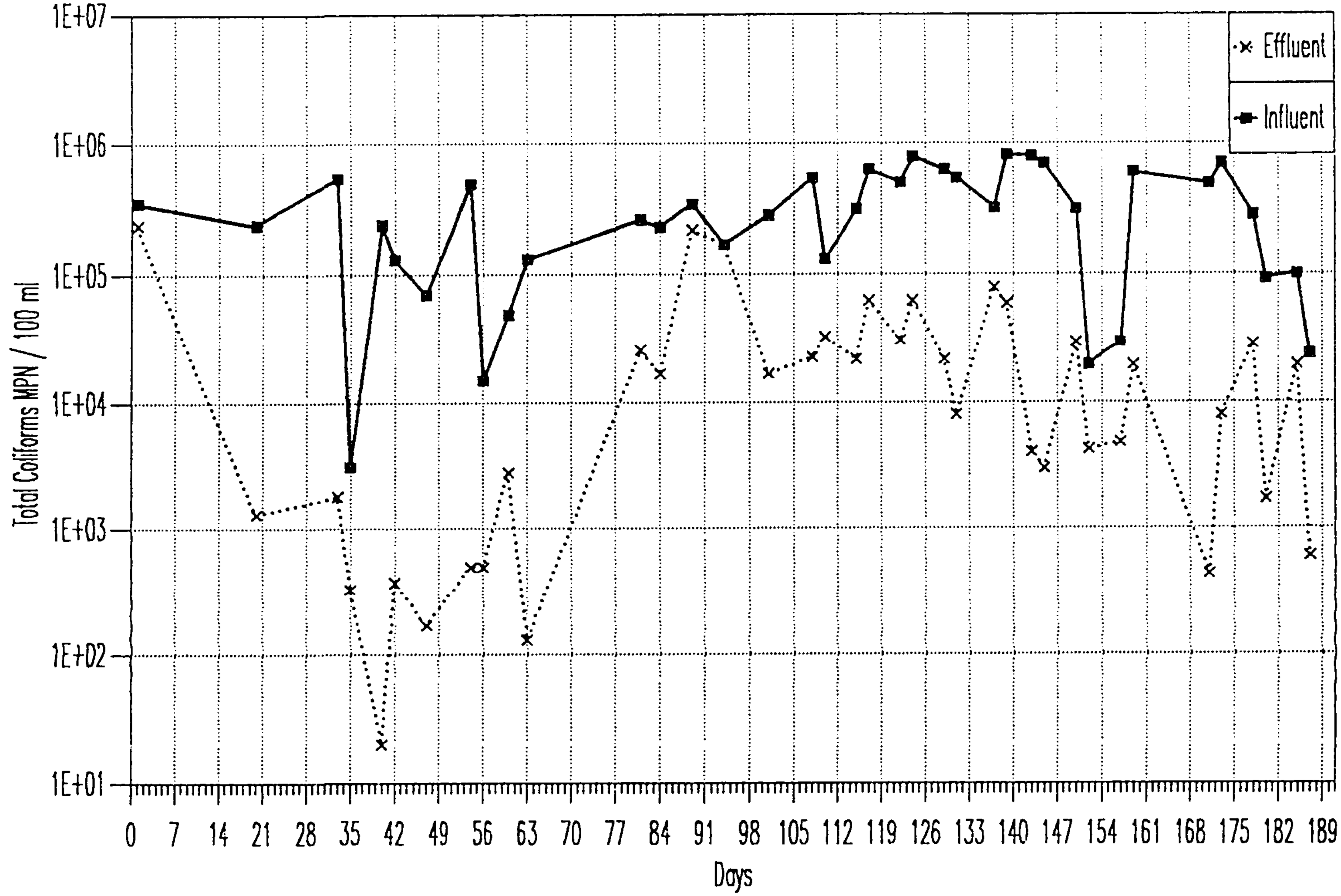


Figure 4.12: Variation of Total Coliforms in Condition 5

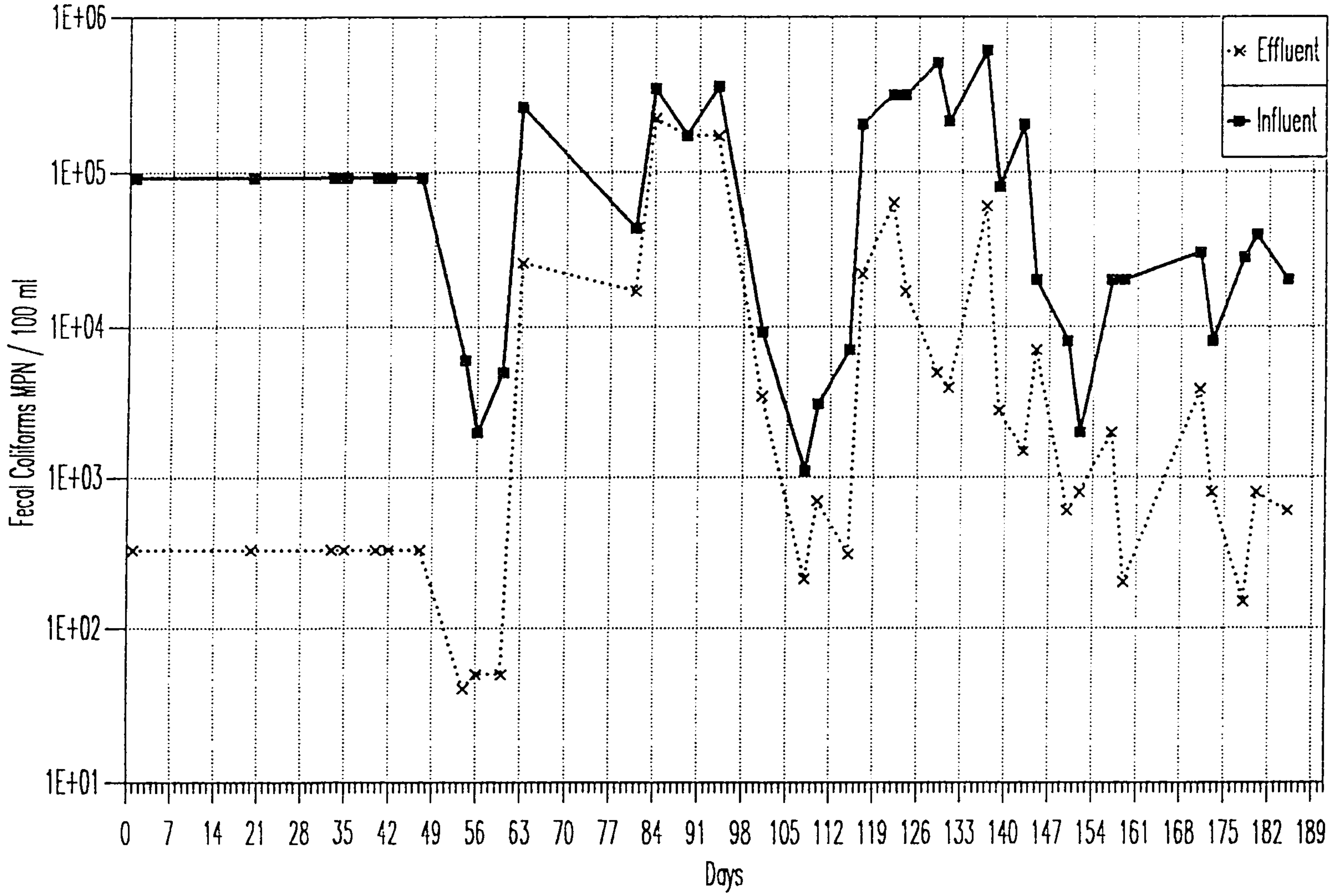


Figure 4.13: Variation of Fecal Coliforms in Condition 5

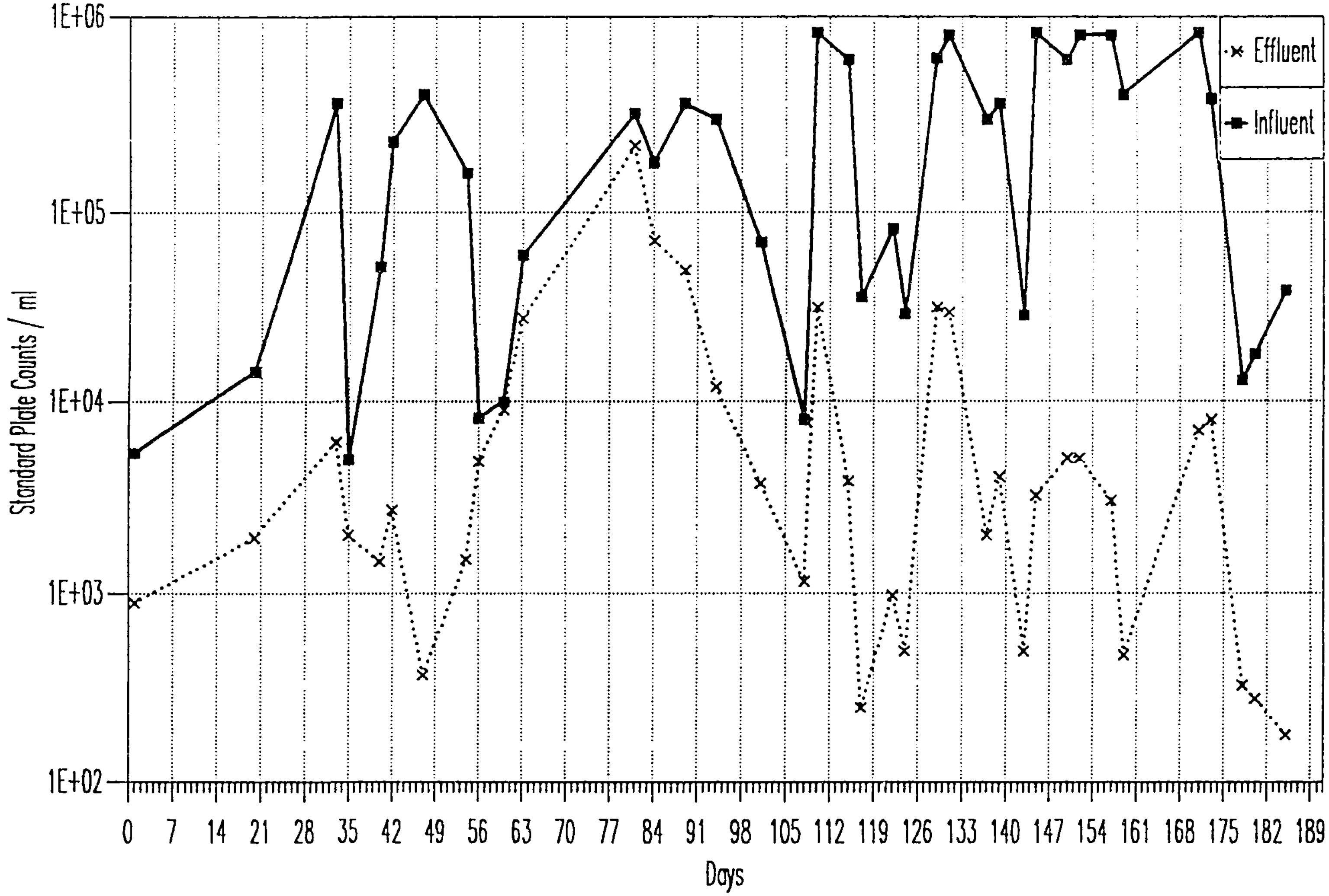


Figure 4.14: **Variation of Standard Plate Counts in Condition 5**

3.39×10^5 MPN/100 ml and 1.20×10^5 MPN/100 ml and 2.95×10^5/ml, respectively, while the average effluent densities were 1.08×10^2/100 ml, 2.60×10^4 MPN/100 ml, 2.60×10^4 MPN/100, 2.17×10^4 MPN/100 ml, and 1.50×10^4/ml, respectively. The variations of percentage removal of the microorganisms are shown in Figure 4.15. The data were quite fluctuating and without any regular trend. The average percentage removal of coliphage, coliforms, fecal coliforms and standard plate counts were 81%, 88%, 86% and 88%, respectively. These percentage removals are quite similar to those obtained in condition #1. Therefore, it can be concluded that there is little effect of flowrates on removal efficiencies of microorganisms.

The flowrate was again increased by 25% in condition #6 compared to condition #5 keeping all other variables constant. The influent and effluent variations for each of the microorganisms are shown in Figures 4.16-4.19. The effluent data of coliphage was quite constant in first 14 days of operation, after which slight fluctuations were observed (Figure 4.16). The data (both influent and effluent) for total coliforms and fecal coliform were fluctuating over the entire period of condition #6 and effluent was followed by influent (Figures 4.17, 4.18). The data for standard plate counts were also fluctuating except in the last 3 effluent samples which indicated a uniform and consistent trend. The average influent densities of coliphage, coliforms, fecal coliforms and standard plate counts were 2.30×10^2/100 ml, 1.92×10^5 MPN/100 ml, 1.20×10^5

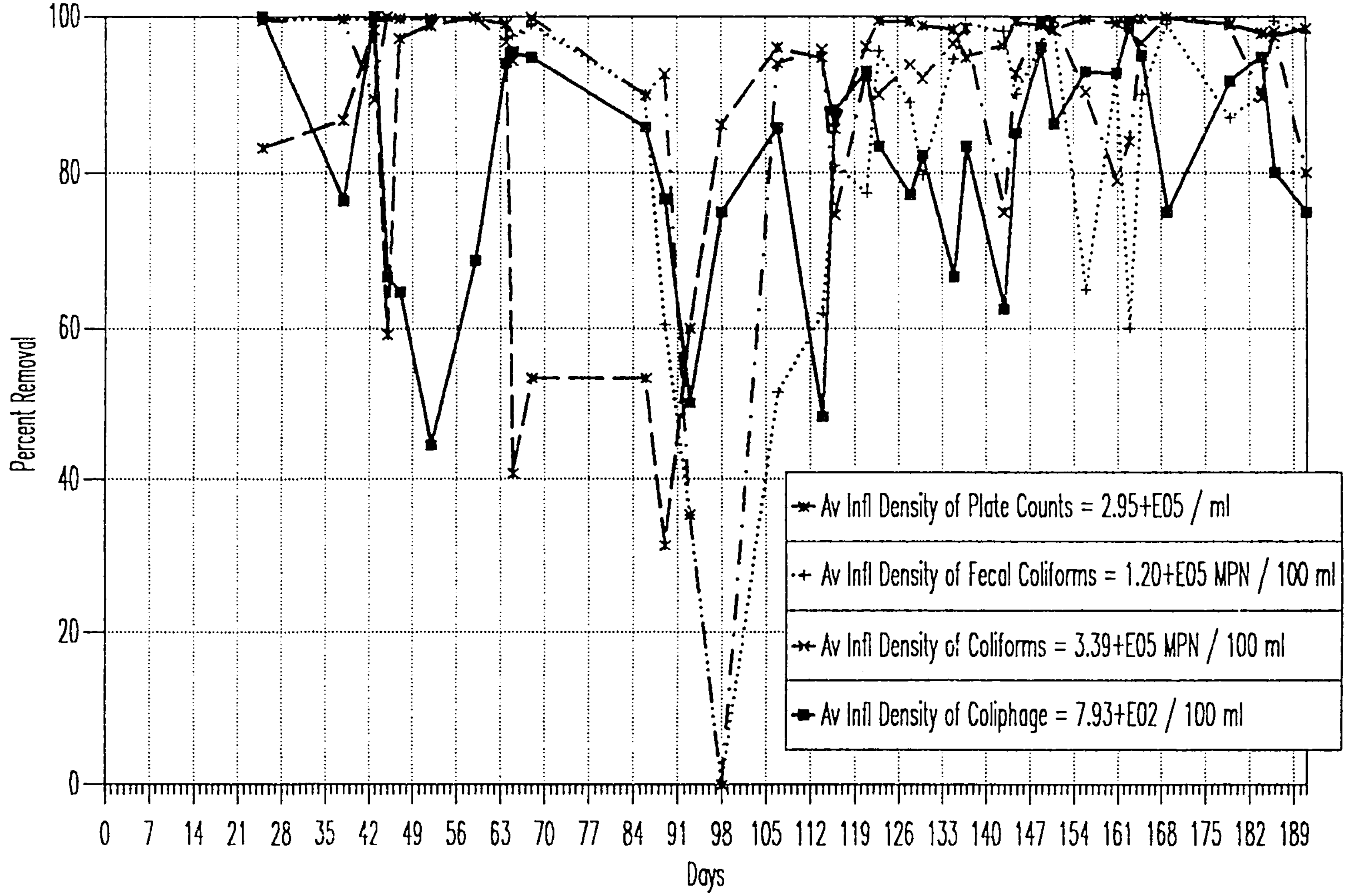


Figure 4.15: **Removal Efficiencies of Various Microorganisms in Condition 5**

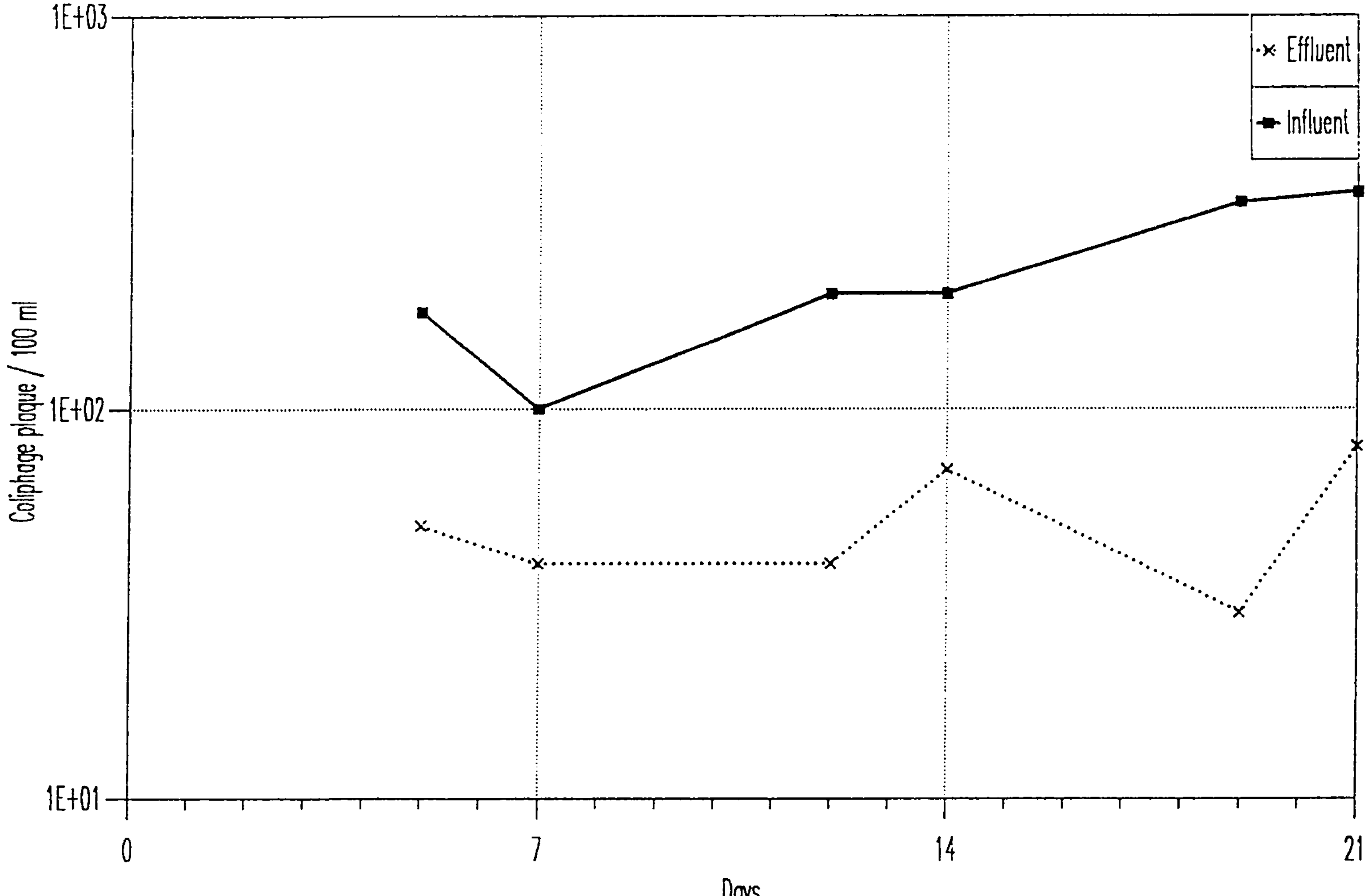


Figure 4.16: Variation of Coliphage plaque in Condition 6

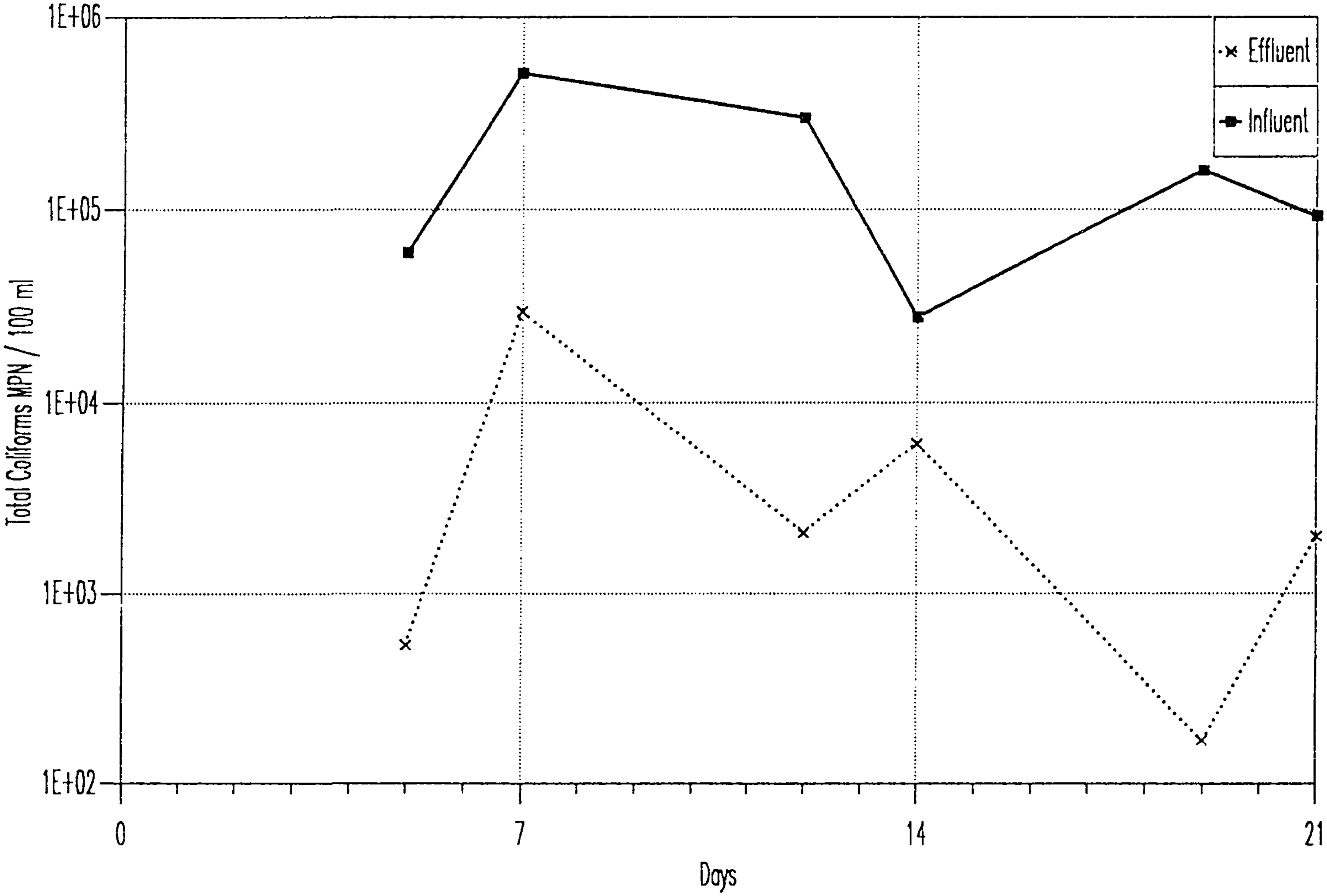


Figure 4.17: Variation of Total Coliforms in Condition 6

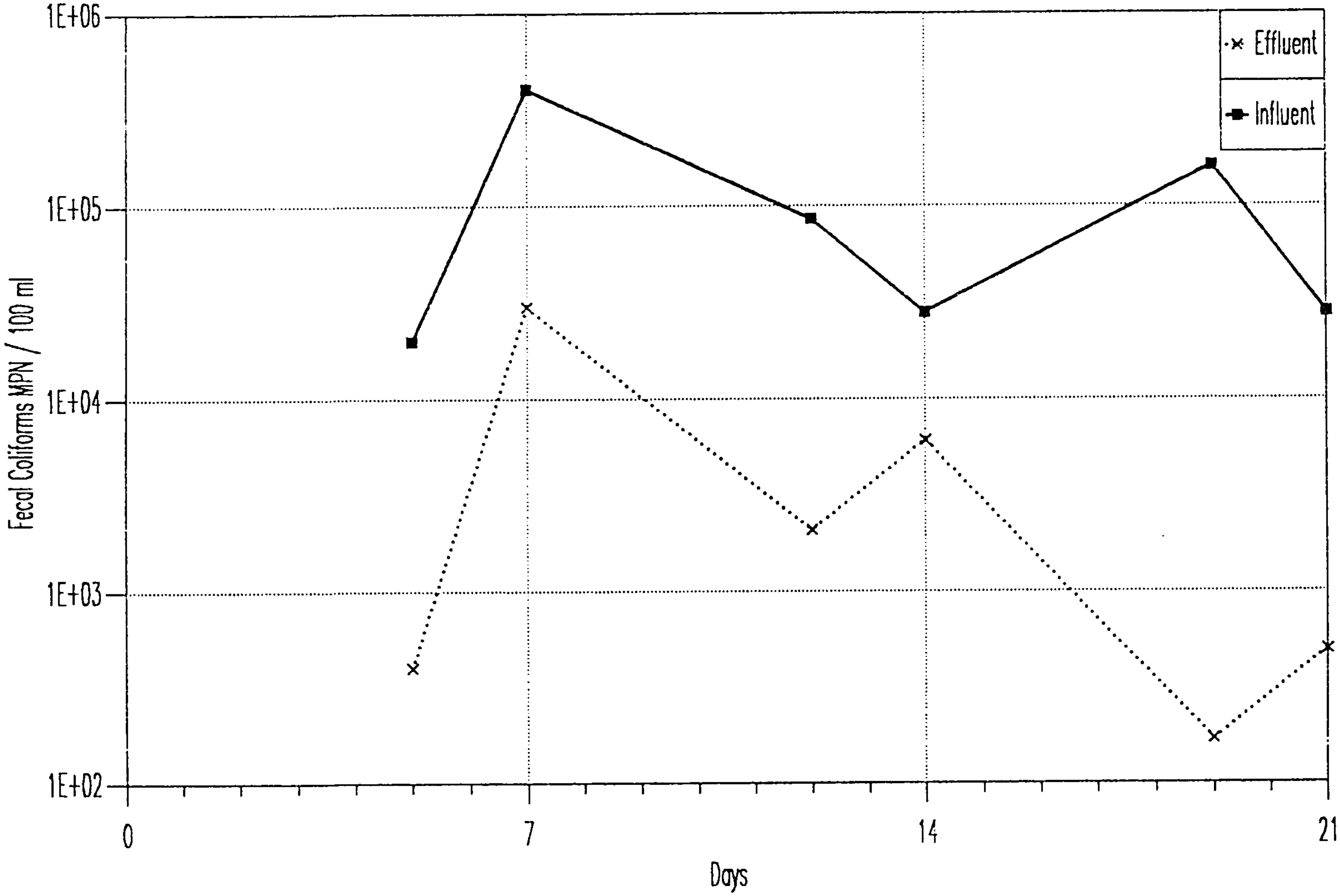


Figure 4.18: Variation of Fecal Coliforms in Condition 6

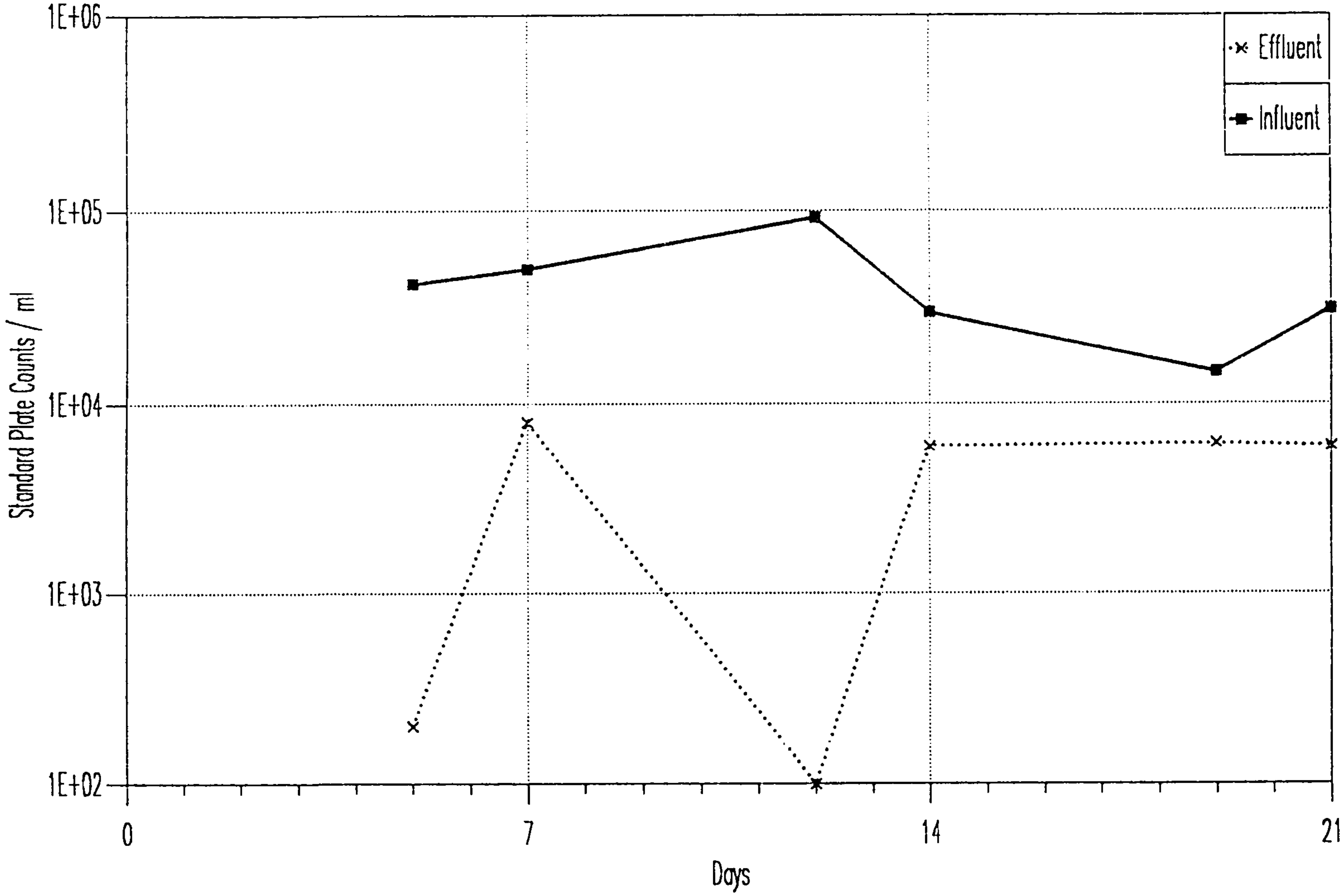


Figure 4.19: Variation of Standard Plate Counts in Condition 6

MPN/100 ml and 4.33 x 10^4/ml respectively. The variations of percentage removal of all four microorganisms are shown in Figure 4.20. The average removal of coliphage, coliforms, fecal coliforms and plate counts were 74%, 95%, 94% and 84% respectively. This indicates slightly higher removal efficiencies of total coliforms and fecal coliforms as compared to the ones in condition #5. Therefore, maturation of sand bed in Filter #2 was indicated by higher efficiencies in conditions #6. This observation is a confirmation of the widely quoted statement *"biological activity within the sand bed has the strongest influence on removal efficiency of total coliform bacteria by slow sand filtration"* [4].

Farooq and Yousef, [15] have suggested that the slow sand filtration should be operated for several days prior to regular operation for any given set of experimental conditions in order to build up the *schumtzdecke* layer, i.e. biological film. Following the development of this layer, the purifying bacteria become well established and play an important part in the treatment process.

Condition #10 was the first stage of operation of Filter #3. Conditions of operation were similar to condition #5 except that condition #5 was operated using finer sand size (0.3 mm). The influent and effluent variations of different microorganisms are presented in Figures 4.21-4.24. Both influent and effluent data fluctuated over the entire period of condition #10, for all the microorganisms, except for fecal coliforms where a consistent trend of effluent

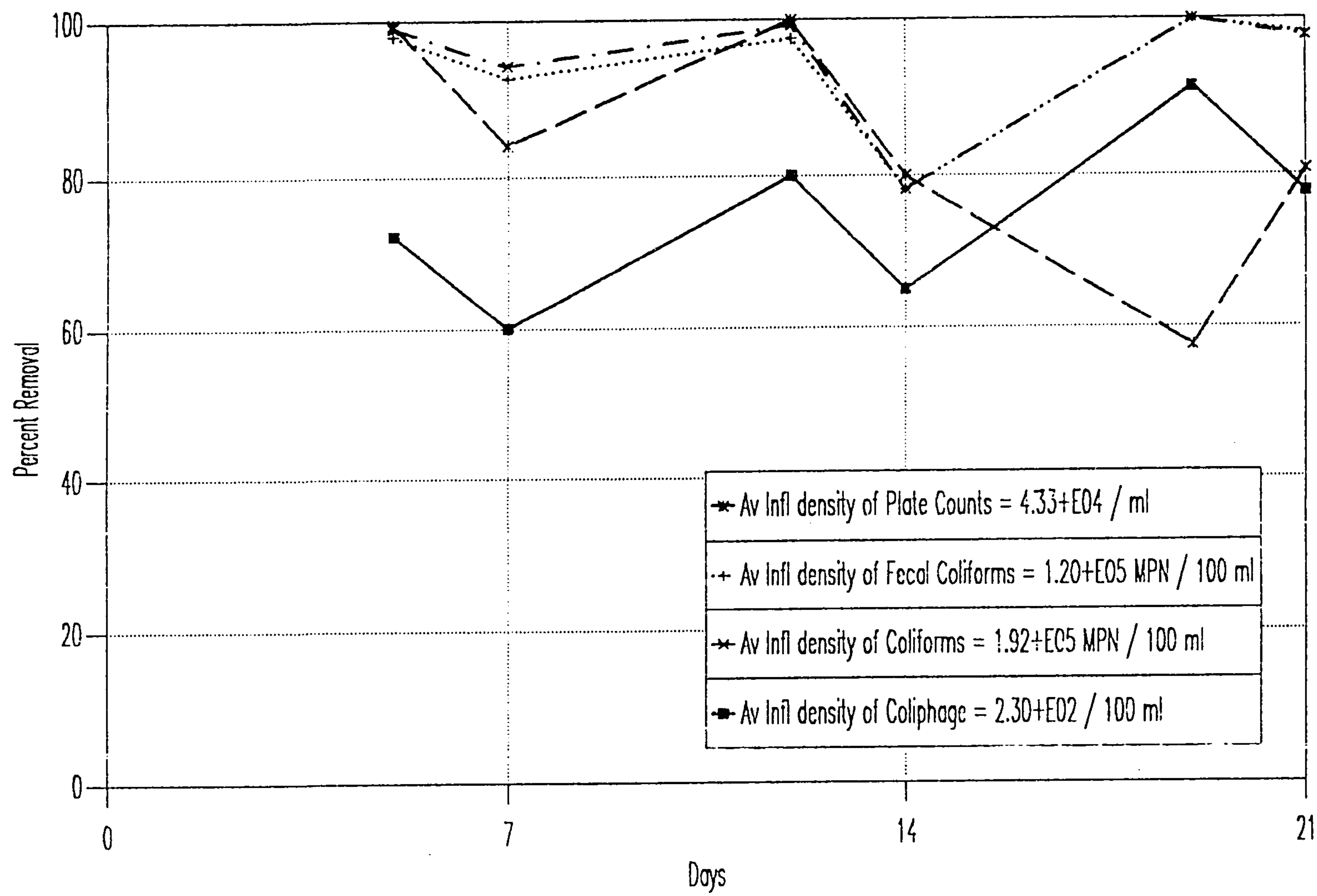


Figure 4.20: Removal Efficiencies of Various Microorganisms in Condition 6

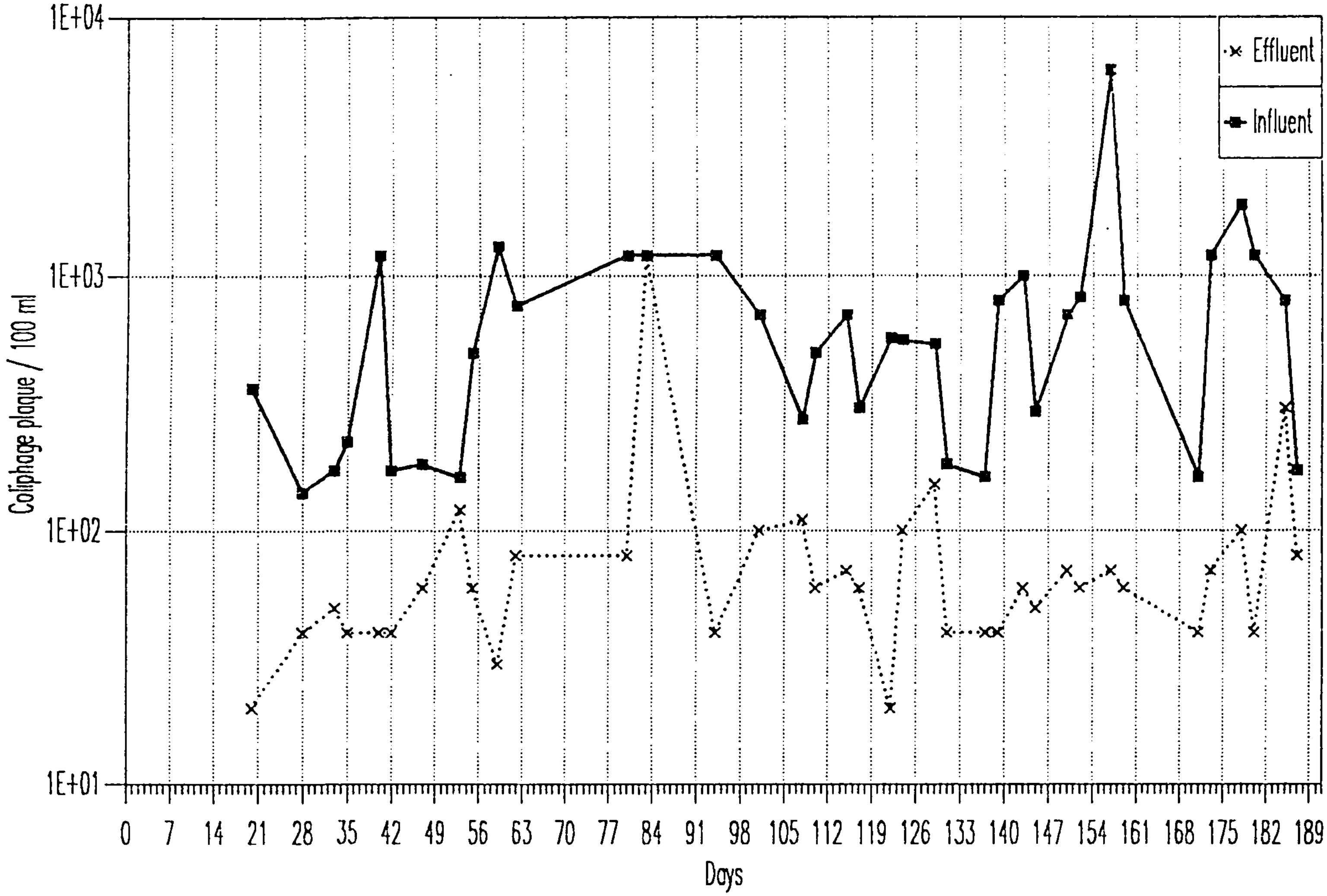


Figure 4.21: Variation of Coliphage plaque in Condition 10

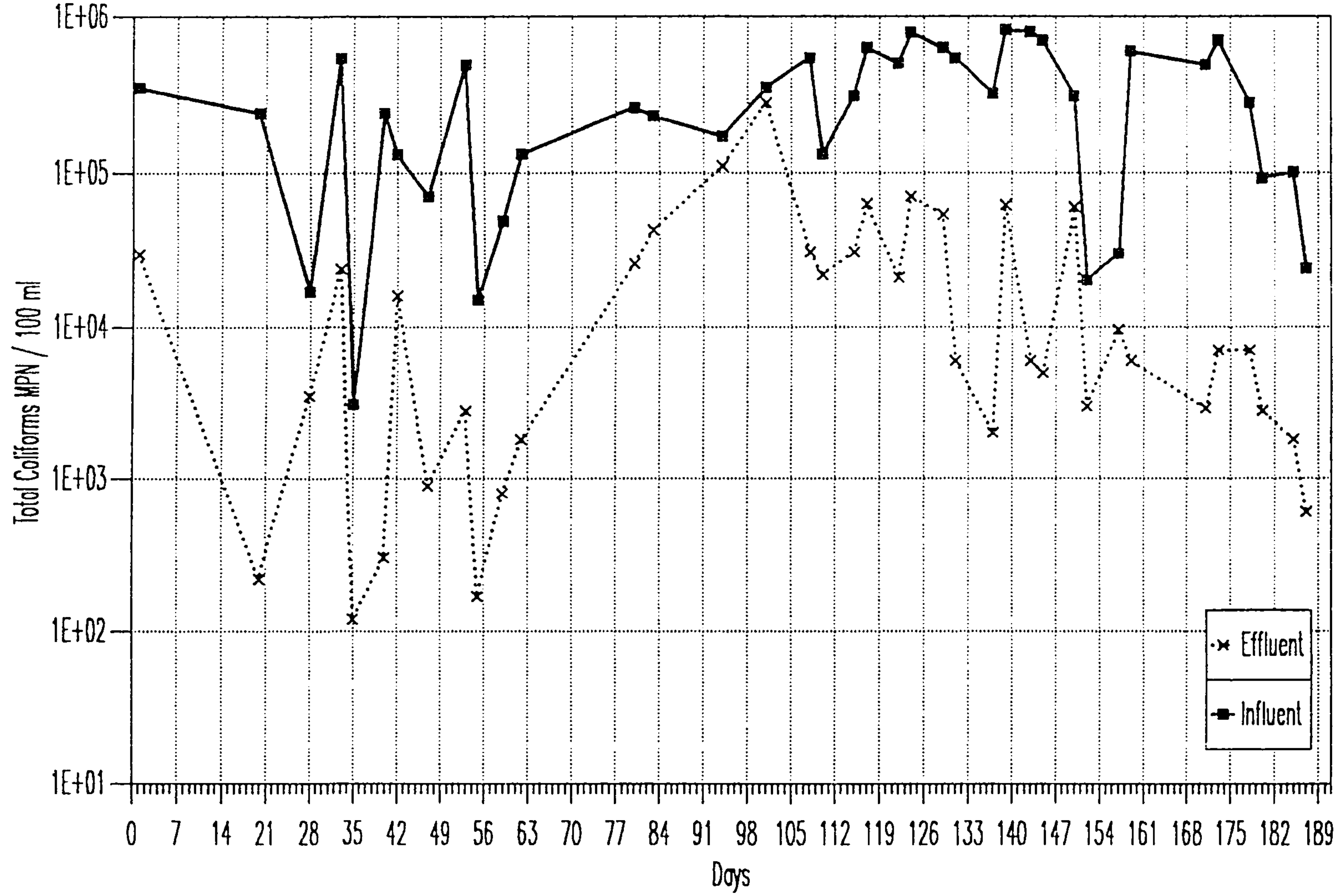


Figure 4.22: **Variation of Total Coliforms in Condition 10**

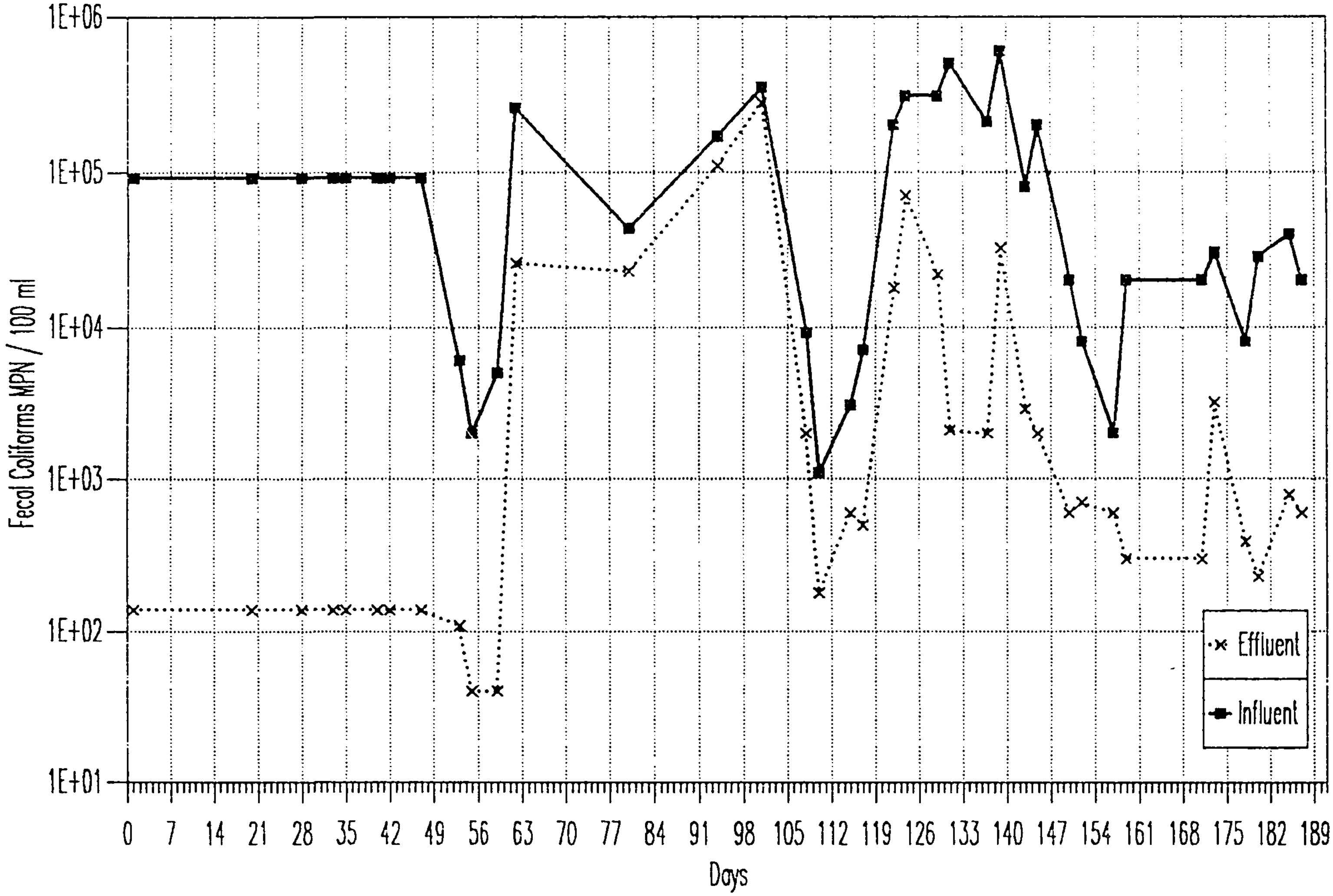


Figure 4.23: Variation of Fecal Coliforms in Condition 10

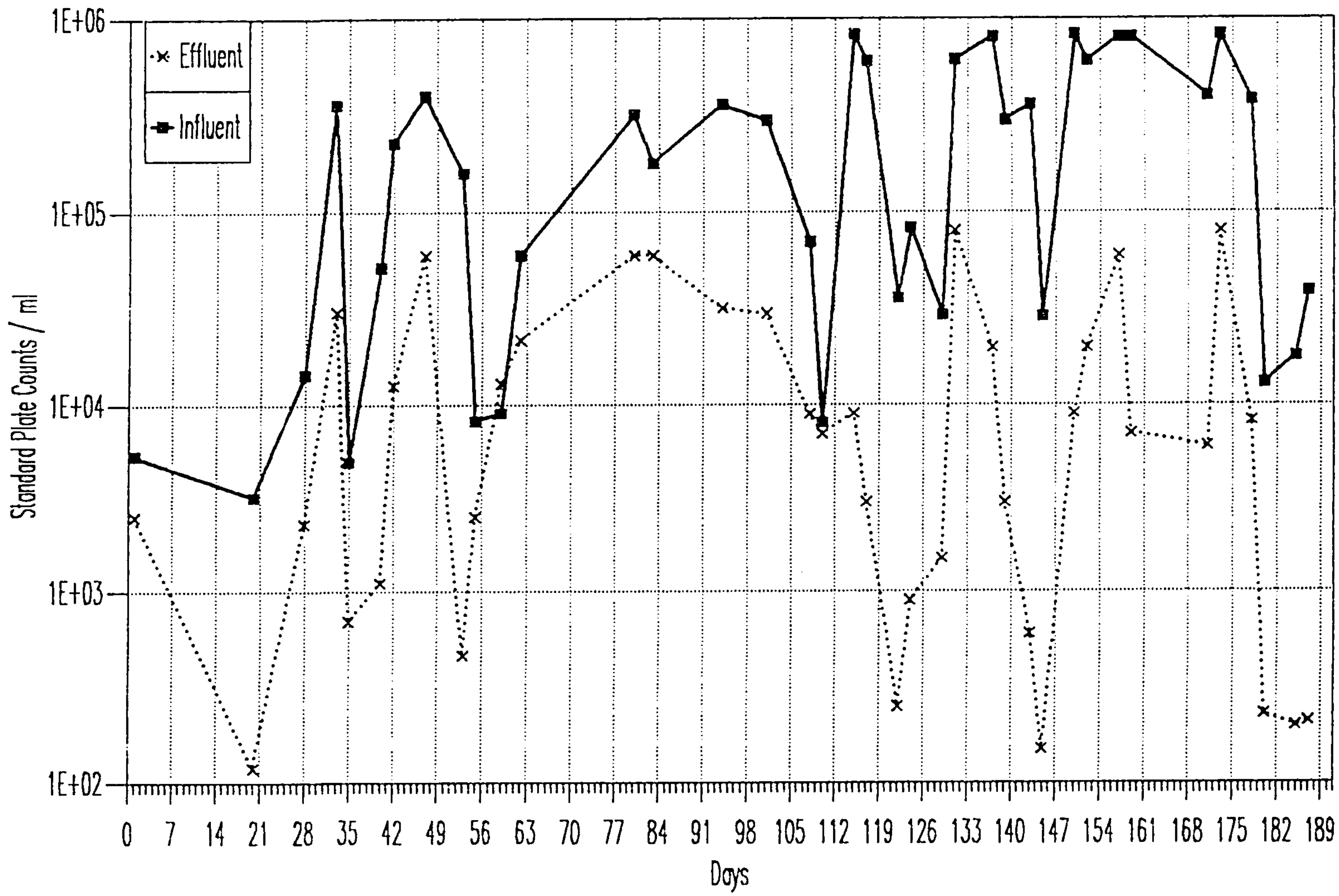


Figure 4.24: Variation of Standard Plate Counts in Condition 10

densities were found for first 50 days of operation. However, at later stage, the fluctuations in the data appeared again. The average influent densities of coliphage, coliforms, fecal coliforms and standard plate counts were 7.64 x 10^2/ml, 3.32 x 10^5 MPN/100 ml, 1.13 x 10^5 MPN/100 ml, and 2.87 x 10^5/ml respectively. Wide range of fluctuations of percentage removals for the microorganisms can be observed in Figure 4.25. The average percentage removal of coliphage, coliforms, fecal coliforms and plate counts were 80%, 89%, 87% and 87% respectively. The percentage removals are quite similar to those obtained in condition #5, indicating no significant effect of sand size on removal efficiencies of microorganisms. Comparing the results of condition #10 (Q =16 l/min) with condition #2 (Q = 10 l/min) it was observed that significantly lower percentage removals were achieved in condition #10. Therefore, the removal efficiencies decreased when the flowrate was increased. Similar conclusions of higher removal at low flowrates are reported in literature [12, 21, 22].

Higher treatment rates, as appreciated by Windle and Taylor [45], markedly reduced the removal of viruses. At flowrate of 4.8 m^3/m^2/day and temperature of 5°C, 99.93% of the viruses were removed along with 99.60% coliform and 99.5% *E.coli*. But this was reduced to 99.78%, 99.4%, and 99.6% respectively at a flowrate of 9.6 m^3/m^2/day. A further increase in flowrate to 12.6 m^3/m^2/day resulted in only a 98.0-5% removal of the viruses

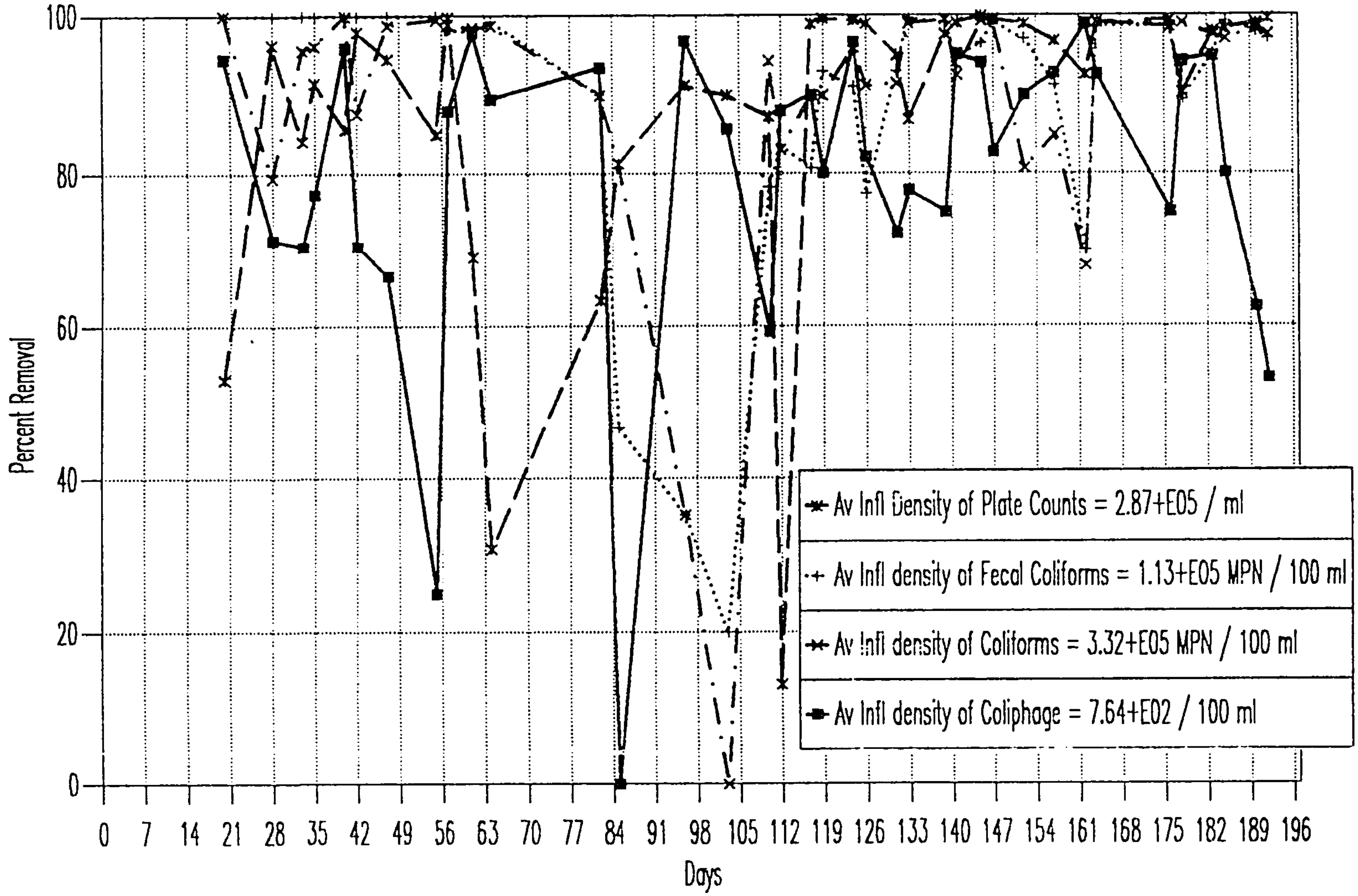


Figure 4.25: **Removal Efficiencies of Various Microorganisms in Condition 10**

together with 93.2% of the coliforms and 97.0% if the *E.coli*.

An investigation into the filtration of secondary sewage treatment works effluent through a horizontal flow gravel filter was carried out at the University of Loughborough [13] using a horizontal prefilter divided into sequential compartments of 150 mm length of 14 to 20 mm gravel, 1500 mm of 5 to 6.3 mm gravel, 100 mm of 6.3 to 10 mm gravel, 1000 mm of 10 to 14 mm gravel, and 150 mm of 14 to 20 mm gravel, very appreciable reductions in both suspended solids and coliform organisms were achieved. In the same study at a flowrate of 2m/hr, suspended solids reduction of from 63 to 62% were achieved, and at the increased rate of 4 m/hr these reductions dropped only to 60%. The percentage reduction in coliform organisms amounted to 86% at a rate of 4.0 m/hr and 99.50% at a rate of 1.2 m/hr.

Figures 4.26-4.29 represent the variations of influent and effluent densities of coliphage, coliforms, fecal coliforms and standard plate counts for condition #11. The percentage removals are presented in Figure 4.30. The average percentage removal of coliphage, coliforms, fecal coliforms and standard plate counts were 75%, 93%, 89% and 87% respectively. Comparing the results with condition #10, only coliphage removal decreased by 6.30% while the removal efficiencies of other microorganisms remained same. Similar results have been reported by Poynter and Slade [23]. They found ten-fold increase in virus removal efficiency when the filter loading was decreased from

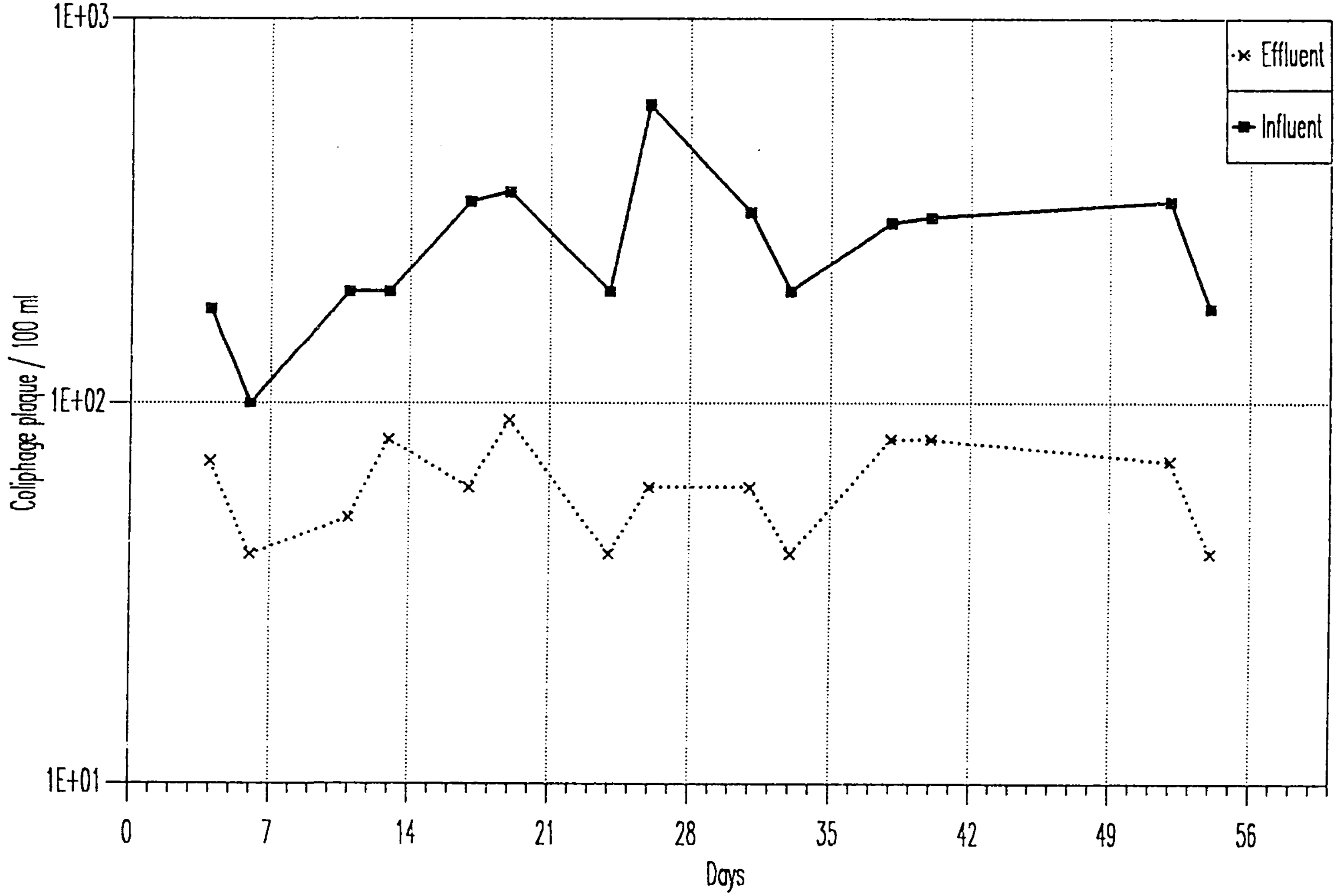


Figure 4.26: Variation of Coliphage plaque in Condition 11

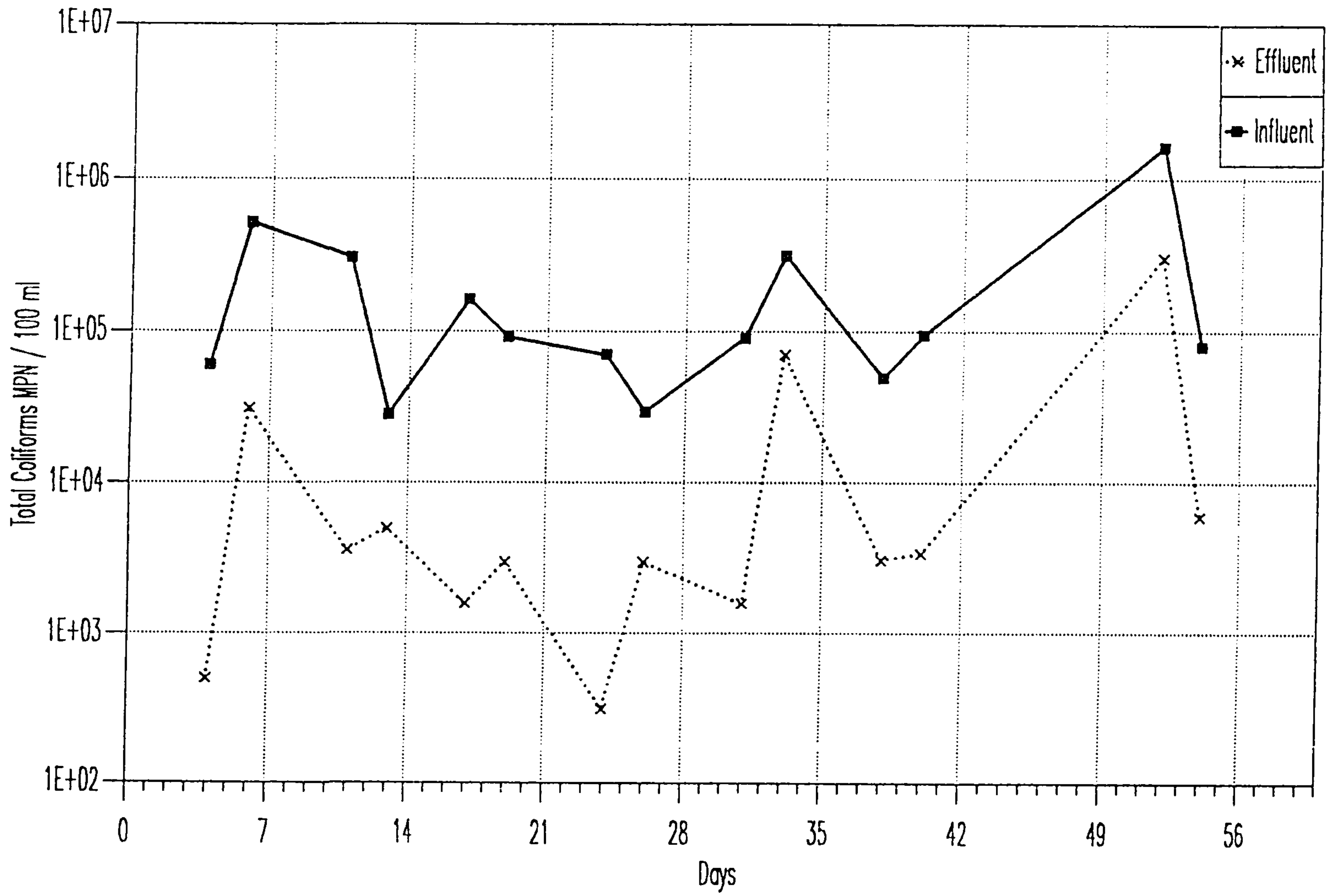


Figure 4.27: Variation of Total Coliforms in Condition 11

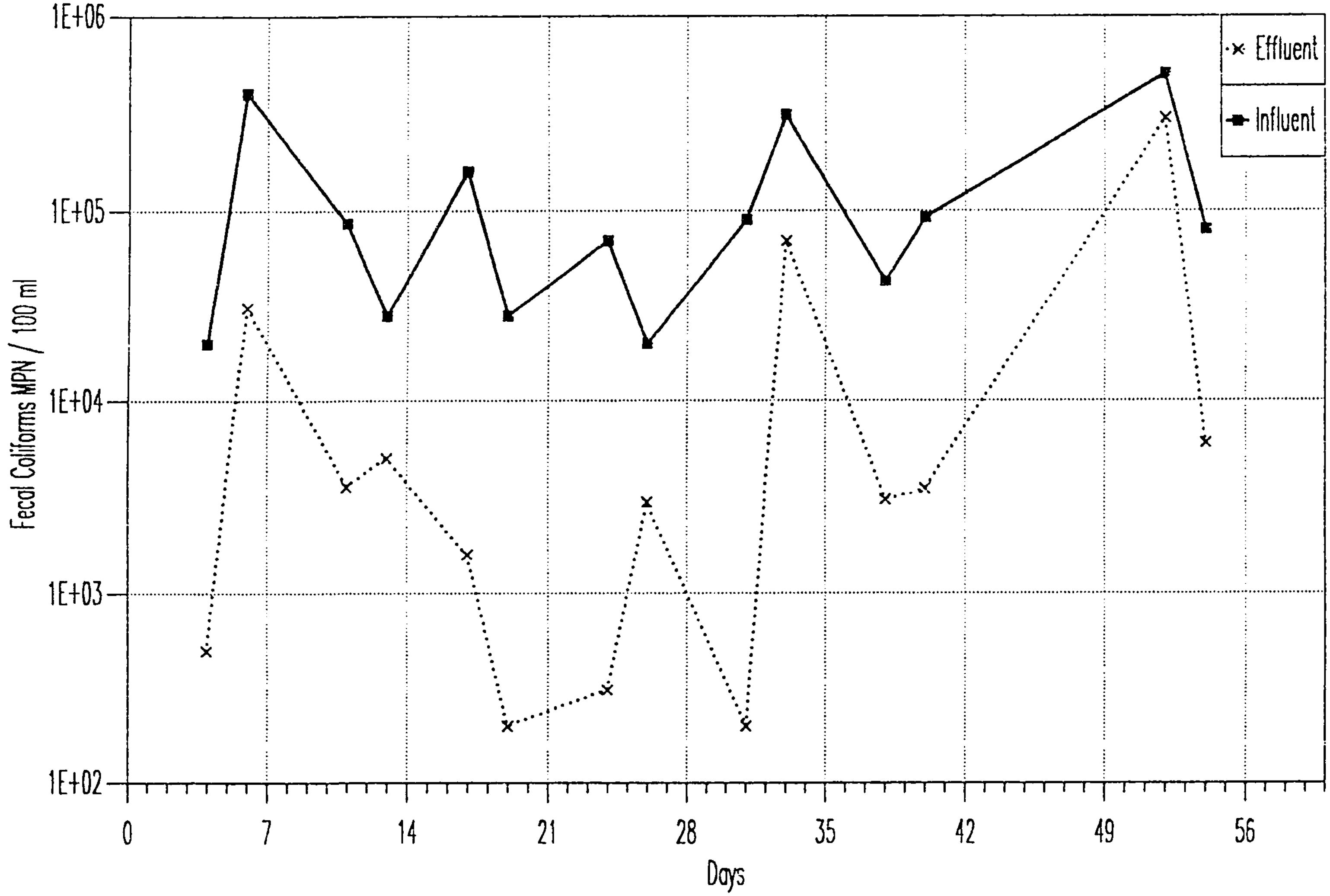


Figure 4.28: Variation of Fecal Coliforms in Condition 11

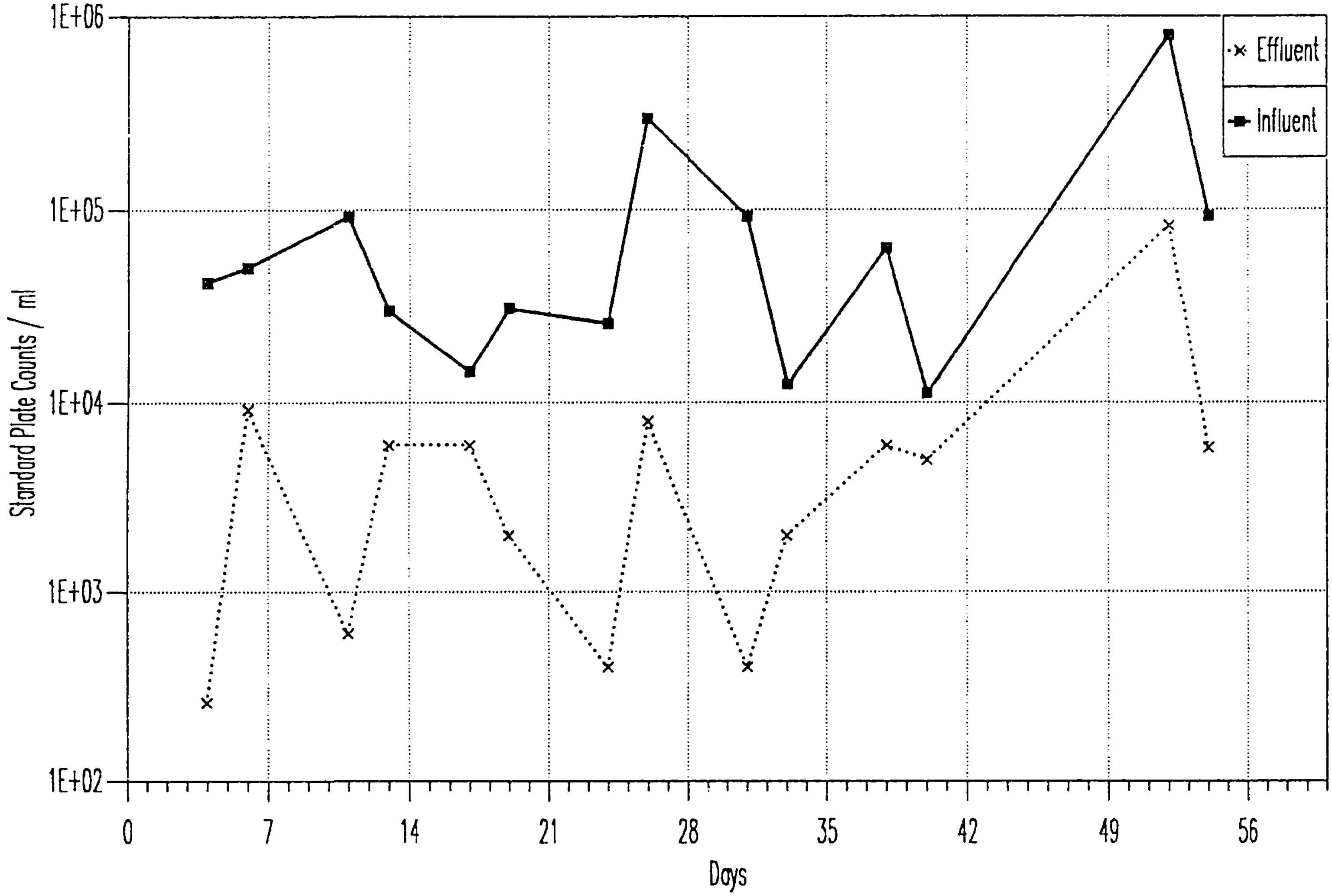


Figure 4.29: Variation of Standard Plate Counts in Condition 11

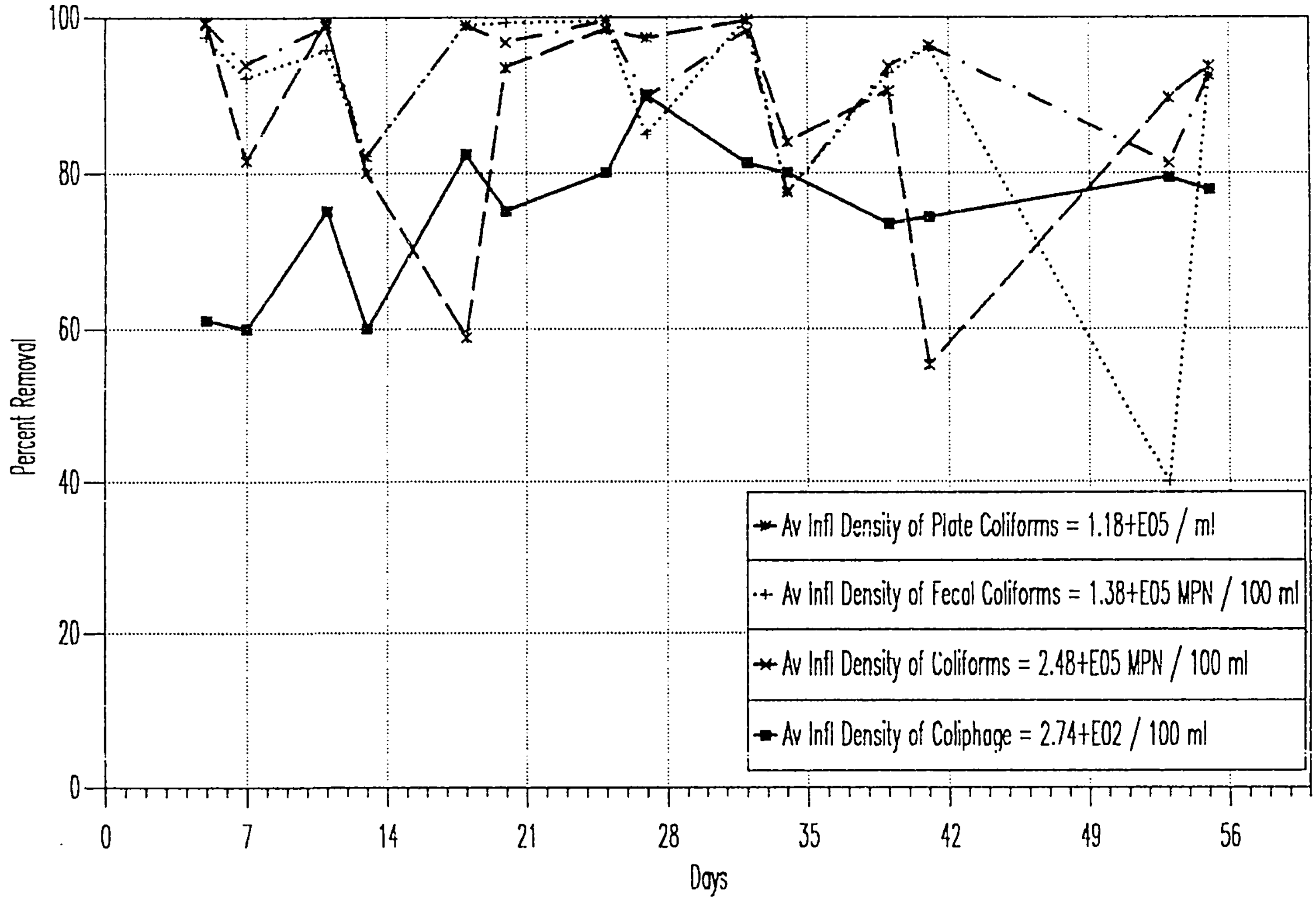


Figure 4.30: Removal Efficiencies of Various Microorganisms in Condition 11

9.6 m/d to 4.8 m/d.

4.2.2 Filter Operations at Flowrates of 10 and 20 l/m, at Sand Depth of 80 cm:

Effecgt of flowrates were studied at three different conditions (i.e., condition #3, #7 and #12) constant sand depth of 80 cm in three different sand filters.

The variation of influent and effluent densities of coliphage, coliforms, fecal coliforms and standard plate counts for condition #3 are presented in Figures 4.31-4.34. The data for total coliphage, coliforms, fecal coliforms and standard plate counts were highly fluctuating, while data (both influent and effluent) were slightly uniform. But no regular trend could be observed for any of the microorganisms. The average influent densities of coliphage, coliforms, fecal coliforms and standard plate counts were 2.84 x 10^2/100 ml, 50.6 x 10^5 MPN/100 ml, 2.65 x 10^5 MPN/100 and 2.00 x 10^5/ml respectively, while the average effluent densities were 51/100 ml, 2.17 x 10^3 MPN/100 ml, 9.73 x 10^2 MPN/100 ml and 1.99 x 10^3/ml respectively. Figure 4.35 presents the variation of percentage removal of microorganisms. The average percentage removal of coliphage, coliforms, fecal coliforms and standard plate counts were 81%, 99%, 99% and 96% respectively. Since these percentage removals are higher as compared to those obtained in conditions #5 and #16 (operated at 150 cm sand

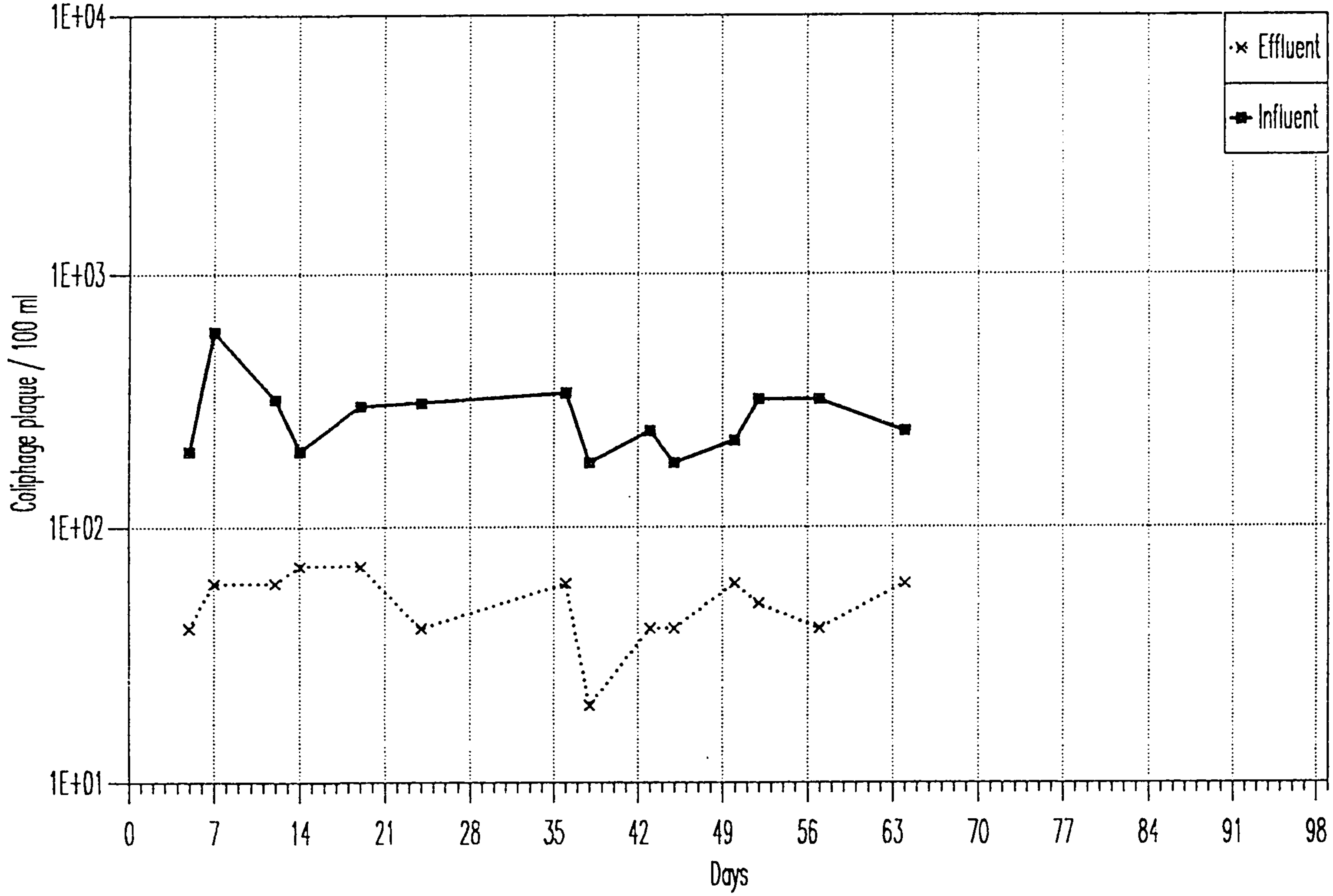


Figure 4.31: Variation of Coliphage plaque in Condition 3

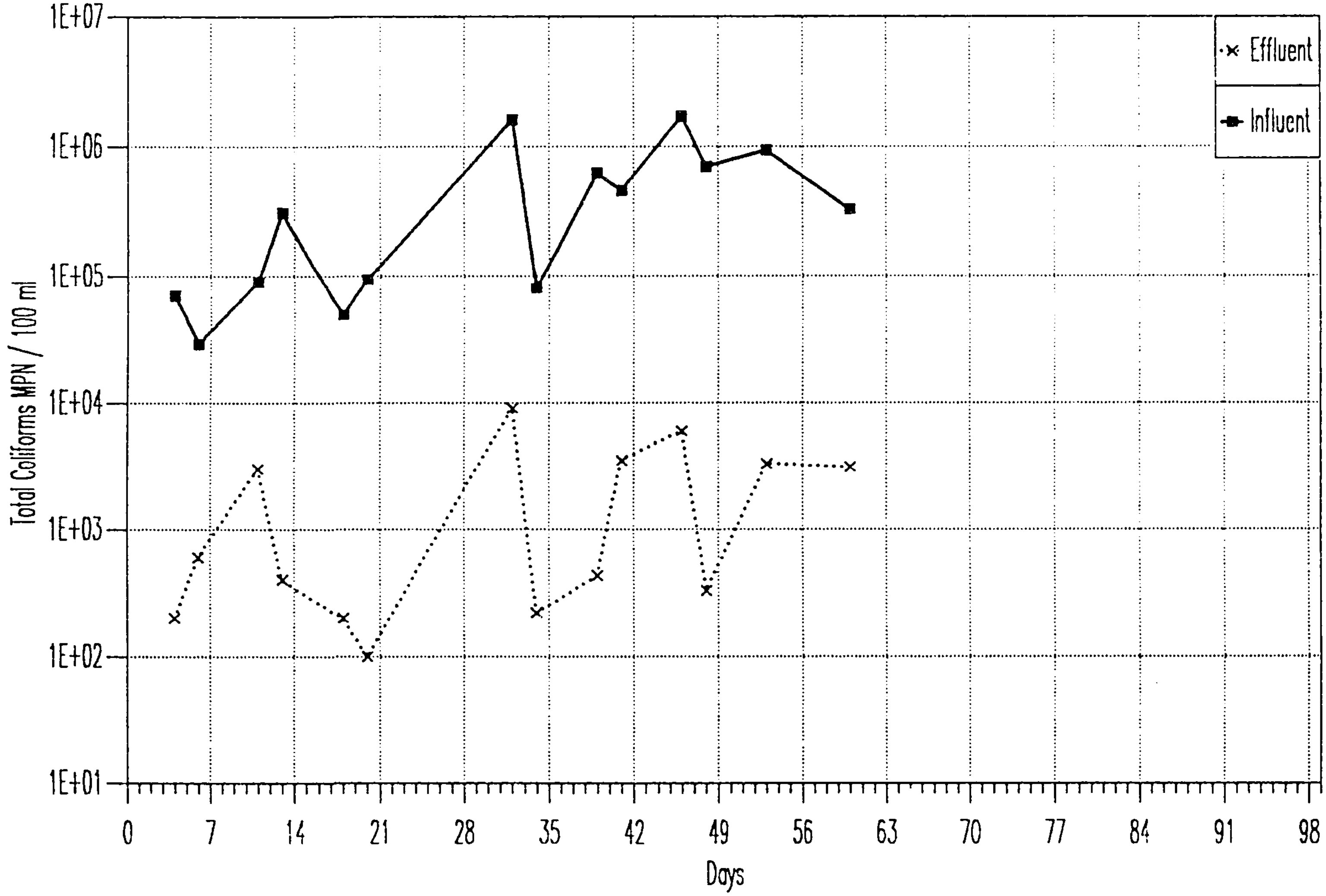


Figure 4.32: **Variation of Total Coliforms in Condition 3**

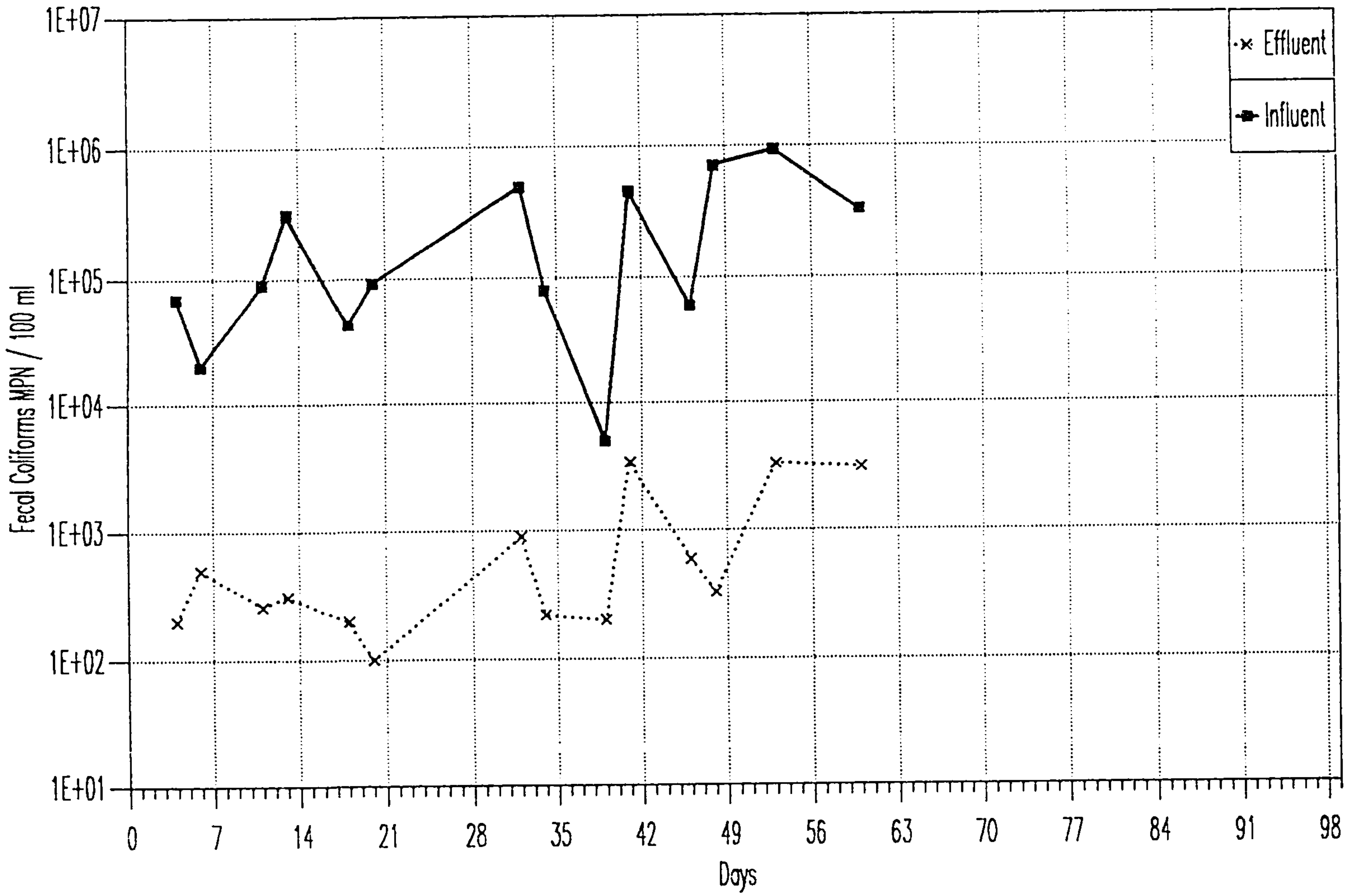


Figure 4.33: Variation of Fecal Coliforms in Condition 3

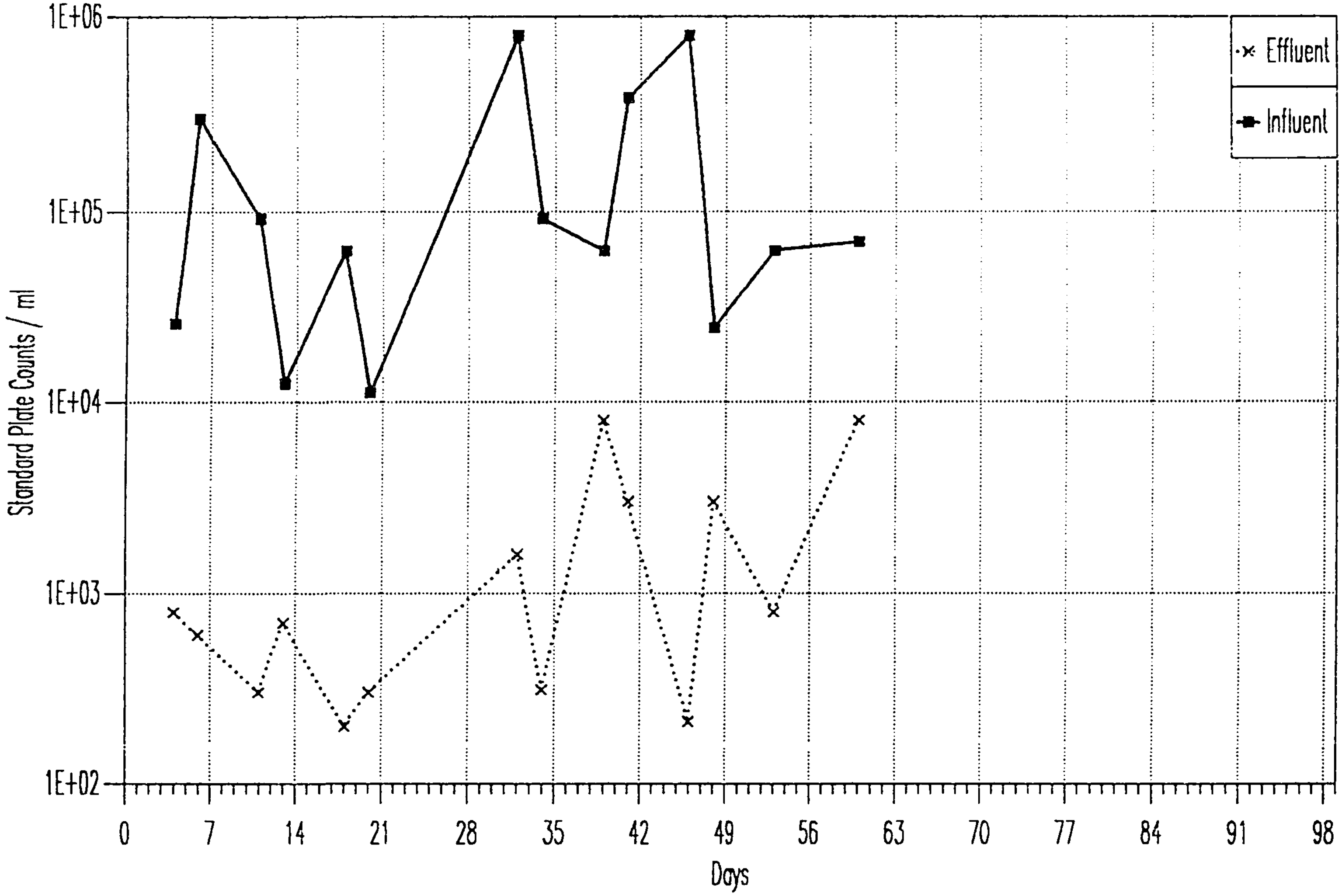


Figure 4.34: Variation of Standard Plate Counts in Condition 3

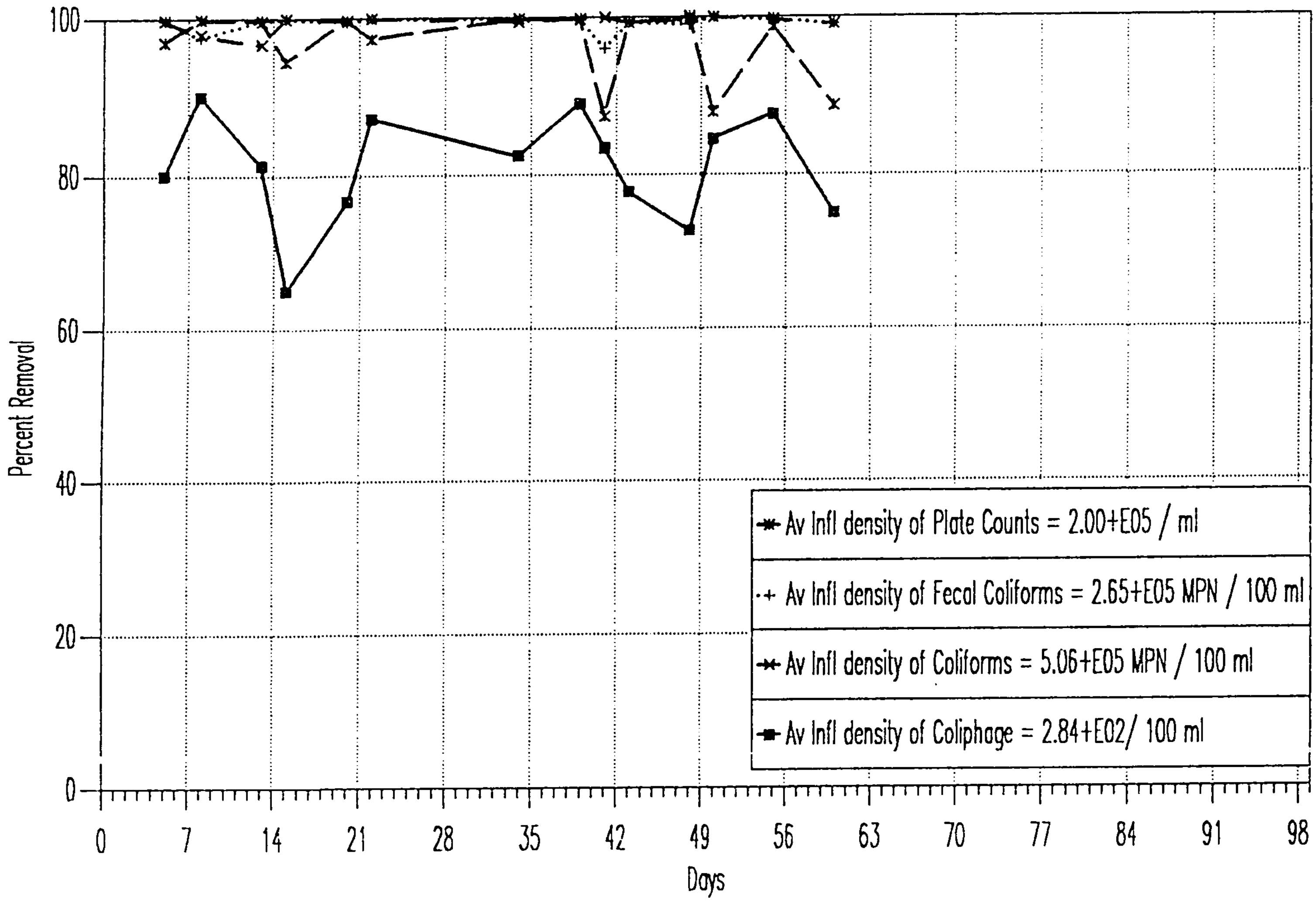


Figure 4.35: Removal Efficiencies of Various Microorganisms in Condition 3

depth), it is clear that sand depth did not show the response of low removal efficiencies at reduced sand depths. Lower flowrate, therefore, was the key variable responsible for higher efficiencies in condition #3 as compared to conditions #5 and #6.

Condition #7 indicated quite fluctuating data (both influent and effluent) for all the microorganisms (Figures 4.36-4.39), except total coliforms where rising trend was observed after 30 days of operation and finally the trend became consistent on the 50th day of operation. The percentage removals were fluctuating (Figure 4.40) and an average removals of 77%, 91%, 88% and 90% were obtained for coliphage, coliforms, fecal coliforms and standard plate counts, respectively. The removal efficiencies were significantly lower as compared to the removal efficiencies achieved in condition #3. Thus, the effect of flowrates giving decreased efficiencies at increased flowrates was more dominant at 80 cm depth.

Figure 4.41 shows a consistent trend of effluent data of coliphage in condition #12. The influent and effluent variations of coliphage, coliforms, fecal coliforms and standard plate counts are shown in Figures 4.41-4.44. The coliform and fecal coliform effluent data indicated a rising trend in densities and then became consistent with time. The variation of percentage removal of all four microorganisms are shown in Figure 4.45. The average removal efficiencies achieved for coliphage, coliforms, fecal coliform and plate counts

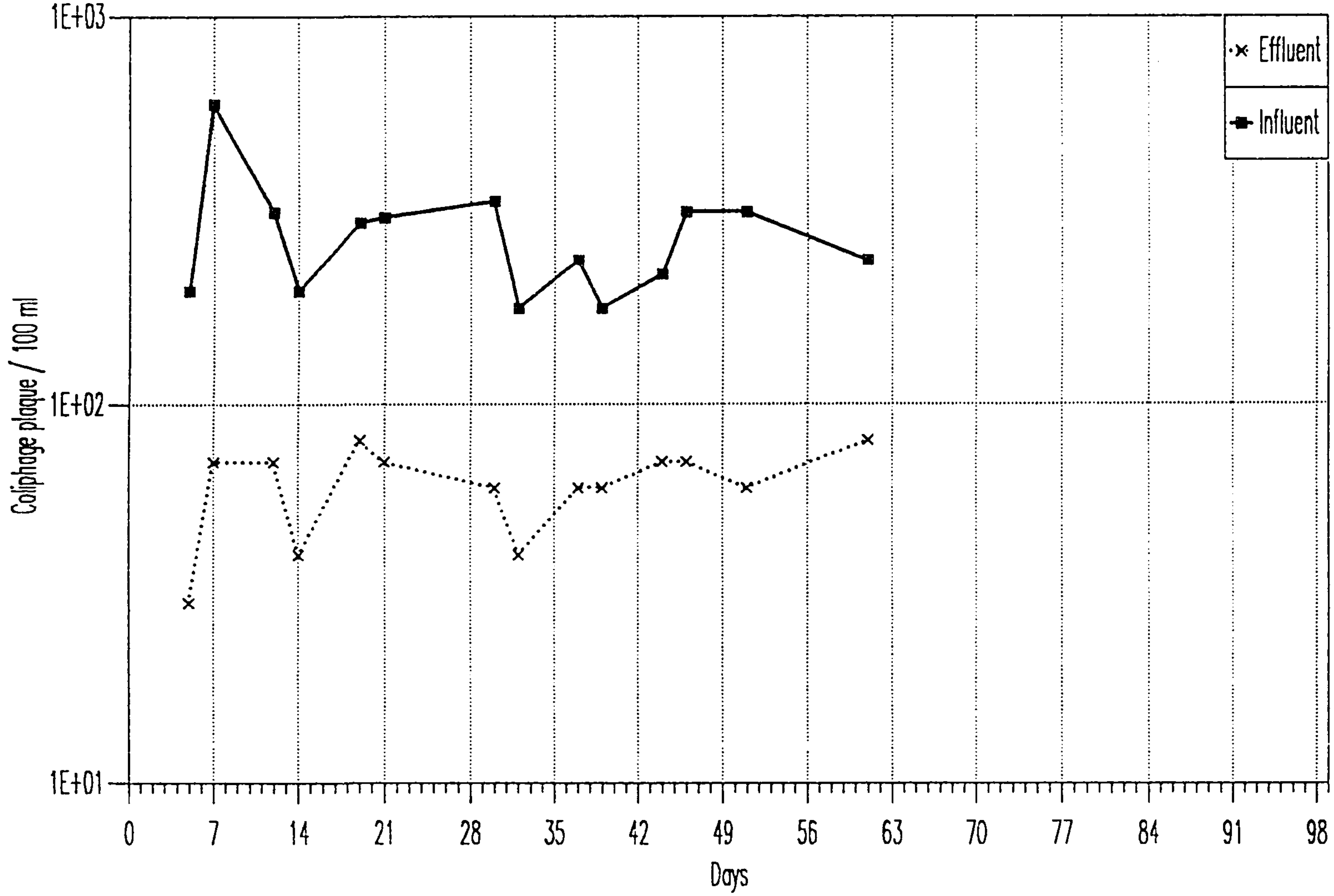


Figure 4.36: Variation of Coliphage plaque in Condition 7

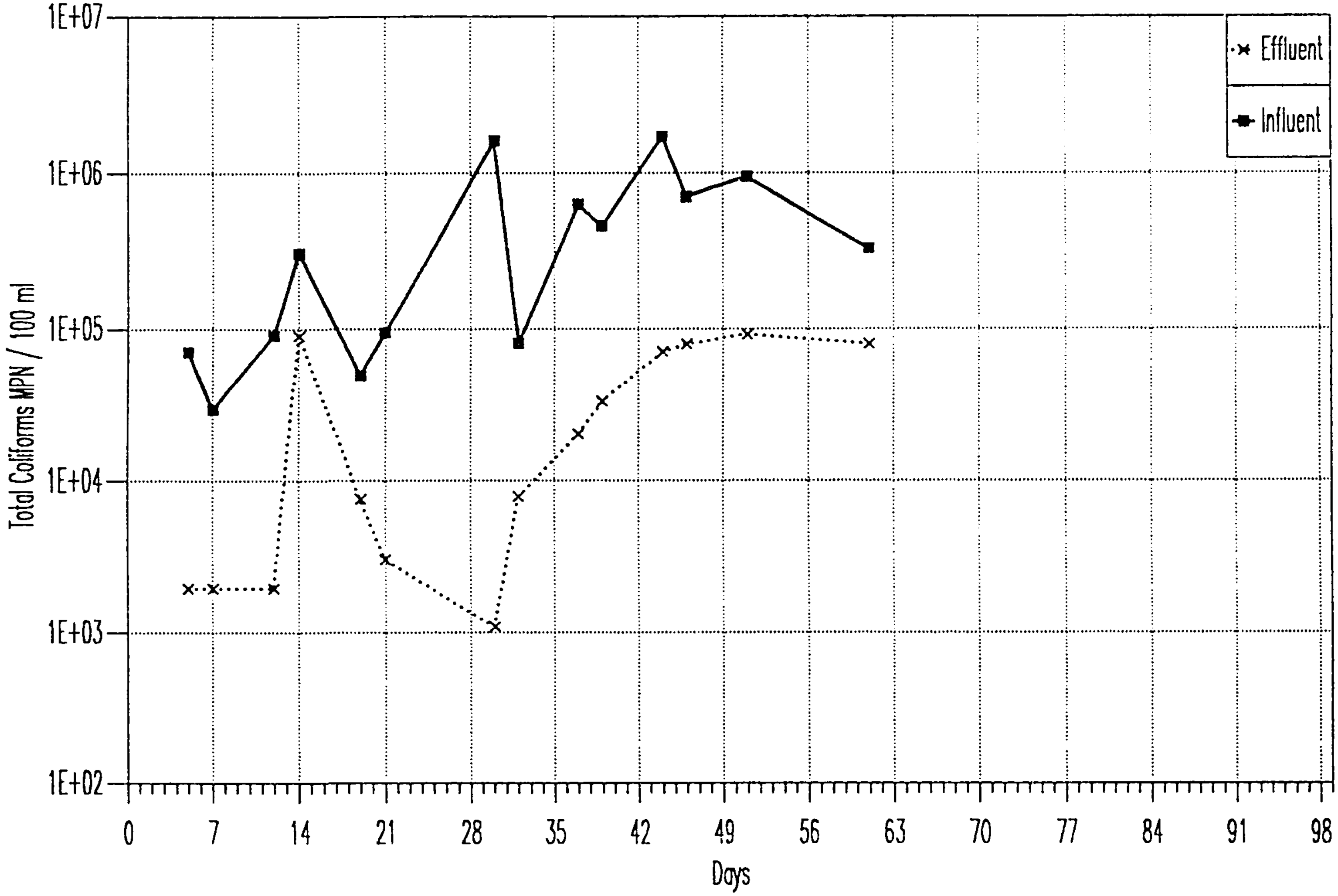


Figure 4.37: **Variation of Total Coliforms in Condition 7**

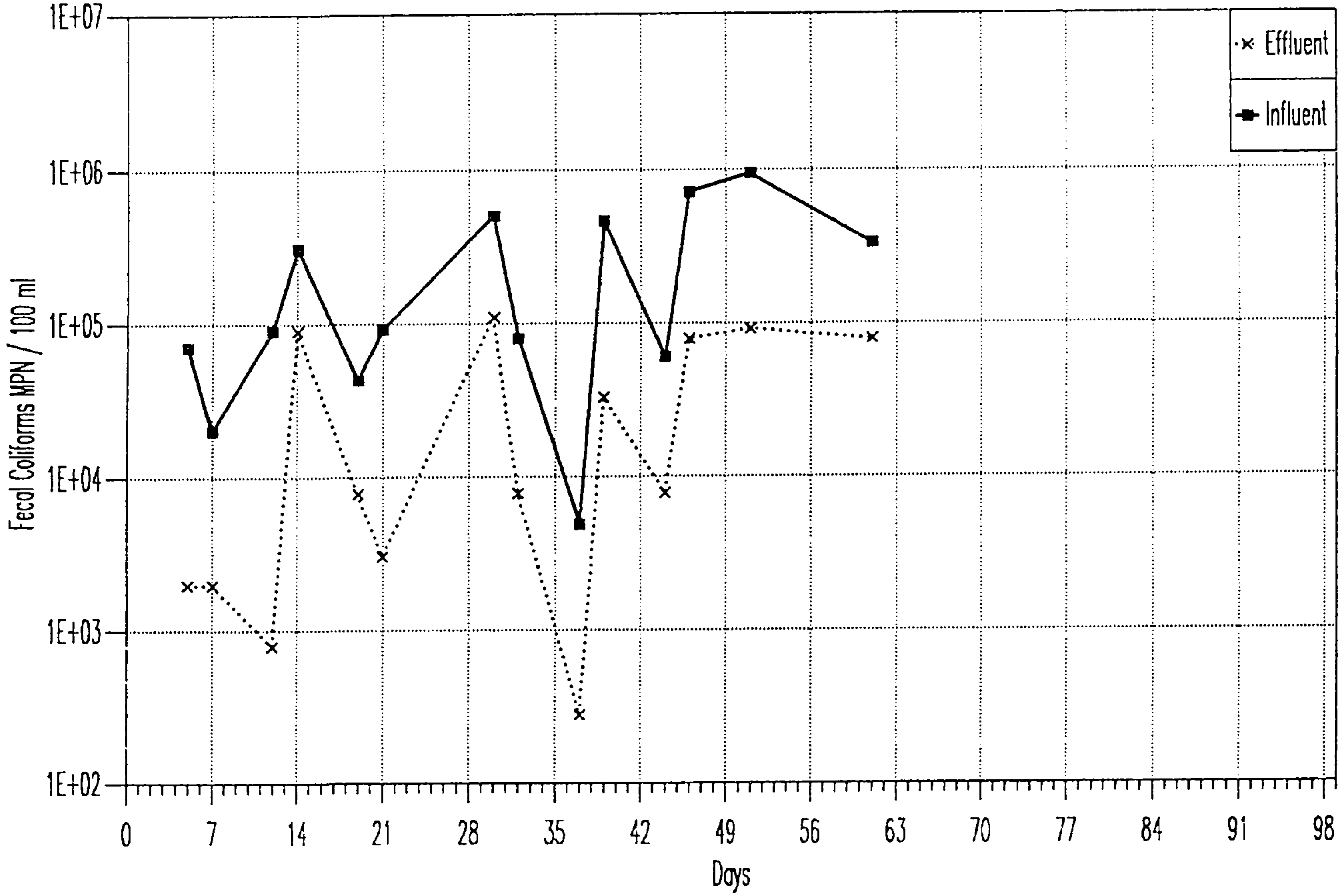


Figure 4.38: Variation of Fecal Coliforms in Condition 7

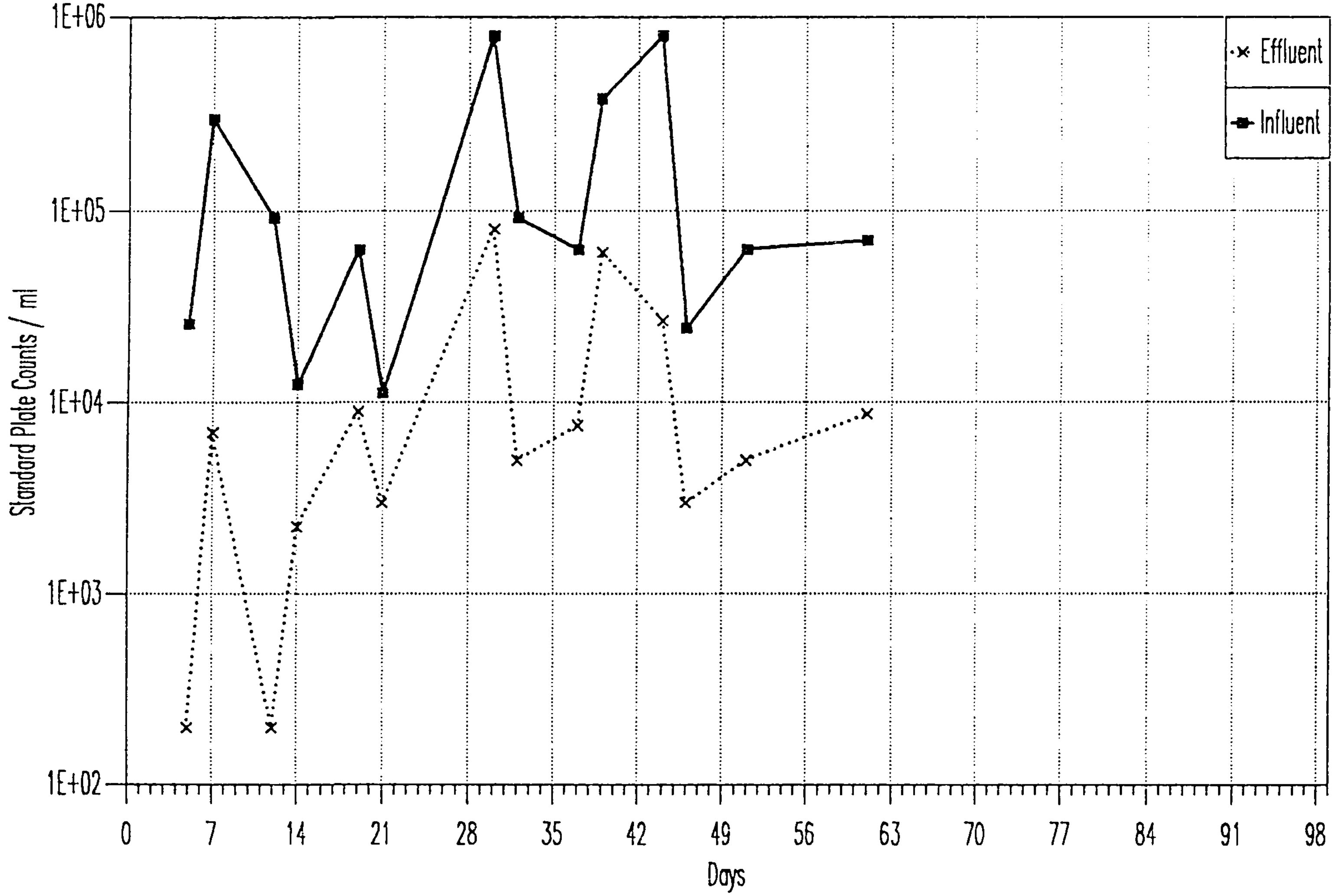


Figure 4.39: Variation of Standard Plate Counts in Condition 7

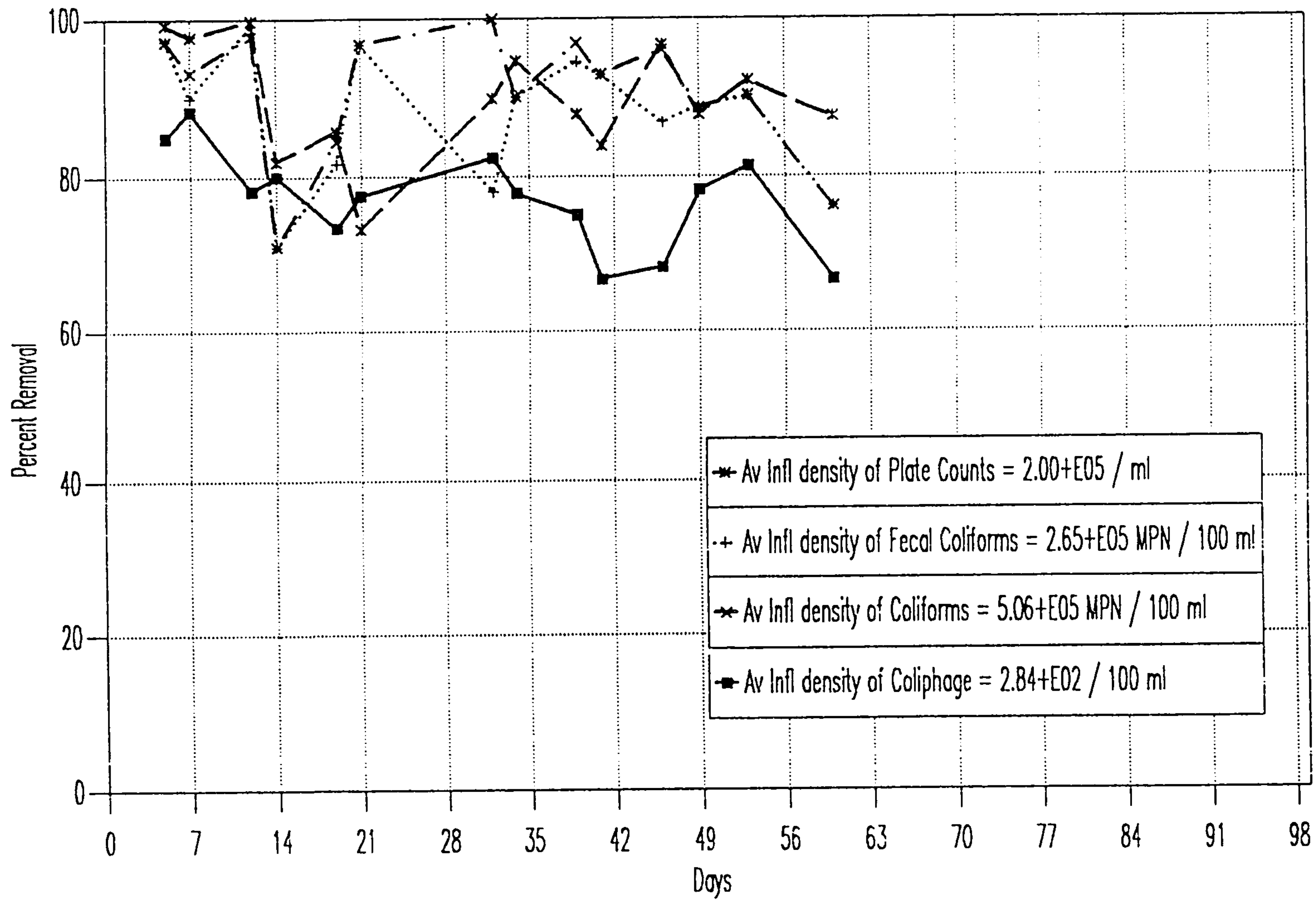


Figure 4.40: **Removal Efficiencies of Various Microorganisms in Condition 7**

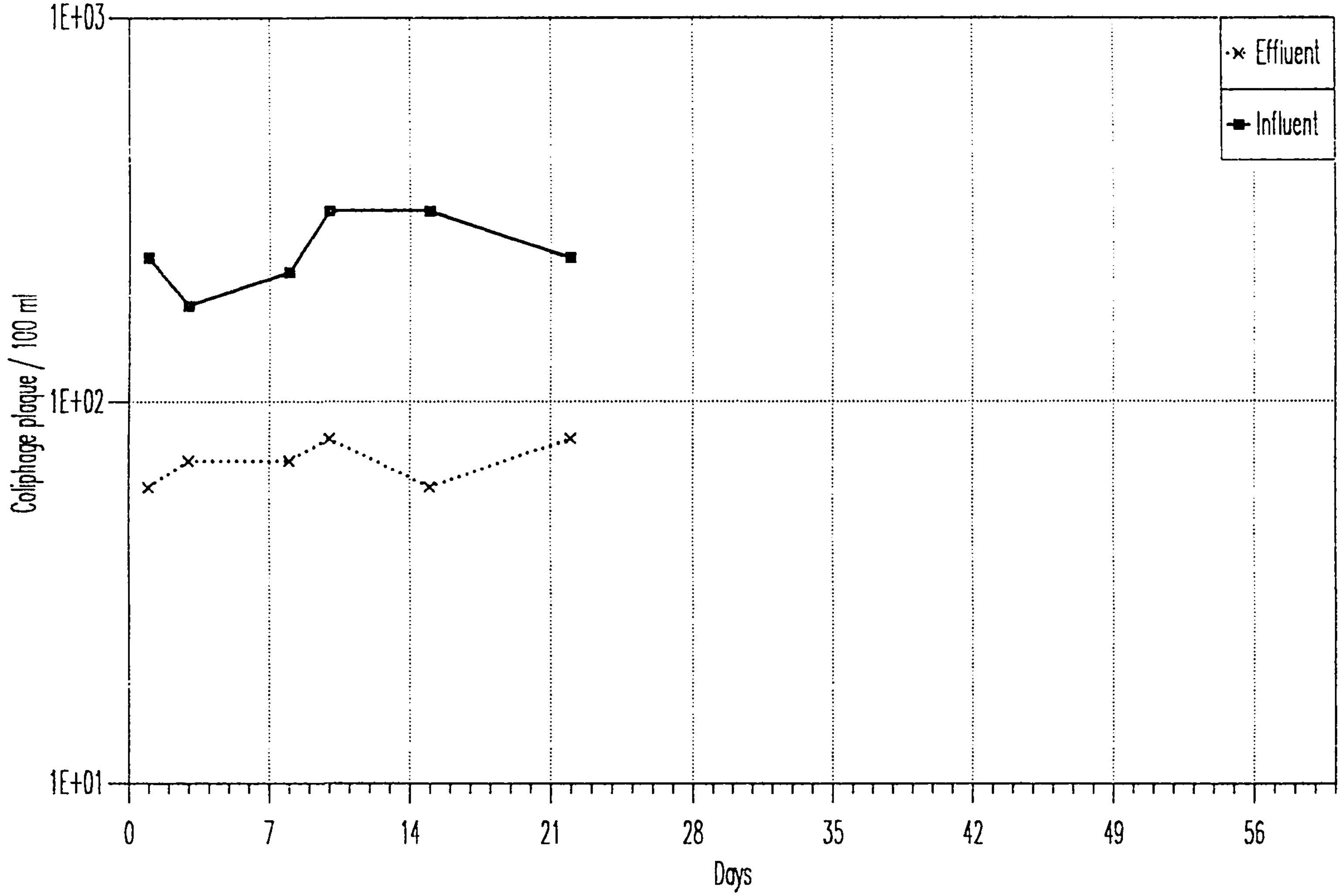


Figure 4.41: Variation of Coliphage plaque in Condition 12

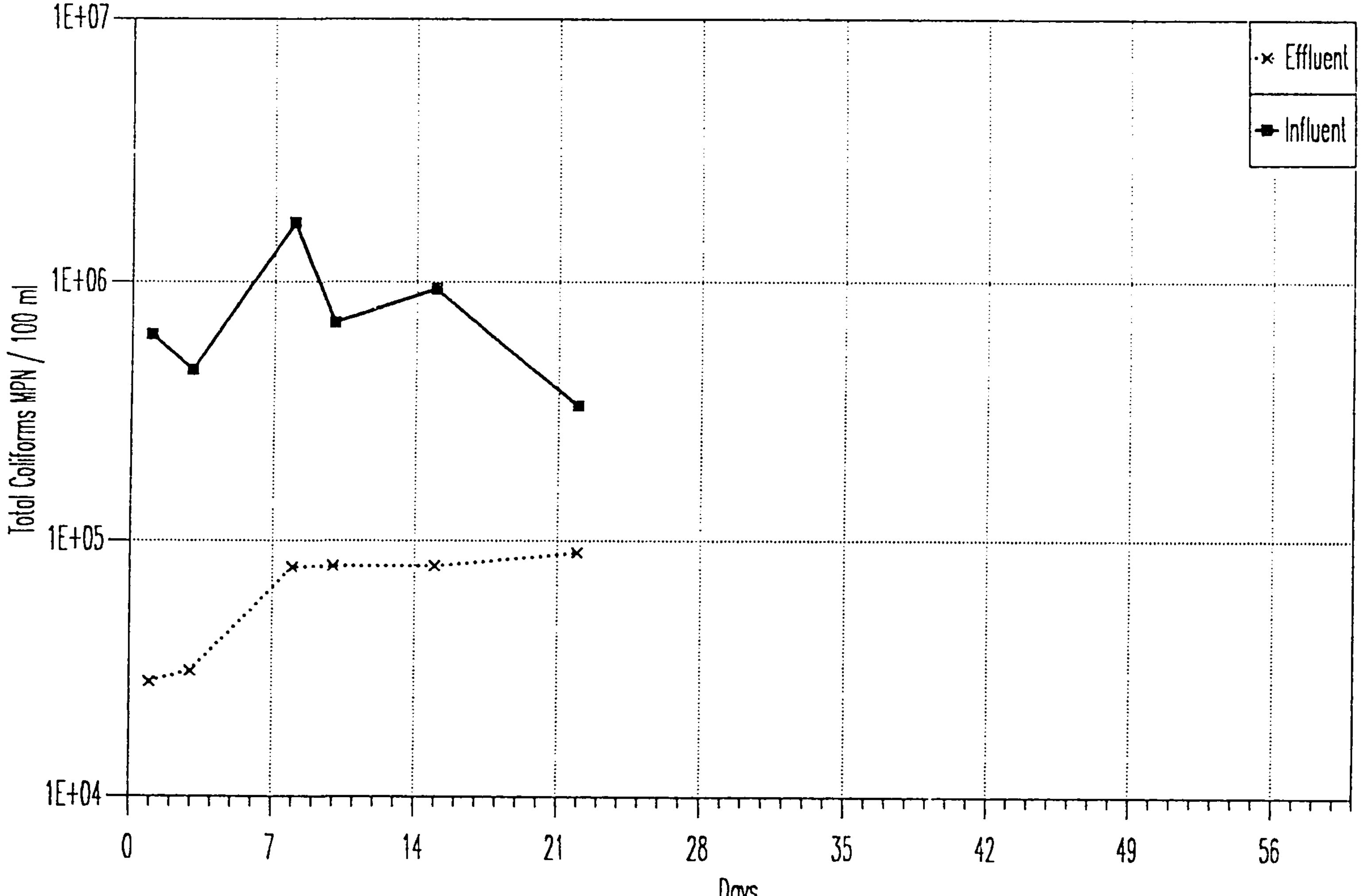


Figure 4.42: Variation of Total Coliforms in Condition 12

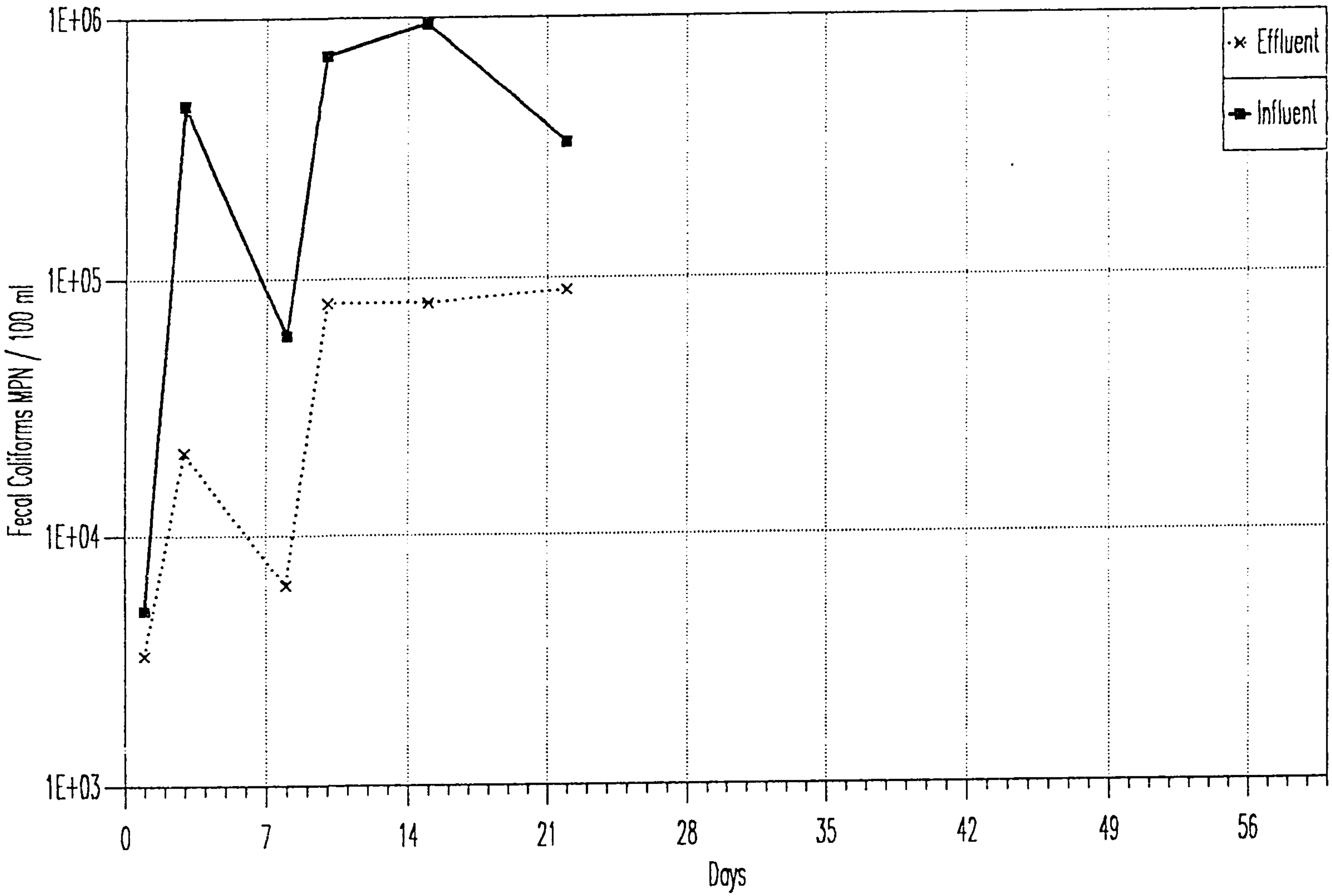


Figure 4.43: Variation of Fecal Coliforms in Condition 12

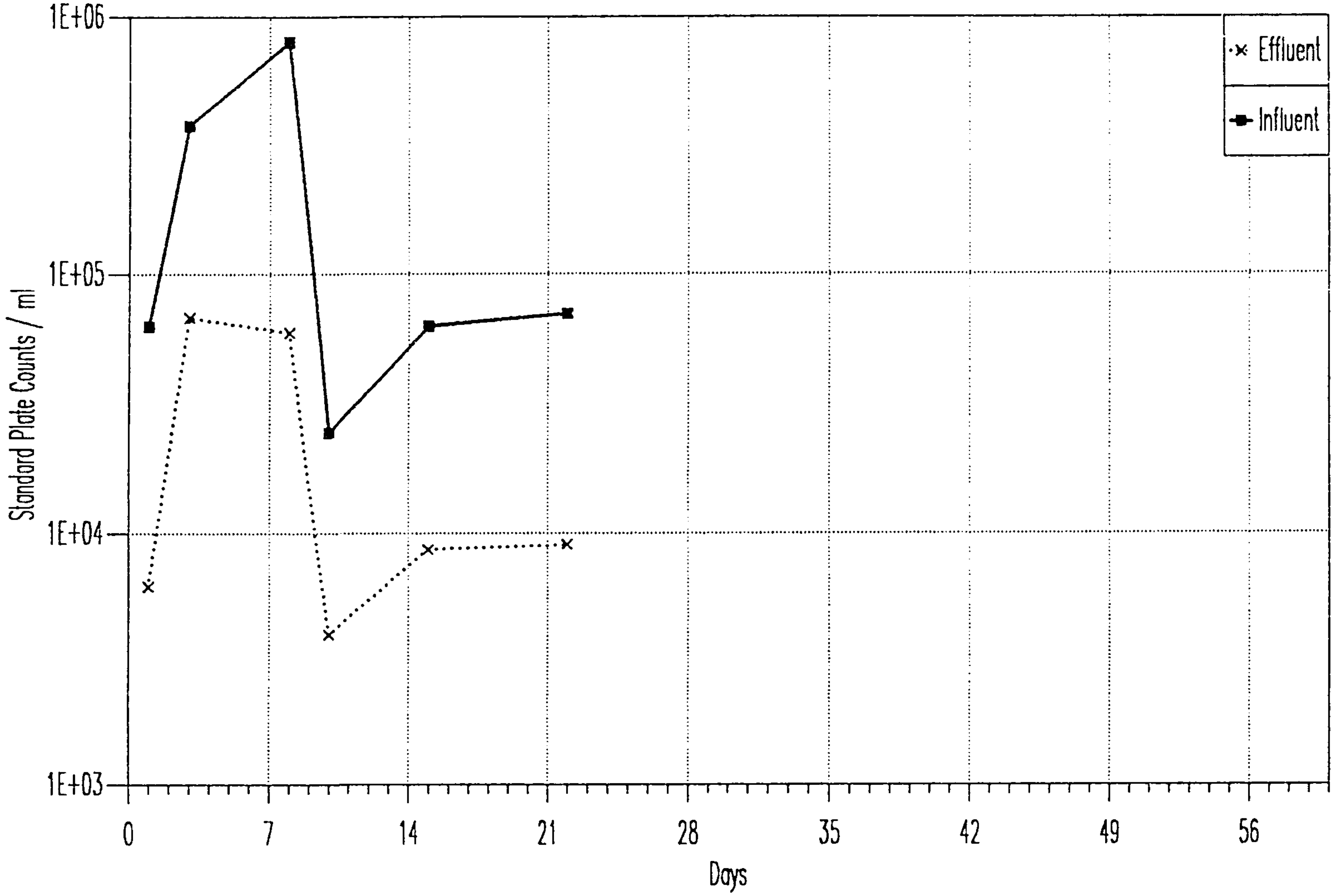


Figure 4.44: Variation of Standard Plate Counts in Condition 12

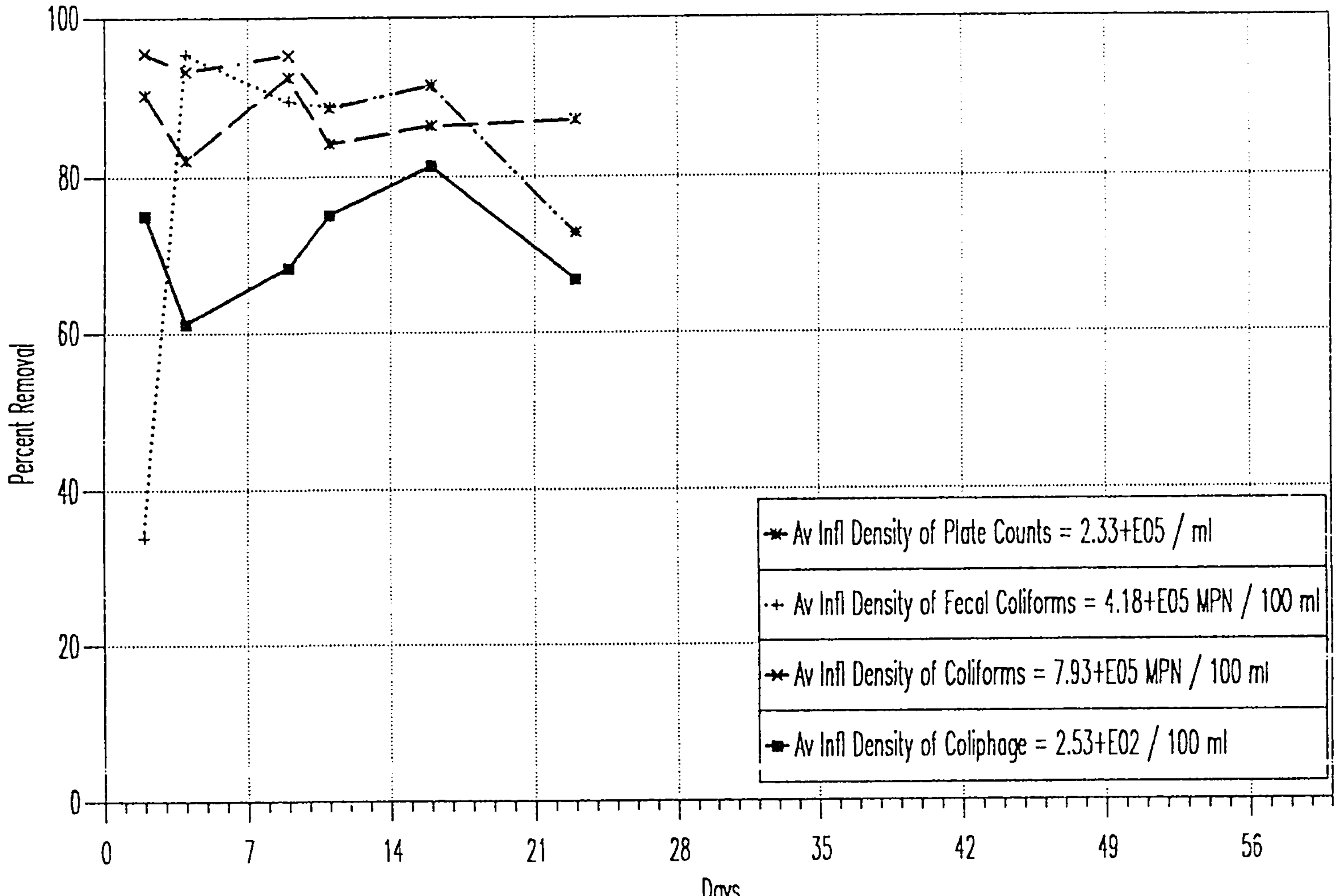


Figure 4.45: **Removal Efficiencies of Various Microorganisms in Condition 12**

were 71%, 89.50%, 79% and 87%, respectively. The removal efficiencies were found quite low as compared to those in condition #3. Therefore, the removal efficiencies were again reduced at higher flowrates when sand depth and sand size were constant.

4.2.3 Filter Operations at Flowrates of 10 and 20 l/m, at Sand Depth of 50 cm:

Effect of flowrates were again investigated in three conditions (condition #4, #8 and #13) at constant sand depth of 50 cm.

The influent and effluent variations of various microorganisms in condition #4 are presented in Figures 4.46-4.49. The data in each case were quite fluctuating, except for coliphage (Figure 4.46) where slightly consistent effluent data was observed. In case of total coliforms, fecal coliforms and plate counts the variation trend of effluent densities were same as observed in the influents. However, there was no regular trend in both the effluent and influent densities. The average influent densities of coliphage, coliforms, fecal coliforms and standard plate counts were 2.92×10^2/100 ml, 6.66×10^4 MPN/100 ml, 3.64×10^4 MPN/100 and 8.80×10^4/ml respectively, whereas the average percentage removal were 76%, 84%, 85% and 86% respectively. The percentage removal variation for all microorganisms is shown in Figure 4.50.

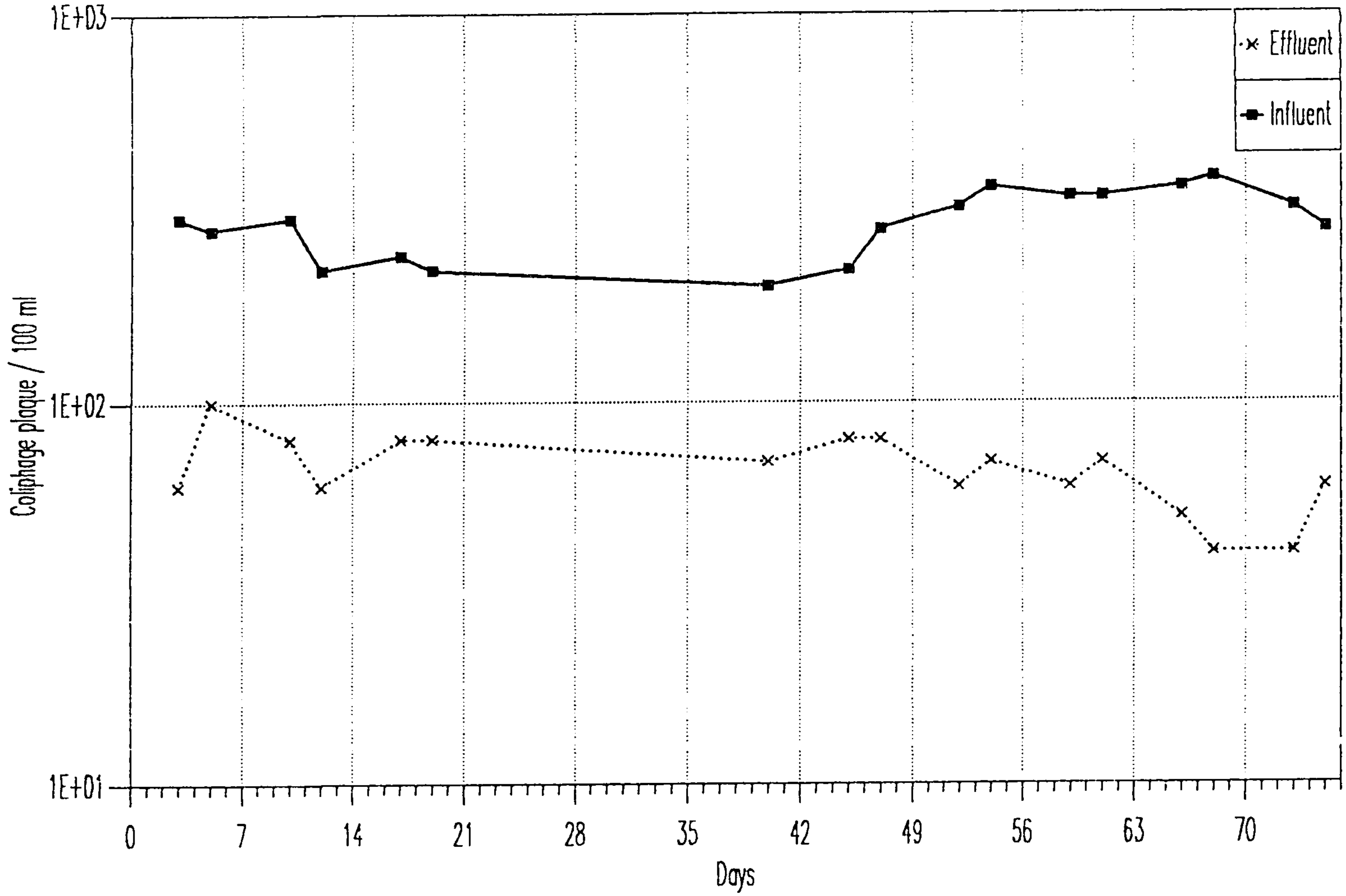


Figure 4.46: Variation of Coliphage plaque in Condition 4

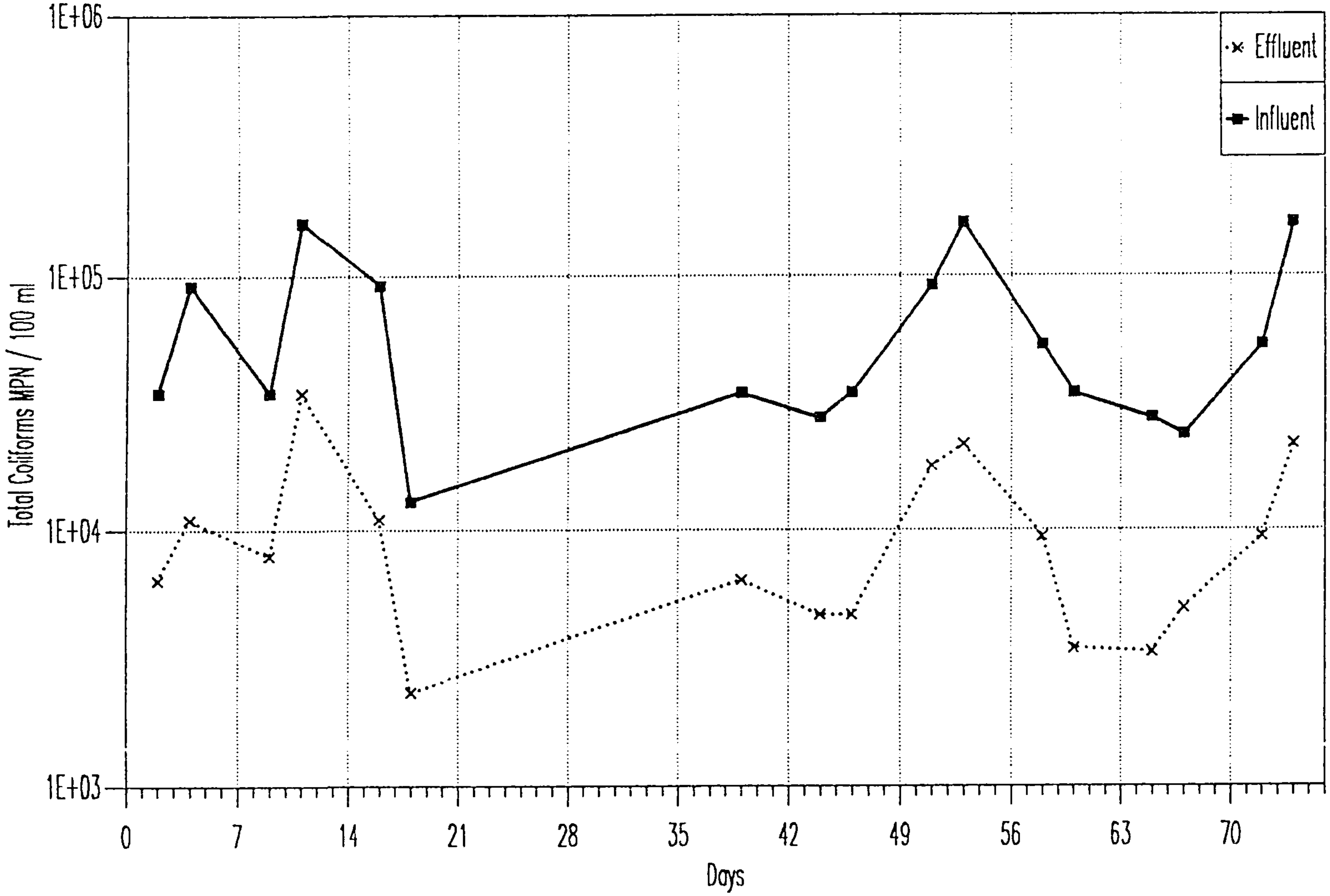


Figure 4.47: Variation of Total Coliforms in Condition 4

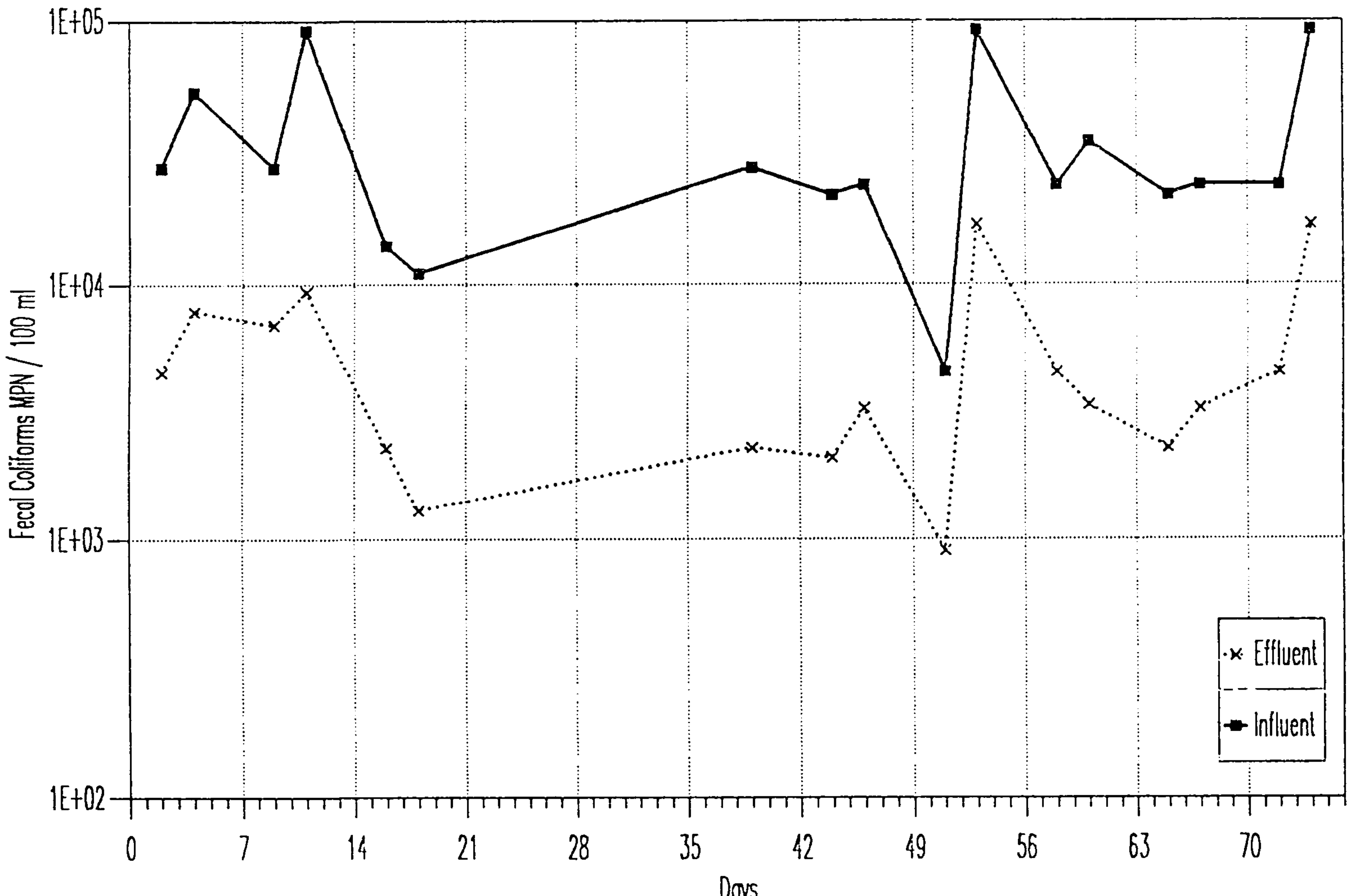


Figure 4.43: Variation of Fecal Coliforms in Condition 4

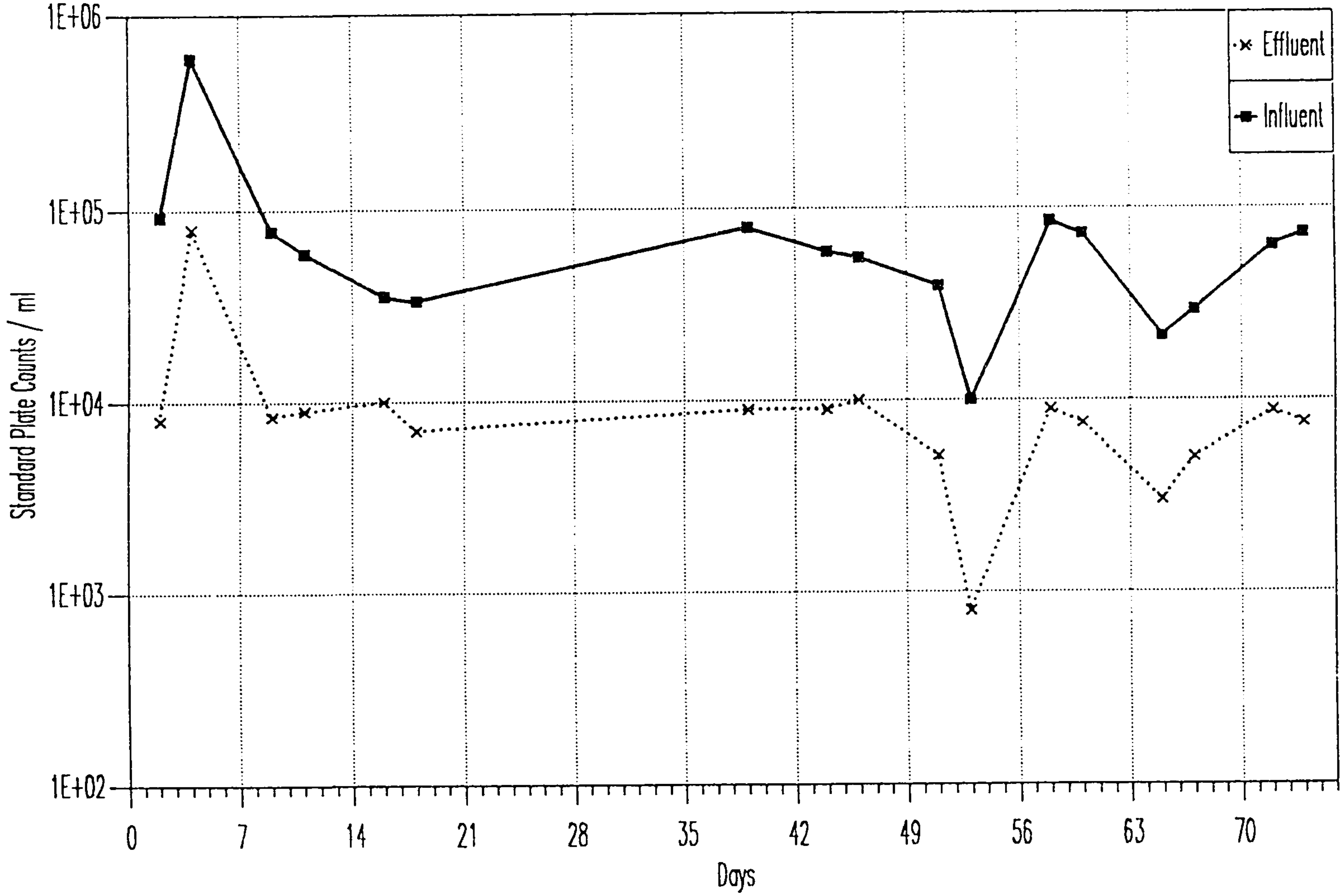


Figure 4.49: Variation of Standard Plate Counts in Condition 4

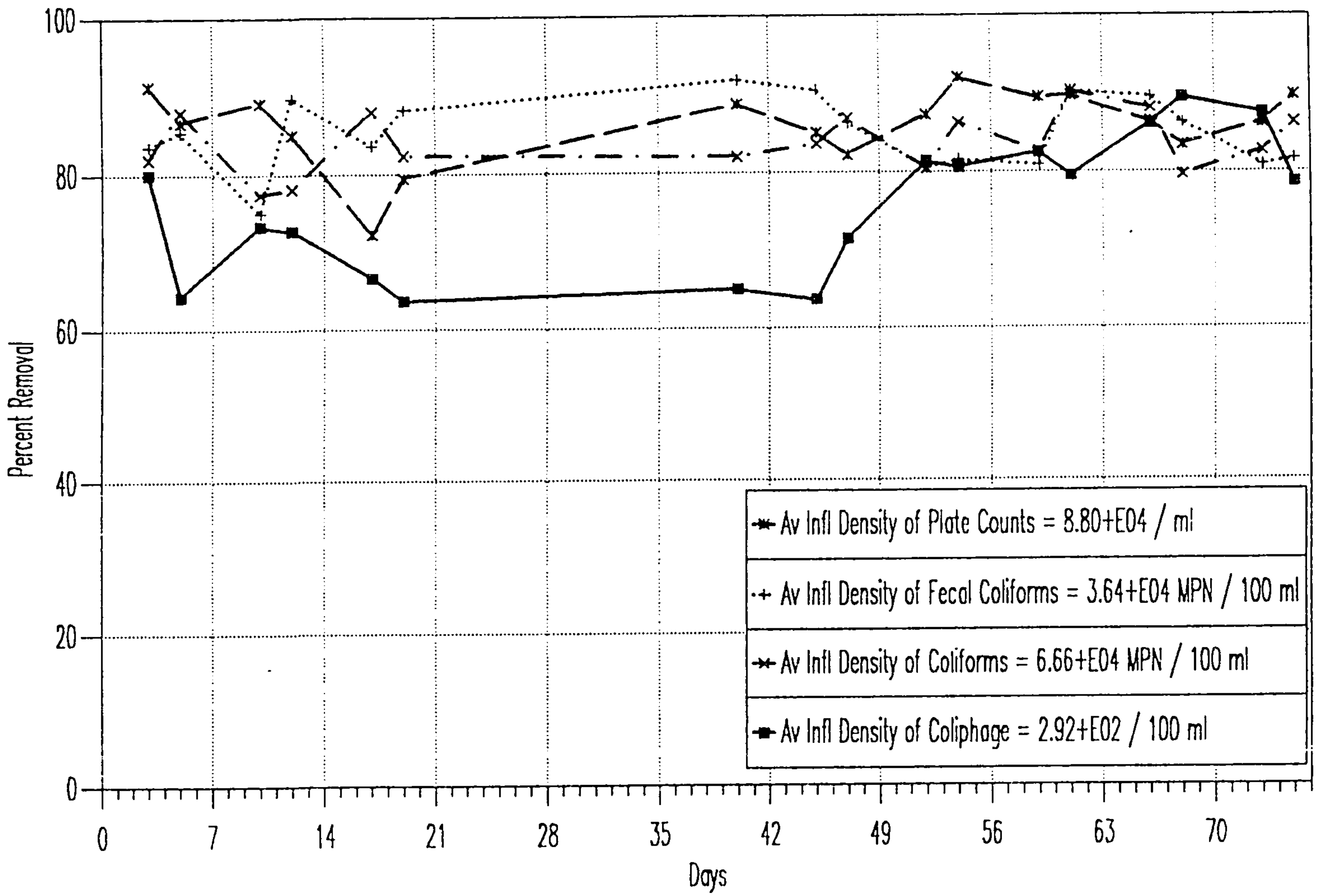


Figure 4.50: **Removal Efficiencies of Various Microorganisms in Condition 4**

Variations of influent and effluent densities of coliphage in condition #8 (Figure 4.51) were consistent again as in condition #4. The variation of densities of total coliforms, fecal coliforms and standard plate counts were quite fluctuating and most of time effluent was followed by influent, as shown in Figures 4.52, 4.53 and 4.54 respectively. The variation of percentage removal for all four microorganisms are shown in Figure 4.55. The average percentage removal in condition #8 were 68%, 79%, 80% and 83% for coliphage, coliforms, fecal coliforms and standard plate counts respectively. Comparison of microorganisms removals at various flowrates indicate that removal efficiencies are effected by flowrates irrespective of sand size at constant depth of 50 cm. Higher efficiencies were achieved at lower flowrates as discussed earlier when comparing the results of [13].

The influent and effluent variations of microorganisms during condition #3 are presented in Figures 4.56-4.59. Again the effluents were followed by influent for total coliforms, fecal coliforms and plate counts. The variation of percentage removals are presented in Figure 4.60. The average percentage removal of coliphage, coliforms, fecal coliforms and plate counts obtained were 69%, 78% 79% and 82% respectively. When these results were compared with condition #4, comparatively lower removal efficiencies were achieved in condition #13. Conclusion similar to previous one can again be restated that in general the removal efficiencies of microorganisms decreased when the

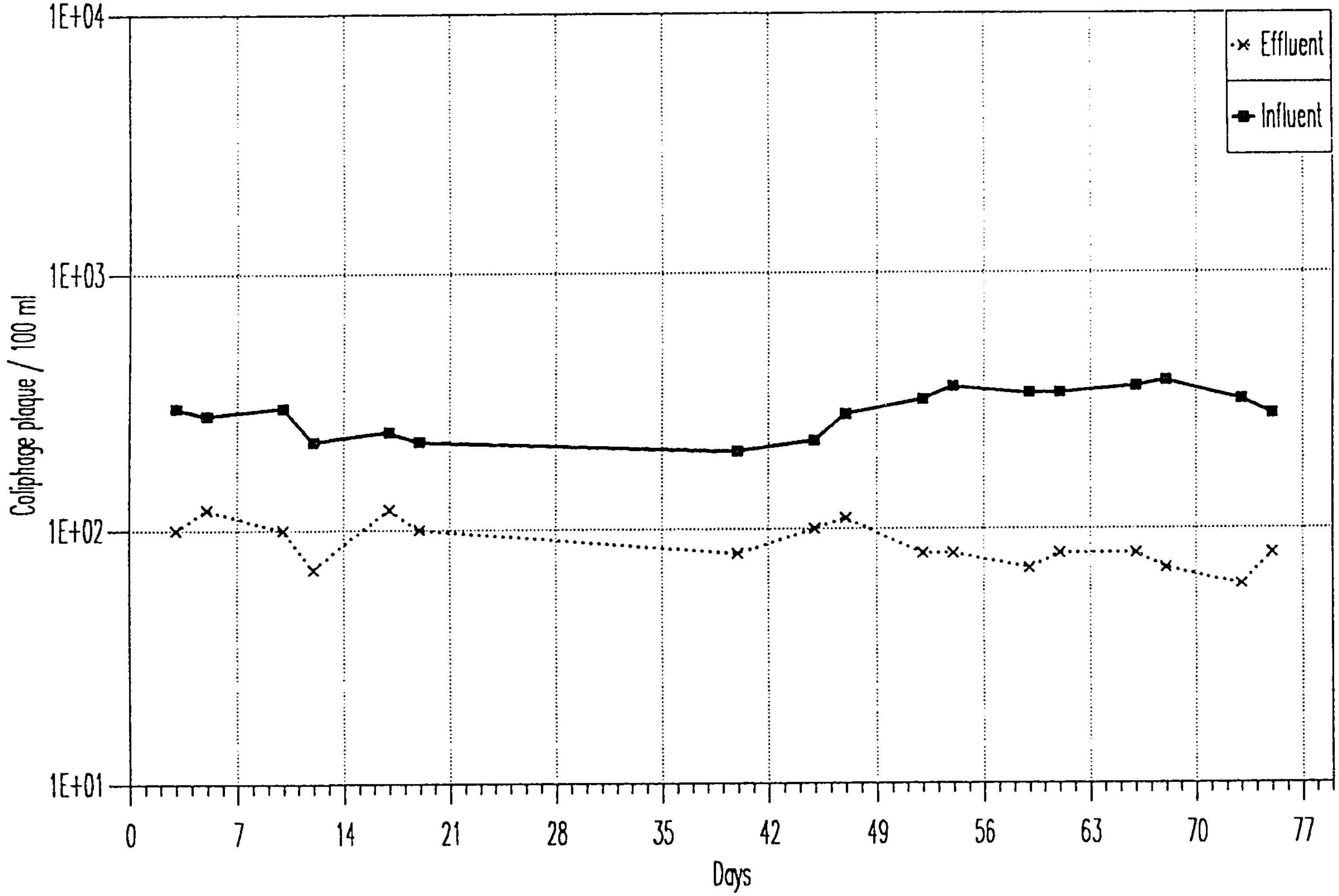


Figure 4.51: Variation of Coliphage plaque in Condition 8

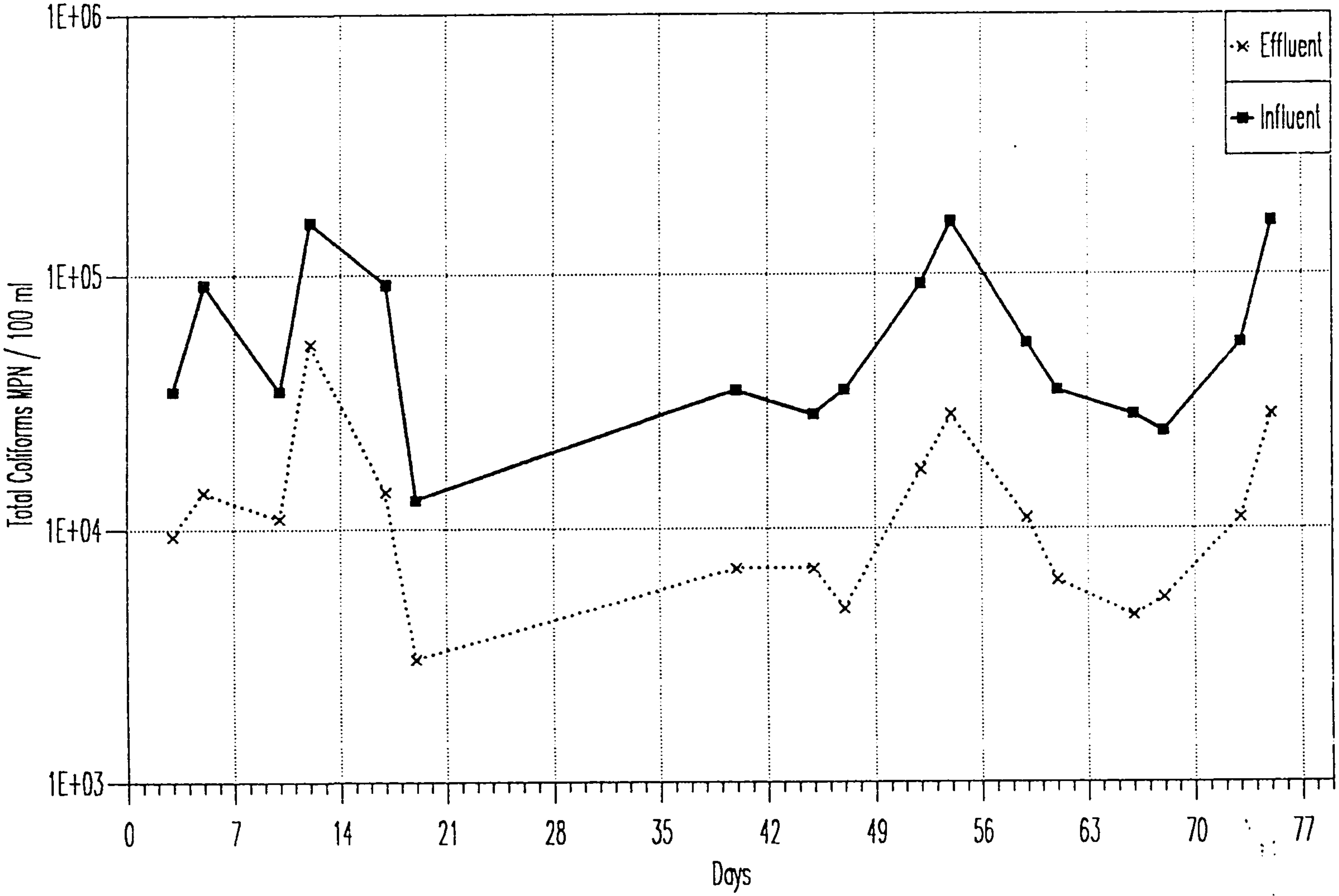


Figure 4.52: **Variation of Total Coliforms in Condition 8**

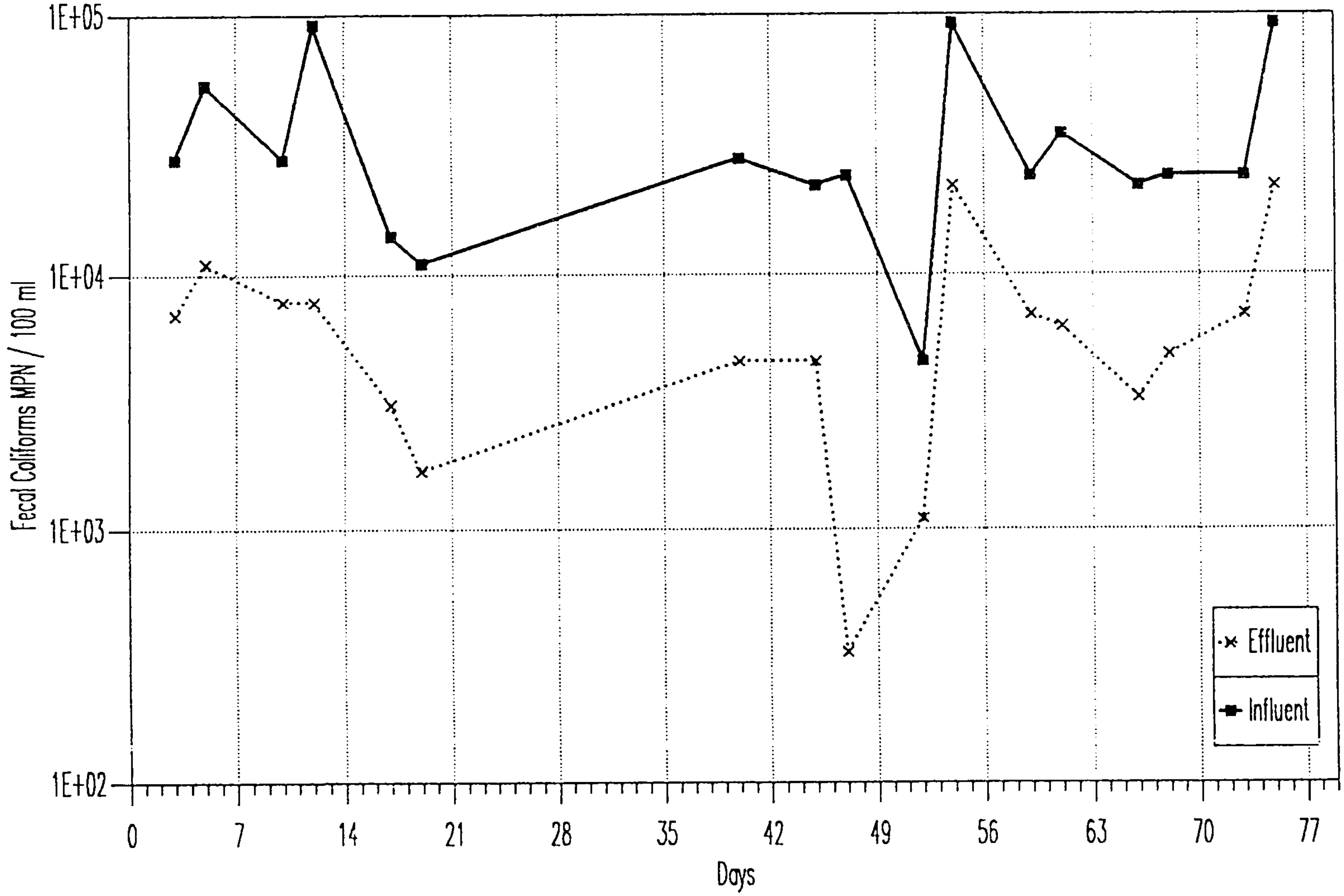


Figure 4.53: **Variation of Fecal Coliforms in Condition 8**

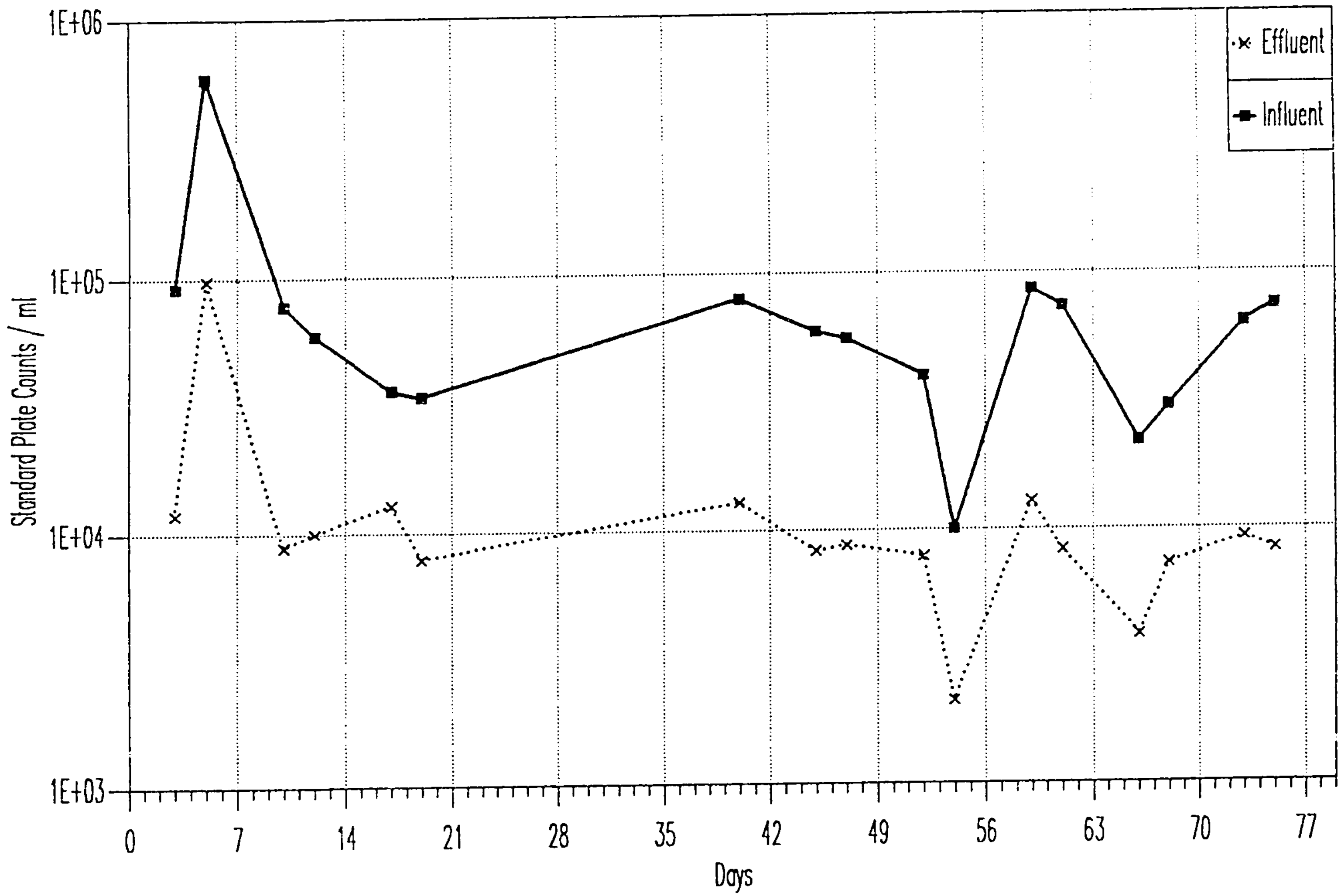


Figure 4.54: Variation of Standard Plate Counts in Condition 8

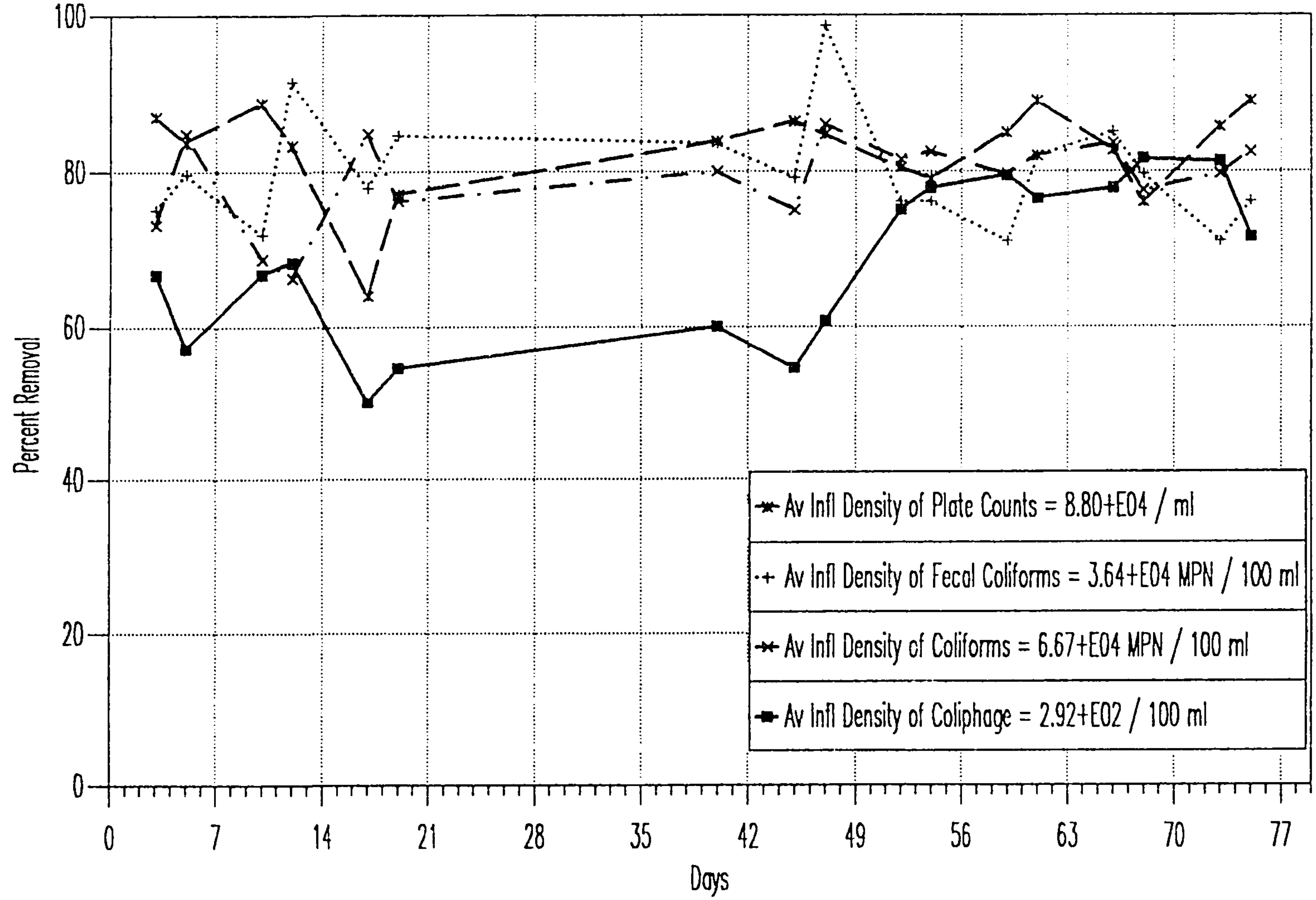


Figure 4.55: **Removal Efficiencies of Various Microorganisms in Condition 8**

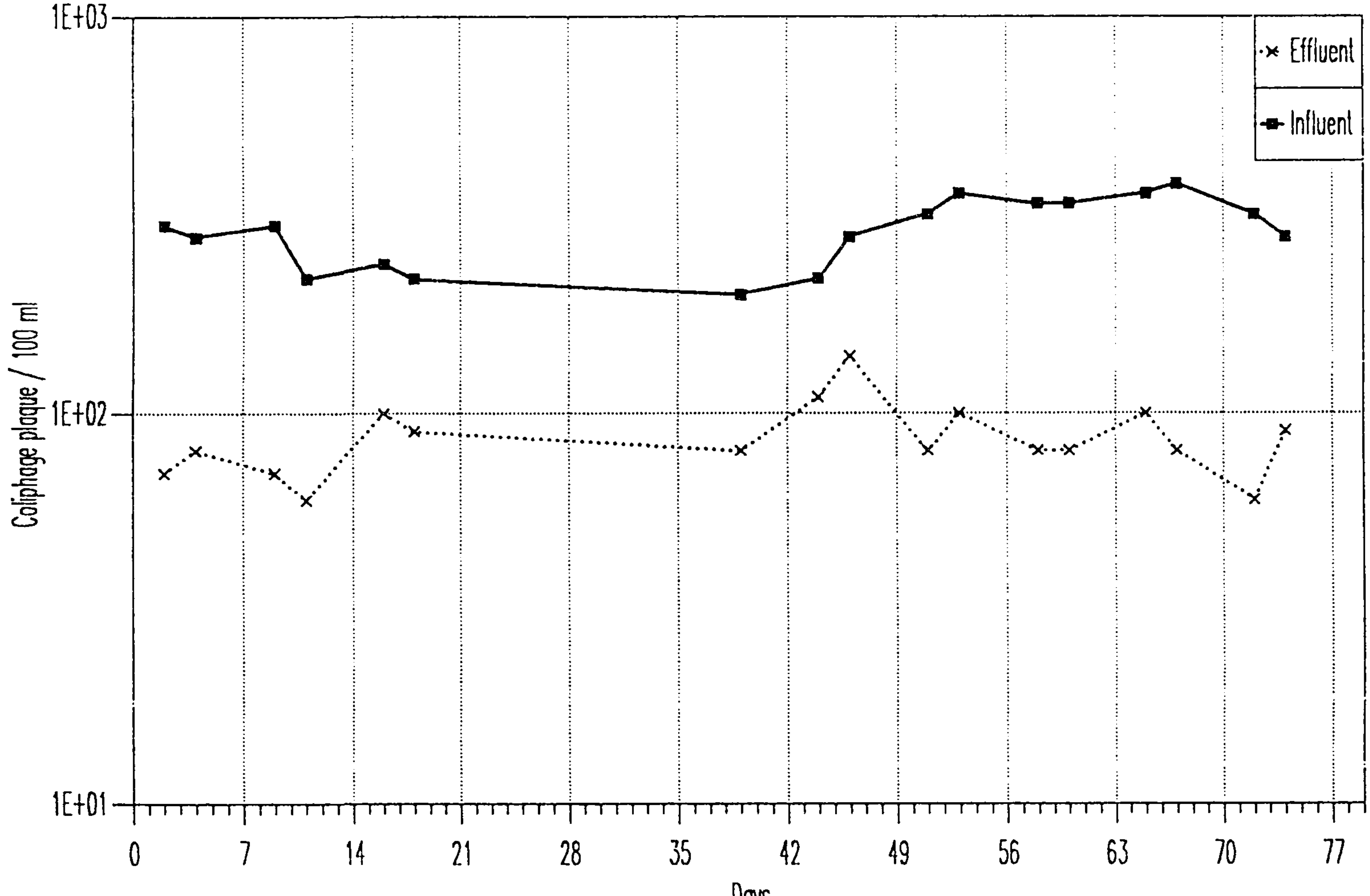


Figure 4.56: **Variation of Coliphage plaque in Condition 13**

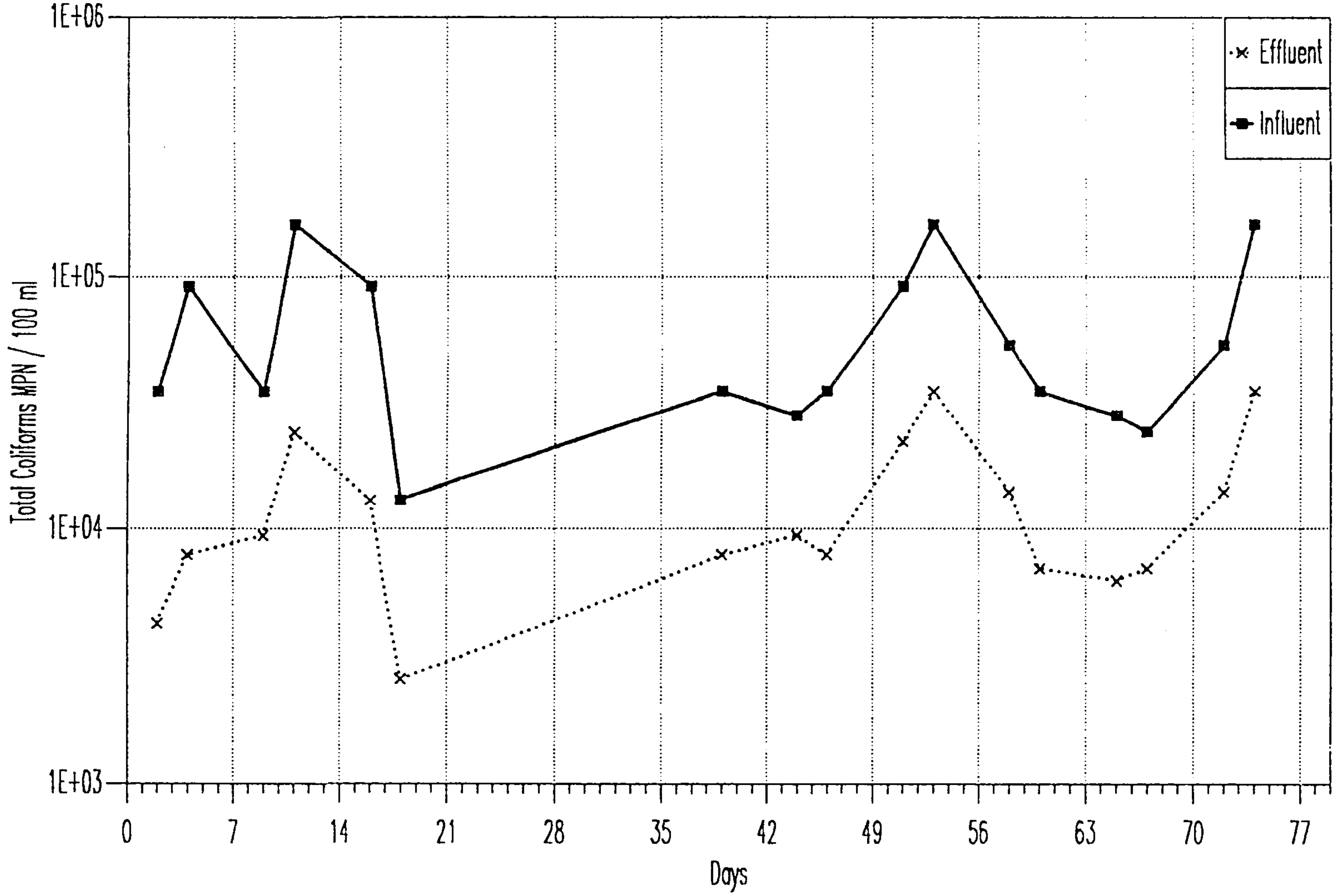


Figure 4.57: Variation of Total Coliforms in Condition 13

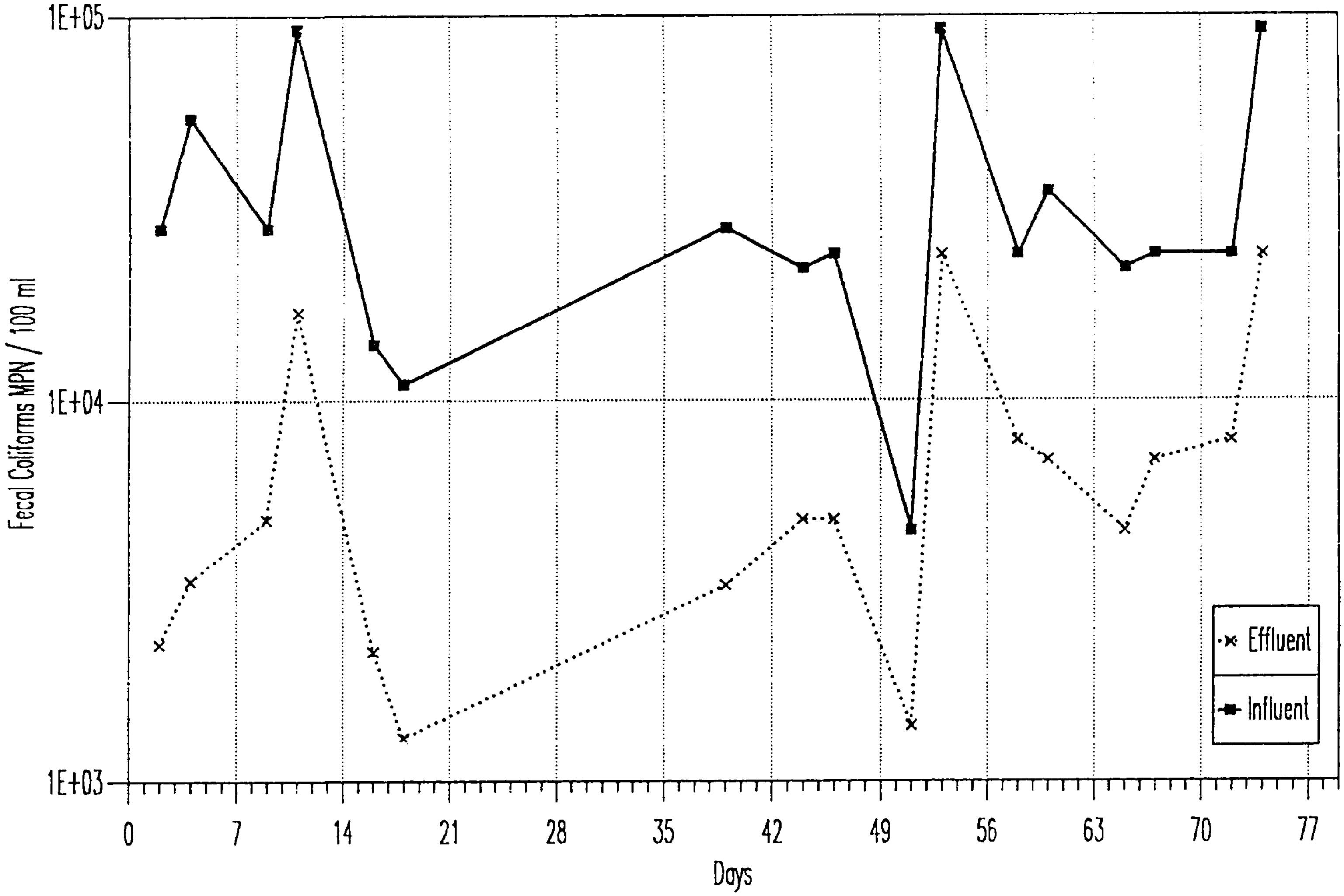


Figure 4.58: Variation of Fecal Coliforms in Condition 13

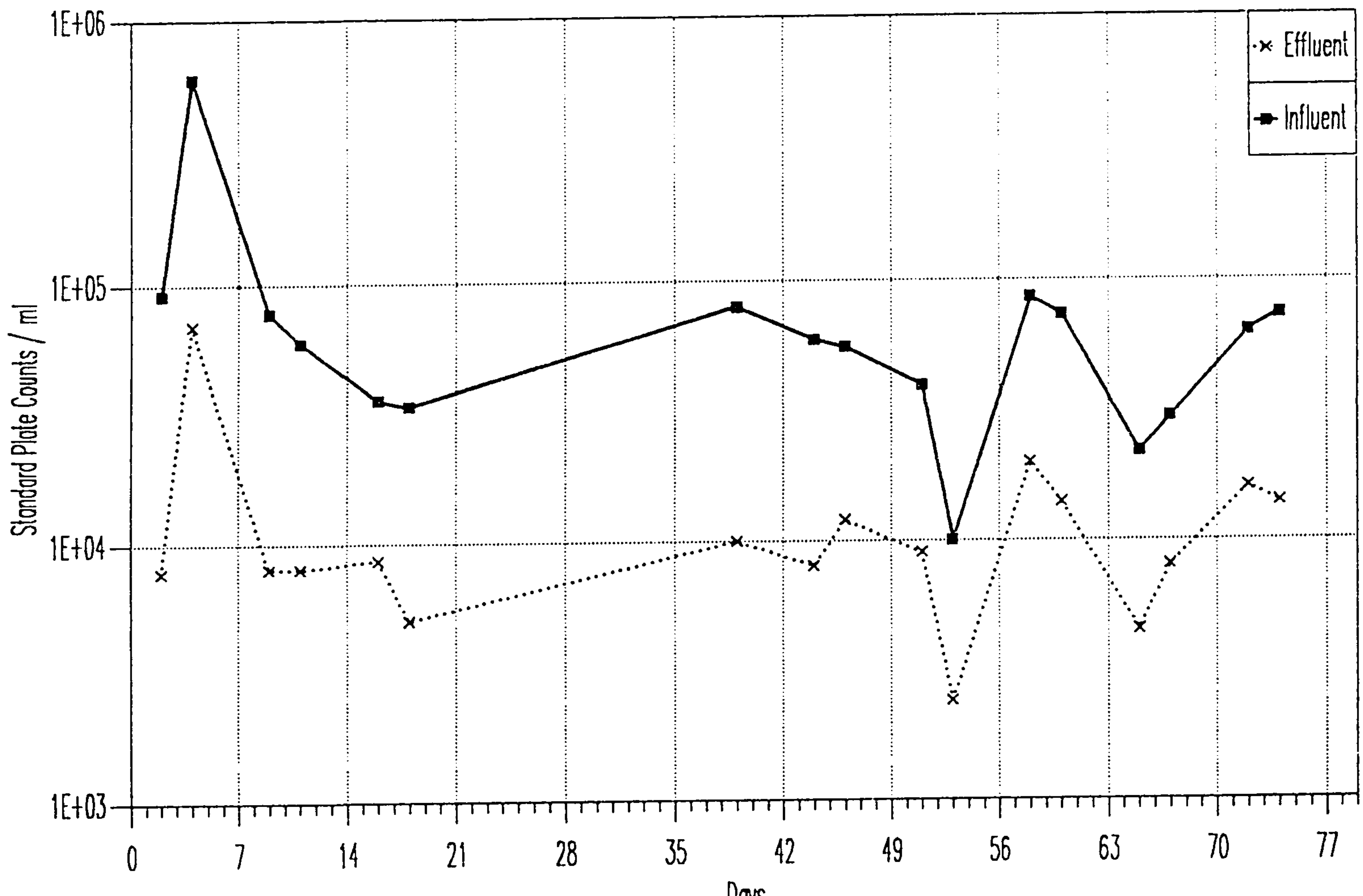


Figure 4.59: **Variation of Standard Plate Counts in Condition 13**

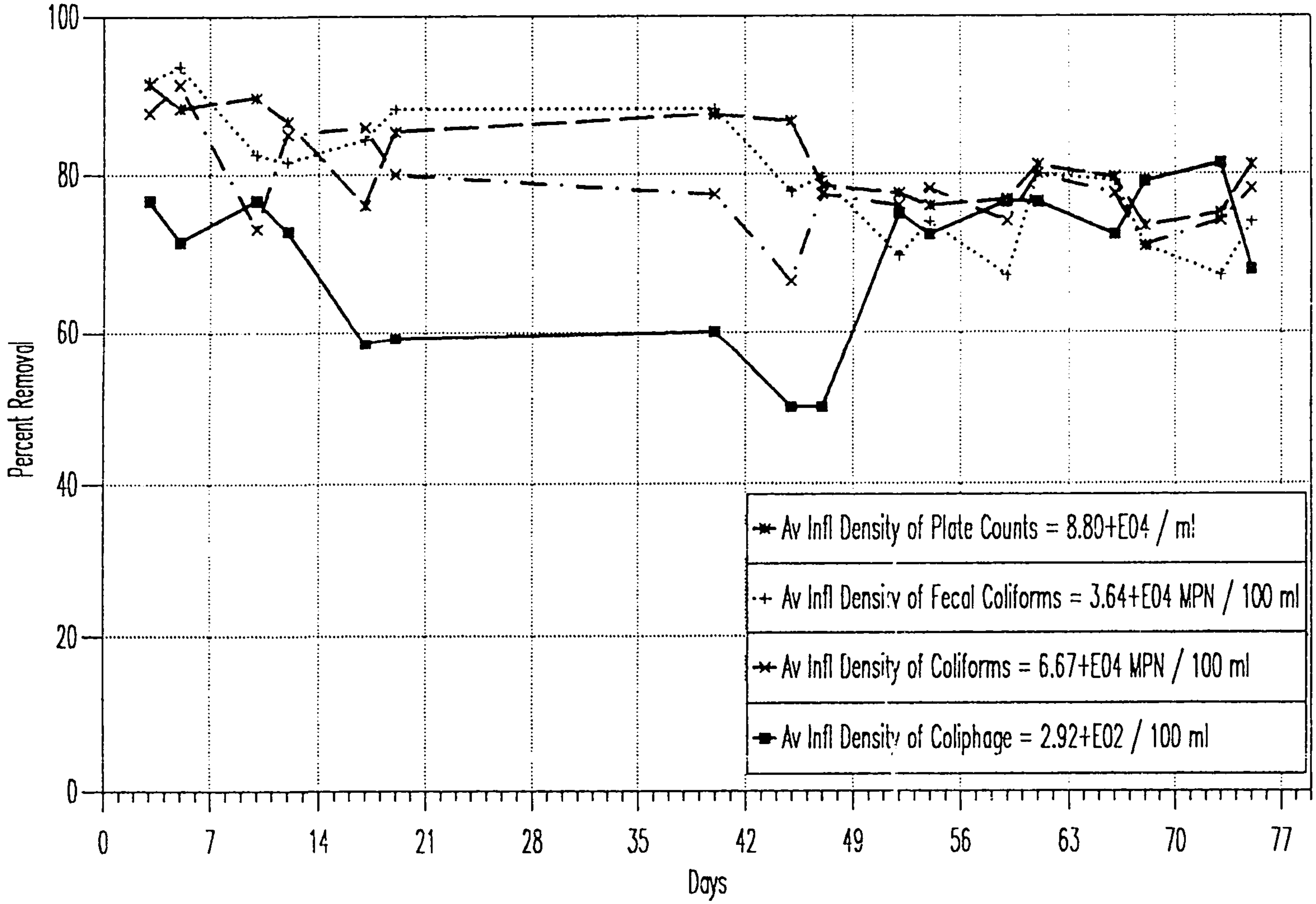


Figure 4.60: Removal Efficiencies of Various Microorganisms in Condition 13

flowrates are increased.

4.2.4 Filter Operations at Sand Sizes of 0.3 and 0.5 mm, at Flowrate of 10 l/m and Sand Depth of 50 cm:

Two conditions (condition #9, #14) were operated to study the effect of sand sizes on removal efficiencies of microorganisms. The influent and effluent variations during condition #9 are shown in Figures 4.61-4.64. The removal efficiencies of all microorganisms are shown in Figures 4.65, whereas for condition #14 the influent and effluent variations are shown in Figures 4.66-4.69 for all four microorganisms.

The densities of coliphage were quite consistent during conditions #9 and #14. Gradual increasing trends were observed in both the influent and effluent densities of total coliforms and fecal coliforms after about 9 days of operation in both conditions #9 and #14. The variation of percentage removal efficiencies of various microorganisms during condition #14 are shown in Figure 4.70. The average removal efficiencies of coliphage, coliforms, fecal coliforms and plate counts during condition #9 were 86%, 86, 87% and 90% respectively whereas in condition #14 the average removal efficiencies were 78%, 84%, 84% and 86% respectively.

Results of condition #14 and condition #9 were compared to investigate the effect of different sand sizes. Since these two conditions received the same influent and were operated under same process variables except for sand size,

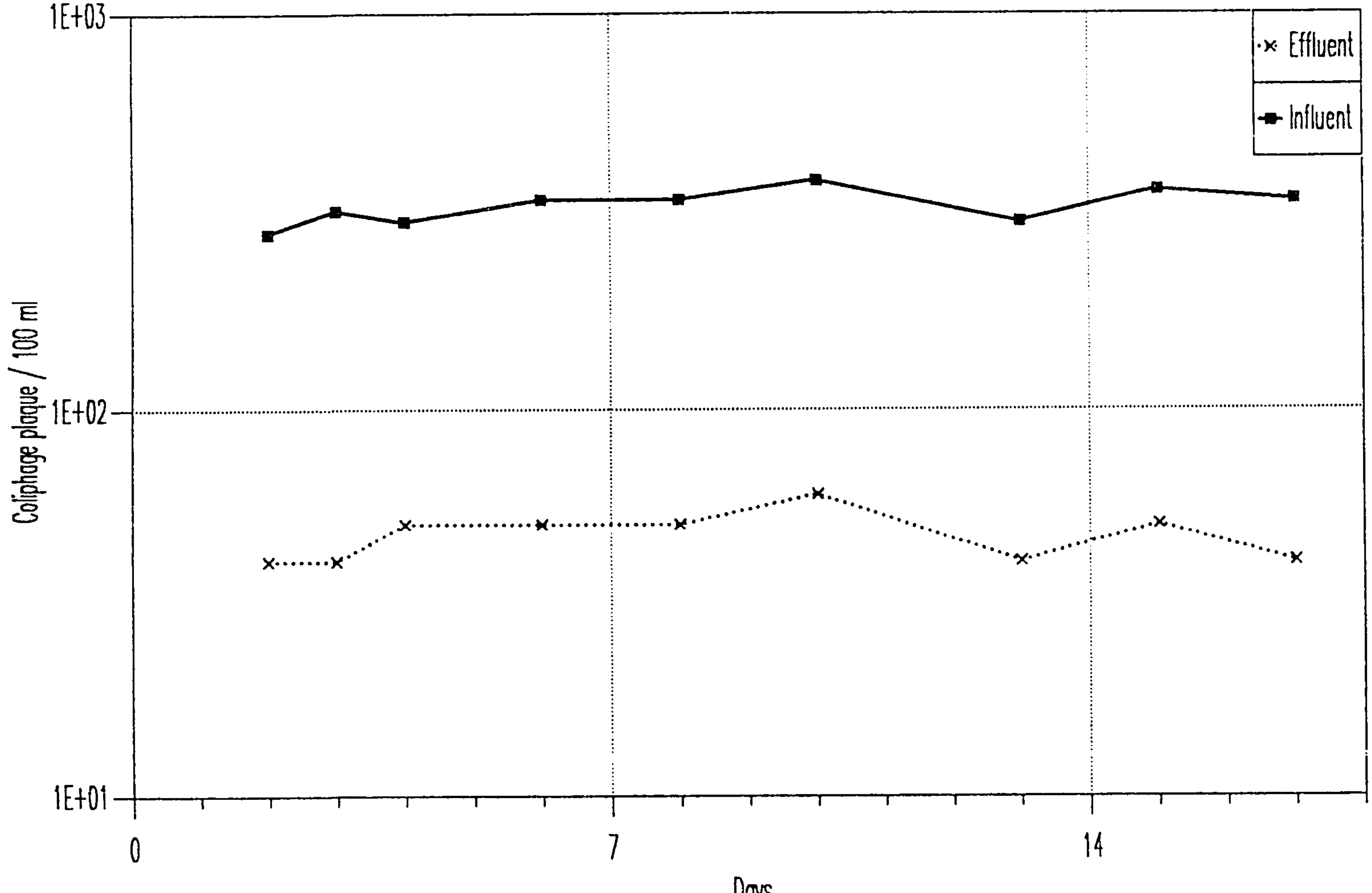


Figure 4.61: Variation of Coliphage plaque in Condition 9

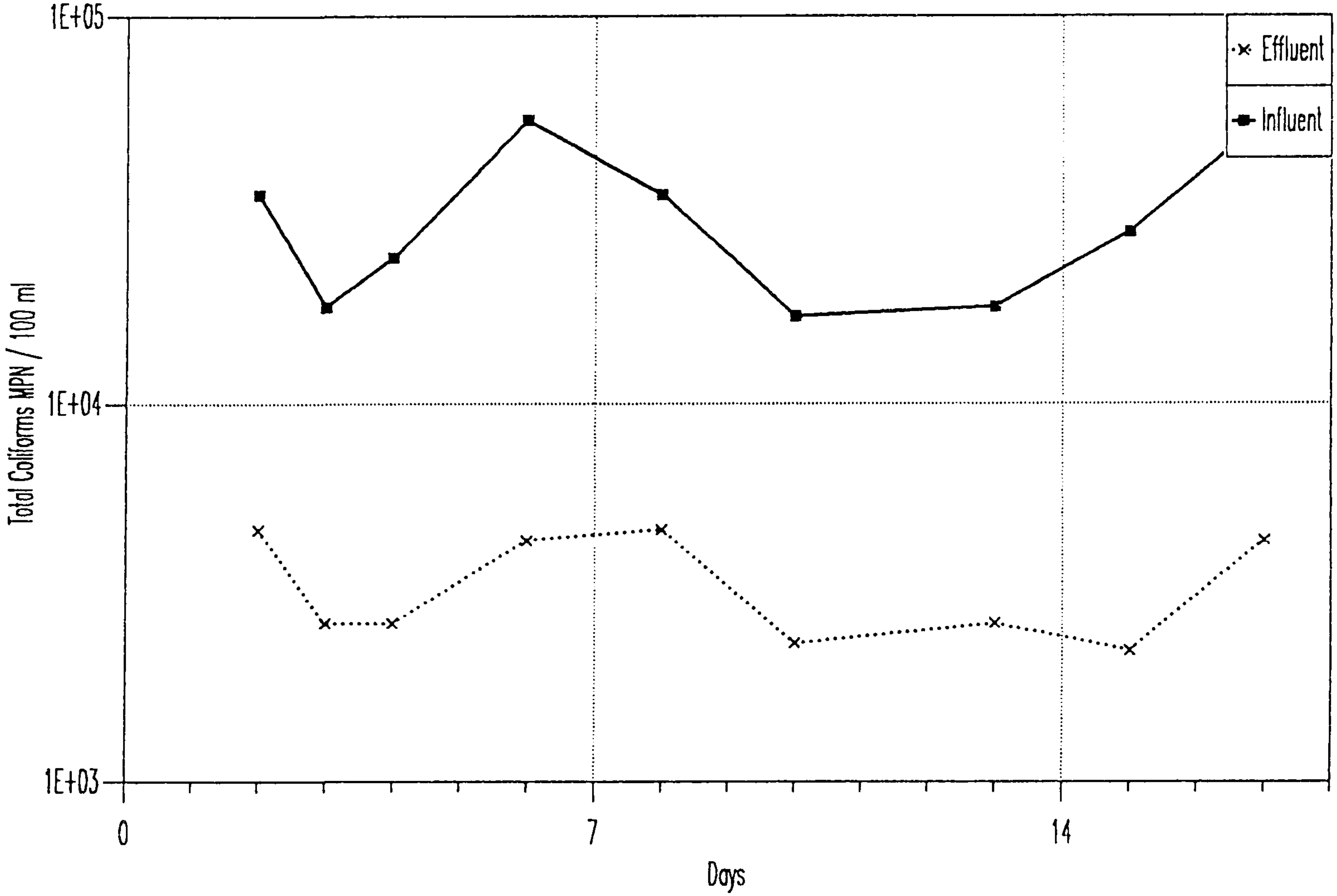


Figure 4.62: Variation of Total Coliforms in Condition 9

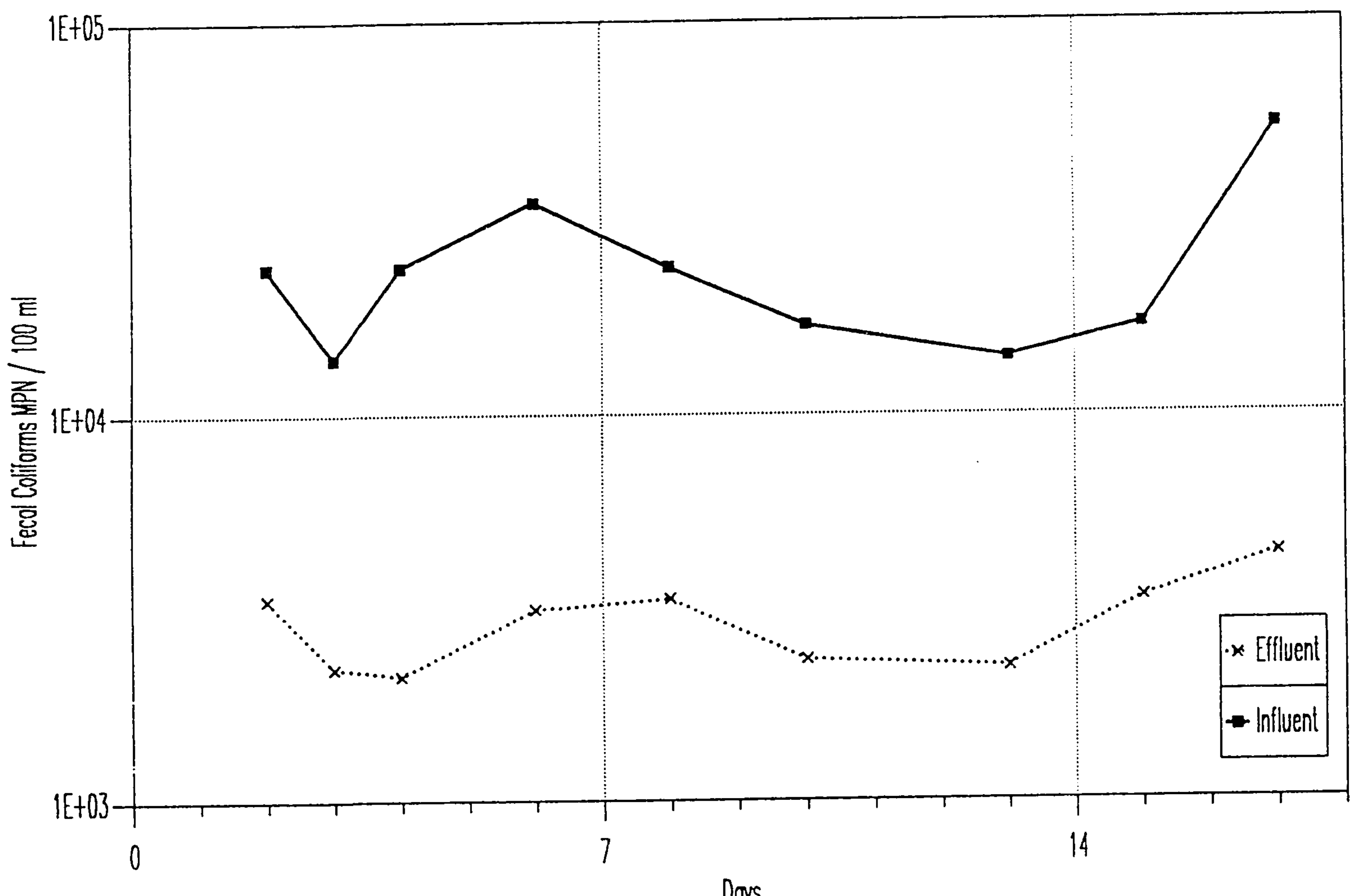


Figure 4.63: Variation of Fecal Coliforms in Condition 9

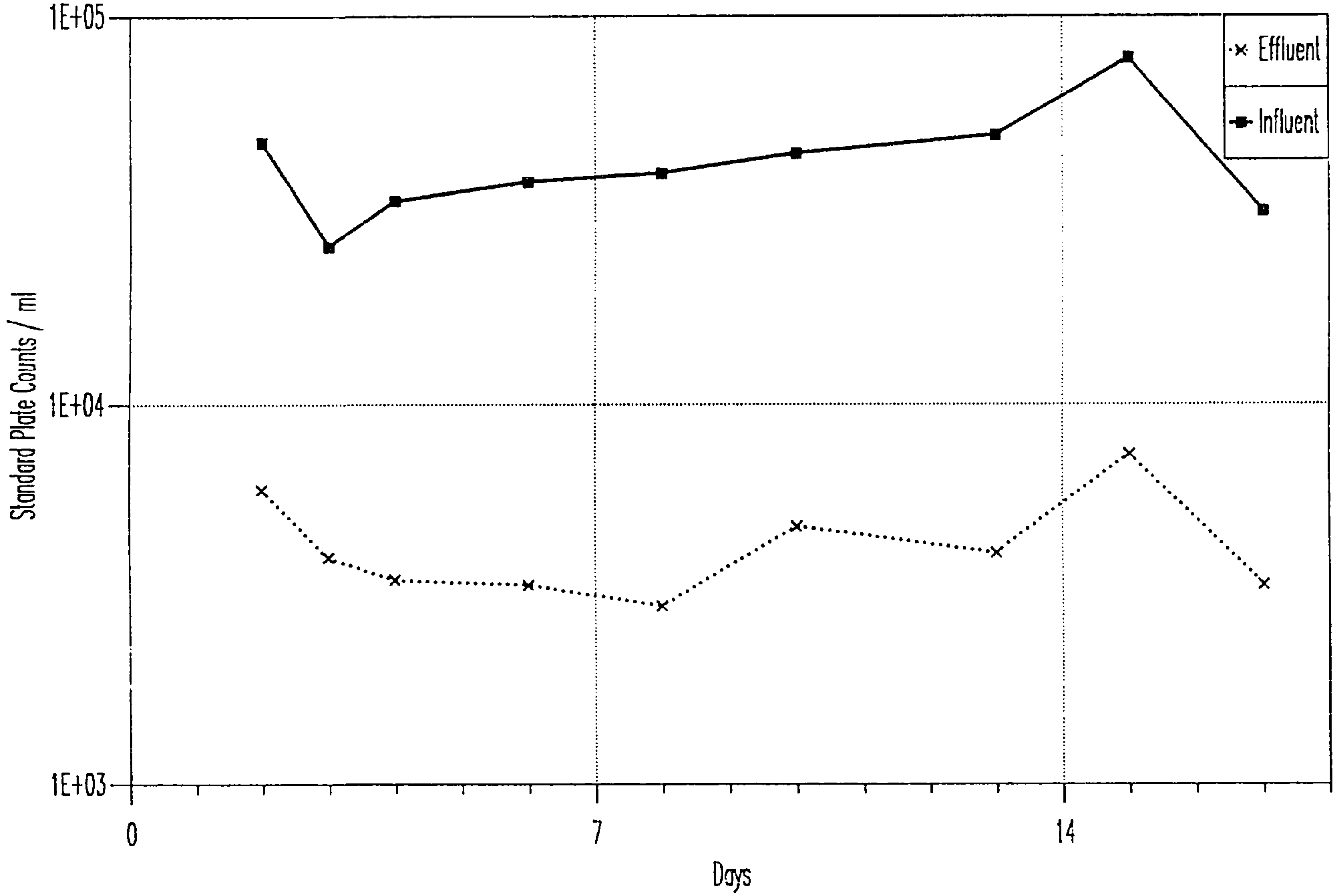


Figure 4.64: Variation of Standard Plate Counts in Condition 9

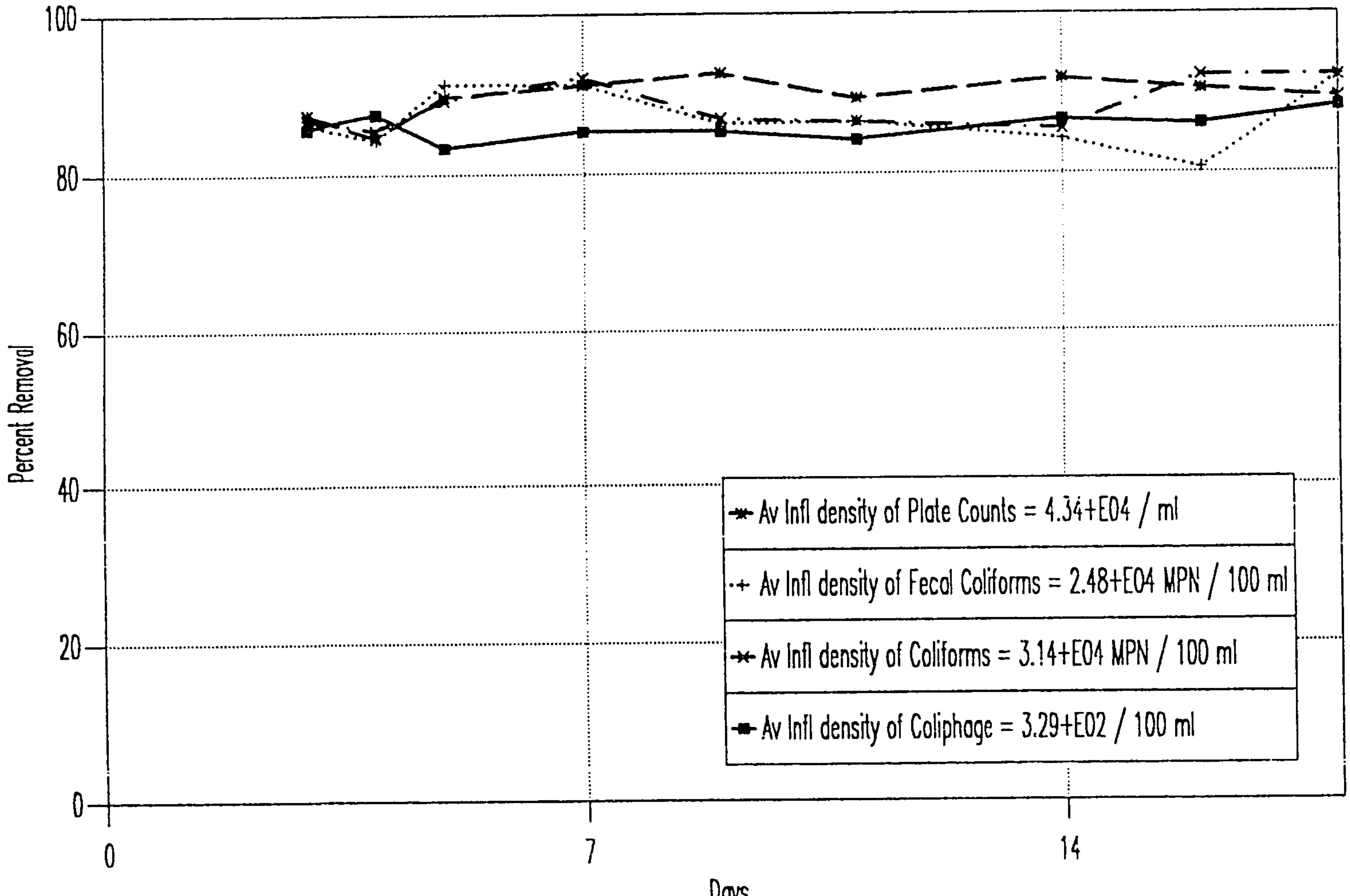


Figure 4.65: **Removal Efficiencies of Various Microorganisms in Condition 9**

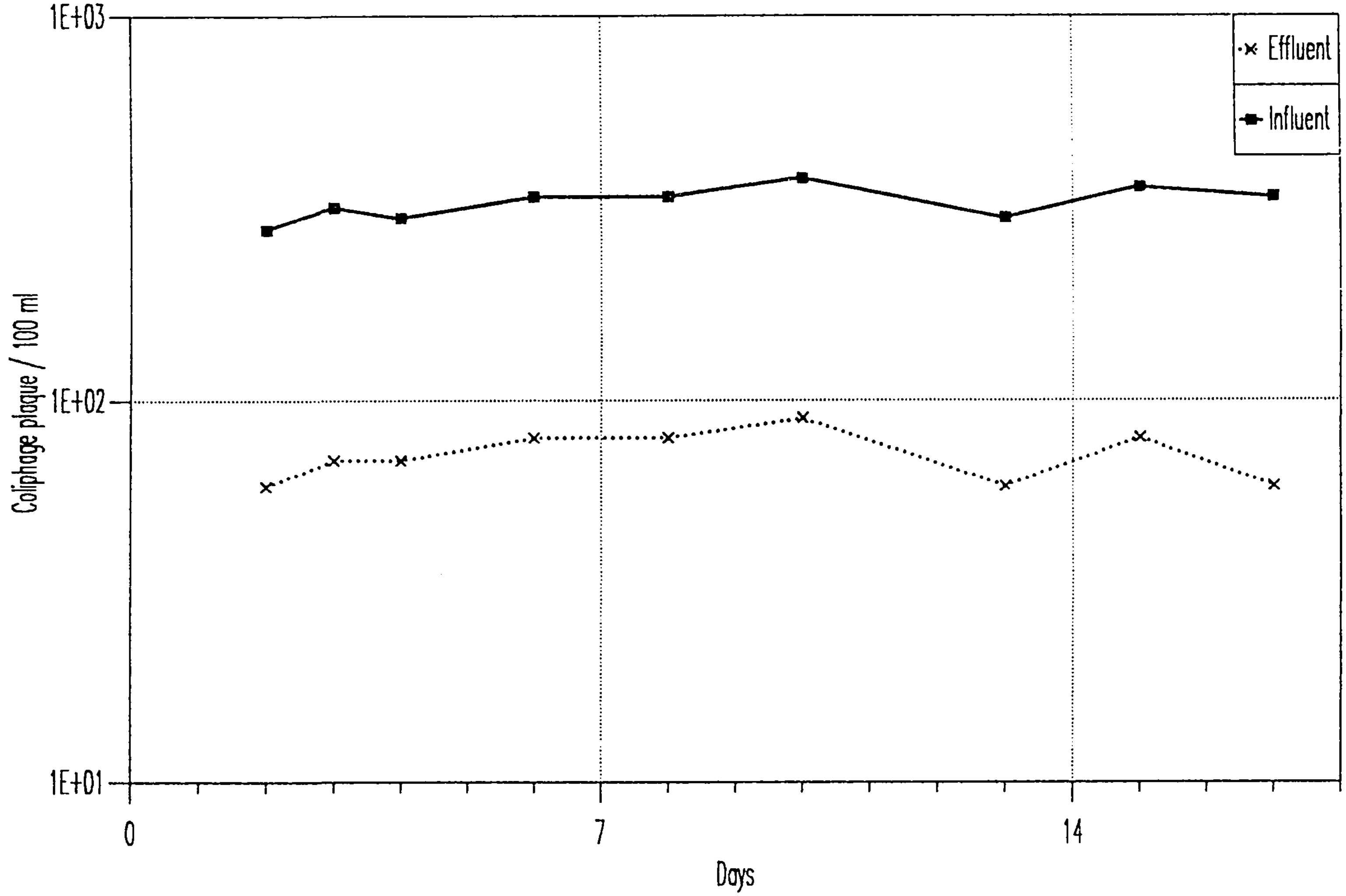


Figure 4.66: Variation of Coliphage plaque in Condition 14

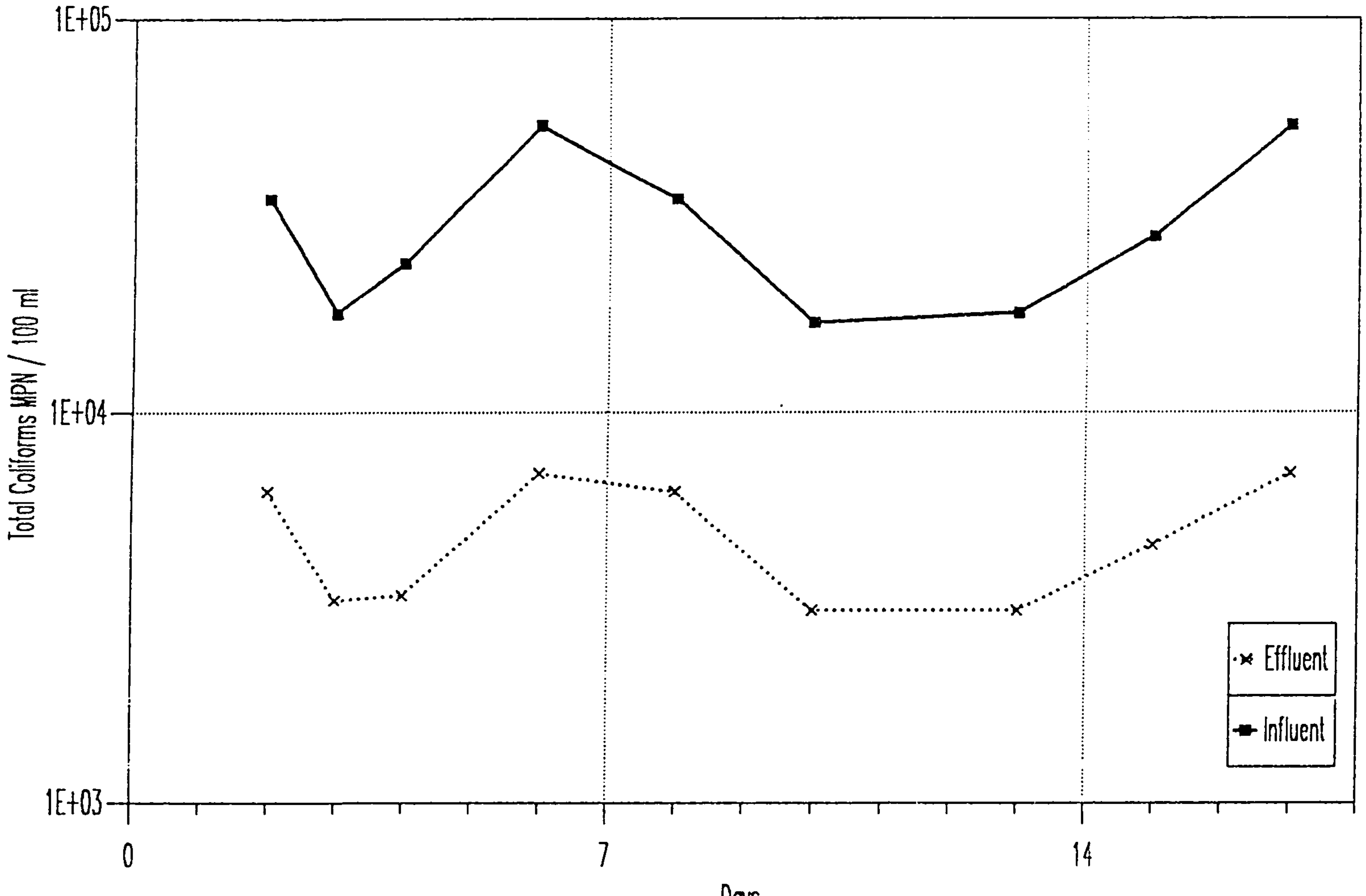


Figure 4.67: Variation of Total Coliforms in Condition 14

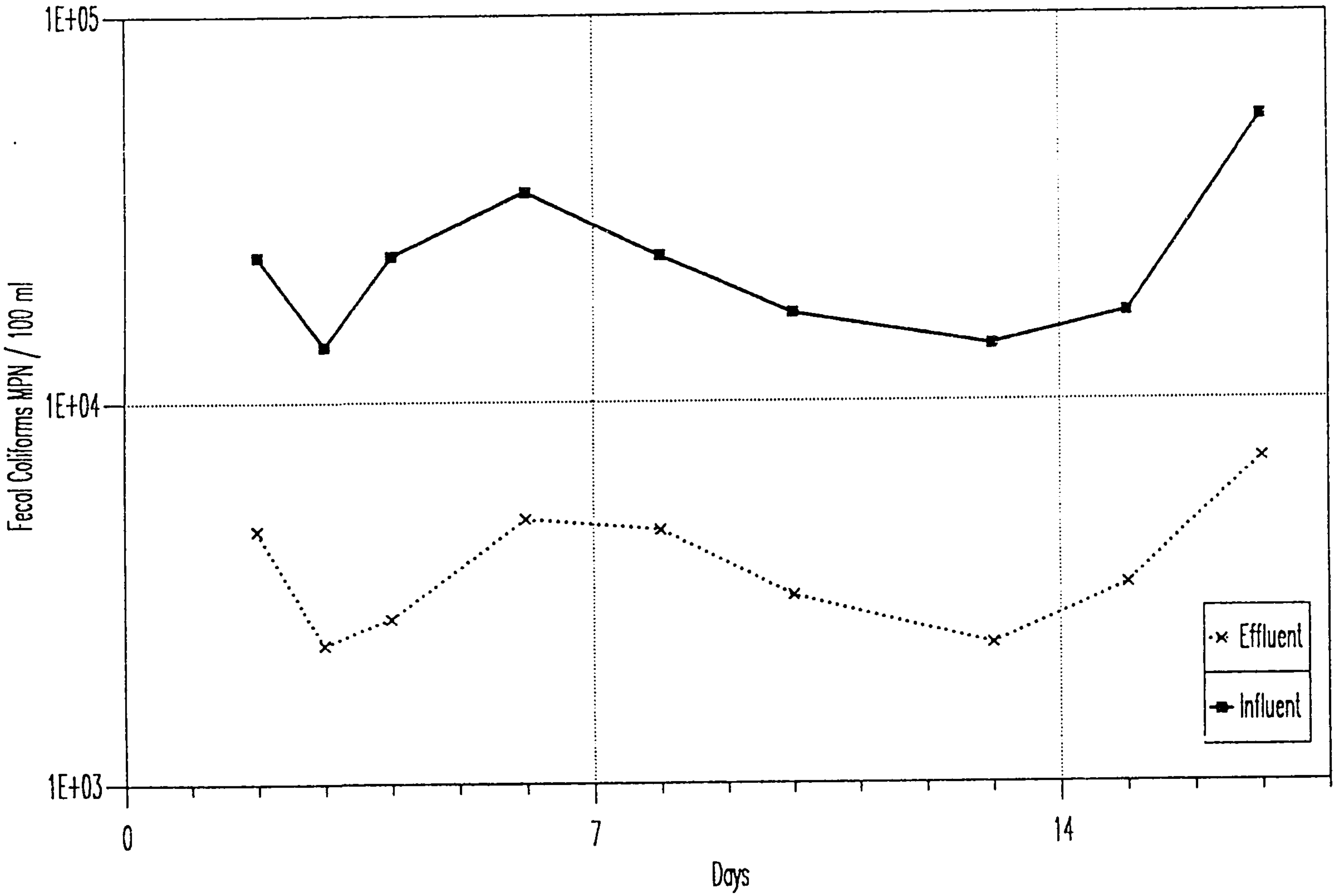


Figure 4.68: **Variation of Fecal Coliforms in Condition 14**

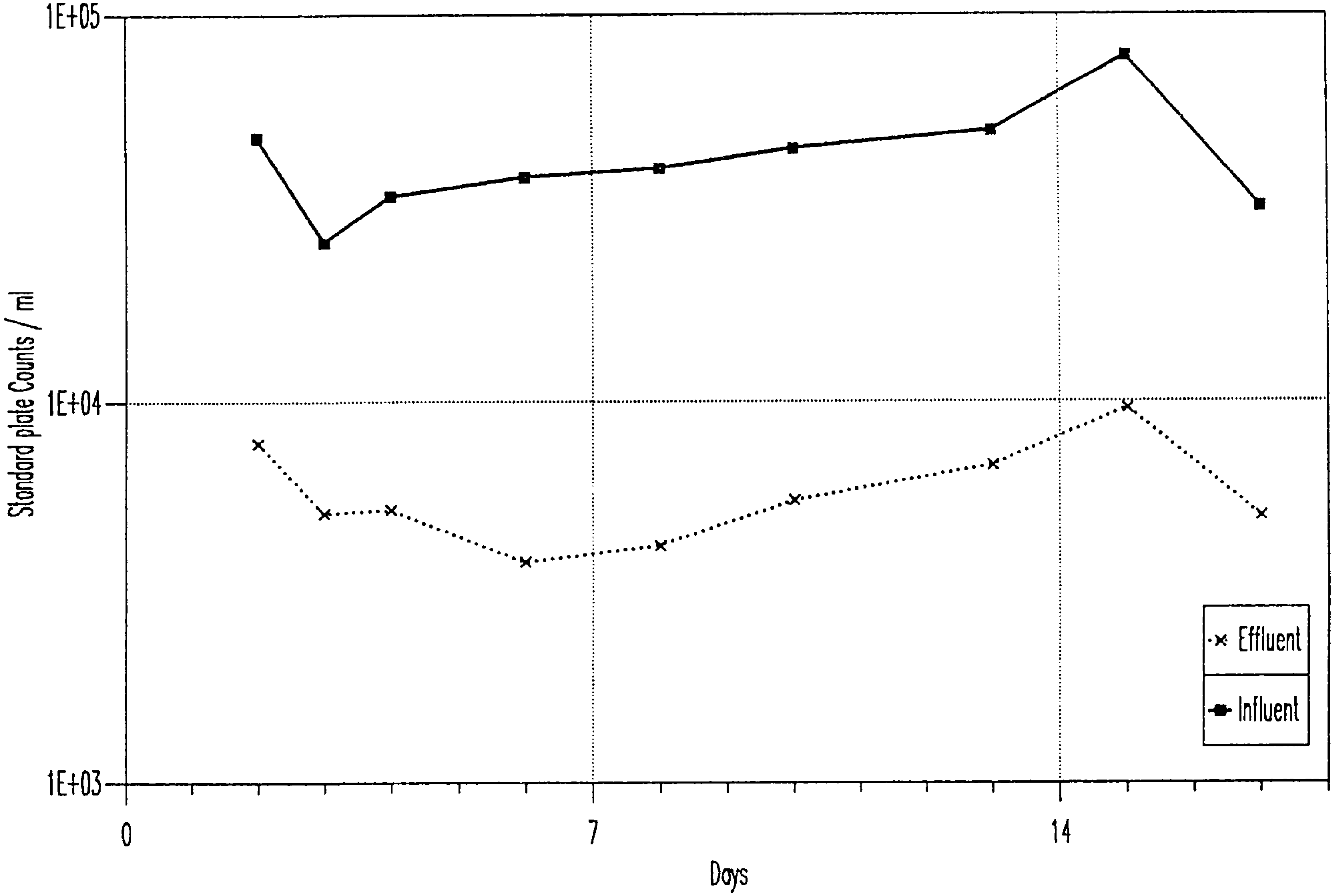


Figure 4.69: Variation of Standard Plate Counts in Condition 14

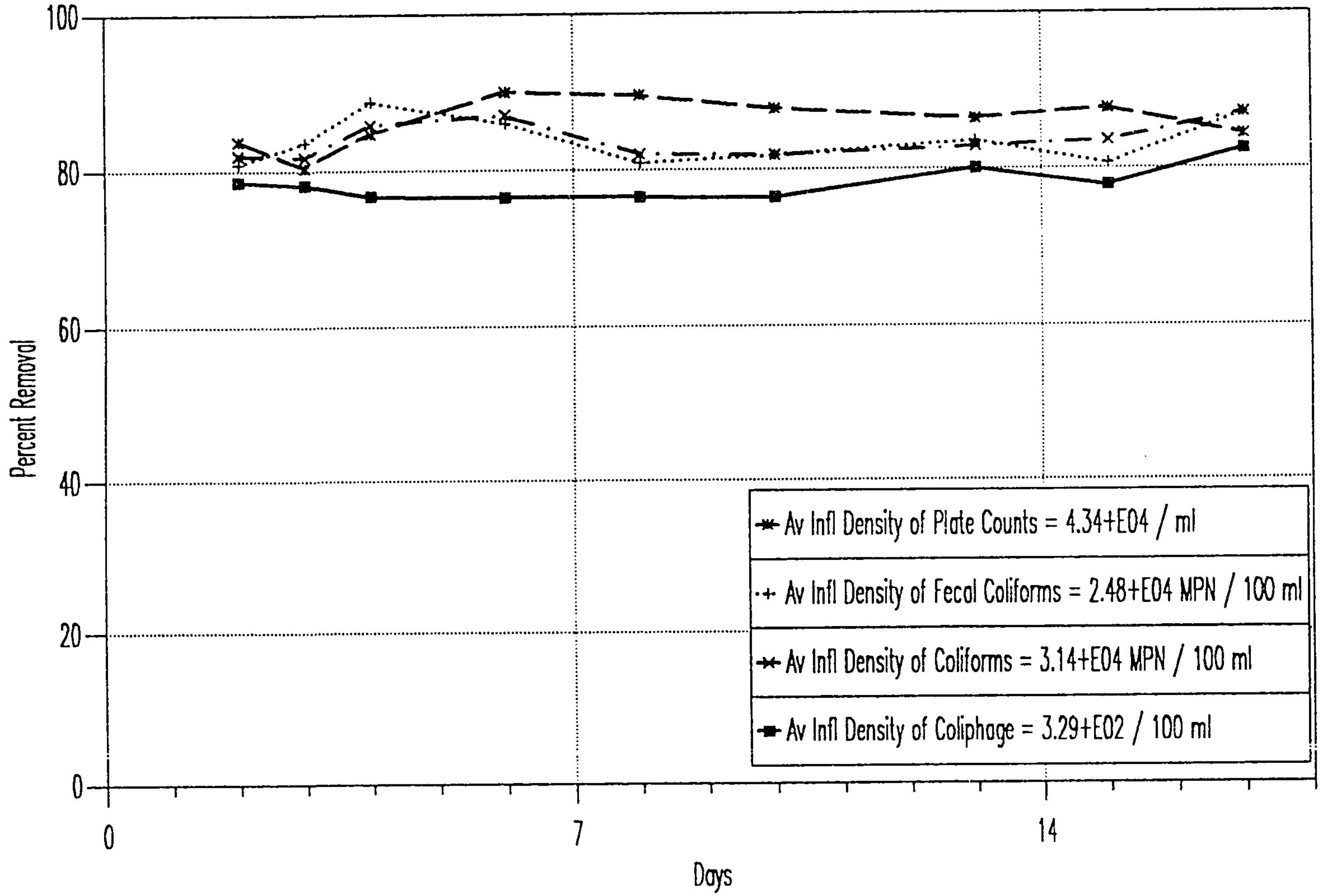


Figure 4.70: **Removal Efficiencies of Various Microorganisms in Condition 14**

therefore, their comparison seems justified. Condition #9 achieved higher coliphage and fecal coliform removal efficiencies by 10% and 4% respectively while coliforms and plate counts removal efficiencies were higher by 2.5% and 4% each. Therefore, higher removal efficiencies were obtained when smaller sand size was used. Bellamy *et al.* [3] in a pilot scale study on slow sand filtration, found similar results and he found that coliform removal efficiency increased from 96% to 98.6% to 99.4% for effective sand sizes of 0.615, 0.278 and 0.128 mm respectively. Bellamy *et al.* [4] also found that 0.278 mm of sand allowed only 470 colonies per ml of plate counts when an influent of 5 x 10^5 colonies per ml was used. These colonies in effluent increased to 1050 per ml when sand size of 0.615 mm was used with same influent. Thus, it was concluded that higher removal of microorganisms were achieved when smaller sand size was used.

4.3 REMOVAL OF SUSPENDED SOLIDS AND TURBIDITY

The presence of suspended solids in high concentrations in wastewater is one of the main problems, therefore, the removal of these suspended solids is one of the primary objectives of treatment. Turbidity, on the other hand, is another parameter of great importance first because of the aesthetic considerations, and second because it shields pathogenic organisms.

The occurrence of suspended solids in both influent and effluent was monitored over the entire period of operation on weekly basis. The turbidity data was monitored on daily basis for the entire period of operation during fourteen different conditions. The percentage removal data of turbidity was averaged over weekly basis and was plotted along with the percentage removal data of suspended solids.

The variations of percentage removal of suspended solids and turbidity during condition #1 is shown in Figure 4.71. The average influent concentrations of suspended solids and turbidity during condition #1 were 13.88 mg/l and 0.66 NTU respectively. The percentage removal of suspended solids ranged from 10% to 54% with an average removal of 33% (Table 4.3). Similarly, the percentage removal of turbidity varied from 12.5% to 52% with an average removal of 35%. The percentage removal data for both suspended solids and turbidity were fluctuating and no regular trend was observed.

The average percentage removal of suspended solids and turbidity during each of the fourteen conditions are reported in Table 4.3. The removal of suspended solids decreased from 32.63% to 28.45% when the flowrate was increased from 8 l/min to 10 l/min using coarse sand. Similar trend was observed for turbidity removal. At constant flowrate and sand size (coarse sand) the removal of suspended solids increased from 28.45% to 38.70% to 43.40% when sand depths were reduced from 150 cm to 80 cm to 50 cm.

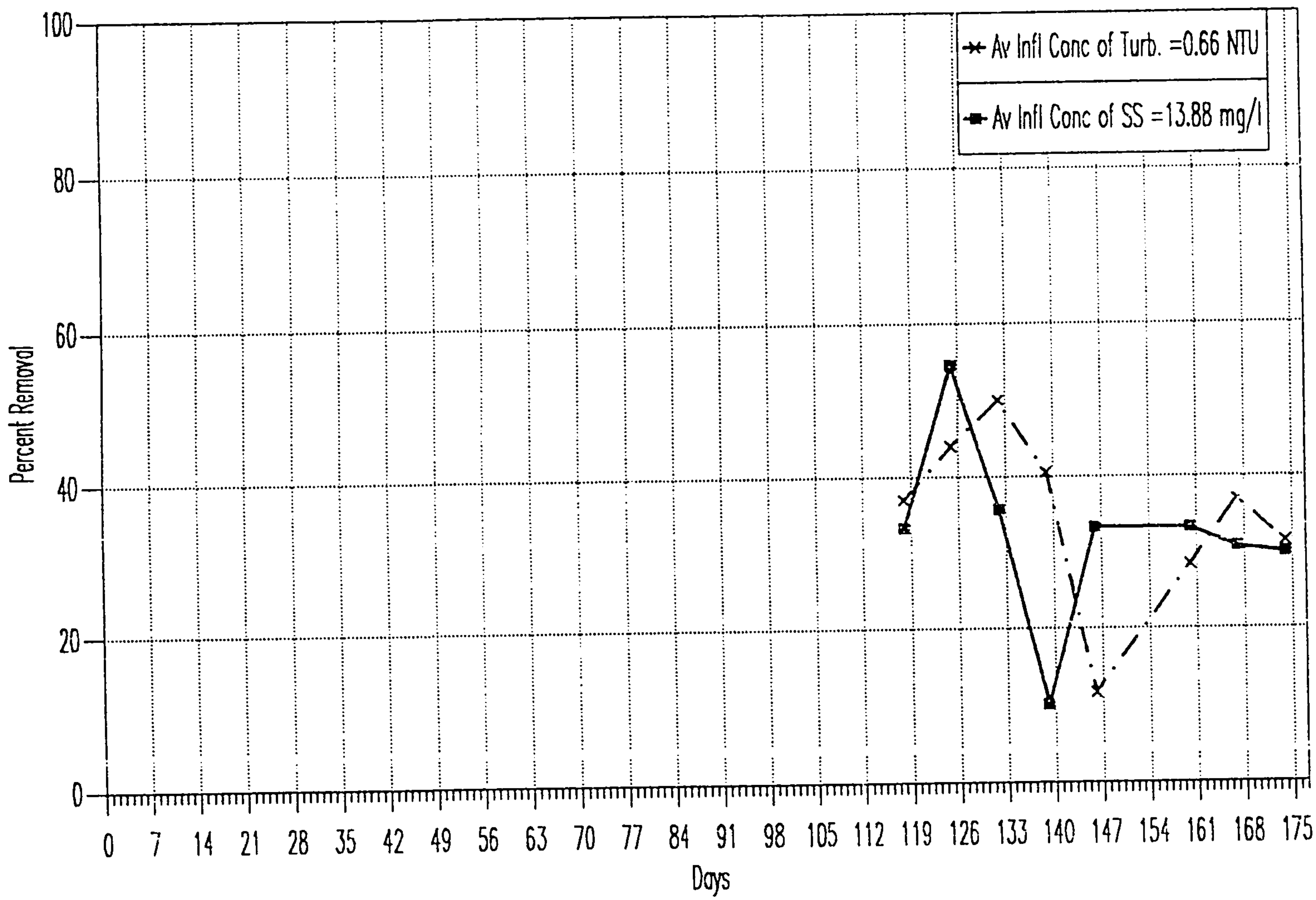


Figure 4.71: **Removal Efficiencies of SS and Turbidity in Condition 1**

Table 4.3 : Average Percentage Removal Efficiencies For Different Conditions

Condition Number	Coliphage plaque	Total Coliforms	Fecal Coliforms	Plate Counts	Suspended Solids	Turbidity
1	79.80	88.41	86.34	86	32.63	35.10
2	79	95.40	95.41	90.60	28.45	33.10
3	80.85	99.31	99.19	96.34	38.70	46.80
4	75.64	83.80	85.01	86.11	43.40	56.42
5	80.81	87.81	85.68	87.83	56.51	51.50
6	74.40	94.74	94.06	83.60	60.50	51.60
7	77	90.77	88.06	89.86	64.24	45.56
8	68.20	79.03	80.19	82.64	49.61	60.27
9	85.82	85.82	86.95	89.60	71	61.70
10	79.70	89.39	87.34	87.49	27.90	50
11	74.96	92.74	89.23	87.23	21.83	57.22
12	71.20	89.50	78.64	87.10	22.42	44.80
13	69.13	78.42	79.35	82	26.44	56.60
14	78.10	83.74	83.66	86.10	51.11	62.52

Similar trends were observed for turbidity removal. These results were not consistent in some cases, e.g. higher depth of sand bed in case of coarse sand did not show response of reduced efficiencies along with depth. Similar trends were obtained in case of find sand except for few cases.of the effects of flowrates and sand depths in removal of suspended solids and turbidity in case of fine sand except for few cases. These inconsistencies in the results may be attributed to some experimental errors involved in measurement of extremely low values of turbidity. Influent turbidity, was consistently less than 1 NTU in most of the cases in both the influent and effluent values. A small variation in the values can give a large change in percent removal.

4.4 STATISTICAL ANALYSIS OF DATA

In order to derive meaningful conclusions, the data were statistically analyzed for fourteen different conditions. The percent removal averages for each operational conditions are calculated separately and compared with each other using t-test to determine the superiority of one condition over the other.

4.4.1 Significance of t-test

Much of the research in engineering and science makes use of statistical analysis to greatly increase the efficiency of the experiment and strengthen the combination of data sets. Statistical analysis refers to the process of planning

various combinations in order to know whether observed difference in the data have any statistical significant difference or not.

Statistical analysis was performed on the data of microorganisms, SS and turbidity removal using 't' test for all the three filters consisting of fine and coarse sand operating at different hydraulic loading and sand depth. The objective of performing this was to find out whether there exists significant statistical difference for the obtained results within the filter and combination with another.

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

$H_0 = \mu_1 = \mu_2$ (Mean of 1 = Mean of 2)

$H_1 = \mu_1 \neq \mu_2$ (Mean of 1 $\neq$ Mean of 2)

To test the above hypothesis studentized t-test was applied assuming unequal variances. The 't' statistics value (t_{cal}) is calculated using the following:

$$t_{cal} = \frac{\mu_1 - \mu_2}{\sqrt{\frac{s_1^2}{n_1} - \frac{s_2^2}{n_2}}}$$

μ_1 = Mean of 1

μ_2 = Mean of 2

s_1^2 = variance of 1

s_2^2 = variance of 2

n_1, n_2 = sample sizes

The t-statistics value (t_{cal}) is compared with t-table value at degrees of freedom = γ and at a confidence internal of 95%. The degrees of freedom γ for unequal variances is computed using the following equation:

$$\gamma = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 - 1}}$$

If t_{cal} is greater than the t-table value then the null hypothesis (H_0) is rejected, which implies that there exists significant statistical difference, else H_0 is accepted which implies that there is no significant statistical difference.

4.4.2 Analysis of Experimental Data

The removal efficiencies of viruses through three different slow sand filters, i.e. F1, F2 and F3 were compared at different flow rates, sand depths and sand sizes using t-tests. In each of the t-tests, two different experimental

conditions were compared with respect to a given variable. For example, condition # 1 (Q = 8 l/m, D = 150 cm, SS = 0.5 mm) was compared with condition # 10 (Q = 16 l/m, D = 150 cm, SS = 0.5 mm) as given in the first row of Table 4.4, with the purpose of determining which flow rate gives better viral removal efficiency. The means and variances obtained during the t-tests are presented in Table 4.4, along with the degree of freedom and t-calculated and t-critical values. The null hypothesis results and inferences derived are presented in the last two columns of the Table 4.4. The significance of each parameter is explained earlier. In above case, hypothesis was not rejected, which means it can be concluded with 95% of confidence that there is no significant difference beteen the two conditions compared with respect to flowrates of 8 and 16 l/min.

a) Effect of Flow Rates:

There were twenty six possible comparisons on which the statistical t-test were applied. Out of which, 11 comparisons were used for different flow rates to determine the effect of high flow rates on the removal efficiencies of coliphages and three different bacterial populations through a given filter at a given sand depth and sand size, i.e., fine or coarse. Nine out of 11 comparisons were carried out in Filters # 1 and #3 as these were composed of coarse sand. While 2 out of 11 comparisons were carried out in Filter #2 with fine sand.

Table 4.4 : Statistical Comparison of Coliphage Removal Efficiencies Through 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	33	79.784	392.11	10	78.991	114.221	-0.164	2.045	29	Cannot Reject Ho	C1 = C2
C1 vs C10	0.5	33	79.784	392.11	37	79.696	414.33	0.018	1.996	67	Cannot Reject Ho	C1 = C10
C1 vs C11	0.5	33	79.784	392.11	14	74.96	80.124	1.149	2.014	45	Cannot Reject Ho	C1 = C11
C2 vs C11	0.5	10	78.991	114.221	14	74.96	80.124	0.974	2.109	17	Cannot Reject Ho	C2 = C11
C2 vs C10	0.5	10	78.991	114.221	37	79.696	414.33	-0.148	2.048	28	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	14	80.855	48.591	6	71.201	52.266	2.766	2.262	9	Reject Ho	C3 ≠ C12
C4 vs C13	0.5	17	75.643	76.660	17	69.138	98.168	2.028	2.037	32	Cannot Reject Ho	C4 = C13
C10vs C11	0.5	37	79.696	414.33	14	74.96	80.124	1.515	2.010	48	Cannot Reject Ho	C10 = C11
C13vs C14	0.5	17	69.138	98.17	9	78.083	4.0711	-3.585	2.100	18	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	37	80.814	218.432	6	74.363	124.935	1.247	2.306	8	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	17	68.186	108.62	9	85.818	23.494	-6.837	2.109	17	Reject Ho	C8 ≠ C9
Effect of Sand Depth												
C2 vs C14	0.5	10	78.991	114.221	9	78.083	4.0711	0.263	2.228	10	Cannot Reject Ho	C2 = C14
C2 vs C3	0.5	10	78.991	114.221	14	80.855	48.591	-0.483	2.145	14	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	14	80.855	48.591	17	75.643	76.660	1.845	2.045	29	Cannot Reject Ho	C3 = C4
C3 vs C14	0.5	14	80.855	48.591	9	78.083	4.0711	1.399	2.119	16	Cannot Reject Ho	C3 = C14
C11vs C13	0.5	14	74.96	80.124	17	69.138	98.168	1.716	2.045	29	Cannot Reject Ho	C11 = C13
C11vs C12	0.5	14	74.96	80.124	6	71.201	52.266	0.989	2.178	12	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	6	71.201	52.266	17	69.138	98.168	0.542	2.178	12	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	6	74.363	124.935	14	77.016	43.094	-0.543	2.365	7	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	6	74.363	124.935	17	68.186	108.62	-1.841	2.306	8	Cannot Reject Ho	C6 = C8
C7 vs C8	0.3	14	77.016	43.094	17	68.186	108.62	2.869	2.052	27	Reject Ho	C7 ≠ C8
Effect of Sand Size								Results of ' t test '				
C4 vs C9	0.5 vs 0.3	17	75.643	76.660	9	85.818	23.494	-4.658	2.100	18	Reject Ho	C4 ≠ C9
C5 vs C10	0.3 vs 0.5	37	80.814	218.432	37	79.696	414.33	0.270	1.996	66	Cannot Reject Ho	C5 = C10
C6 vs C11	0.3 vs 0.5	6	74.363	124.935	14	74.96	80.124	-0.116	2.306	8	Cannot Reject Ho	C6 = C11
C7 vs C12	0.3 vs 0.5	14	77.016	43.094	6	71.201	52.266	1.693	2.621	9	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	17	68.186	108.62	17	69.138	98.168	-0.273	2.037	32	Cannot Reject Ho	C8 = C13

Among the 9 comparisons of flow rates for coarse sand in Filters 1 and 3 (Table 4.4) as indicated by top 9 rows of Table 4.4, there were 7 comparisons which showed that the virus removal efficiencies were not significantly different at a confidence interval of 95%. In all these 7 comparisons the t-critical values were higher than t-calculated values and the null hypothesis could not be rejected. The mean values of the two conditions in each comparison were either equal or slightly higher for those conditions which operated under low flow rates. The remaining 2 of the 9 comparisons showed significantly unequal efficiencies of the filters as shown in rows 6 and 9 of Table 4.4. For example when condition # 3 (Q = 10/m, D = 80 cm, SS = 0.5 mm) was compared with condition # 12 (Q = 20/m, D = 80 cm, SS = 0.5 mm) as given in row 6, the t-calculated and t-critical values were |2.766| and |2.2621|, respectively. The higher t-calculated values rejected the null hypothesis and inferred that the two conditions were not equal. The average removal efficiencies of coliphage in condition #3 and condition # 12 were 81% and 71% respectively. Higher efficiency of condition # 3 showed it to be a better one with a significant difference. The result was well according to the expectations, i.e. higher removal efficiency at lower flow rate.

Among the same 9 comparisons, the total coliforms data indicated no significant difference in 6 of the comparisons, while remaining three indicated higher removal of coliforms at lower flow rates (Table 4.5). The results were

Table 4.5 : Statistical Comparison of Coliforms Removal Efficiencies Through 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	34	88.41	375.44	10	95.38	52.71	-1.72	2.022	39	Cannot Reject Ho	C1 = C2
C1 vs C10	0.5	34	88.41	375.44	38	89.38	363.46	-0.215	1.994	69	Cannot Reject Ho	C1 = C10
C1 vs C11	0.5	34	88.41	375.44	14	92.74	54.91	-1.12	2.012	46	Cannot Reject Ho	C1 = C11
C2 vs C11	0.5	10	95.38	52.71	14	92.74	54.91	0.869	2.085	20	Cannot Reject Ho	C2 = C11
C2 vs C10	0.5	10	95.38	52.71	38	89.38	363.46	1.556	2.021	40	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	14	99.31	0.8572	6	89.49	74.24	2.784	2.570	5	Reject Ho	C3 ≠ C12
C4 vs C13	0.5	17	83.79	14.53	17	78.426	39.65	3.009	2.055	26	Reject Ho	C4 ≠ C13
C10vs C11	0.5	38	89.38	363.46	14	92.74	54.91	-0.914	2.008	50	Cannot Reject Ho	C10 = C11
C13vs C14	0.5	17	78.426	39.65	9	83.74	5.1666	-3.118	2.073	22	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	38	87.81	446.57	6	94.74	69.87	-1.432	2.100	18	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	17	79.03	31.899	9	85.82	2.3494	-4.641	2.085	20	Reject Ho	C8 ≠ C9
Effect of Sand Depth												
C2 vs C14	0.5	10	95.38	52.71	9	83.74	5.166	4.813	2.200	11	Reject Ho	C2 ≠ C14
C2 vs C3	0.5	10	95.38	52.71	14	99.31	0.857	-1.702	2.262	9	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	14	99.31	0.8572	17	83.79	14.5310	16.20	2.100	18	Reject Ho	C3 ≠ C4
C3 vs C14	0.5	14	99.31	0.8572	9	83.74	5.1666	19.53	2.228	10	Reject Ho	C3 ≠ C14
C11vs C13	0.5	14	92.74	54.91	17	78.426	39.65	5.725	2.055	26	Reject Ho	C11 ≠ C13
C11vs C12	0.5	14	92.74	54.91	6	89.49	74.24	0.805	2.306	8	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	6	89.49	74.24	17	78.426	39.65	2.885	2.364	7	Reject Ho	C12 ≠ C13
C6 vs C7	0.3	6	94.74	69.87	14	90.76	71.862	0.969	2.228	10	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	6	94.74	69.87	17	79.03	31.899	4.272	2.364	7	Reject Ho	C6 ≠ C8
C7 vs C8	0.3	14	90.76	71.862	17	79.03	31.899	4.432	2.073	22	Reject Ho	C7 ≠ C8
Effect of Sand Size								Results of ' t test '				
C4 vs C9	0.5 vs 0.3	17	83.79	14.53	9	85.82	2.35	-1.91	2.068	23	Cannot Reject Ho	C4 = C9
C5 vs C10	0.3 vs 0.5	38	87.81	446.57	38	89.38	363.46	-0.340	1.992	73	Cannot Reject Ho	C5 = C10
C6 vs C11	0.3 vs 0.5	6	94.74	69.87	14	92.74	54.91	0.506	2.262	9	Cannot Reject Ho	C6 = C11
C7 vs C12	0.3 vs 0.5	14	90.76	71.862	6	89.49	74.24	0.304	2.262	9	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	17	79.03	31.89	17	78.43	39.65	0.295	2.036	32	Cannot Reject Ho	C8 = C13

similar to the one of virus removal except that condition # 4 indicated significantly higher removal than condition # 13 in case of coliform removal efficiency as indicated in row 7 of Table 4.5. Similarly, fecal coliforms showed significant statistical difference in 3 of the 9 comparisons by rejecting null hypothesis. The results were quite similar to total coliforms except that condition #2 achieved significantly higher removal than condition #1. The percentage removal difference was approximately 10% higher in condition #2 with high variance value of 400 as shown in the first row of Table 4.6. This indicated higher removal at higher flow rate and was against the earlier observed trend. This result might be attributed to some operational changes in the filter before the collection of the sample.

Standard plate counts results (Table 4.7) were exactly similar to those of coliphage plaque where significantly higher removal efficiencies were obtained in 3 of the 9 comparisons. This indicated higher removal efficiencies at lower flow rates. All those comparisons which indicated no significant difference of removal of microorganisms, only slightly higher efficiencies were obtained at lower flow rates. Thus, the results of higher removal efficiencies were well according to the expectations [3].

Similar were the results of suspended solids, where the t-critical values were higher than t-calculated values in 7 out of 9 cases (Table 4.8) and therefore, the null hypothesis could not be rejected. Thus, the removal of

Table 4.6 : Statistical Comparison of Fecal Coliforms Removal Efficiencies Through 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	33	86.34	400.72	10	95.42	53.36	-2.171	2.022	39	Reject Ho	C1 ≠ C2
C1 vs C10	0.5	33	86.34	400.72	37	87.34	327.82	-0.218	1.997	65	Cannot Reject Ho	C1 = C10
C1 vs C11	0.5	33	86.34	400.72	14	89.23	249.11	-0.528	2.039	31	Cannot Reject Ho	C1 = C11
C2 vs C11	0.5	10	95.42	53.36	14	89.23	249.11	1.286	2.093	19	Cannot Reject Ho	C2 = C11
C2 vs C10	0.5	10	95.42	53.36	37	87.34	327.82	2.144	2.024	38	Reject Ho	C2 ≠ C10
C3 vs C12	0.5	14	99.19	1.2482	6	78.65	538.93	2.166	2.57	5	Cannot Reject Ho	C3 = C12
C4 vs C13	0.5	17	85.01	21.53	17	79.35	67.98	2.466	2.059	25	Reject Ho	C4 ≠ C13
C10vs C11	0.5	37	87.34	327.82	14	89.23	249.11	-0.366	2.051	27	Cannot Reject Ho	C10 = C11
C13vs C14	0.5	17	79.35	67.98	9	83.66	8.9764	-1.927	2.073	22	Cannot Reject Ho	C13 = C14
C5 vs C6	0.3	37	85.68	470.067	6	94.06	66.51	-1.717	2.093	19	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	17	79.88	53.22	9	86.95	14.73	-3.236	2.063	24	Reject Ho	C8 ≠ C9
Effect of Sand Depth												
C2 vs C14	0.5	10	95.42	53.36	9	83.66	8.9764	4.672	2.178	12	Reject Ho	C2 ≠ C14
C2 vs C3	0.5	10	95.42	53.36	14	99.19	1.2482	-1.62	2.262	9	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	14	99.19	1.2482	17	85.01	21.53	12.18	2.100	18	Reject Ho	C3 ≠ C4
C3 vs C14	0.5	14	99.19	1.2482	9	83.66	8.9464	14.90	2.262	9	Reject Ho	C3 ≠ C14
C11vs C13	0.5	14	89.23	249.11	17	79.35	67.98	2.116	2.093	19	Reject Ho	C11 ≠ C13
C11vs C12	0.5	14	89.23	249.11	6	78.65	538.93	1.020	2.364	7	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	6	78.65	538.93	17	79.35	67.98	-0.072	2.570	5	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	6	94.06	66.51	14	88.06	71.88	1.491	2.228	10	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	6	94.06	66.51	17	79.88	53.22	3.639	2.306	8	Reject Ho	C6 ≠ C8
C7 vs C8	0.3	14	88.06	71.88	17	79.88	53.22	2.833	2.055	26	Reject Ho	C7 ≠ C8
Effect of Sand Size								Results of ' t test '				
C4 vs C9	0.5 vs 0.3	17	85.01	21.53	9	86.95	14.73	-1.138	2.093	19	Cannot Reject Ho	C4 = C9
C5 vs C10	0.3 vs 0.5	37	85.68	470.067	37	87.34	327.82	-0.35	1.994	73	Cannot Reject Ho	C5 = C10
C6 vs C11	0.3 vs 0.5	6	94.06	66.51	14	89.23	249.11	0.899	2.109	17	Cannot Reject Ho	C6 = C11
C7 vs C12	0.3 vs 0.5	14	88.06	71.88	6	78.65	538.93	0.966	2.447	6	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	17	79.88	53.22	17	79.35	67.98	0.199	2.037	32	Cannot Reject Ho	C8 = C13

Table 4.7 : Statistical Comparison of Plate Counts Removal Efficiencies Through 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	33	85.98	373.74	10	90.58	98.11	-1.001	2.042	30	Cannot Reject Ho	C1 = C2
C1 vs C10	0.5	33	85.98	373.74	38	87.49	375.92	-0.328	1.995	68	Cannot Reject Ho	C1 = C10
C1 vs C11	0.5	33	85.98	373.74	14	87.23	206.58	-0.245	2.034	33	Cannot Reject Ho	C1 = C11
C2 vs C11	0.5	10	90.58	98.11	14	87.23	206.58	0.676	2.074	22	Cannot Reject Ho	C2 = C11
C2 vs C10	0.5	10	90.58	98.11	38	87.49	375.92	0.697	2.045	29	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	14	96.35	23.41	6	87.09	14.75	4.553	2.178	12	Reject Ho	C3 ≠ C12
C4 vs C13	0.5	17	86.11	23.85	18	81.98	32.13	2.314	2.034	33	Reject Ho	C4 ≠ C13
C10vs C11	0.5	38	87.49	375.92	14	87.23	206.58	0.052	2.039	31	Cannot Reject Ho	C10 = C11
C13vs C14	0.5	18	81.98	32.13	9	86.06	9.413	-2.428	2.059	25	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	37	87.83	480.55	6	83.59	244.05	0.577	2.262	9	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	17	82.64	38.34	9	89.59	5.697	-4.093	2.068	23	Reject Ho	C8 ≠ C9
Effect of Sand Depth												
C2 vs C14	0.5	10	90.58	98.11	9	86.06	9.413	1.373	2.201	11	Cannot Reject Ho	C2 = C14
C2 vs C3	0.5	10	90.58	98.11	14	96.35	23.41	-1.699	2.179	12	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	14	96.35	23.41	17	86.11	23.85	5.835	2.048	28	Reject Ho	C3 ≠ C4
C3 vs C14	0.5	14	96.35	23.41	9	86.06	9.413	6.236	2.079	21	Reject Ho	C3 ≠ C14
C11vs C13	0.5	14	87.23	206.58	18	81.98	32.13	1.292	2.119	16	Cannot Reject Ho	C11 = C13
C11vs C12	0.5	14	87.23	206.58	6	87.09	14.75	0.034	2.109	17	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	6	87.09	14.75	18	81.98	32.13	2.482	2.160	13	Reject Ho	C12 ≠ C13
C6 vs C7	0.3	6	83.59	244.05	14	89.86	55.70	-0.936	2.447	6	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	6	83.59	244.05	17	82.64	38.34	0.146	2.447	6	Cannot Reject Ho	C6 = C8
C7 vs C8	0.3	14	89.86	55.70	17	82.64	38.34	2.889	2.059	25	Reject Ho	C7 ≠ C8
Effect of Sand Size								**Results of ' t test '**				
C4 vs C9	0.5 vs 0.3	17	86.11	23.85	9	89.59	5.697	-2.443	2.064	24	Reject Ho	C4 ≠ C9
C5 vs C10	0.3 vs 0.5	37	87.83	480.55	38	87.49	375.92	0.069	1.994	71	Cannot Reject Ho	C5 = C10
C6 vs C11	0.3 vs 0.5	6	83.59	244.05	14	87.23	206.58	-0.488	2.262	9	Cannot Reject Ho	C6 = C11
C7 vs C12	0.3 vs 0.5	14	89.86	55.70	6	87.09	14.75	1.089	2.109	17	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	17	82.64	38.34	18	81.98	32.13	0.329	2.037	32	Cannot Reject Ho	C8 = C13

Table 4.8 : Statistical Comparison of Suspended Solids 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	8	32.63	144.82	5	28.45	135.67	0.620	2.262	9	Cannot Reject Ho	C1 = C2
C1 vs C10	0.5	8	32.63	144.82	10	27.87	311.22	0.677	2.119	16	Cannot Reject Ho	C1 = C10
C1 vs C11	0.5	8	32.63	144.82	7	21.84	141.69	1.742	2.160	13	Cannot Reject Ho	C1 = C11
C2 vs C11	0.5	5	28.45	135.67	7	21.84	141.69	0.961	2.262	9	Cannot Reject Ho	C2 = C11
C2 vs C10	0.5	5	28.42	135.67	10	27.87	311.22	0.075	2.178	12	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	7	38.66	89.19	3	22.42	117.63	2.252	3.182	3	Cannot Reject Ho	C3 = C12
C4 vs C13	0.5	4	43.38	3.72	4	26.44	16.82	7.474	2.776	4	Reject Ho	C4 ≠ C13
C10vs C11	0.5	10	27.87	311.22	7	21.84	141.69	0.842	2.131	15	Cannot Reject Ho	C10 = C11
C13vs C14	0.5	4	26.44	16.82	6	51.11	72.61	-6.109	2.306	8	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	10	56.51	125.44	3	63.88	162.03	-0.905	3.182	3	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	4	49.61	356.44	6	70.97	66.85	-2.133	2.776	4	Cannot Reject Ho	C8 = C9
Effect of Sand Depth												
C2 vs C14	0.5	5	28.45	135.67	6	51.11	72.61	-3.617	2.364	7	Reject Ho	C2 ≠ C14
C2 vs C3	0.5	5	28.45	135.67	7	38.66	89.19	-1.616	2.306	8	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	7	38.66	89.19	4	43.38	3.72	-1.278	2.364	7	Cannot Reject Ho	C3 = C4
C3 vs C14	0.5	7	38.66	89.19	6	51.11	72.61	-2.499	2.200	11	Reject Ho	C3 ≠ C14
C11vs C13	0.5	7	21.84	141.69	4	26.44	16.82	-0.931	2.306	8	Cannot Reject Ho	C11 = C13
C11vs C12	0.5	7	21.84	141.69	3	22.42	117.63	-0.076	2.776	4	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	3	22.42	117.63	4	26.44	16.82	-0.609	4.302	2	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	3	63.88	162.03	7	60.63	98.81	0.394	3.182	3	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	3	63.88	162.03	4	49.61	356.44	1.193	2.570	5	Cannot Reject Ho	C6 = C8
C7 vs C8	0.3	7	60.63	98.81	4	49.61	356.44	1.085	2.776	4	CannotReject Ho	C7 = C8
Effect of Sand Size								Results of ' t test '				
C4 vs C9	0.5 vs 0.3	4	43.38	3.72	6	70.97	66.85	-7.94	2.447	6	Reject Ho	C4 ≠ C9
C5 vs C10	0.3 vs 0.5	10	56.51	125.44	10	27.87	311.22	4.333	2.131	15	Reject Ho	C5 ≠ C10
C6 vs C11	0.3 vs 0.5	3	63.88	162.03	7	21.84	141.69	4.879	2.776	4	Reject Ho	C6 ≠ C11
C7 vs C12	0.3 vs 0.5	7	60.63	98.81	3	22.42	117.63	5.232	2.776	4	Reject Ho	C7 ≠ C12
C8 vs C13	0.3 vs 0.5	4	49.61	356.44	4	26.44	16.82	2.398	3.182	3	Cannot Reject Ho	C8 = C13

suspended solids were either equal or only slightly higher for the conditions operating at lower flow rates. Only 2 of the 9 comparisons indicated significantly higher removal at lower flow rates by rejecting the null hypothesis. The removal of suspended solids correlated well with the removal of colipahage, total coliform, fecal coliform, and standard plate counts.

In case of statistical comparison of turbidity removal (Table 4.9), four of the nine comparisons indicated higher removal at higher flow rates and the results were not consistent with respect to the removal of four microorganisms and suspended solids. For example, as shown in second row of Table 4.9, (condition #1 versus condition # 10), the t-critical and t-calculated values were |1.987| and |-2.743|, respectively. Higher t-calculated rejected the null hypothesis. The average percentage removal of turbidity was approximately 29% [(48.73-37.65)(100)/37,65)] higher in condition # 10, thus the result was against the trend observed in the case of four different microorganisms and suspended solids. Only 1 of the 9 comparisons indicated significantly high removal efficiency of turbidity at lower flow rate as indicated by ninth row of Table 4.9. Since, the turbidity values (both influent and effluent) were extremely low (less than 1 NTU) the slow sand filters failed to give the similar response of higher removal at lower flow rates. This inconsistency can be attributed to erroneous measurement of low turbidity values or any changes in the operation of the filter before the collection of samples.

Table 4.9 : Statistical Comparison of Turbidity Removal Efficiencies Through 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	39	37.649	294.615	29	37.693	624.067	-0.008	2.011	47	Cannot Reject Ho	C1 = C2
C1 vs C10	0.5	39	37.649	294.615	53	48.733	465.025	-2.743	1.987	89	Reject Ho	C1 ≠ C10
C1 vs C11	0.5	39	37.649	294.615	40	57.068	515.426	-4.295	1.993	73	Reject Ho	C1 ≠ C11
C2 vs C11	0.5	29	37.693	624.067	40	57.068	515.426	-3.303	2.002	57	Reject Ho	C2 ≠ C11
C2 vs C10	0.5	29	37.693	624.067	53	48.733	465.025	-2.006	2.007	51	Cannot Reject Ho	C2 = C10
C3 vs C12	0.5	52	47.099	196.332	27	58.34	185.64	-3.444	2.005	54	Reject Ho	C3 ≠ C12
C4 vs C13	0.5	19	56.163	133.552	19	51.100	132.548	1.353	2.028	36	Cannot Reject Ho	C4 = C13
C10vs C11	0.5	53	48.733	465.0252	40	57.068	515.426	-1.791	1.989	82	Cannot Reject Ho	C10 = C11
C13vs C14	0.5	19	51.100	132.548	14	62.826	112.547	-3.026	2.045	29	Reject Ho	C13 ≠ C14
C5 vs C6	0.3	52	49.624	236.943	15	46.653	1001.326	0.352	2.119	16	Cannot Reject Ho	C5 = C6
C8 vs C9	0.3	20	54.855	172.38	13	59.60	203.77	-0.963	2.063	24	Cannot Reject Ho	C8 = C9
Effect of Sand Depth												
C2 vs C14	0.5	29	37.693	624.067	14	62.826	112.547	-4.623	2.019	41	Reject Ho	C2 ≠ C14
C2 vs C3	0.5	29	37.693	624.067	52	47.099	196.332	-1.87	2.024	38	Cannot Reject Ho	C2 = C3
C3 vs C4	0.5	52	47.099	196.332	19	56.163	133.552	-2.757	2.023	39	Reject Ho	C3 ≠ C4
C3 vs C14	0.5	52	47.099	196.332	14	62.826	112.547	-4.573	2.052	27	Reject Ho	C3 ≠ C14
C11vs C13	0.5	40	57.068	515.426	19	51.100	132.548	1.338	2.002	57	Cannot Reject Ho	C11 = C13
C11vs C12	0.5	40	57.068	515.426	27	58.34	185.64	-0.286	1.669	64	Cannot Reject Ho	C11 = C12
C12vs C13	0.5	27	58.34	185.64	19	51.100	132.548	1.945	2.018	42	Cannot Reject Ho	C12 = C13
C6 vs C7	0.3	15	46.653	1001.326	52	55.978	167.2402	-1.115	2.131	15	Cannot Reject Ho	C6 = C7
C6 vs C8	0.3	15	46.653	1001.326	20	54.855	172.38	-0.945	2.101	18	Cannot Reject Ho	C6 = C8
C7 vs C8	0.3	52	55.978	167.2402	20	54.855	172.38	0.326	2.032	34	CannotReject Ho	C7 = C8
Effect of Sand Size								Results of ' t test '				
C4 vs C9	0.5 vs 0.3	19	56.163	133.552	13	59.60	203.77	-0.722	0.239	22	Cannot Reject Ho	C4 = C9
C5 vs C10	0.3 vs 0.5	52	49.624	236.943	53	48.733	465.0252	0.244	1.988	94	Cannot Reject Ho	C5 = C10
C6 vs C11	0.3 vs 0.5	15	46.653	1001.326	40	57.068	515.426	-1.167	2.086	20	Cannot Reject Ho	C6 = C11
C7 vs C12	0.3 vs 0.5	52	55.978	167.2402	27	58.34	185.64	-0.744	2.008	50	Cannot Reject Ho	C7 = C12
C8 vs C13	0.3 vs 0.5	20	54.855	172.38	19	51.100	132.548	0.951	2.026	37	Cannot Reject Ho	C8 = C13

As evident from the literature [22], the higher filtration rates offer less retention of suspended and organic particles on the sand bed and therefore these particles are passed through the bed at a faster rate. On the other hand, lower filtration rates allow sufficient retention time for biological activity to develop over the sand surface and adsorb other suspended and colloidal particles. Therefore, lower filtration rates are preferred for the biological activity to grow and hence, remove the viruses and other organic and suspended matter.

The effect of flow rates was also checked using fine sand involving two comparisons out of 11 for the flow rates as defined earlier. The comparison of condition # 5 (Q = 16 l/m, D = 150 cm, SS = 0.3 mm) with condition # 6 (Q = 20 l/m, D = 150 cm, SS = 0.3 mm) gave higher t-critical value in case of coliphage removal (Table 4.4) and therefore, the null hypothesis could not be rejected. It led to the conclusion that the two conditions achieved same virus removal efficiencies. Although slightly higher removal efficiency was obtained for condition # 5 as compared to condition #6. The comparison of condition # 8 (Q = 20 l/m, D = 50 cm, SS = 0.3) versus condition #9 (Q = 10 l/m, D = 50 cm, SS = 0.3 mm) showed the t-critical value lower than the t-calculated (Table 4.4) which inferred that the null hypothesis should be rejected and hence the two conditions achieved significantly different removal efficiencies. The average removal of viruses in condition # 8 and condition # 9 were 68% and 86%, respectively, again showing that the results were according to earlier

findings, i.e. higher removal at lower flow rates.

Similar results were obtained for total coliforms, fecal coliforms and standard plate counts where condition # 5 and condition # 6 achieved no significant difference in the removal efficiencies, whereas comparison of condition # 8 and condition # 9 led to the conclusion of rejecting null hypothesis. The average percentage removals were significantly high in condition # 8 and thus achieved significantly greater removal. Similarly, the null hypothesis could not be rejected in case of suspended solids and turbidity and both the comparisons for these two parameters indicated statistically no significant difference.

It can be concluded that out of two comparisons one comparison between C5 and C6 for fine sand showed that there is no significant difference in the removal of coliphage, coliform, fecal coliform, plate counts, SS, and turbidity (Table 4.4). However, some differences were observed in C8 and C9, i.e. higher removal of all four different organisms in fine sand as compared to the coarse sand. Although no difference was assumed in the removal of SS and turbidity (Table 4.4).

b) Effect of Sand Depth:

The comparisons were also made to check the effect of various sand depths, i.e. 150 cm, 80 cm, and 50 cm, on removal of microorganisms, SS, and turbidity through slow sand filters. The effect of sand depth was carried

out using coarse sand in Filter # 1 and # 3 under seven different comparisons. The t-critical values of these 5 comparisons for data on coliphage removal are given in Table 4.4. The comparison of condition # 3 (Q = 10 l/m, D = 80 cm, SS = 0.5 mm) with condition # 4 (Q = 10 l/m, D = 80 cm, SS = 0.5 mm) showed that t-calculated and t-critical values were |1.8447| and |2.0452|, respectively. Higher t-calculated value inferred not to reject null hypothesis. Thus, these two conditions were same in performance. The average removal efficiencies for condition # 3 and # 4 were 81% and 76% respectively as indicated in fifteenth row of Table 4.4. Though the difference was not significantly large but slightly higher efficiency was obtained for condition # 3 operating at higher depth. Similarly, the remaining six comparisons gave slightly higher removals for the higher sand depths although not significant based on t-test at confidence interval of 95%.

Effects of sand depth were more reflected in case of total coliforms, fecal coliforms and plate counts when coarse sand was used. The null hypothesis was rejected in five of the seven comparisons for coliforms data, four of the seven comparisons for fecal coliforms data, and three of the seven comparisons for plate counts data. Those conditions which operated at higher sand depths achieved significantly higher removal in all of the above cases.

Farooq, et al. [15] found that the removal of total coliforms decreased with the decrease in sand depth, for both coarse and fine sands. The percent

coliform removal for fine sand decreased from 99% to 96% to 93% as the slow sand filter sand depth decreased from 135 to 105 to 55 cm, respectively. Similarly, in the case of coarse sand, the removal decreased from over 97% to 97% to 93% as the filter bed decreased from 135 to 105 to 55 cm respectively.

Windle and Taylor [45] found that the removal of viruses through slow sand filtration was increased by four times when the sand depth was increased from 300 cm to 600 cm. The results clearly indicated the importance of the appreciable retention time available for the water in the slow sand filter above the sand bed.

Most of the comparisons which indicated little or no significant difference, the removal efficiencies were either equal or slightly higher for the conditions which operated at higher sand depths, except few of them. The removal of SS and turbidity were significantly higher for the conditions which operated at smaller sand depths. The results were against the earlier observed trend, i.e. higher removal at higher sand depth.

Effect of sand depth was also investigated using fine size sand (0.3 mm). There were three comparisons where fine sand size was used. Total of two of the three comparisons showed that there was no significant difference in the removal efficiencies of the viruses. However, only one comparison (twenty second row of Table 4.4.) showed significant difference in removal efficiencies, i.e. when condition # 7 (Q = 20 l/m, D = 80 cm, SS = 0.3 mm) was

compared with condition # 8 (Q = 20 l/m, D = 50 cm, SS = 0.3 mm). Condition # 7 achieved about 13% higher efficiency than condition # 8, which indicated that higher removal efficiency was obtained at higher depths.

The results of plate counts were similar to those obtained for coliphage plaque. Condition # 7 achieved significantly higher removal than condition # 8. In addition to the above results, the total coliforms and fecal coliforms achieved significantly higher removal in condition # 6 as compared to condition # 8. The total coliforms and fecal coliforms removal were higher by 19% and 17.5%, respectively in condition # 6. For suspended solids and turbidity no statistical significant effect of sand depth could be obtained for fine sand. Although, the removal efficiencies of suspended solids were higher by 22% and 29.50% in condition # 6 and condition # 7 respectively as compared to condition # 8, but due to high variability of the data (Table 4.8), the statistical test failed to give any significant effect.

From the past experience it is learned that biological activity decreases with reduced depth. In other words, the biological activity is enhanced in increased depths. Therefore, the viruses and other suspended and organic matter have to travel more through the sand bed and chances of removal of these impurities are greatly increased. That is why, higher removal efficiency is expected at higher sand depths [13, 22].

c) Effect of Sand Size:

The effect of sand size was investigated on two different sizes of sands, i.e. 0.5 mm and 0.3 mm, using 5 different set of comparisons. The results of t-test are reported in Tables 4.4 to 4.9 There were four comparisons which showed higher t-critical values in case of coliphage removal data (Table 4.4), and thus, it was concluded that the conditions under these four comparisons were equal in performance. Although the t-tests showed no significant different but the average removals were either equal or slightly higher for the conditions operating with smaller sand size. Only one of the five comparisons, i.e., between conditions # 4 (Q = 10 l/m, D = 50 cm, SS = 0.5 mm) and condition # 9 (Q = 10 l/m, D = 50 cm, SS = 0.3 mm) gave different results. Higher modulus value of t-calculated showed that the two conditions were significantly different in removal efficiencies as indicated in twenty fourth row of Table 4.4. Condition # 9 achieved about 13.50% higher removal efficiency indicating thereby, that higher removal efficiency was obtained at smaller sand size. No statistically significant effects of sand size were observed for total coliforms, fecal coliforms, plate counts and turbidity. The removal efficiencies of the above parameters were either equal or slightly higher for the conditions which were operated using smaller sand size. The effect of sand size was more pronounced in removal of suspended solids. The null hypothesis was rejected in four of the five comparisons in suspended solids data and significantly higher

removal of suspended solids were achieved at smaller sand size. The result confirms the earlier finding that fine grains of sand are more closely packed and the interstitial spaces are smaller as compared to coarser sands. Therefore, the organic and suspended matter is more likely to be retained on the surface or upper layers of sand depth as compared to the depths containing coarser sand, and hence the effluent is of better quality.

d) Summary of Statistical Results

The summary of statistical analysis to study the effect of flow rate, sand depth and sand size on the removal efficiencies of microorganisms, suspended solids and turbidity are presented in Table 4.10a-c respectively. These tables were prepared by combining the inferences given in the last column of Tables 4.4 to 4.9 for all organisms, suspended solids and turbidity. These inferences were based on t-test analysis. The inferences were also derived based on the actual percentages taken from Table 4.3 for various parameters. These actual values are given below the statistical inferences for each set of comparison. The purpose of this was to show that there is consistent trend, i.e., higher removal at lower flows although t-test indicated that there is no significant effect of flowrate within 95% of confidence interval.

According to Table 4.10a, most of the conditions indicated no statistically (according to t-test) significant difference at 95% confidence interval. When

Table 4.10a: Summary of Statistical Analysis for the Effect of Flow Rate

Condition Description	Condition Number	Coliphage plaque	Total Coliform	Fecal Coliform	Plate Counts	SS	Turb
* ** *** * ** *** C1 = 8, 150, 0.5 ; C2 = 10, 150, 0.5	C1 vs C2	C1 = C2	C1 = C2	C1 < C2	C1 = C2	C1 = C2	C1 = C2
Actual Averages	C1 vs C2	C1 > C2	C1 < 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	C1 = C10	C1 < C10
Actual Averages	C1 vs C10	C1 > C10	C1 < 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	C1 = C11	C1 < C11
Actual Averages	C1 vs C11	C1 > C11	C1 < 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	C2 = C11	C2 < C11
Actual Averages	C2 vs C11	C2 > C11	C2 > 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	C2 = C10	C2 = C10
Actual Averages	C2 vs C10	C2 < C10	C2 > 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	C3 = C12	C3 < C12
Actual Averages	C3 vs C12	C3 > C12	C3 > 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	C4 > C13	C4 = C13
Actual Averages	C4 vs C13	C4 > C13	C4 > C13	C4 > C13	C4 > C13	C4 > C13	C4 > C13
C10 =16, 150, 0.5 ; C11 = 20, 150, 0.5	C10vs C11	C10 = C11	C10 = C11	C10 = C11	C10 = C11	C10 = C11	C10 = C11
Actual Averages	C10vs C11	C10 > C11	C10 < C11	C10 < C11	C10 > C11	C10 > C11	C10 < C11
C13 = 20, 50, 0.5 ; C14 = 10, 50, 0.5	C13vs C14	C13 < C14	C13 < C14	C13 = C14	C13 < C14	C13 < C14	C13 < C14
Actual Averages	C13vs C14	C13 < C14	C13 < C14	C13 < C14	C13 < C14	C13 < C14	C13 < C14
C5 = 16, 150, 0.3 ; C6 = 20, 150, 0.3	C5 vs C6	C5 = C6	C5 = C6	C5 = C6	C5 = C6	C5 = C6	C5 = C6
Actual Averages	C5 vs C6	C5 > C6	C5 < 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	C8 = C9	C8 = C9
Actual Averages	C8 vs C9	C8 < C9	C8 < C9	C8 < C9	C8 < C9	C8 < C9	C8 < C9

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

Table 4.10b : Summary of Statistical Analysis for the Effect of Sand Depth

Condition Description	Condition Number	Coliphage plaque	Total Coliform	Fecal Coliform	Plate Counts	SS	Turb
* ** *** * ** *** C2 = 10, 150, 0.5 ; C14 = 10, 50, 0.5	C2 vs C14	C2 = C14	C2 > C14	C2 > C14	C2 = C14	C2 < C14	C2 < C14
Actaual Averages	C2 vs C14	C2 > C14	C2 > 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	C2 = C3	C2 = C3
Actaual Averages	C2 vs C3	C2 < C3	C2 < C3	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	C3 = C4	C3 < C4
Actaual Averages	C3 vs C4	C3 > C4	C3 > 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	C3 < C14	C3 < C14
Actaual Averages	C3 vs C14	C3 > C14	C3 > C14	C3 > C14	C3 > C14	C3 < C14	C3 < C14
C11 = 20, 150, 0.5 ; C13 = 20, 50, 0.5	C11vs C13	C11 = C13	C11 > C13	C11 > C13	C11 = C13	C11 = C13	C11 = C13
Actaual Averages	C11vs C13	C11 > C13	C11 > C13	C11 > C13	C11 > C13	C11 < C13	C11 > C13
C11 = 20, 150, 0.5 ; C12 = 20, 80, 0.5	C11vs C12	C11 = C12	C11 = C12	C11 = C12	C11 = C12	C11 = C12	C11 = C12
Actaual Averages	C11vs C12	C11 > C12	C11 > C12	C11 > C12	C11 > C12	C11 < C12	C11 < C12
C12 = 20, 80, 0.5 ; C13 = 20, 50, 0.5	C12vs C13	C12 = C13	C12 > C13	C12 = C13	C12 > C13	C12 = C13	C12 = C13
Actaual Averages	C12vs C13	C12 > C13	C12 > 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	C6 = C7	C6 = C7
Actaual Averages	C6 vs C7	C6 <C7	C6 >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	C6 = C8	C6 = C8
Actaual Averages	C6 vs C8	C6 > C8	C6 > 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	C7 = C8	C7 = C8
Actaual Averages	C7 vs C8	C7 > C8	C7 > C8	C7 > C8	C7 > C8	C7 > C8	C7 > C8

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

Table 4.10c : Summary of Statistical Analysis for the Effect of Sand Size

Condition Description	Condition Number	Coliphage plaque	Total Coliform	Fecal Coliform	Plate Counts	SS	Turb
* ** *** * ** *** C4 = 10, 50, 0.5 ; C9 = 10, 50, 0.3	C4 vs C9	C4 < C9	C4 = C9	C4 = C9	C4 < C9	C4 < C9	C4 = C9
Actual Averages	C4 vs C9	C4 < C9	C4 < 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	C5 > C10	C5 = C10
Actual Averages	C5 vs C10	C5 > C10	C5 < 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	C6 > C11	C6 = C11
Actual Averages	C6 vs C11	C6 = C11	C6 > 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	C7 > C12	C7 = C12
Actual Averages	C7 vs C12	C7 > C12	C7 < 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	C8 = C13	C8 = C13
Actual Averages	C8 vs C13	C8 < C13	C8 > C13	C8 > C13	C8 > C13	C8 > C13	C8 > C13

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

actual averages of the respective conditions under each comparison was observed, the conditions which operated at lower flowrates indicated higher removal efficiencies. Similarly Table 4.10b indicated statistically no significant difference of the effect of sand depth in most of the 9 comparisons. Comparing the actual averages of the different conditions under each of the 9 comparisons, it was found that the average removals were slightly higher for conditions which operated at higher sand depths as compared to conditions which operated at lower sand depths.

Similarly Table 4.10c illustrated the effect of sand size. Most of the five comparisons indicated higher removal efficiencies (based on actual averages) for the conditions which operated at finer sand as compared to the conditions which were operawted using sand.

4.5 REMOVAL OF MICROORGANISMS WITH RESPECT TO DEPTH

To investigate the removal of indicator bacteria and viruses with respect of depth, the sample were collected from the three slow sand filters operating in parallel. Samples of supernatant and interstitial water were taken in duplicate from the mature filters. Sampling ports enabled depth samples to be taken at 0 cm, 25 cm, 50 cm, 75 cm, 100 cm, 125 cm and 150 cm from top of the sand surface. Samples were assayed within four hours of collection and the results (in terms of percent removal versus depth) are described in Table 4.11a-c. The

Table 4.11a: Percent Removal of Various Microorganisms at Successive Sand Depths at Q = 10 l/m, SS = 0.5 mm

Sand Depth (cm)	Coliphage plaque	Total Coliforms	Fecal Coliforms	Standard Plate Counts
0	0	0	0	0
25	31.25	42.50	41.30	20
50	50	66.25	73.91	56
75	62.50	93.125	88.04	81
100	68.75	95.06	91.40	87.60
125	75	95.62	92.39	90
150	75	96.06	93.15	90.4

Table 4.11b: Percent Removal of Various Microorganisms at Successive Sand Depths at Q = 20 l/m, SS = 0.3 mm

Sand Depth (cm)	Coliphage plaque	Total Coliforms	Fecal Coliforms	Standard Plate Counts
0	0	0	0	0
25	37.50	42.50	41.30	36
50	56.25	66.25	61.96	60
75	75	42.50	23.91	32
100	75	85	91.41	80.80
125	81.25	95.06	94.67	88
150	81.25	95.62	94.67	92

Table 4.11c: Percent Removal of Various Microorganisms at Successive Sand Depths at Q = 20 l/m, SS = 0.5 mm

Sand Depth (cm)	Coliphage plaque	Total Coliforms	Fecal Coliforms	Standard Plate Counts
0	0	0	0	0
25	43.75	42.50	41.30	40
50	56.25	78.12	61.96	56
75	68.75	0	41.30	24
100	75	66.25	73.91	81.60
125	81.75	85	91.41	84
150	87.5	93.12	96.41	85.2

percentage removals are expressed as the percentage of original inoculum. The initial densities of microorganisms were same for all the three filters.

The percent removal of various microorganisms (i.e. coliphage plaque, total coliform, fecal coliforms, standard plate counts) from Filter #1 is presented in Figure 4.72. The filter designated as Filter #1 operated at 10 l/min of flow with sand size of 0.5 mm. The initial density of coliphage plaque was 320 per 100 ml. At 50 cm of depth, 50% of coliphage were removed and percent removal increased further to 62.5% at 75 cm depth. After 75 cm increase in percent removal became quite stable and total of 75% of coliphage removal was achieved at full depth of 150 cm.

In case of total coliforms, the initial density was 1.6×10^5 MPN per 100 ml. First 50 cm of depth, showed 66.75% of the reduction in coliform density (Fig. 4.72). At 75 cm of depth, the percent removal obtained was 93.135%. Therefore, a significant amount of percent removal was obtained for coliforms at 75 cm depth. From 75 cm to 150 cm of depth the removal was almost uniform. The removal of 96.10% of coliforms were obtained at 150 cm depth of sand bed (Table 11a). Fecal coliforms occurred with a density of 9.20×10^4 MPN per 100 ml. The removal trend was similar to total coliforms. First 50 cm of depth gave about 74% removal of fecal coliforms. The removal increased to about 88.04% at 75 cm depth after which it became consistent and uniform from 75 cm of depth to 150 cm of depth.

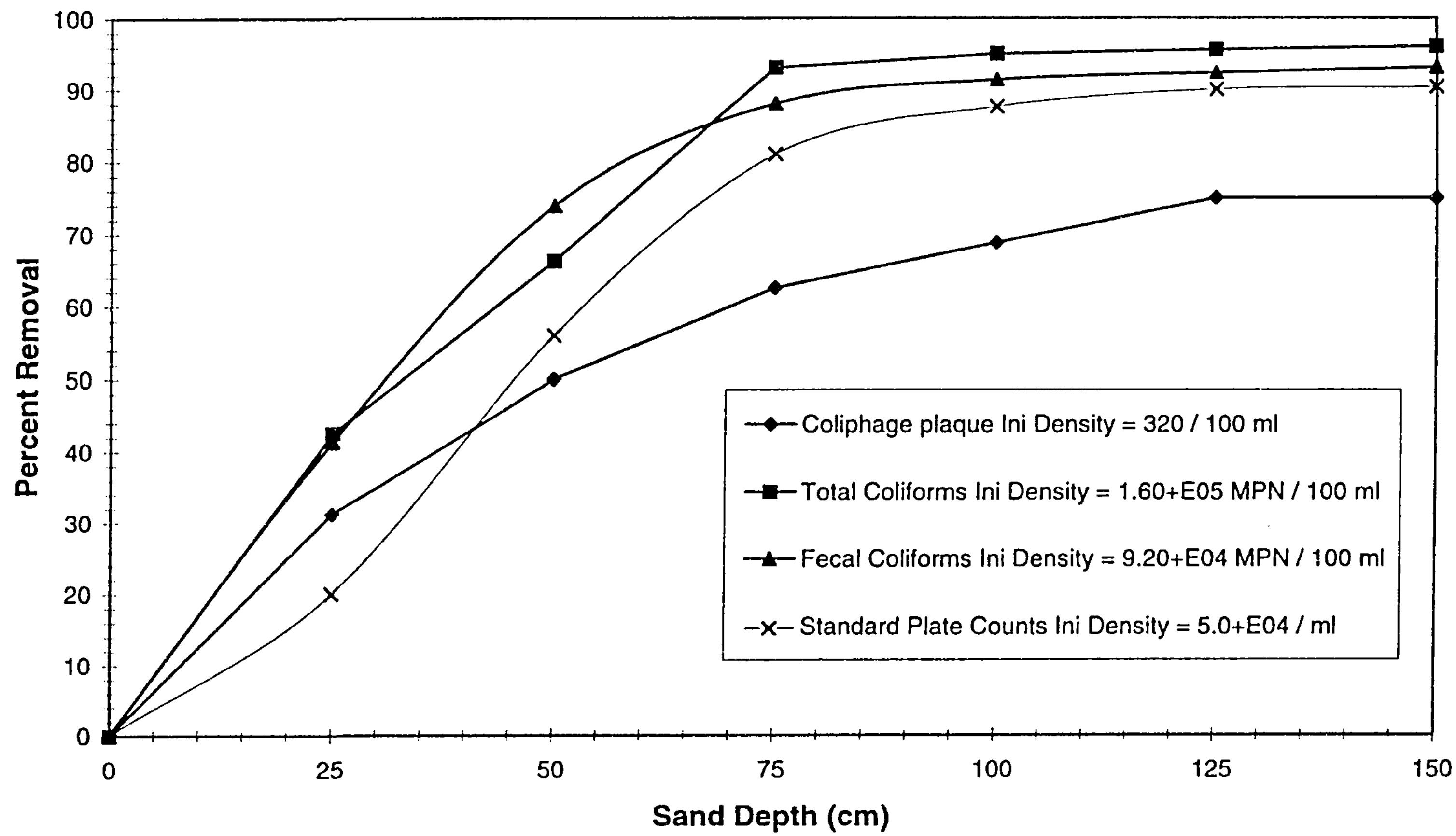


Figure 4.72: **Percent Removal of Coliphage and Bacteria at Successive Sand Depths at Flowrate of 10 l/m and SS of 0.5 mm**

The standard plate counts found at 50 cm depth were 5 x 10^4 per ml. Plate counts attenuated 56% at 50 cm depth (Fig. 4.72). Further, at 75 cm depth, the percent removal increased to 81.2%. The removal was consistent and uniform from 75 cm to 150 cm (like other microorganisms) and at 150 cm depth, removal of 90% was obtained.

Another filter designated as Filter #2 composed of fine sand of size 0.3 mm operating at filtration rate 20 l/min shows the attenuation of coliphage and bacteria along the depth in Figure 4.73. Since the same secondary effluent was fed into the three filters, therefore, the initial densities of coliphage, total coliform, fecal coliform, plate counts were same. The first 50 cm of depth showed a percent removal of more than 55% for coliphage plaque. The percentage removal increased to 75% at 100 cm depth. Therefore, a total of 75% removal was achieved at 100 cm depth. From 100 cm to 150 cm depth, the percentage removal became uniform sand only slight increase in removal was noted. At the full sand depth (i.e. 150 cm) the overall percentage removal was 81.75% of coliphage.

The results for total coliforms (Fig. 4.73) indicate an approximately 66% attenuation at 50 cm depth. The removal declined to 42.5% at 75 cm of depth indicating the presence of higher density of coliforms. The attenuation of coliforms increased significantly at 100 cm depth (i.e. 85%) and then it became uniform. The overall percentage removal of 95.62% was achieved at

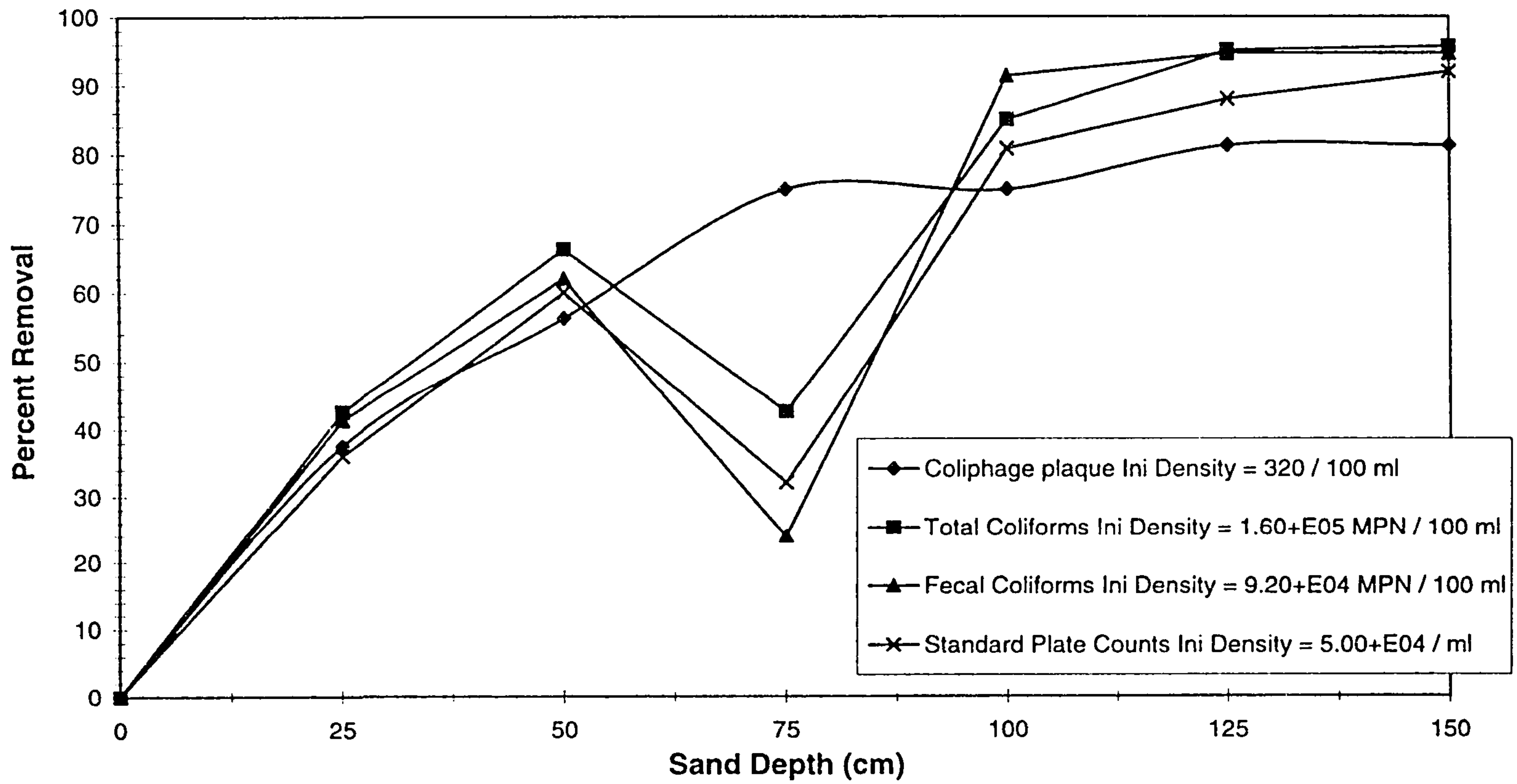


Figure 4.73: **Percent Removal of Coliphage and Bacteria at Successive Sand Depths at Flowrate of 20 l/m and SS of 0.3 mm**

150 cm of sand depth.

Results of fecal coliforms were quite similar to that of total coliforms (Fig. 4.73). At 50 cm depth, the attenuations were about 62% and then at 75 cm depth, the removal declined to 24% (Table 4.11b). About 91% of removal of fecal coliforms was achieved at 100 cm depth and overall removal at 150 cm sand depth was 94.6%.

For standard plate counts, the removal was 60% in the first 50 cm of sand depth. The removal declined to 32% at 75 cm depth, before it is significantly increased to 81% at 100 cm depth. At 125 cm and 150 cm of depths, the removals were 88% and 92% respectively. It is evident from Fig. 4.73 that percent removal became almost uniform from 100 cm to 150 cm of depth of sand. It should be remembered that the percent removals of total coliforms, fecal coliforms and plate counts decreased rapidly at 75 cm of depth. Therefore, it was concluded that large densities of above microorganisms had accumulated at 75 cm depth and they appeared in 75 cm depth same and thus resulted in lower percentage removals at this depth.

Figure 4.74 illustrates the attenuation of microorganisms (i.e. coliphage plaque, total coliforms, fecal coliforms and standard plate counts with depth in Filter #3, operated at 20 l/min of flow rate and with sand size of 0.5 mm. Marginally, more than 55% of coliphage were eliminated at 50 cm depth, and the coliphage removal increased further to 69% at 75 cm depth. The

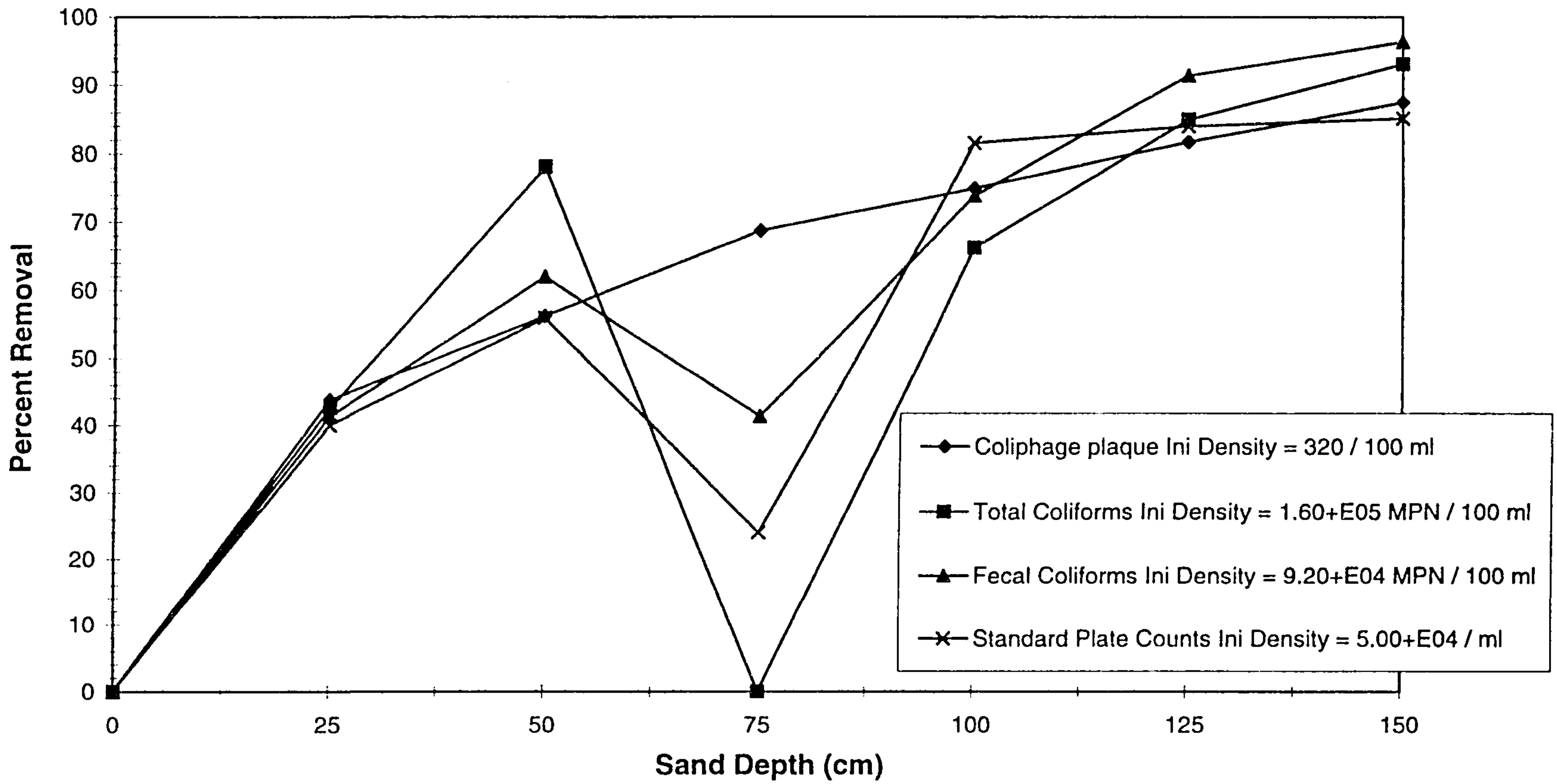


Figure 4.74: **Percent Removal of Coliphage and Bacteria at Successive Sand Depths at Flowrate of 20 l/m and SS of 0.5 mm**

elimination of coliphage further increased from 69% to 87.5% at full depth of 150 cm. As evident from Figure 4.74, the removal of coliphage plaque was very rapid in first 75 cm depth, after which, the percent removal increased gradually. In case of total coliforms, the percent removal at 50 cm depth was found to be as high as 78% for total coliforms. The percent removal of total coliforms decreased to 0 at 75 cm depth. The density at 75 cm found equal to initial density indicating, thereby the large accumulation of coliforms at depth between 50 - 75 cm of sand bed. The percent removal increased from 0% to 93.25% at depths of 75 cm to 150 cm respectively. For fecal coliforms, the initial density decreased by 62% at 50 cm depth. At 75 cm of depth, only 41.3% of the percent removal was found. The decrease in percent removal by about 50% was found between the depths of 50 and 75 cm. From 75 cm to 150 cm of depth, the removal efficiency for fecal coliforms increased from 41.3% to 96.4% respectively.

The initial 50 cm depth showed a significant removal of 56% for plate counts. The efficiency decreased at 75 cm depth (about 24%). The sharp decrease in percent removal from 56% to 24% from 50 cm depth to 75 cm shows large populations of plate counts deposited at 75 cm depth. At 100 cm depth the percent removal increased to 81.60%. Significant amount of percent removal was increased at 100 cm of depth. From 100 cm to 150 cm there was a slight but relatively uniform increase. At 150 cm of sand depth, the overall

percent removals; of 85.20% was noted for standard plate counts.

The above data show that in first 50 cm of depth the removal of all microorganisms was significantly high in Filter #1 when coarse sand was used. Moreover, most of the microorganisms were found accumulated near 75 cm depth (Figures 4.73, 4.74). It may be possible that due to high operating flowrate (i.e. 20 l/min), the microorganisms passed through the bed along with water infiltration and got accumulated at about 75 cm of depth of sand bed. It can be concluded from the above discussion that the attenuation of microorganisms is very high in first 50 cm of depth. The percent removal becomes gradual and almost uniform from 100 cm to 150 cm of depth of sand bed.

The linear best fit curves were also plotted (Figure 4.75) for removal of coliphage and bacteria through Filter #1 where 0.5 mm sand size was used and filter was operated at 10 l/min of flowrate. The curves for all four microorganisms follow a rising trend along the depth and indicate that removal of microorganism increased with depth. The regression R^2 value are reported which indicate the scatter of data with reference to best fit curves. High R^2 values of approximately 0.85 were obtained for coliphage and plate counts indicating only slight deviation from linear curve. Also, R^2 value of 0.78 and 0.75 were obtained for total coliforms and fecal coliforms. Though the R^2 values were not high but the obtained values seem reasonable.

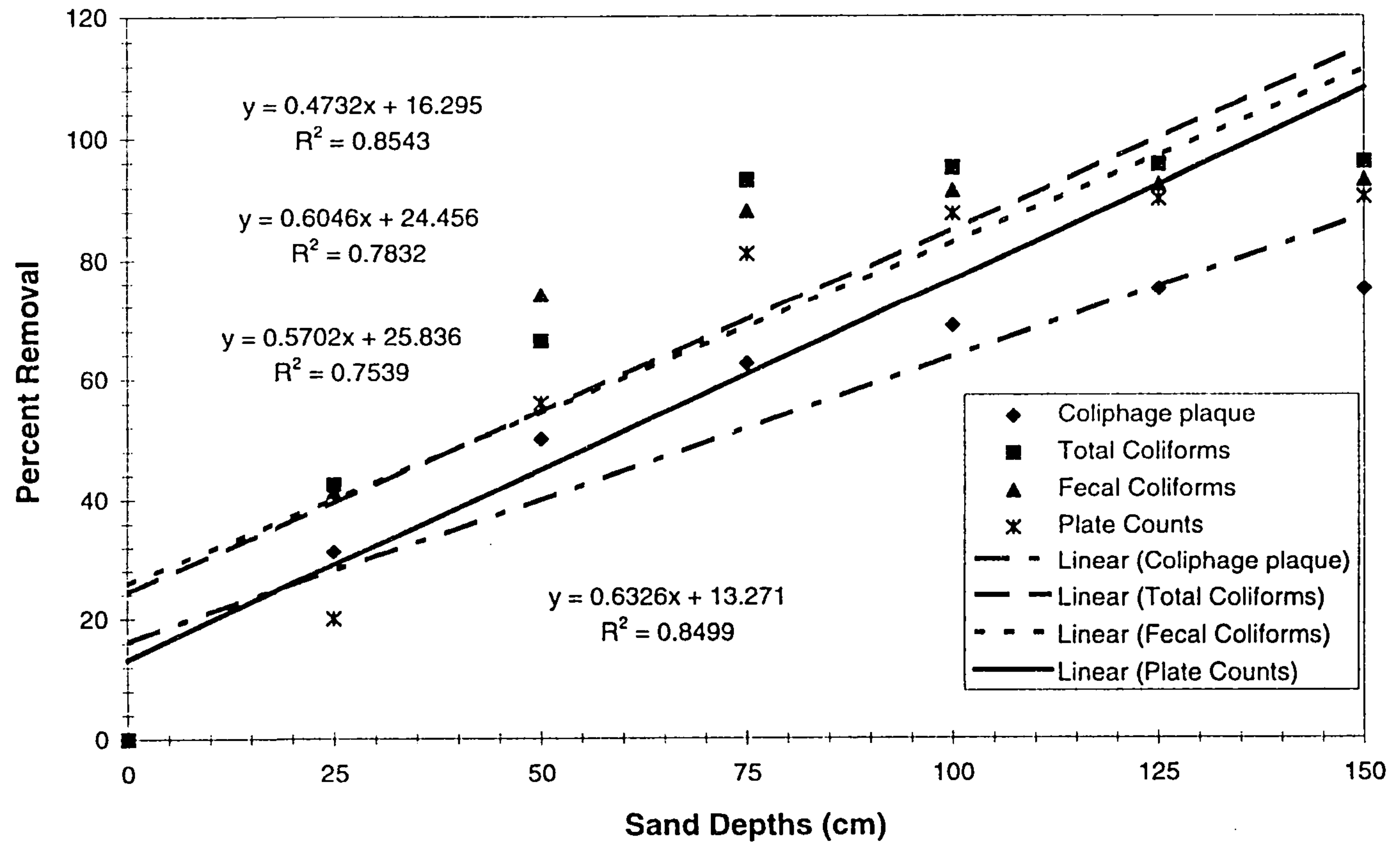


Figure 4.75: **Percent Removal of Coliphage and Bacteria at Successive Sand Depths at Flowrate of 10 l/m and Sand Size of 0.5 mm**

The linear best fit curve for Filter #2 (Figure 4.76) showed similar rising trend for all four microorganisms indicating increased removal efficiencies along the depth from 0 to 150 cm. The R^2 values for coliphage, coliforms, fecal coliforms and plate counts were 0.80, 0.82, 0.73 and 0.81 respectively.

The linear best fit curves for Filter #3 indicated similar rising trends along the sand depth for all four microorganisms (Figure 4.77). Largest scatter with low R^2 value of 0.48 was observed for total coliforms. The 0% removal at 75 cm of depth for total coliform had largely resulted in low R^2 value.

4.6 EFFECT OF FLOWRATE AND SAND DEPTH ON REMOVAL EFFICIENCIES

A comprehensive review of the impact of process variables, i.e. flowrate and sand depths on the removal of coliphage plaque, coliforms, fecal coliforms and plate counts was carried out in this study. Percent removal of above microorganisms was used to evaluate filtration effectiveness and filter response to test conditions. Only one variable was changed and all others were held constant. Filtration efficiencies through the filters were then compared. As stated earlier, three pilot slow sand filters were operated in parallel with a common secondary effluent to be treated. Operating conditions for each filter are given in Table 4.1.

Figure 4.78 represents the best fit curve showing effect of flowrates on microorganisms removal efficiencies. The filters were operated under four

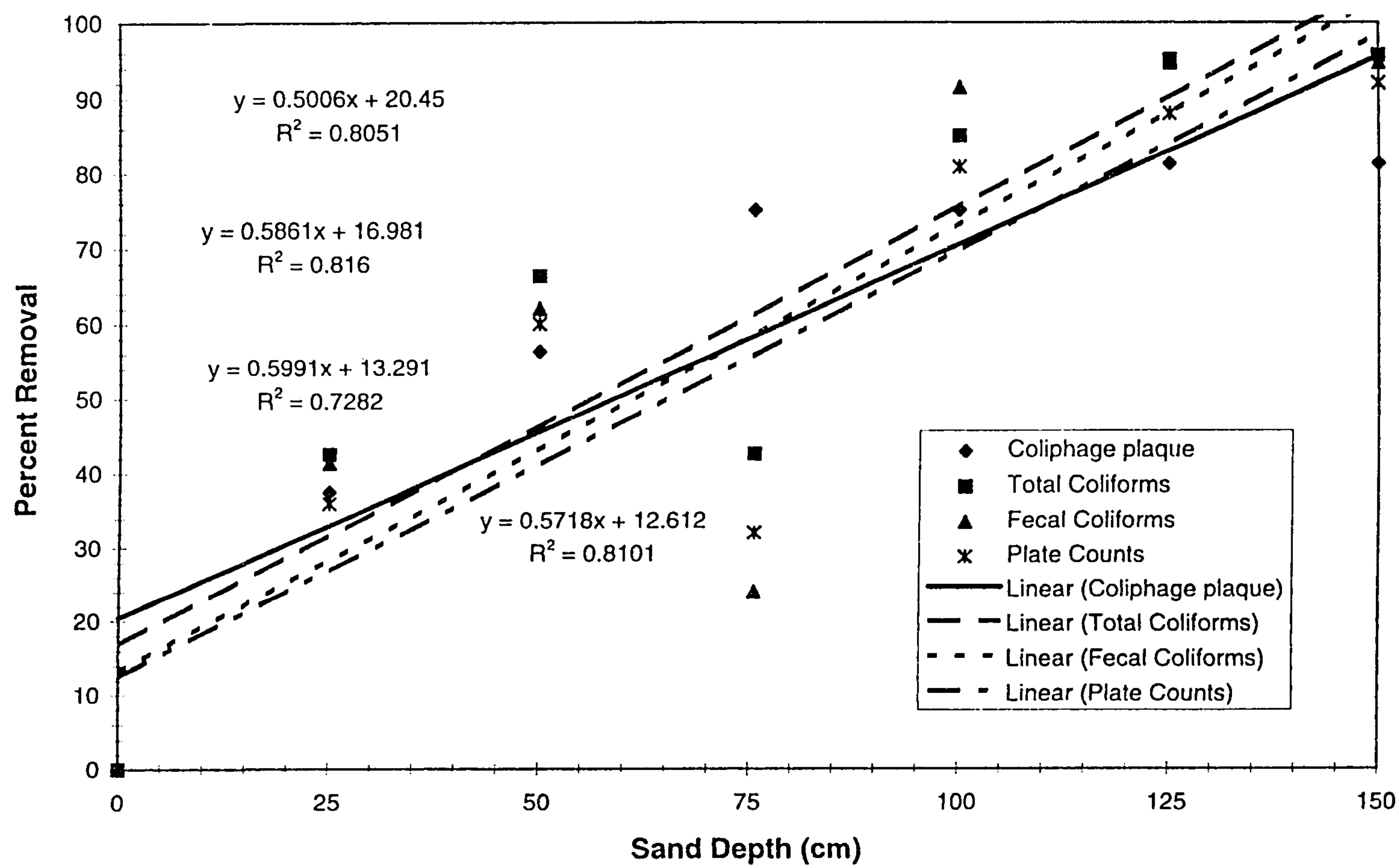


Figure 4.76: **Percent Removal of Coliphage and Bacteria at Successive Sand Depths at Flowrate of 20 l/m and Sand Size of 0.3 mm**

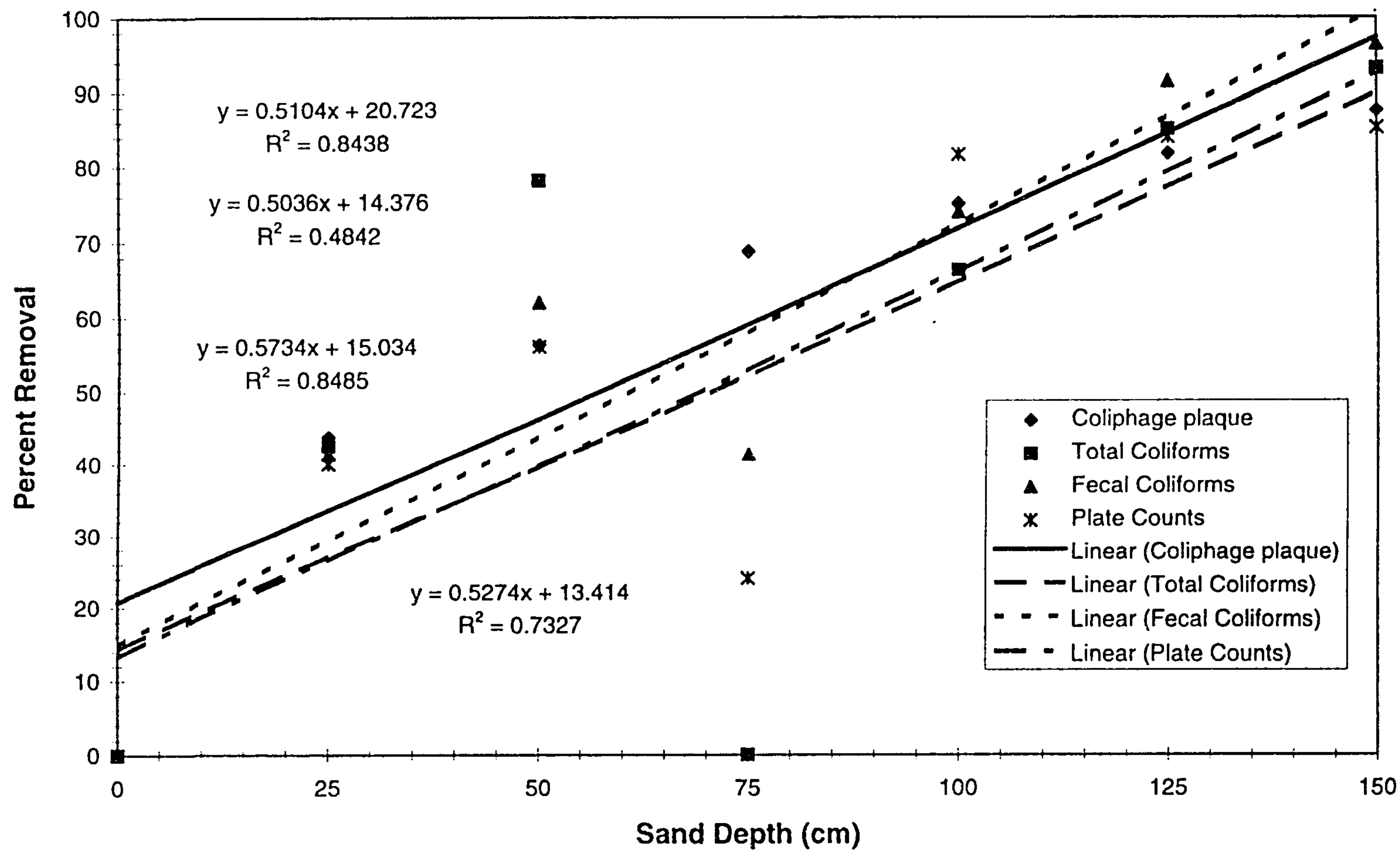


Figure 4.77: **Percent Removal of Coliphage and Bacteria at Successive Sand Depths at Flowrate of 20 l/m and Sand Size of 0.5 mm**

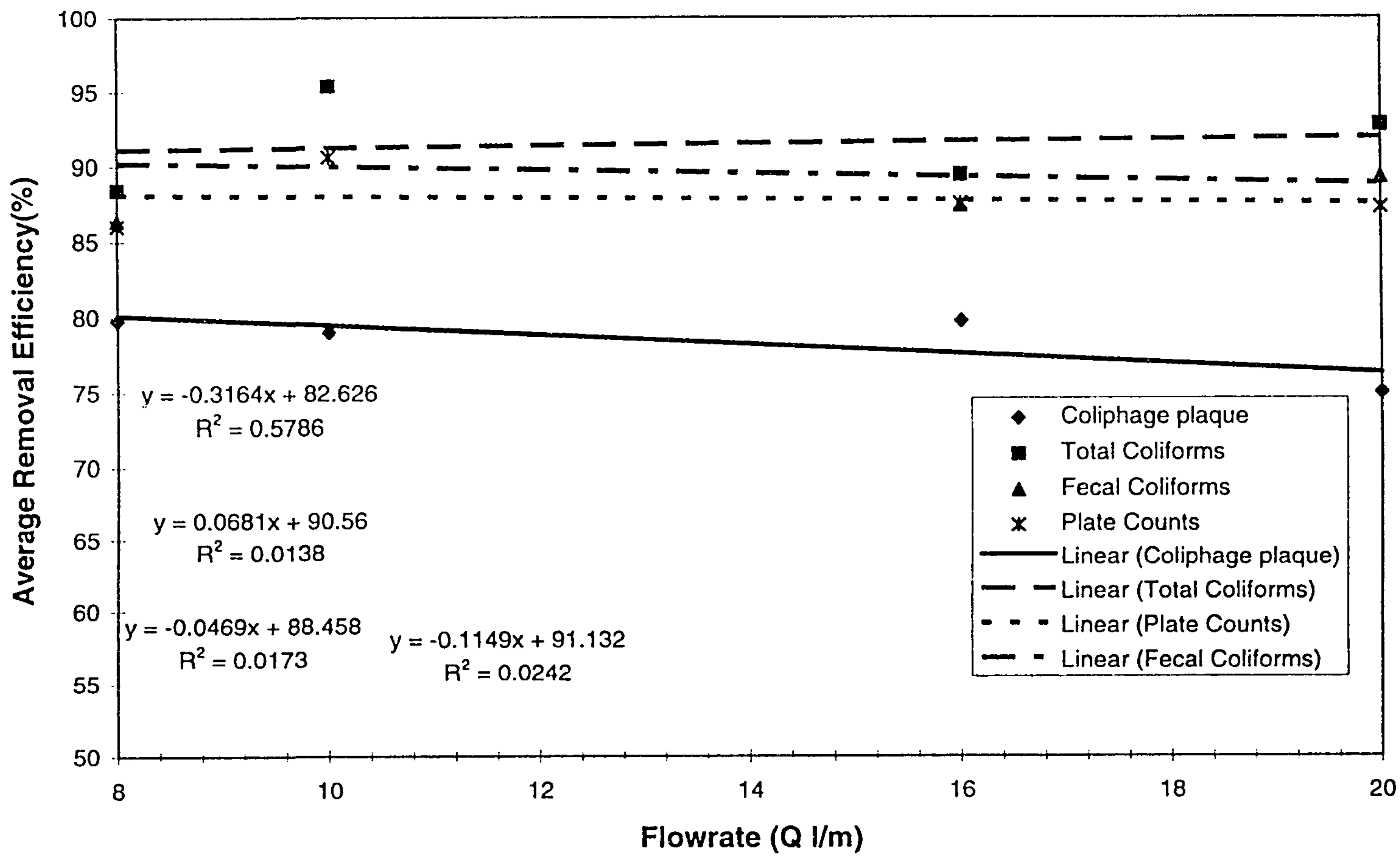


Figure 4.78: **Linear Best Fit Curve for Effect of Flowrate at Sand Depth of 150 cm and Sand Size of 0.5 mm**

different flowrates of 8, 10, 16 and 20 l/min at constant depth of 150 cm and sand size of 0.5 mm and these four stages were represented by conditions #1, #2, #10 and#11 respectively as shown in Table 4.1. Except for coliphage plaque, which showed slight decrease in removal efficiencies with increased flowrates, the remaining microorganisms indicated no significant effect of flowrate as was observed earlier by t-test.

The effect of sand depth was investigated where the filter was operated at various depths of 150 cm, 80 cm and 50 cm at flowrate of 10 l/min and sand size of 0.5 cm. These three stages of filter operation were designated by condition #2, #3 and #4 as shown in Table 4.2. To study the trend in removal efficiencies of the above three conditions linear best fit curves were plotted and are shown in Figure 4.79. As the Figure 4.79 shows, a rising trend of removal efficiencies for all four microorganisms were observed with increased sand depths. Since the level of bacterial activity decreased with decrease in sand depth through the sand bed, lower efficiencies were obtained at low sand depths.

The effect of sand depth was further investigated in conditions #6, #7 and #8 where depths of 150 cm, 80 cm and 50 cm were used. The flowrate of 20 l/min in above three conditions was held constant, and constant sand size of 0.3 mm was used (Figure 4.80). Higher removal efficiencies of the microorganisms were found at higher sand depth. The linear best fit curves

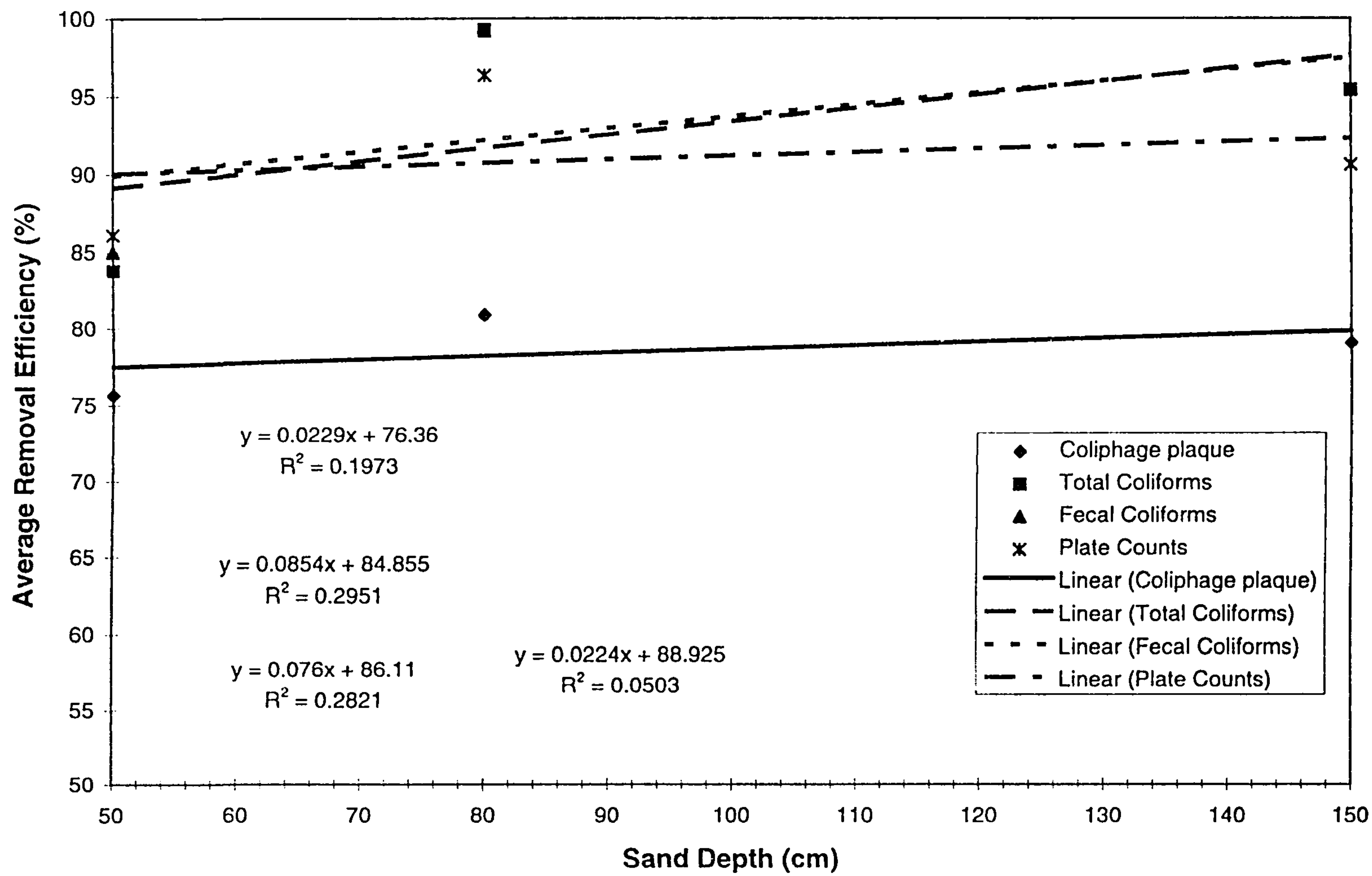


Figure 4.79: **Linear Best Fit Curve for Effect of Sand Depth at Flowrate of 10 l/m and Sand Size of 0.5 mm**

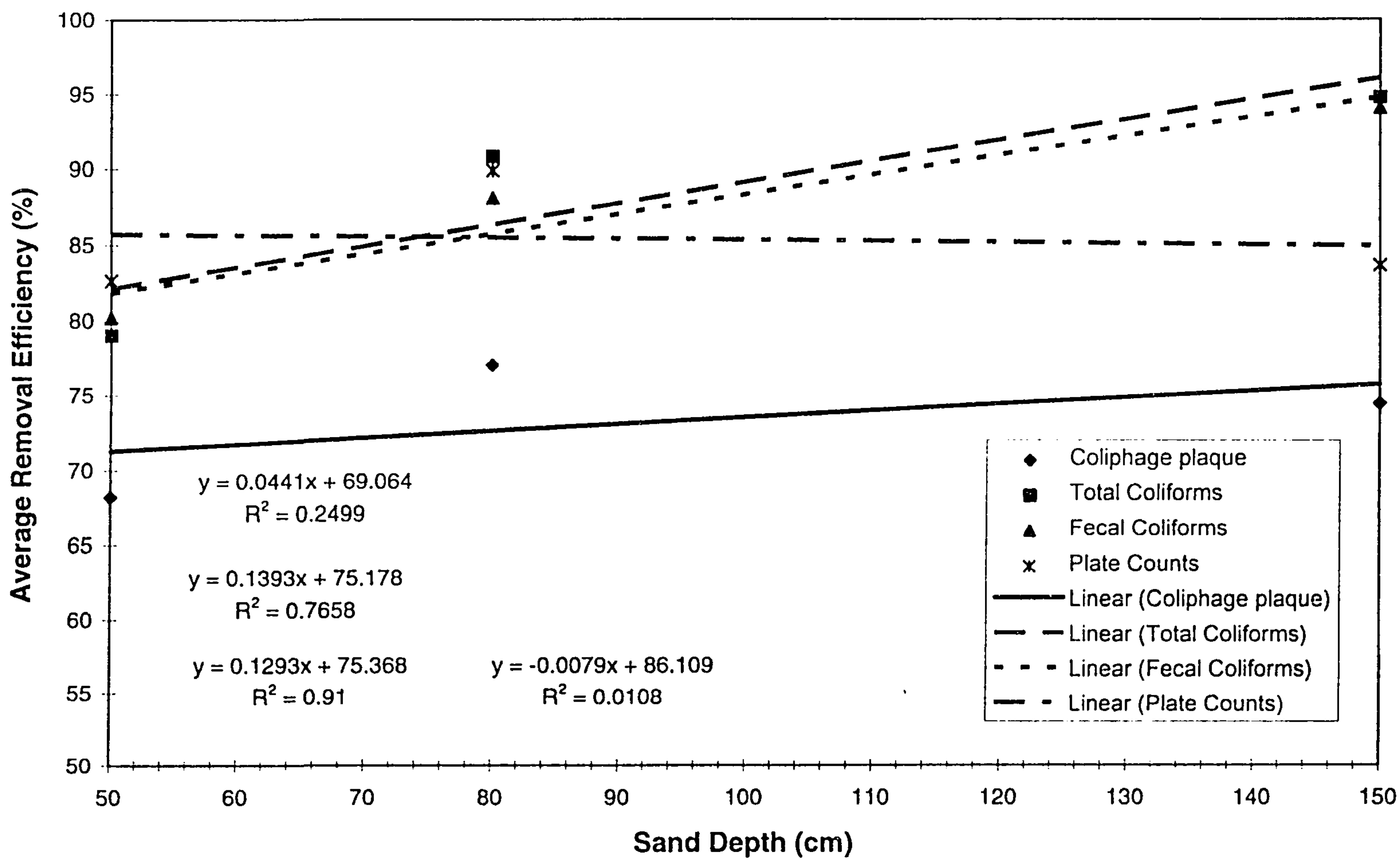


Figure 4.80: **Linear Best Fit Curve for Effect of Sand Depth at Flowrate of 20 l/m and Sand Size of 0.3 mm**

indicated the regular trend of increased removal efficiencies at reduced sand depths.

Another three conditions, i.e. condition #11, #12 and #13 were operated to investigate the effect of sand depth on removal efficiencies of microorganisms. These three conditions were operated at 150 cm, 80 cm and 50 cm of sand depths respectively and a constant flowrate of 20 l/min and a constant size of 0.5 mm were used. The removal efficiency of coliphage declined from 75% to 71% to 69% when the sand depth was reduced from 150 cm to 80 cm and 50 cm. Similar were the trends for other remaining microorganisms. The linear best fit curve (Figure 4.81) indicated a trend of increased removal efficiencies at higher sand depths. Thus, an overall conclusion can be drawn that the removal efficiencies of the microorganisms decreased when the sand depths were reduced.

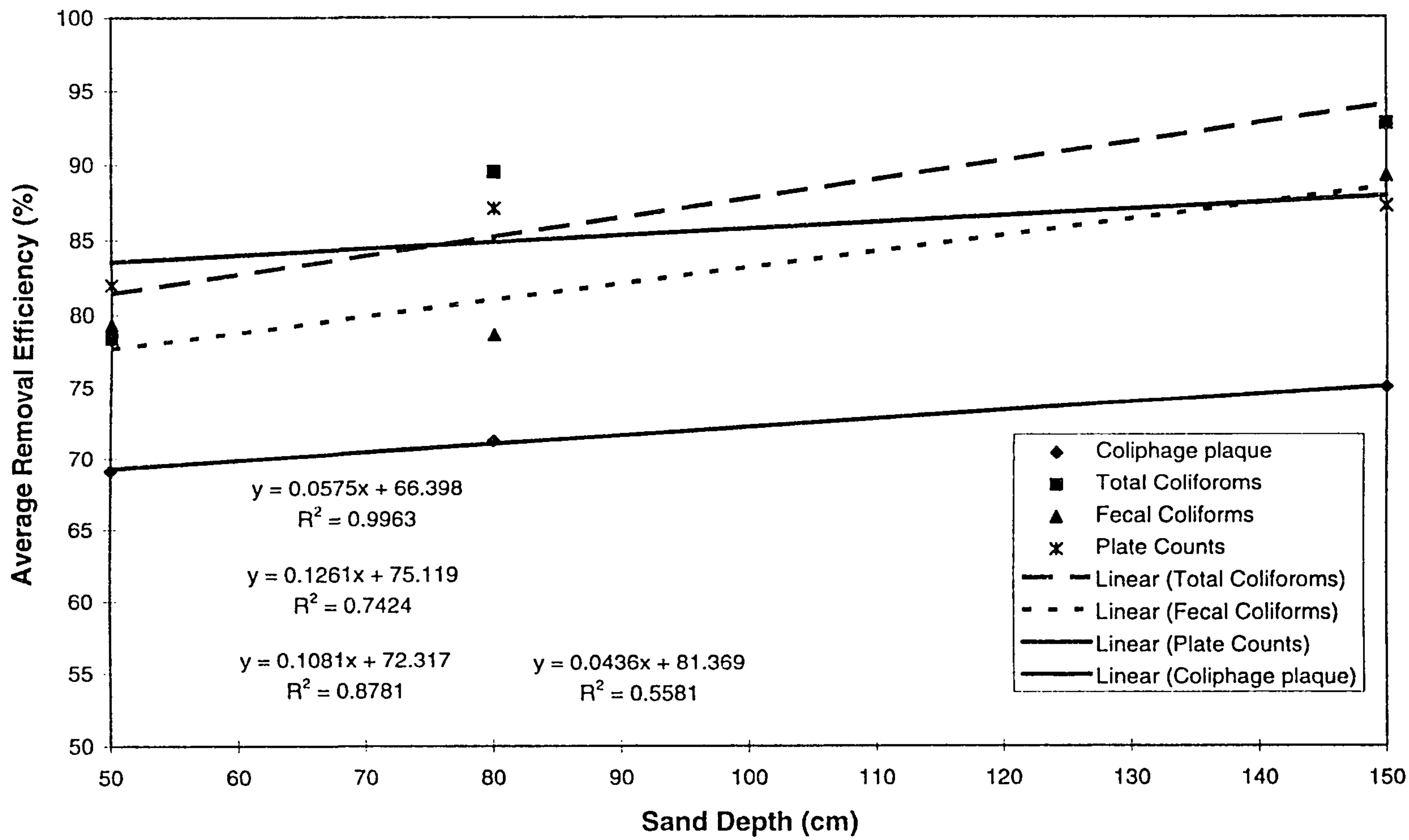


Figure 4.81: **Linear Best Fit Curve for Effect of Sand Depth at Flowrate of 20 l/m and Sand Size 0.5 mm**

Chapter 5

CONCLUSIONS

This study was aimed to evaluate slow sand filtration as tertiary treatment of secondary wastewater effluents at pilot scale under field conditions. The influent wastewater was taken from Al-Khobar Sewage Treatment Plant (STP) located in Eastern Province of Kingdom of Saudi Arabia. Three units of slow sand filters were constructed at the site. These filters were operated in parallel over a period of one year. Effects of flowrate, sand depth and sand size on percent removal of microorganisms, suspended solids and turbidity were investigated. Four different flowrates of 8, 10, 16 and 20 l/min, three different sand depths of 150, 80 and 50 cm, and two different sizes of sand of 0.5 mm, and 0.3 mm were used. Data generated over the entire period of operation was grouped under fourteen different operational conditions. Statistical analysis using t-test was performed on the entire data to find out whether there existed significant statistical difference among fourteen operational conditions. The specific conclusions drawn from the study are given as follows:

1. The influent densities during entire period of operation of 15 months for coliphage ranged from 1×10^2 to 6.2×10^3 per 100 ml, for total coliforms ranged from 3.10×10^3 to 1.6×10^6 MPN per 100 ml, for

fecal coliform ranged from 1.10×10^3 to 6×10^5 MPN per 100 ml and that for standard plate counts the influent densities ranged from 3.20×10^3 to 8.206×10^5 per ml.

2. The slow sand proved quite effective in removing coliphage and bacteria during the study. The average removal efficiencies among fourteen different operational conditions ranged from 68 to 86% for coliphage, 78 to 99% for total coliforms, 79 to 99% for fecal coliforms, 82 to 96% for standard plate counts, 22 to 64% for suspended solids and 33 to 62% for turbidity.

3. With respect to effect of flow rate, the removal efficiency of coliphage decreased from 79% to 75% when the flowrate was increased from 10 to 20 l/min keeping the sand depth and sand size constant. Similar trends of reduced efficiencies at increased flowrates were found for total coliforms, fecal coliforms and standard plate counts at 150 cm sand depth and 0.5 mm of sand size.

4. With respect to effect of sand depth, at a constant sand size and flowrate, the removal of coliphage decreased from 79% to 80.85% to 75.64% when the sand depth was reduced from 150 cm to 80 cm to 50 cm respectively. Similar trends were obtained for total coliforms,fecal coliforms and plate counts.

5. With respect to effect of sand size, at a constant flowrate and sand depth,

the removal of coliphage increased from 75.64% to 85.82% when the sand size was decreased from 0.5 mm to 0.3 mm respectively. Similar trends of increased removal efficiencies with decreased sand size were obtained for total coliforms, fecal coliforms and standard plate counts.

6. The samples at various sand depths of each of the filters were taken to study the removal of coliphage and bacteria. It was found that most of the removal of coliphage and bacteria occurred in the top layers of sand bed (75 cm) of the filter where low flowrates and coarse sand was used. In case of high flowrates the maximum removal was achieved at 100 cm for both coarse and fine sand filters.

7. The influent concentrations of suspended solids and turbidity ranged from 8 to 22 mg/l and 0.20 to 0.95 NTU respectively. Low values of turbidity (less than 1 NTU) were encountered throughout the entire period of operation. The removal of suspended solids and turbidity in the coarse sand filters were low ranging from 21.83 to 43.40% and 33.10 to 56%, respectively. The fine sand filter attained suspended solids removal in the range of 49.61 to 71% and turbidity reduction of 40 to 62%.

8. In order to make objective evaluation of entire data from 14 different operational conditions, the effects of flowrates, sand depths and sand sizes were investigated using a t-test analysis at 95% confidence interval.

In most of the cases, the t-test showed that there was no significant effect of flowrate on removal of different microorganisms , except few cases where it was shown that higher flowrates results in lower removal efficiencies.

9. Among various comparisons made to study the effect of sand depth, most of the comparisons showed that the removal efficiencies of microorganisms significantly decreased when the sand depths were decreased.

10. Among various comparisons made to study the effect of sand size, the t-test showed no significant effect of sand size on removal of different microorganisms, except for few cases where it was shown that larger sand size results in lower removal efficiencies.

11. When t-test results were compared with the actual average percentage removal of microorganisms, it was consistenyly found that in most of the cases the trends were higher removal efficiencies were obtained at lower flowrates, higher sand depths and smaller sand size, respectively.

12. In most of the cases the t-test indicated no significant effect of flowrate and sand depth on removal of suspended solids.

13. Among various comparisons carried out to study the effect of sand size on suspended removal, most of the comparisons indicated significantly higher removal of suspended solids at smaller sand size.

14. In case of turbidity most of the twenty six comparisons carried out to study the effects of flowrates, sand depths and sand sizes; it was observed that removal of turbidity was inconsistent with respect to trends observed in case of removal of coliphage, total coliforms, fecal coliforms, standard plate counts and suspended solids, i.e. higher removal of turbidity at higher flowrates, lower sand depths and larger sand size. These inconsistencies were primarily due to measurement of small values (less than 1 NTU) of turbidity. Small error in the measurement resulted in large percentage error with respect to removal efficiencies.

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