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# DESIGN OF NITRIFYING TRICKLING FILTERS

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## ABSTRACT

The United Kingdom is in the middle of the third 5 year Asset Management Program (AMP 3) since privatisation began in England and Wales. At the outset of AMP 3 the Environment Agency set new ammonia discharge permits for many existing works.

Most of these new works require the addition of tertiary treatment to meet these new discharge permits and nitrifying trickling filters (NTF)s may provide a cost effective solution for a considerable number of these works.

This paper examines the performance of two existing works where plastic media NTFs have been incorporated into the treatment process. The analysis concentrates on the performance of the NTFs with respect to the ammonia discharge quality they can be expected to meet. In addition the paper presents data to demonstrate their effect on BOD, suspended solids and alkalinity.

A reliable and simple method for the engineer to size the filters is essential for the successful implementation of this technology. This paper uses 2 popular design methods to model the predicted performance of the NTFs and compares the results to the actual performance from the filters under known conditions.

The results show that a NTF tertiary treatment plant can reliably meet an ammonia quality of 3mg/l for a 95percentile of samples, in a UK type climate.

## KEYWORDS

nitrifying trickling filters, design, tertiary treatment, ammonia, nitrification, fixed film, alkalinity

## INTRODUCTION

The United Kingdom is in the middle of the third 5 year Asset Management Program (AMP 3) since privatisation began in England and Wales. At the outset of AMP 3 the Environment Agency set new ammonia discharge permits for many existing works. The challenge for the utility companies in the UK has been how to meet these new discharge permits at the lowest whole life cost. The prohibitive cost of building complete new works, of purchasing new land and writing off existing assets has led to the conclusion that the most cost effective option is to add tertiary treatment. Of the numerous tertiary treatment processes available for ammonia removal NTFs can provide a favourable option. They have relatively low capital cost and are regarded by operators as simple to run and maintain.

To progress this option through to implementation the engineer needs to know with some certainty the discharge standard that the process is capable of meeting and have a reliable means of sizing the process units. The aim of this paper is to take a pragmatic approach to the design of NTFs by using 2 commonly adopted NTF models to predict the performance from existing filters and compare the predicted results to the actual performance of the filters.

In addition the paper goes on to examine how the NTFs perform with regard to BOD removal and solids yield and finally brief examination is made of the relationship between alkalinity and nitrification.

The analysis described above is based on the results presented from two works that have NTFs as a tertiary treatment stage. For both works the NTFs are of a similar design; tall towers filled with structured plastic media.

The 2 design methods examined were:
- Albertson and Okey procedure
- Gujer and Boller procedure

**Albertson and Okey Procedure.** In brief the Albertson and Okey procedure splits the filters into two regions. At the top of the filter where the concentration of ammonia is highest the rate of nitrification is taken to be zero order with respect to the ammonia concentration. As the concentration of the ammonia falls the rate of nitrification becomes proportional to the concentration of ammonia in the bulk liquid. In the zero order region the nitrification rate commonly used in the literature is 1.2 $g/m^2/d$. In the first order region the nitrification rate was calculated using the equation below.

$$k_n^* = k_n(N_e/N_T)^{0.75}$$

where

$k_n^*$ = first order nitrification rate, $g/m^2d$
$k_n$ = zero order nitrification rate, $g/m^2d$
$N_T$ = transition ammonium nitrogen, mg/l
$N_e$ = effluent ammonium nitrogen, mg/l

Temperature correction was not used as the influent was above 10°C throughout the tests.

**Gujer and Boller.** Gujer and Boller derived their design equations from Ficks Law. For the purpose of design the equation is presented in the form given below.

$$h= (1/-k_x)Ln[1-k_x v_h/ak_{nmax}e^{0.044(T-10)}(Ni-No+N_s Ln(N_i/N_o))]$$

where

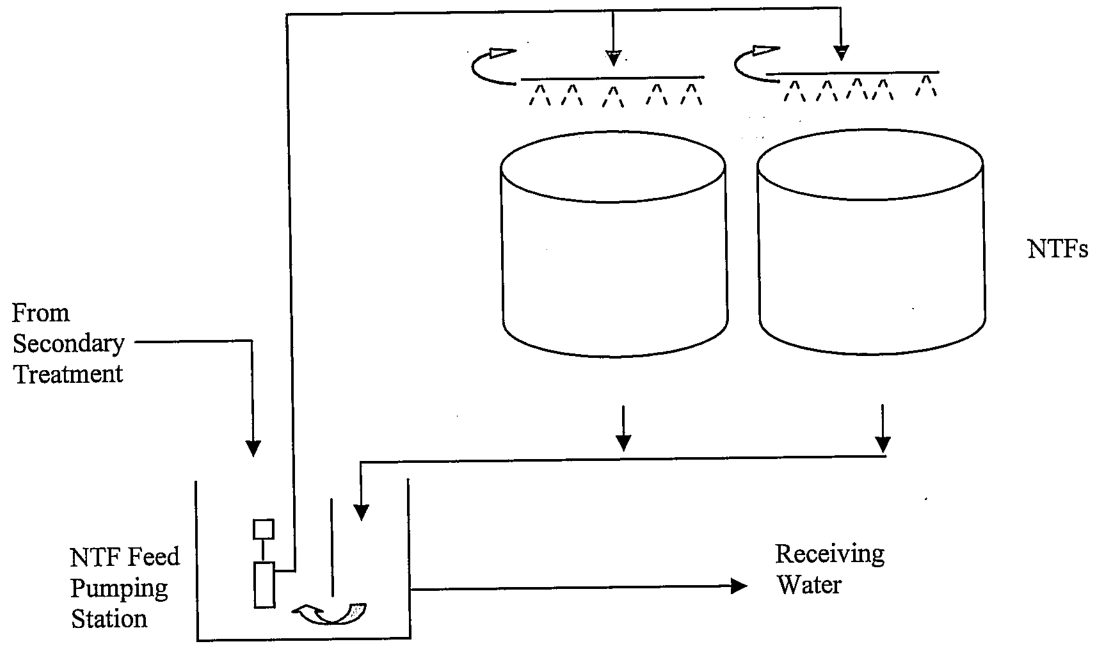
h= filter depth, m
$k_x$= constant to characterise the decline in the nitrification rate with depth in the filter, $m^{-1}$ (typically 0 to 0.2)
$v_h$ = wetting rate, m/h
$k_{nmax}$ = nitrification rate at the top of the filter, $g/m^2d$
$N_i$ = concentration of ammoniacal nitrogen in the influent, mg/l
$N_o$ = concentration of ammoniacal nitrogen in the effluent, mg/l
$N_S$ = saturation parameter for substrate limitation, mg/l
a = specific surface area of the media, $m^2/m^3$

## METHODOLOGY

The performance of NTFs at two waste water treatment works were studied to produce the results for this paper. For reference purposes they shall be referred to as works R and works F. Most of the results presented are from works R with data from works F used for validation.

A process flow diagram for works R is show below

**Figure 1-Process Flow Diagram for NTF at Works R**



Works R feed pumps were fixed speed so the NTFs received a constant flow. This allowed the analysis of the filter influent and effluent ammonia concentration as a substitute for load.

Works F had a similar set up to works R except the NTF Feed Pumps were variable speed, controlled from water level in the NTF Feed Pumping Station and there was no recirculation between the influent and effluent chambers; so the flow varied according to the diurnal flow received by the works.

The filter media for both works was plastic structured cross flow media. It had an angle of inclination of 60 degrees and a specific surface area of 150 $m^2/m^3$. The filters for both works had forced down draft ventilation. The volume of the media at works R was 2213 $m^3$, and at works F was 1079$m^3$. The flow to works R was constant at 12.96 Ml/d during period 1 and 13.08Ml/d during period 2. Maximum flow to full treatment at works F was 17 Ml/d.

The temperature of the influent was between 11 and 13 °C throughout the periods of intense sampling and the dissolved oxygen concentration in the effluent was above 6 mg/l. The Sk factor for filter R was 35 mm per pass.

The results presented are based on two intensive sample periods in May 2001 and April 2002, and validated against the works performance throughout the year. During the intensive sampling periods composite samples were taken from the influent to the filters and effluent from the filters every two hours. As well as normal quality parameters of total BOD, soluble BOD, suspended solids and ammoniacal nitrogen; others parameters such as temperature, alkalinity and dissolved oxygen were also monitored.

The combined data set was analysed and influent ammonia concentration was used as an input to the Albertson and Okey and Gujer and Boller design procedure, with flow as a constant value for each of the two separate data sets. A number of options were examined in order to establish the model of best fit. The parameters which were varied for the Albertson and Okey design procedure were the ammonia transition concentration and the initial nitrification rate. The parameters that were varied for the Gujer and Boller design procedure were the decline in nitrification rate with depth, the initial rate of nitrification and the saturation parameter for substrate limitation.

For each design procedure, design parameters were varied within the ranges commonly quoted in the literature.

Goodness of fit was based on comparison of the mean and the 95 percentile values of resulting data set and the mean values of the residual and the absolute residual when compared against actual data.

## RESULTS

Figure 2 and 3 shows the relationship between the influent and effluent ammonia concentration for the two intensive sample periods during May 2001 and April 2002. A summary of the performance of plant R with respect to ammonia removal during these two periods is shown Table 1.

**Table 1-Summary of the NTF Performance with Respect to Ammonia Removal for Plant R**

| Period | Average Ammoniacal Nitrogen Concentration mg/l | | 95 percentile Ammoniacal Nitrogen Concentration mg/l | |
|---|---|---|---|---|
| | Influent | effluent | influent | effluent |
| May 2001 | 10.3 | 0.4 | 18.3 | 1.0 |
| April 2002 | 12.7 | 0.4 | 18.3 | 0.7 |
| May 2001 to 2002 | | 1.1 | | 2.8 |

The results in Table 1 shows that the NFTs were able to produce an effluent containing less than 1 mg/l of ammonium during the periods of intense sampling and met a 95 percentile consent of 3mg/l throughout the year. The consistency of the effluent can be assessed comparing the average to the 95 percentile concentration of the effluent. For all periods the 95 percentile concentration results are between 2 to 3 times the average concentration.

Figure 4 compares the load applied to the load removed for the combined data set of period 1 and 2. It can be seen that ammonia removal is directly proportional to load applied up to a loading of 1g/m$^2$d. The overall efficiency of removal for the data set was 97 percent.

A comparison of the predicted ammonia effluent concentration with measured data is made in Table 2. The parameters of the Transition Point and initial nitrification rate have been varied within the expected ranges quoted in the literature to get a best fit with the measured data.

**Table 2 – Comparison of Residuals for Varying Design Parameters Using the Albertson and Okey Model.**

| Transition point | Initial nitrification rate | mean | 95 percentile | Mean res | Abs res |
|---|---|---|---|---|---|
| 4.0 | 1.0 | 0.50 | 0.77 | -0.08 | 0.20 |
| **4.0** | **1.1** | **0.42** | **0.62** | **-0.001** | **0.16** |
| 4.0 | 1.15 | 0.39 | 0.56 | -0.03 | 0.15 |
| | | | | | |
| 4.5 | 1.2 | 0.45 | 0.64 | -0.03 | 0.17 |
| **4.5** | **1.25** | **0.42** | **0.60** | **-0.01** | **0.17** |
| 4.5 | 1.3 | 0.39 | 0.54 | 0.02 | 0.15 |
| *5.0* | *1.2* | *0.54* | *0.77* | *-0.13* | *0.23* |
| actual | | 0.42 | 0.84 | | |

A similar procedure to the above was adopted for the Gujer and Boller design procedure. The parameters varied were the decline in the nitrification rate, the initial nitrification rate and the saturation parameter for substrate limitation.

**Table 3 – Comparison of Residuals for Varying Design Parameters Using the Gujer and Boller Model.**

| $k_x$ | $N_s$ | $k_n$, max | ave | 95 percentile | mean res | abs res |
|---|---|---|---|---|---|---|
| | | | | | | |
| 0.10 | 0.50 | 0.90 | 0.39 | 1.92 | -0.06 | 0.52 |
| 0.09 | 0.70 | 0.90 | 0.41 | 1.92 | -0.04 | 0.51 |
| 0.08 | 0.85 | 0.90 | 0.41 | 1.84 | -0.05 | 0.50 |
| | | | | | | |
| **0.11** | **1.05** | **1.00** | **0.41** | **1.77** | **-0.04** | **0.48** |
| 0.12 | 0.90 | 1.00 | 0.42 | 1.85 | -0.04 | 0.5 |
| 0.13 | 0.75 | 1.00 | 0.42 | 1.92 | -0.04 | 0.51 |
| | | | | | | |
| Actual | | | 0.42 | 0.84 | | |

Figure 7 and 8 makes a similar comparison to Figure 5 and 6 but compares the effluent ammonium concentration from the Gujer and Boller design procedure with the measured data.

Although the prime purpose of NTFs is ammonia removal, it is nevertheless interesting to see what effect they have on BOD reduction and how this interacts with solids production, as this will in some instances decide the need for down stream solids removal process. Figures 9 and 10 show the relationship of total BOD to soluble BOD and how this is affected by passage through the NTFs.
The average BOD in the influent to the filters was 7.5 mg/l of which the soluble fraction was reasonably consistent at 70 percent. Through the NTFs the reduction in total BOD was approximately 18 percent and the reduction in soluble BOD 11 percent.

The conversion of BOD into solids and the behaviour of the filter with respect to solids can be seen in Figures 11 and 12. The concentration of the solids in the influent is fairly typical of a good quality secondary effluent. Over the period considered the average solids in was 3 mg/l less than the solids out. However this is a relatively short period of time to assess the solids yield of the filters. The solids yield of the filters has been considered further in the discussion section of the paper. A summary of the effect of the NTF on suspended solids is given in Table 4 below.

**Table 4-Summary of the Effect of NTFs on Suspended Solids**

| Period | Average Suspended Solids Concentration mg/l | | 95 percentile Suspended Solids Concentration mg/l | |
|---|---|---|---|---|
| | Influent | effluent | influent | effluent |
| May 2001 | 14.1 | 14.4 | 29.8 | 24.0 |
| April 2002 | 13.0 | 16.1 | 24.6 | 24.6 |

The process of nitrification uses up alkalinity in the water and insufficient alkalinity in the water can inhibit nitrification. Figure 13 shows that the relationship between the amount of alkalinity used and ammonia removed is a linear one and that approximately 7g of alkalinity are used per gramme of ammoniacal nitrogen removed. It was observed that nitrification appeared uninhibited provided small levels (5 to 10 mg/l as $CaCO_3$) were present in the effluent.

## DISCUSSION

The daily ammonia load on the filters shown in Figures 2 and 3 reflecting the two sample periods shows a similar pattern. Typically the load to the plant drops off significantly after midnight and remains low until 6:00am in the morning, at 8:00am the load increases sharply. Between midnight and 6.00am the works is very lightly loaded and the ammonia concentrations in the effluent are usually below 0.2 mg/l to 0.3 mg/l. Between 6:00 am and 8:00 am most mornings of the test programme there was a 4 fold increase in the load that was applied to the filters, whilst ammonia removal efficiency remained above 95 percent.

High concentrations of ammonia were found in the effluent when the influent concentration was above that which was typical of the daytime peak load to the filters. This can be seen from examining Figure 2, a spike of ammonia in the influent causes a spike in the concentration of ammonia in the effluent. Typically over that sample period the ammonia removal efficiency was 97 percent but in response to the spike of ammonia in the influent the overall efficiency of removal dropped to 83 percent.

It appears that the filters are able to cope with rapid changes of ammonia load provided they are within the typical sustained peak daily load but the efficiency of removal drops off when the load on the filters increases beyond this.

It is possible that the biological load to the NTFs will support the growth of a certain quantity of biomass. This mass is capable of treating a set biological load but once the load increases beyond the point where it can be readily assimilated by the biomass the efficiency of treatment drops significantly.

For design engineers the implication is that it is the day time sustained load that should be used for design purposes. In the data set presented the average load to the filters was increased by approximately 20 percent once the data between midnight and 6:00am was removed. The filters appear to have maintained their removal of efficiency for loads within the 95 percentile load. It would appear that to design filters with additional area to cope with short term spike loads will not give effective treatment. Where a works is susceptible to peak day time loads the designer should consider ways of balancing these loads so they can be fed to the works over a longer period or at night.

Figure 4 shows the overall removal efficiency for the data set was 97 percent for applied loadings up to 1 $g/m^2d$; but the data set is bias by data at much lower loading rates, in addition it only requires a small changes in the efficiency of removal to have a large effect on the ammonia concentration in the effluent. Figure 4 provides a simple guide to what can be achieved with an NTF but a more sensititive design procedure is required for sizing filters that have to achieve low ammonia discharge standards.

From Table 2 it can be seen that there are two versions of the Albertson and Okey model which fit the mean value closely. They both have similar mean absolute residual values that are quite large, which arises from the failure of the model to predict the extremes of performance exhibited in the actual data. These models are good at predicting the overall average performance but do not follow the trends very closely.

The graphs shown in Figure 5and 6 use a transition point of 4.5 mg/l and a reaction rate of 1.25 $g/m^2/d$.

This again shows a good prediction of the average performance, but in general spikes in the actual performance are more pronounced than in the theoretical results.

Table 3, shows the effect of varying design parameters for the Gujer and Boller model, only combinations of parameters that give a good match with the average final effluent concentration were used in the analysis. It can be seen that the best fit (lowest absolute residual) is for $k_x = 0.11$, $N_s = 1.05$ and $k_n$ max = 1.00. The graph for this model is shown in Figures 7 and 8.

Again, this model is good at predicting the overall average performance, but shows more significant peaks and troughs than either the sample data or the Albertson and Okey model. The absolute mean residual values are higher than those given by the Albertson and Okey model.

The reason for this difference appears to be due to the way that each method models the drop in nitrification rate with depth through the filter. With parameters used in this analysis the Albertson and Okey leads to a rapid drop in nitrification rate as the ambient ammonia concentration falls below the transition point. Therefore significant changes in influent concentration lead to less dramatic variations in effluent concentration, as long as the effluent concentration is well below the transition point.

In the Gujer and Boller model used with the design parameters quoted in Table 3 the reduction in nitrification rate with reduced ammonia concentrations is less pronounced.

The main application of NTFs is to achieve an ammonia discharge permit on an existing works. For this they are installed down stream of existing secondary treatment. As such the BOD in the influent to the NTF is normally in the region of 5 to 15mg/l as an average value. Under these conditions the designer needs to know whether the NTFs achieve further BOD reduction and if they do the, contribution made to solids production.

The increase in the average solids content of the effluent shown in Table 4 cannot be directly attributed to the conversion of BOD into solids. A detailed examination of the influent and effluent suspended solids profile shown in Figures 11 and 12 shows there is no direct correlation. It can be seen from Figures 11 and 12 that solids accumulate in the filter and then release over a period of time. This effect is most pronounced when a peak short term suspended solids load comes into the filter instead of a correspondingly high effluent concentration being observed the solids are released over a period of time, resulting in a correspondingly lower concentration of solids in the effluent than might be expected. This is reflected by the data given in Table 2, this shows that the ratio between the average and 95 percentile suspended solids is less in the effluent to that in the influent, even though the average concentration remained the same or increased.

## CONCLUSIONS

This study provides useful design data for engineers and validation of existing design models for the sizing of NTFs to meet low ammonia discharge permits. The main conclusions of the study are given below:

- NTFs are a suitable tertiary treatment process to discharge an effluent of 3mg/l for 95 percentile of effluent samples in a UK type climate.
- The Albertson and Okey design procedure gives a good prediction of the general filter ammonia removal performance, provided the influent load remained within its "normal" day time load. It generally under estimated the magnitude of the filter response to peak ammonia loads.
- The NTFs provided efficient treatment of normal loads but efficiency dropped off for abnormal loads. Load profile information is an important part of the design data that should be gathered for the design of NTFs. Where necessary the feed of high ammonia loads to the NTFs should be balanced out or fed to the filters at night.
- Ammonia removal efficiency of better than 95 percent was typically achieved provided the load to the filters stayed within the 95 percentile of the average load.
- Based on typical secondary influent to the NTF the reduction in BOD in the NTF will be relatively low, in this study this was less than 20 percent.

- During this study the consumption of alkalinity per gramme of ammoniacal removed was approximately 7 grammes. Nitrification appeared uninhibited despite low concentration of alkalinity in the effluent of in some instances less than 10mg/l as $CaCO_3$.

## ACKNOWLEDGEMENTS

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Figure 2 - Influent and Effluent Ammonia Vs time for Site R, 2001

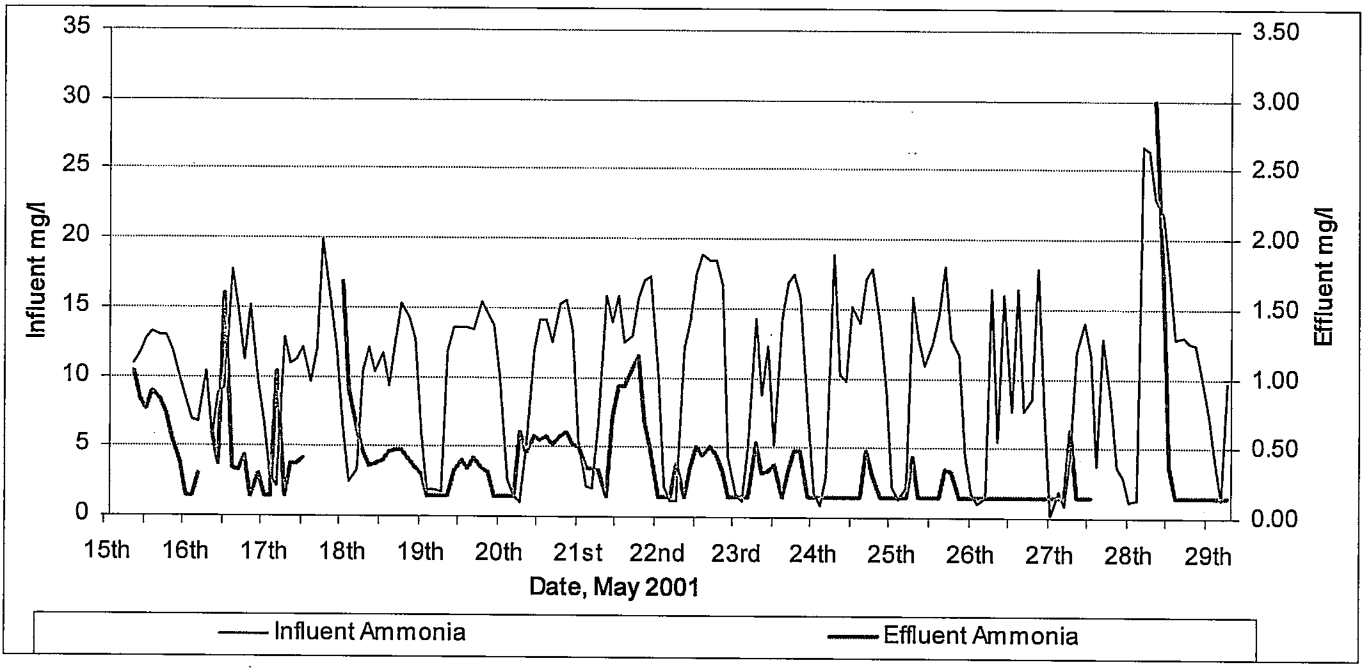


Figure 3 - Influent and Effluent Ammonia Vs time for Site R, 2002

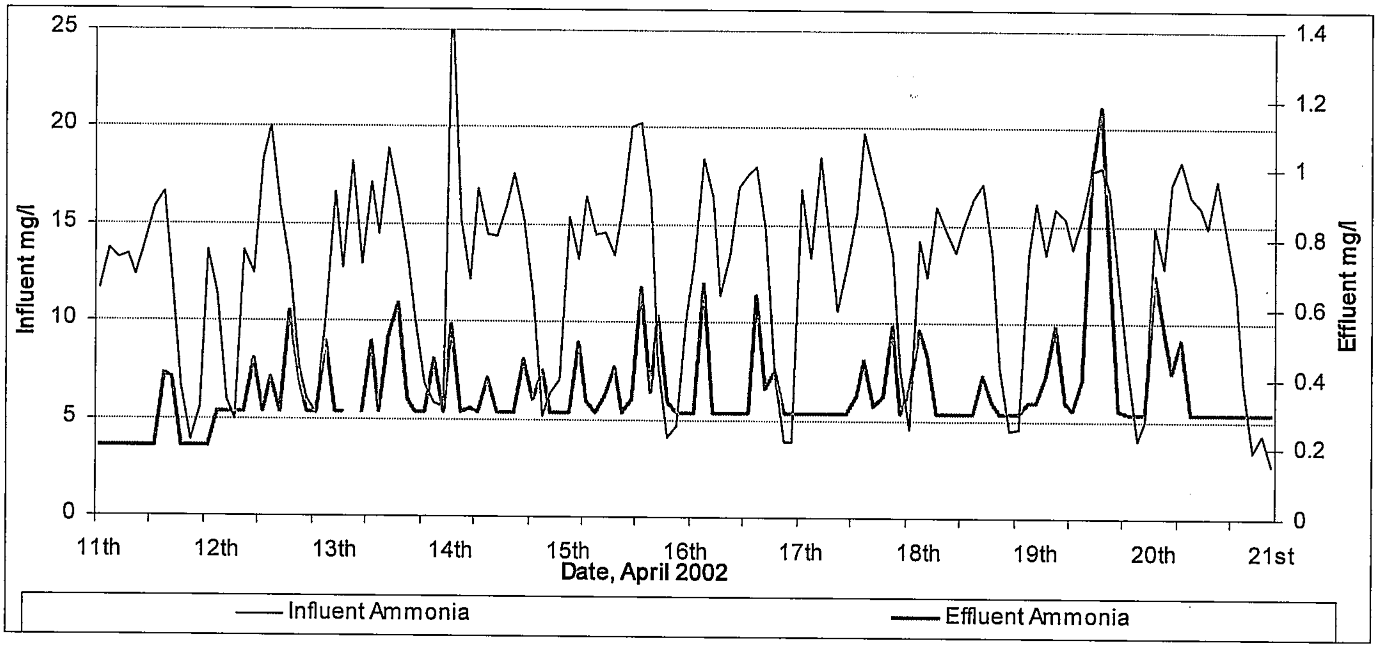


Figure 4 - Load Applied Vs Load Removed

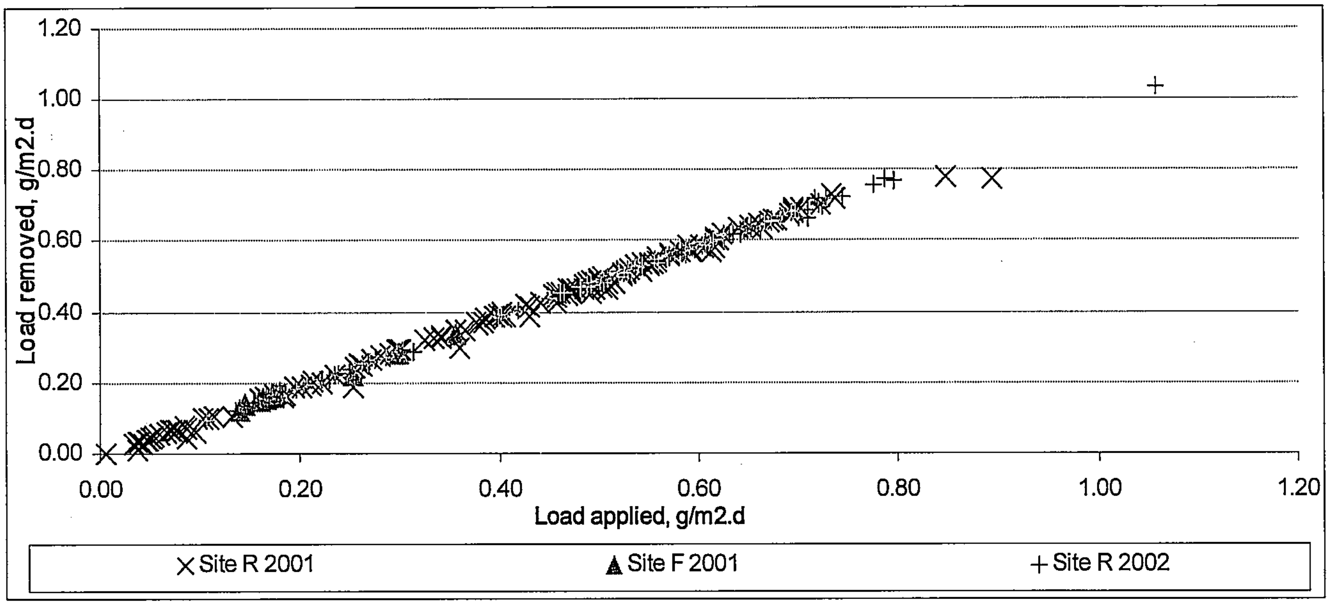


Figure 5 - Albertson and Okey Model Vs Actual Performance at Site R, 2001

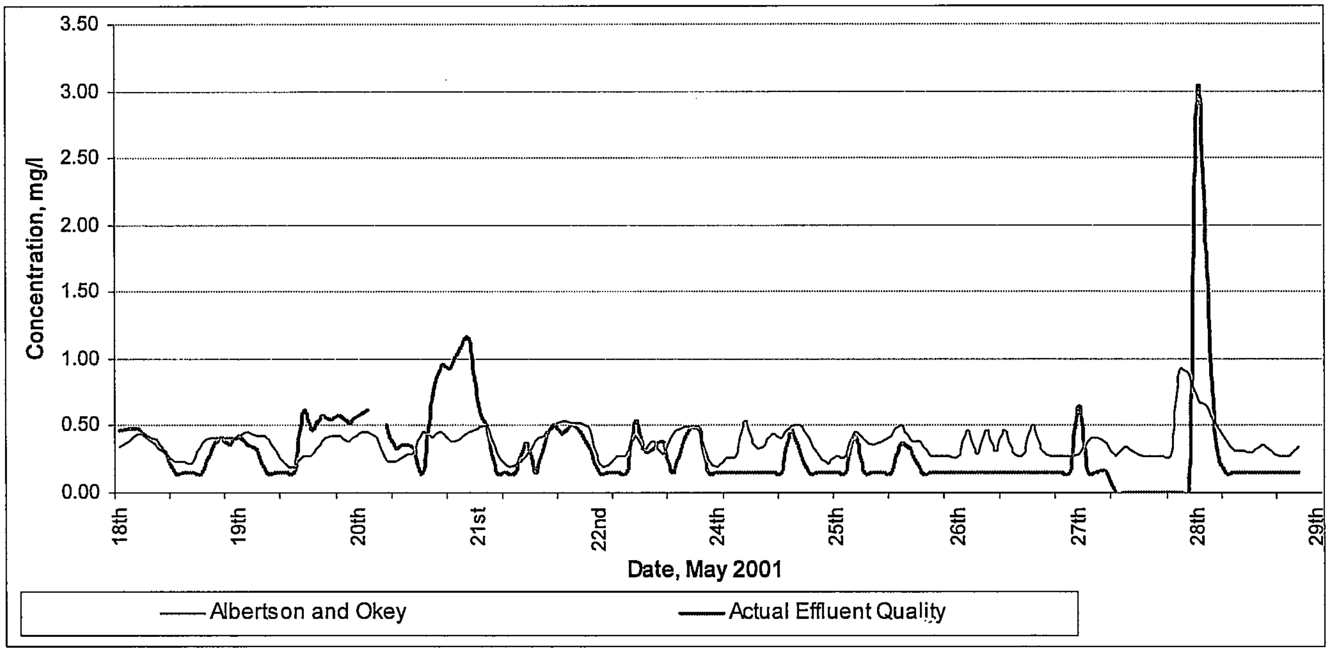


**Figure 6 - Albertson and Okey Model Vs Actual Performance at Site R, 2002**

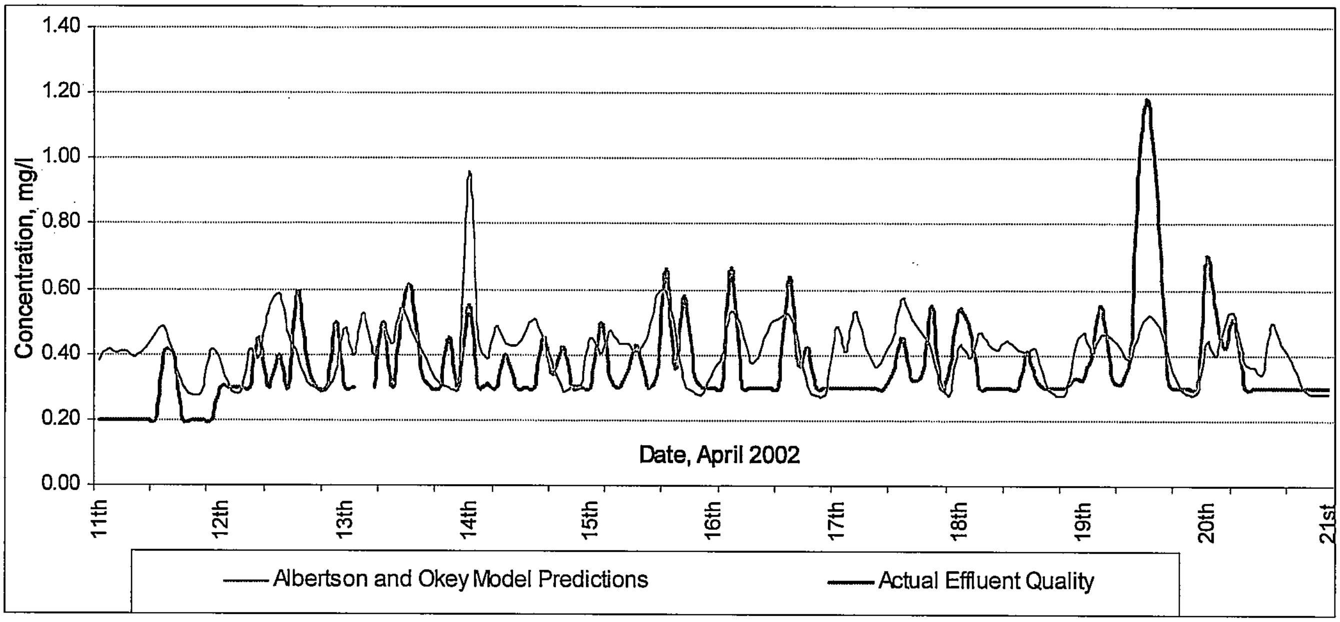
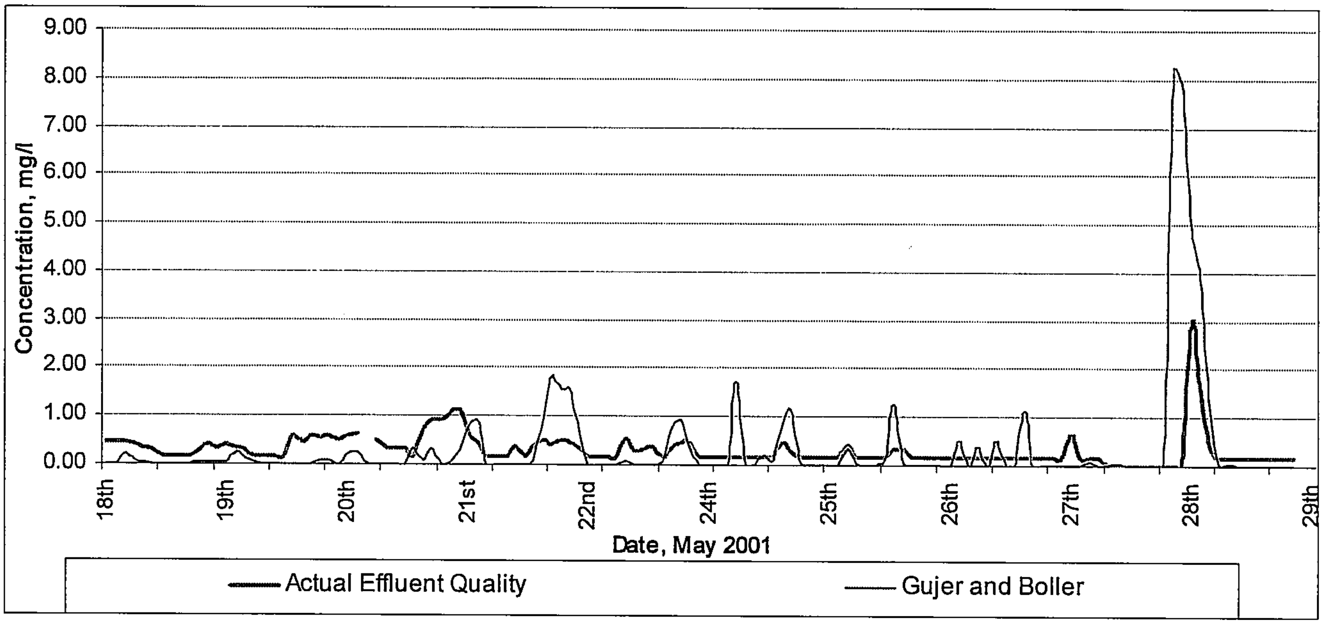
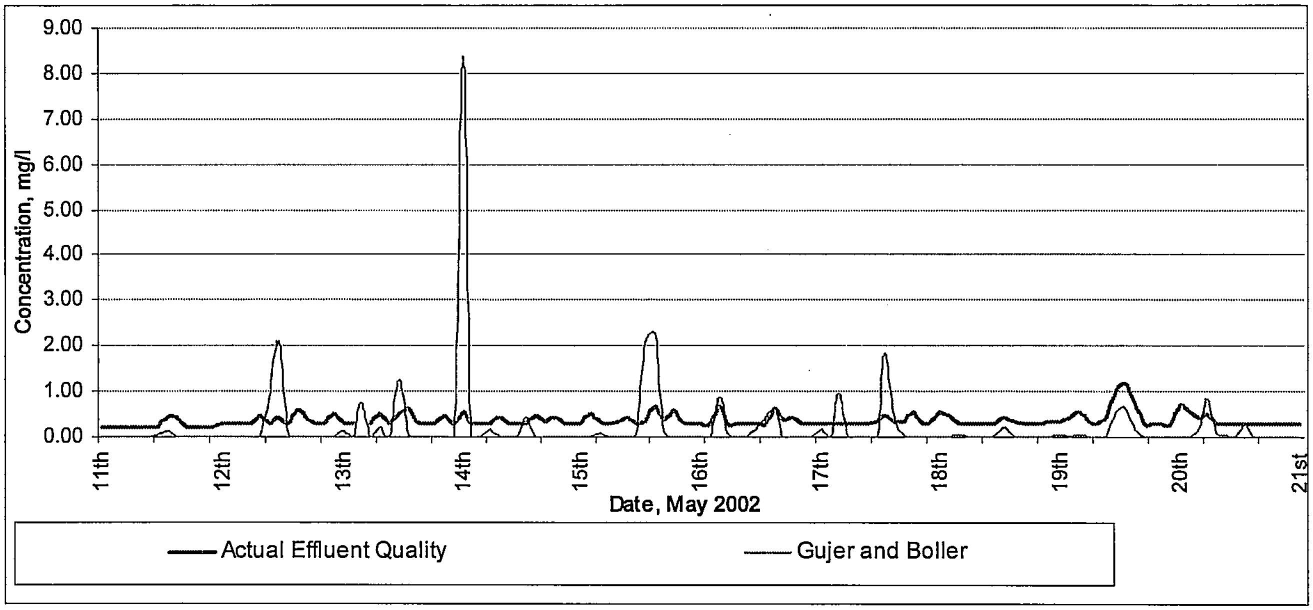


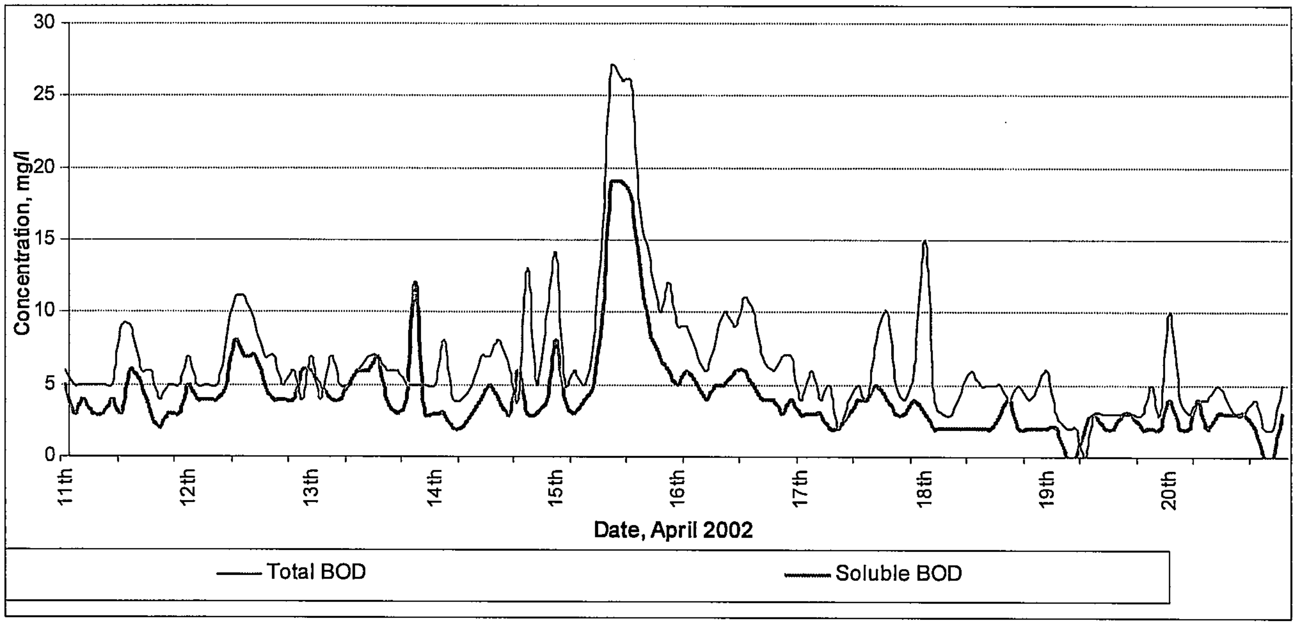
**Figure 7 - Gujer and Boller Model Vs Actual Performance at site R, 2001**



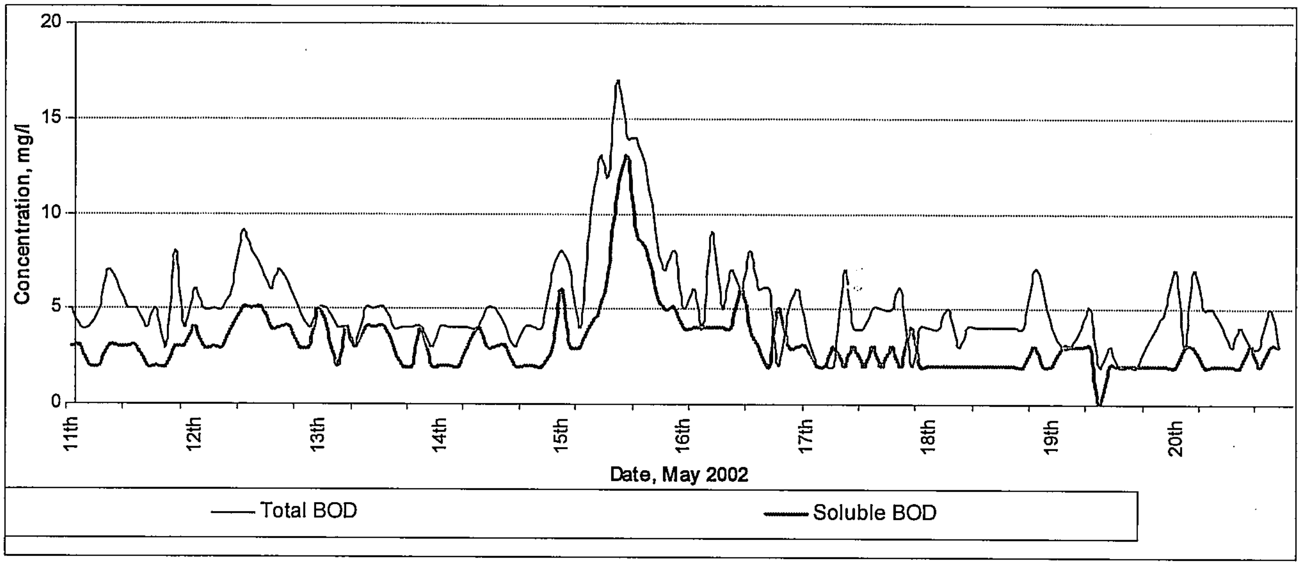
## Figure 8 - Gujer and Boller Model Vs Actual Performance at site R, 2002



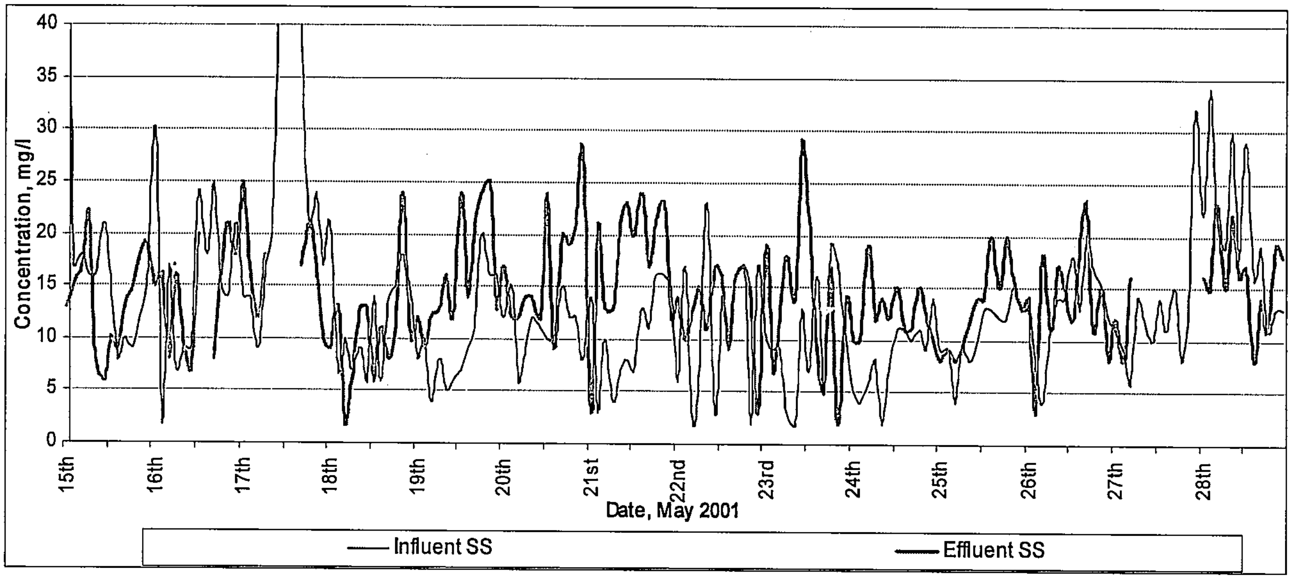
## Figure 9 - BOD and Soluble BOD in Vs Time, 2002



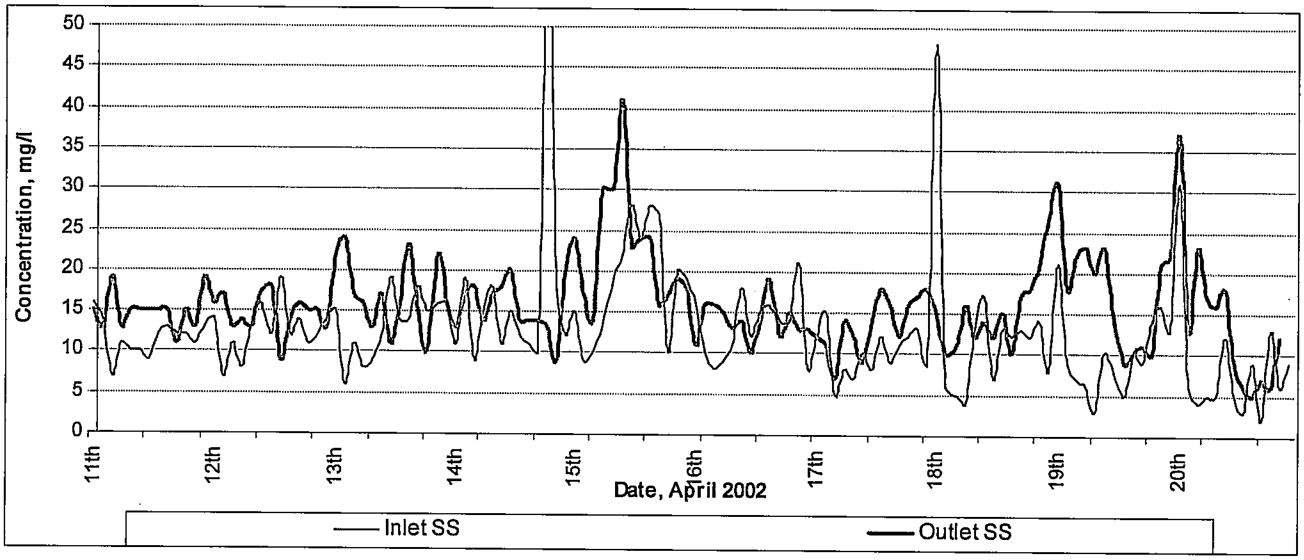
## Figure 10 - BOD and Soluble BOD out Vs Time, 2002



## Figure 11 - Solids in and out Vs time, 2001



## Figure 12 - Solids in and out Vs Time, 2002



## Figure 13 - Alkalinity Removed Vs Ammonia Removed