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AERATED CoUFs - A PILOT SCALE STUDY INTO THE IMPACTS OF CHANGING VARIABLES ON NITRIFICATION PERFORMANCE

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This paper describes the findings of a long term study of the nitrification performance of a purpose built, large-scale, pilot plant consisting of two mirrored, aerated, continuously operated upflow filters (ACoUFs) operating under realistic conditions. The effect of temperature, liquid flow rate, aeration rate and media types on the performance of each of these filters is reported. After a start-up period of 2-3 weeks each plant performed consistently and the performance, expressed as a concentration change between influent and effluent, was found to depend directly on temperature and aeration but inversely on flow rate, with little interaction between the variables. The introduction of these aerated CoUF variants can have a considerable role to play in increasing effluent quality.

INTRODUCTION

Fixed bed sand filters, either upflow or downflow, have been utilised for a number of years for suspended solids removal in both potable water and wastewater treatment. Processes in these filters are generally well understood Kiely, (1998); Metcalfe and Eddy, (2002). However, in the 1980's a subgroup of these filters, Continuously Operated Upflow Sand Filters (CoUFs), was developed which has significant differences to standard sand filters. CoUFs are operated with a slow upflow of the bed which allows them to be continuously cleaned without the need for shutting down the treatment process for a cleaning backwash cycle. As a result CoUFs are generally operated at higher flow rates than are fixed bed filters. Despite their acceptance and use, descriptions of research on the performance of CoUFs filters are lacking in the literature.

The unique design of the CoUF, as shown in Figure 1, removes the need for a separate backwash cleaning stage as the sand bed is constantly being removed from the base of the filter, cleaned by a counter-current flow and agitated labyrinth system and returned to the top of the filter bed, thus giving CoUFs an operational and performance advantage, Sanz, et al (1996) and Hultman et al (1994). The adoption of these filters has increased particularly under the third Asset Management Programme (AMP 3) in the highly regulated United Kingdom framework and these units are now deployed on a large number of wastewater treatment sites.

1. Wastewater is introduced at the bottom of the filter and spread across the available surface by a number of distribution arms.
2. The water flows up through the sand bed where solid particles are captured.
3. Most of the cleaned water (filtrate) passes over the fixed final filtrate weir.
4. A small percentage travels up through the sand washing labyrinth, where entrained solid particles are released from the sand grains as they fall down through the washer.
5. The sand bed moves down the filter and over the sand distribution cone as a result of the action of an air-lift pump.

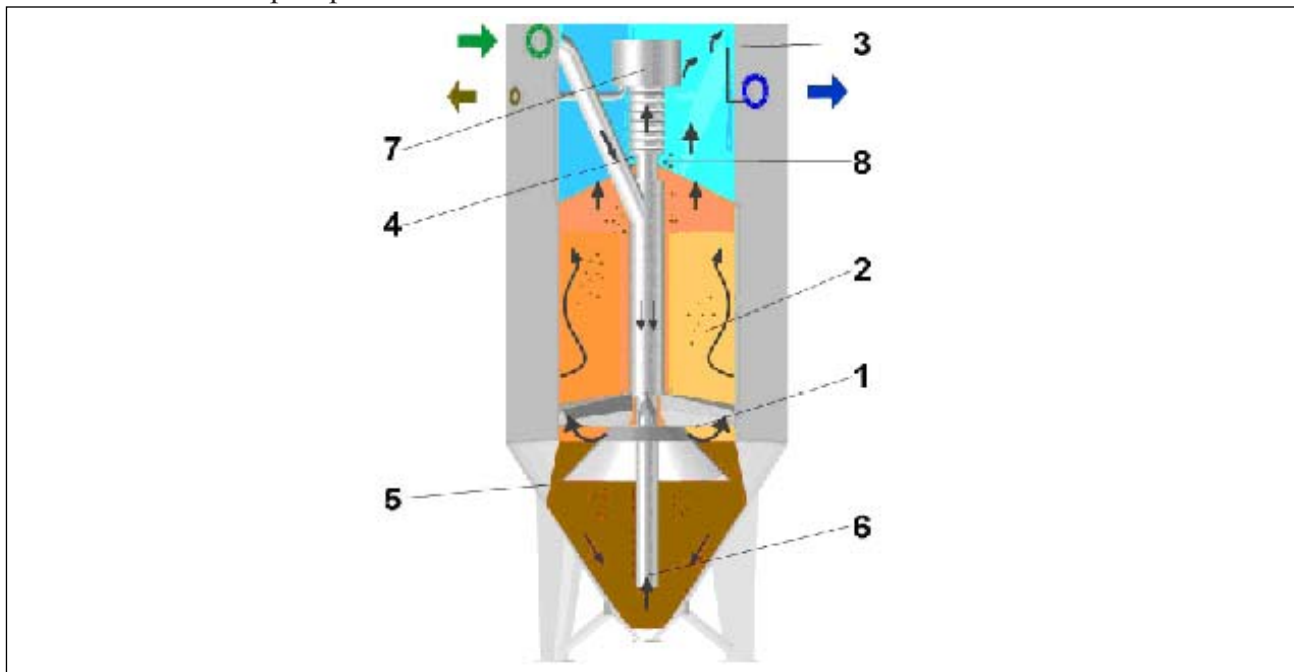


Figure 1. Schematic to illustrate the operation of a DynaSand® filter.

6. Sand, trapped solid particles and water are pulled through the air-lift pump to the washing section.

7. The sand particles, because of their greater size and density fall through the sand washer, against a counter current of process filtrate, which carries the lighter effluent particles over the wash-water weir and out of the system.

8. The clean sand is returned to the top of the bed. By adjusting the washwater weir height (and therefore its relationship with the filtrate weir), the amount of washwater generated can be increased or decreased.

There are more than 15000 filters in operation globally and though currently the great majority are only concerned with suspended solids removal, a few have an additional aeration ring which allows them to simultaneously filter and nitrify. Although limited nitrification has been shown to take place without additional aeration (Gujer, 2010) the addition of an aeration ring at the base of the filter bed has been shown to be effective at removing ammonia through a biofilm nitrifying step, even at much higher levels of loading, Barter and Smith (2007). Since unaerated variants are so widespread a programme of upgrading them to an aerated variant could offer a cost effective approach to offering ammonia removal from the final effluent at treatment works.

ACoUF variants are currently on the market both as new build plants as well as plants upgraded with aeration rings due to the need for improvements of effluent quality driven mainly by legislation such as the EU Water Framework Directive, (European Commission, 2000). The media selected for these filters has always predominantly been a standard washed rounded river gravel filter sand with a particle size of around 1-1.2mm which gives the necessary filter characteristics. This media also meets the headloss and flow characteristics of the filter as well as being the correct sizing to be cleaned by the air lift pump drawing up the dirty filter media at the base and returning to the top of the filter bed. Some work, such as reported by Horan and Lowe (2007), has examined the use of alternative media in tertiary filtration. However, their study did not examine nitrification. Although there has been much work on sand filters there has been little work carried out at full (industrial) scale, utilising genuine wastewater treatment work effluent. Some modelling work has been carried out on sand filters of this type utilising the activated sludge model, Sanz et al (1996), Henze (2000). However, even less is known about the dynamics involved in ACoUFs and how their performance might be influenced in changing parameters such as aeration, liquid flow and media type. As a result this experimental platform was developed to test different media and operational regimes at large scale on an operational wastewater treatment works.

MATERIALS AND EXPERIMENTAL METHODS

The study was undertaken on an operational wastewater treatment works with a population equivalent of approximately 100,000. The WwTw treats wastewater from the local conurbation and large industrial estate immediately adjacent to site. The treatment at the works consists of a single initial grit removal stage after which the flow at the works is split into two equivalent streams. Each stream has primary sedimentation followed by subsequent secondary biological treatment with activated sludge plants and finally clarification by settling before discharge. No fixed tertiary treatment was present on site at the time of the trial. The pilot plant was designed, installed and built as an experimental platform on which variables could be manipulated under realistic conditions without affecting the operation of the works. The experimental platform consisted of two DST07 DynaSand® filters upgraded to DynaOxy® status by the installation of an aeration ring directly

above the influent distribution arms at the base of the unit. A photograph of the pilot plant is shown in Figure 2. The installation was of comparable scale to the trials described by Anderson et al (1991) and Sanz et al (1996).

These units consisted of a 0.7m² bed loading area and a 1.7-2m bed height. Bed height varied slightly between the two different filters due to the different properties of the media itself. One filter used standard filter sand as would be supplied with any Dynasand® filter and the other was filled with DynaActiv™ filter media (a basalt based ground rock product) as shown in Figure 3. The whole experimental installation was designed to allow a comparison between the two filters.

The pilot plant was run from July 2009-February 2011 with visits carried out regularly over that period. Influent was taken directly from the discharge by the works and sent to a common header



Figure 2: The pilot plant on site showing the two filter units with the common header to equalise flow..

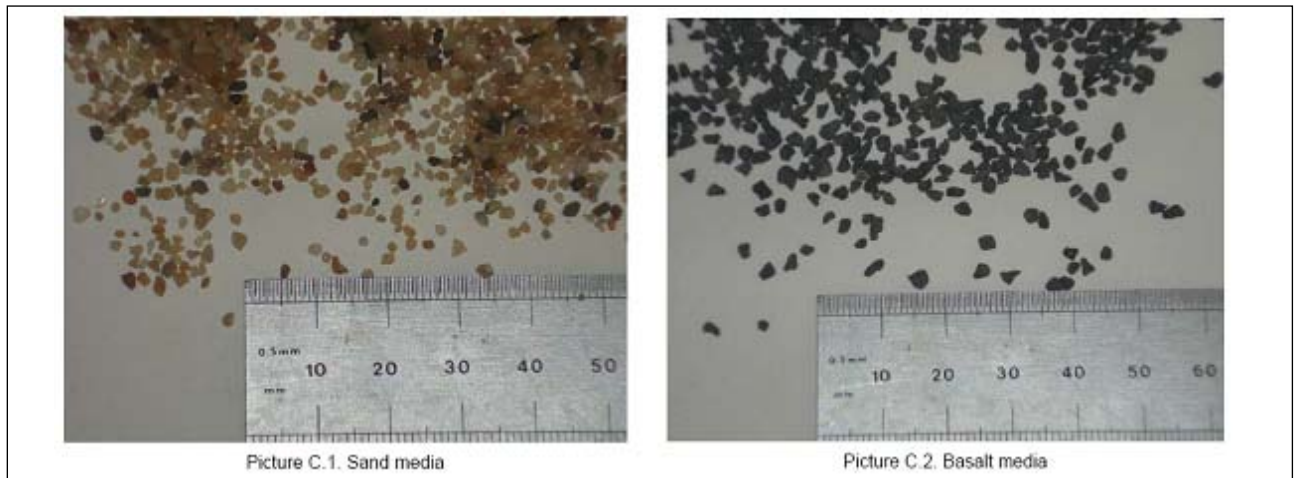


Figure 3: Bed materials.

tank to provide a balanced flow. Flow rates were measured using two Siemens MAG5000 flow meters. Air for the solids recycling and the aeration was provided from a common source, a screw compressor with a 100l reservoir operating at 10bar. Air flow was measured by in line flow meters to each filter. Measurements were taken of the ammonium ion concentration on the inlet to the plants and the outlets of the two filters using Hach Lange LCK304 reagents and DR2800 spectrophotometer to allow for speed of examining results on site. This method is also a standard method used in industry so as to also mirror how these units might be assessed in the field. In general the two units were operated as far as practicable under identical conditions with aeration and flow rate being kept the same between the two filters. On few occasions flow differences were noted due to operational conditions on site. Typically, sections of one bed could become blocked therefore requiring that filters to be put into 'clean mode'. When this occurred the flow of both were modified to try and match each other as closely as possible. Where deliberate changes were made to investigate other variables e.g. to investigate the effect of flow rate on performance the changes were made over a short period of time so that the specific activity of the biofilm could be considered as constant i.e. flow rate changes between the filters were not carried out over a period of time of more than 4 hrs. This is comparable to the methodology used by Anderson et al (1991), Plaza (1995) and Sanz et al (1996),

RESULTS

Overall Performance Comparison

The ammonium ion concentrations of the influent and effluent, recorded on individual visits over a period of eighteen months, are shown in Figure 4. Throughout the period both filter beds were consistently able to remove ammonia, though the data set shows some variation in performance due to the seasonal temperature cycle, flow rate effects and aeration differences. Over the period of the experiment the temperature of the influent varied from 6.5°C to 19.9°C. The loading rates were generally in the upper flow range of the unit, so typically from 8.5-11.5 m.hr⁻¹ and aeration was typically at 30 l.min⁻¹ air per filter. In general the performance of the two systems was effective. After the start-up period, ammonia was consistently removed by both filters as shown in Figure 4.

The performance of the two filters, in terms of each effluent from a common influent, is shown in Figure 5. Variability caused by transient changes in operating conditions of individual units away

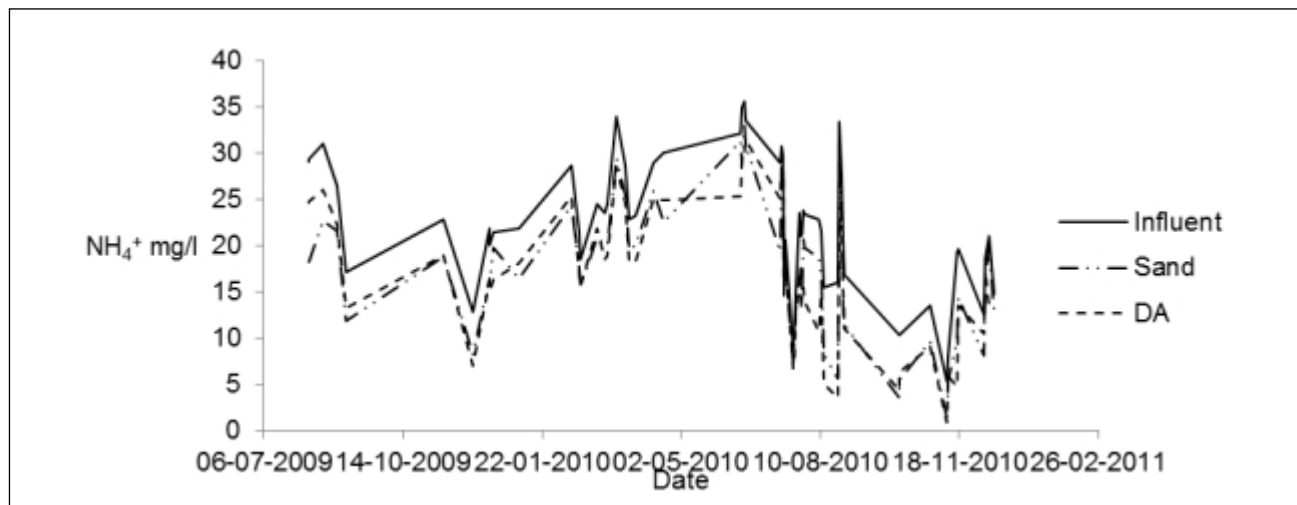


Figure 4. Overall influent and effluent NH₄⁺ values in mg/l for both filters over time.

from the standard liquid and air flows at the time of measurement is thought to be the main cause of the more significant departures from the linear correlation. The principle confounding influence was flow rate as discussed later, but aeration rate, temperature and start-up period also had an effect. It should be noted that these results were generated at the normal flow range operated at in the trial but despite careful attention it was impossible to exactly the same flow in both filters and performance would vary with flow. The regression equations showed that the removal was effectively independent of the influent concentration. For sand the slope of the regression was 1.04 with 95% confidence limits 0.922, 1.087, and for DynaActiv the slope of the regression was 0.956 with 95% confidence limits 0.849, 1.067, $p = 0.000$ in both cases. For sand the intercept was 4.28 mg.l⁻¹ with 95% confidence limits 2.40, 6.16 mg.l⁻¹. For DynaActiv the intercept was 4.26 mg.l⁻¹ with 95% confidence limits 1.78, 6.75 mg.l⁻¹. This effectively indicates that the removal was independent of the influent concentration and that both filters gave a similar performance with modelled removal of 4.3 mg.l⁻¹. This can be explained by the relatively high influent concentration, larger than found at many treatment works, so that the filters were effectively working to maximum capacity.

Interestingly however, the filter loaded with DynaActiv™ showed a small but significant improvement in average performance with a mean effluent concentration of 16.38 mg.l⁻¹ NH₄⁺, compared with the value for the sand filter 17.45 mg.l⁻¹ NH₄⁺, $p=0.0003$ (t-test for means from paired samples). Nevertheless, the performance of the two filters was similar which can be ascribed to saturation from the high ammonia content of the influent.

When flow rate is taken into account ammonia removal can be expressed in terms of kg.day⁻¹ as shown in Figure 6. Presented this way a difference in performance emerges. The DynaActiv filter generally achieved a higher removal rate than the sand filter as shown in Figure 6.

If these results from the two units are compared as in Figure 7 then they suggest the removal rate for DynaActiv filter media in this trial was approximately 30% higher than for sand, though

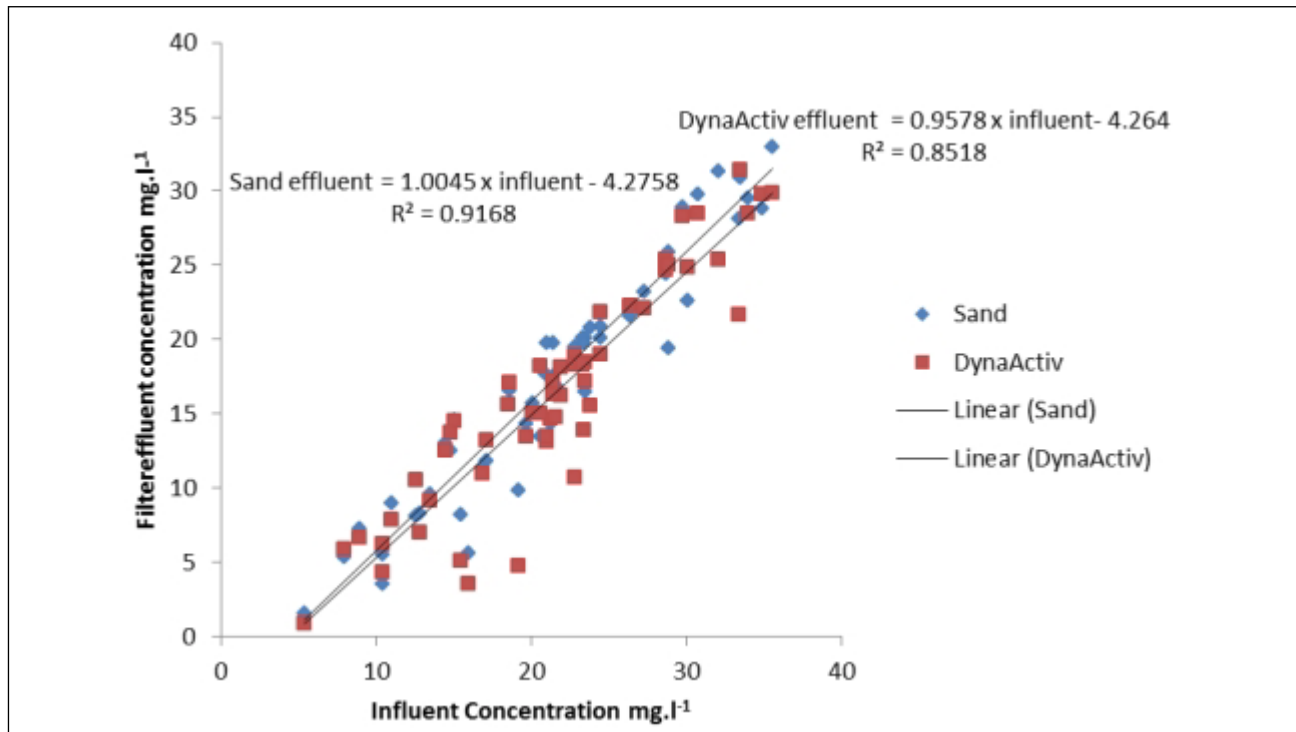


Figure 5. Influent NH₄⁺ against effluent NH₄⁺ for both filters.

the correlation is rather weak. However, the differences in mean values from all data taken over the period of the trial are significantly different from one another (paired t-test, p two-tail = 0.0001.)

The relationship between concentration change and rate of removal is simply.

Equation 1: Removal rate (kg.day⁻¹) = concentration change kg.m⁻³ x flow rate (m³.day⁻¹)

Thus if the flow rates differs between plants the performance will reflect the difference. It appears that despite efforts to ensure that the flow rates were the same for each plant they did in fact differ. Since the flow was generated from a common header tank it follows that the difference in flow should be reflected by a difference in headloss between the two systems. Measurements of pressure drop across the fully developed bed support this.

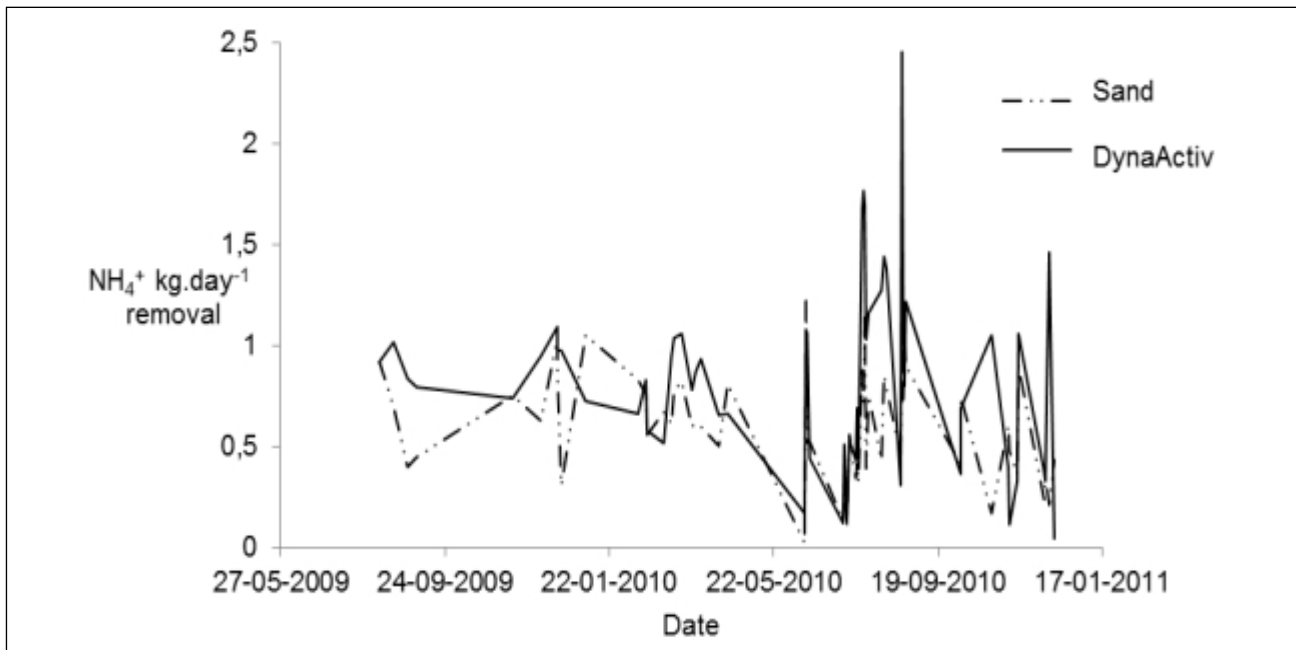


Figure 6. Removal in kg/day NH₄⁺ (where flow is taken into account) over time.

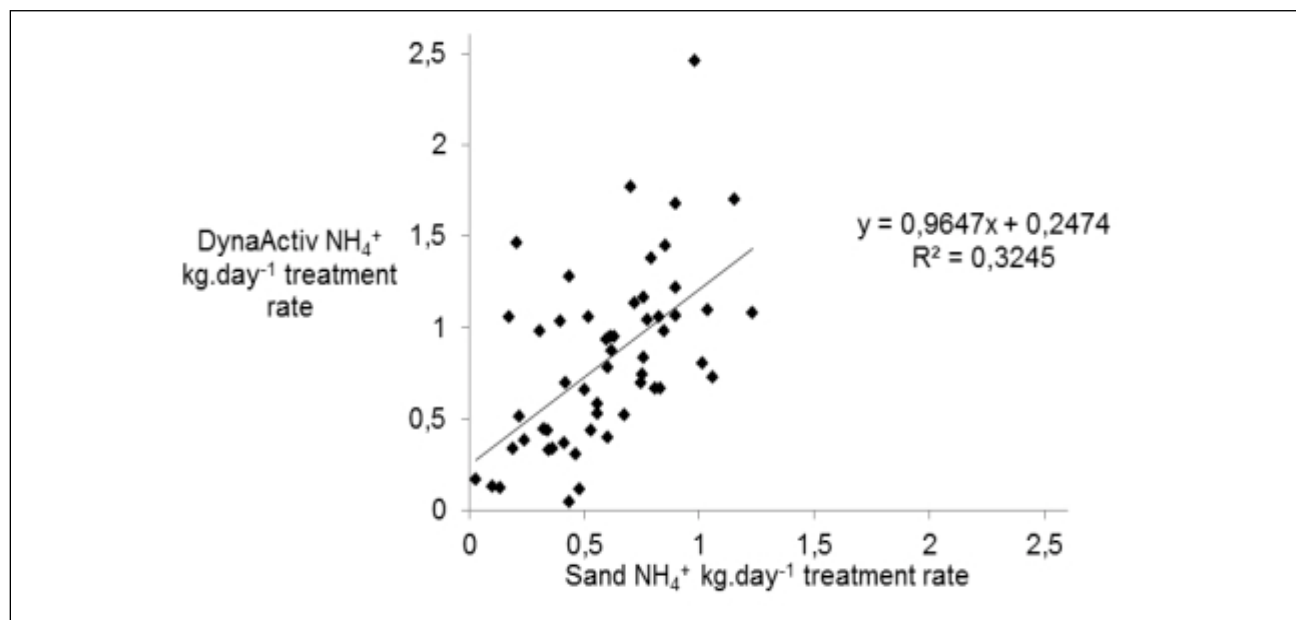


Figure . Sand kg/day NH₄⁺ removal against DynaActiv kg/day NH₄⁺.

The Effect of Liquid Flow Rate on Performance

In addition to the comparison of the media, an investigation was also made into the effect of flow rate on the performance of the filters. In the example shown in Figure 8 the aeration was kept constant at 30 l.min⁻¹ and the influent concentration ranged from 29.7 mg/l NH₄⁺ – 30.8 mg/l NH₄⁺, which was considered to be constant. The liquid flow rates were varied with the filter allowed to equilibrate between changes for 3 residence times calculated for that flow rate. The results indicate that increasing flow leads to an increase in NH₄⁺ concentration in the effluent. This can be simply related to the reduced contact time at higher flow rates. Conversely the performance expressed as kg.day⁻¹ NH₄⁺ removal increases with flow rate up to the maximum used here. Thus final ammonium ion concentration and required plant size must be optimised based on expected flows.

Experiments were then undertaken where the liquid:air ratio was kept constant, i.e. the air rate introduced into the filter was varied with liquid flow rate to maintain the same ratio, using the liquid flow rate as the controlling determinant and the removal efficiencies at the different liquid flow rates was identified. These results are shown below in Figure 9 and clearly show a reduction of improving performance at higher flow rates where beyond a certain flow rate the removal might be constant or drop-off again.

The entire dataset has been examined in detail and the effect of flow (with a variable liquid/air ratio) is shown as a response surface in Figure 10. The results confirm the importance of flow as an operating parameter and are in line with the experimental results for instantaneous flow rate change shown in Figure 9. i.e. lower final effluent concentrations in terms of NH₄⁺ mg/l occur at lower flow rates. The plot in Figure 10 would potentially allow an operator to calculate a likely effluent value at a given flow rate.

The Effect of Air Flow Rate on Performance

In addition to quantifying the role of liquid flow rate the role of aeration, at constant liquid flow rate ~11 m³.hr⁻¹, was examined (Figure 11).

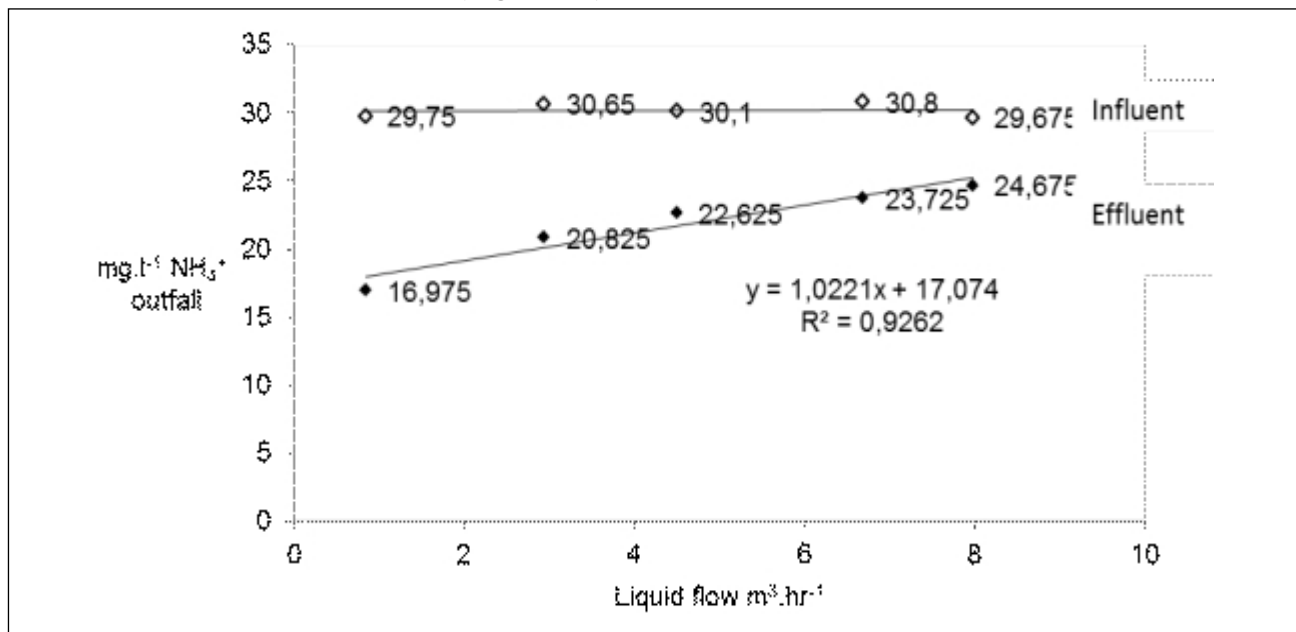


Figure 8. Influent NH₄⁺ values against effluent NH₄⁺ values when the flow rate is changed to that indicated.

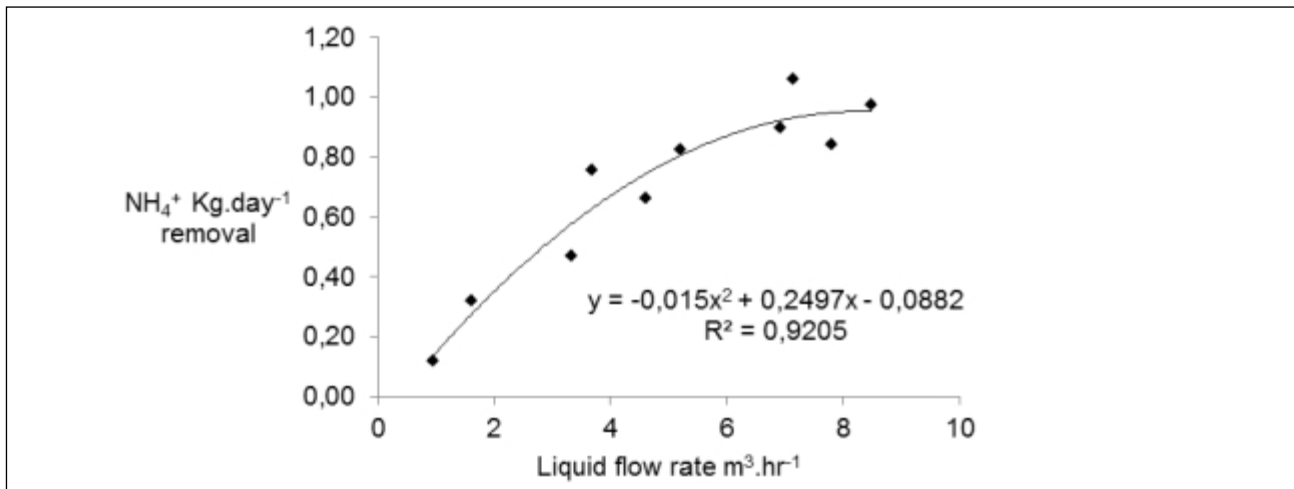


Figure 9. Flow rate vs NH₄⁺ kg/day removal.

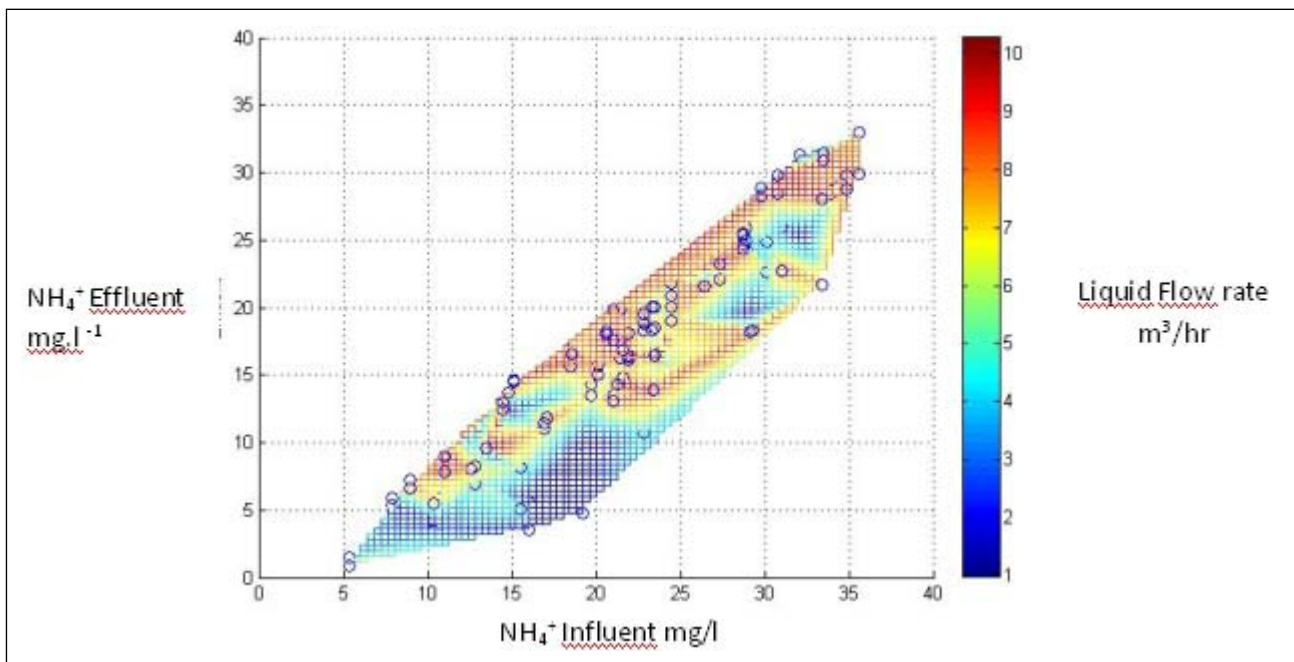


Figure 10. MATLAB surface profile interpretation for the DynaActiv dataset with influent, effluent and flow rate on the X,Y and Z axis respectively but focussed solely on the X-Y.

Figure 11 shows how removal in the sand filter, expressed as NH₄⁺ kg/day varied at different aeration rates. There is some indication that ammonium ion removal is possible even when aeration is low which has been observed in other studies also (Nakhla and Farooq, 2003), though of course it is not clear if this would continue to be the case if aeration was shut down for a long period of time as the biofilm was developed in an aerated setting (Characklis and Marshall, 1990; Gerardi, 2002).

The recovery of the units after a 6 week shutdown due to operational problems was also monitored. Full recovery of the DynaActiv filter was around 2 weeks for it to return to high level treatment of around 1.5 – 2.0 NH₄⁺ kg/day removal after this shutdown, although reasonable performance was noted after about a week suggesting the recovery of the nitrifying biofilm. It should be noted that the filters had been operating during a summer temperature period before the enforced shutdown and restart took place. This trace has obvious implications as regards initial start-up times. The recovery when plotted showed performance picking up after re-start then plateauing out as the maximum treatment rate was reached after approximately 30 days.

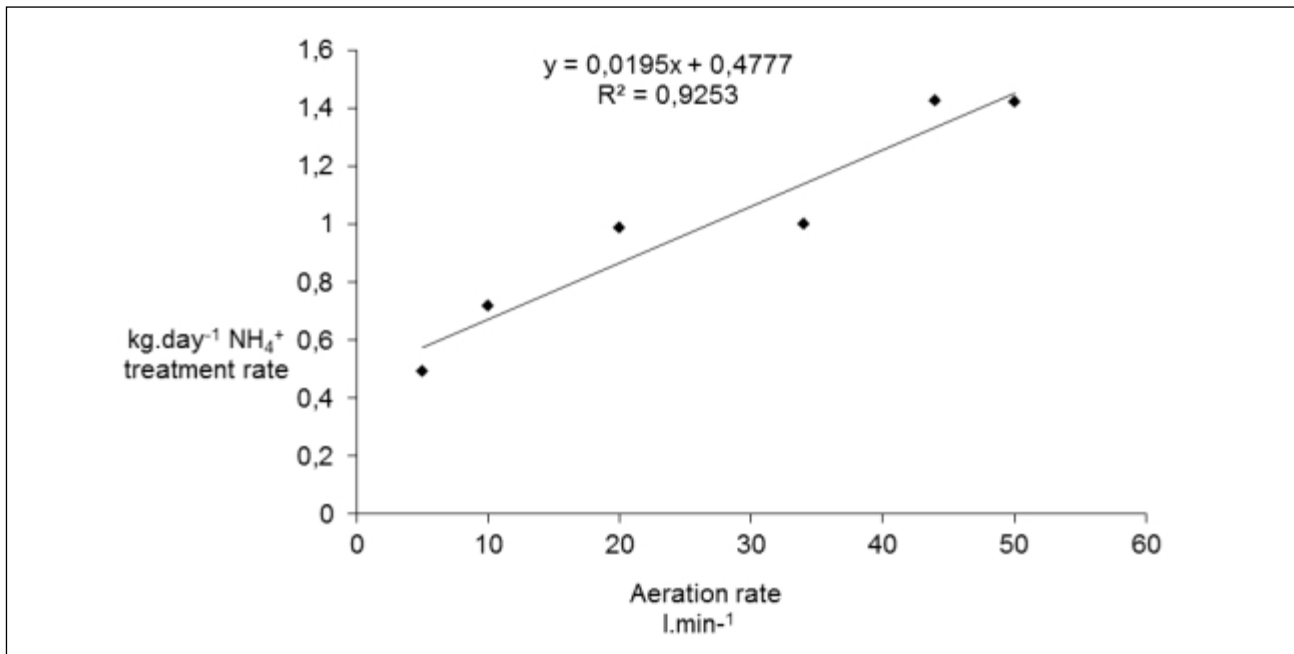


Figure 11. Variable aeration rate effects on NH₄⁺ kg.day⁻¹ removal when flow rate is constant within the sand filter.

The Effect of Temperature

Unlike the other variables examined it was not possible to control the temperature of the influent, which in turn modified the operating temperature of the plant. A result temperature-rate data was necessarily collected over a much longer period and so there was much more scatter in the results. Consequently the data is presented as a response surface which broadly indicates that the rate of removal increases with temperature.

CONCLUSIONS

This response surface (Figure 12) clearly shows higher treatment rate at higher influent temperatures and higher flow rates as would be expected from the nitrification reaction and agrees with many of the other studies into sand filtration (Sanz et al., 1996; Vigne et al., 2010; Vigne et al., 2011).

Results obtained to date showed that the removal of the ammonium ion, expressed as the change in concentration between influent and effluent varied only slightly over the range of influent concentration measured and was quite similar for the two filter media tested here. However, when expressed as a rate of removal NH₄⁺ kg/day the DynaActiv media outperformed the sand filter media in this trial showing that media selection can influence the nitrification rate. This could be due to media characteristics such as harbouring the biofilms from sloughing or providing a more beneficial micro hydraulic conditions for the air/water/biofilm interface (Kluelleberg and Givskov, 2007).

The effect of flow (both air and liquid) has been quantified and the change in performance with change in flow rates was shown to be predictable. The findings of effects of the aeration and flow rate changes were broadly in line with the findings of (Vigne et al., 2011) who found that flow rate had a greater impact on performance than aeration. Temperature was identified as one of the most important variables.

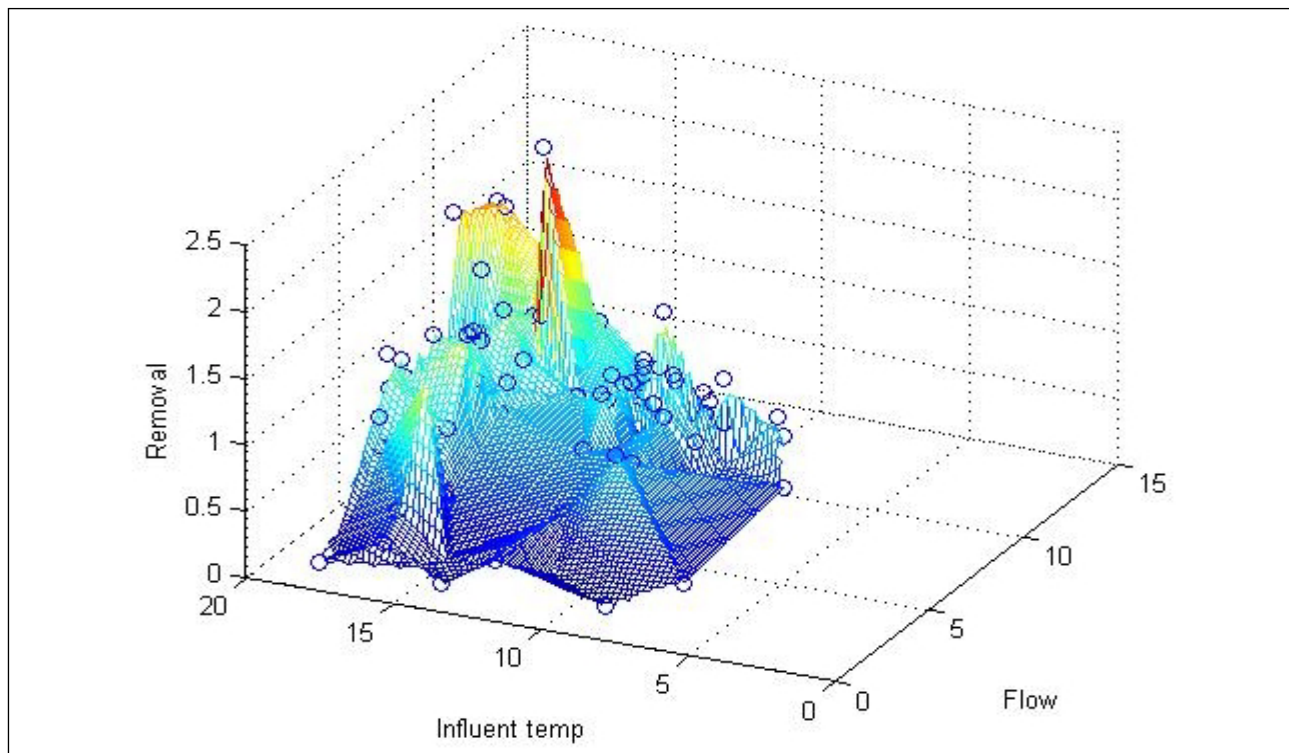


Figure 12. Surface interpretation analysis with the DynaActiv dataset with flow, temperature and removal in the X,Y, and Z axis respectively.

Some unexplained fluctuations in filter performance were noticed, this was thought to be due to the difficulty in consistently maintaining the cleaning rates and aeration rates at the same level. This can be partially attributed to the size of the units which are considerably smaller in terms of bed area than full scale plant (0.7 m² as opposed to 5 m²).

Work carried out on the filter suggests that re-colonization and startup time in this system during a summer period was ~ 2 weeks, with peak efficiency occurring after ~30 days which is acceptable. Removals of ammonium ion were observed to be occurring within a shorter time period

It should also be noted that the performance differences described took place on a works with a particular influent in terms of relatively high levels of ammonia in the final effluent of the wastewater treatment works for operational reasons. It may be that performance differences of the size and range noted in this study may not be as pronounced on other works where influent concentrations and characteristics may affect the biofilm type and growth.

Future work will attempt to model the process for use in a predictive performance and control system at works other than where the trial was located.

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