Pergamon

0273-1223(94)00287-8

Wat. Sci. Tech. Vol. 29, No. 10–11, pp. 127–134, 1994.

0273–1223/94 $7·00 + 0·00

COMBINED NITROGEN AND PHOSPHORUS REMOVAL IN A FULL-SCALE CONTINUOUS UP-FLOW SAND FILTER

B. Hultman*, K. Jönsson** and E. Plaza*

** Department of Water Resources Engineering, Royal Institute of Technology, S-100 44 Stockholm, Sweden*
*** Nordic Water Products AB, Box 1004, S-149 25 Nynäshamn, Sweden*

ABSTRACT

An attractive method for post–denitrification may be the use of sand filters. In this paper, a description and evaluation are given of full scale studies of the use of a continuous sand filter for the combined removal of suspended solids, phosphorus and nitrogen. Experiments were performed using methanol as a carbon source for denitrification and ferric chloride for an improved phosphorus removal. The studied continuous sand filter was a DynaSand filter marketed by Nordic Water Products AB. The filter has a surface area of 4.7 m^2 and a maximum possible bed height of 6 m. The bed consisted of sand with 1.2–2 mm grain size. The tested bed heights were 3.5–4.8 m, and the hydraulic load varied between 5.4 and 24.5 m/h. The effluent from the Loudden treatment plant in Stockholm was supplied to the filter. Influent nitrate concentrations up to 20 mg N/l were tested and they decreased to 0.5–2 mg N/l. The methanol dosage was controlled by the measurement of nitrate continuously in the effluent by a dr Lange meter.

The denitrification rate followed a half order reaction down to low values of nitrate. Results showed that an effluent concentration of 0.15 mg P/l could easily be obtained. It was found that the influence of phosphate concentration is small on the denitrification rate if the phosphate concentration is above 0.1 mg P/l. The reject has a low sludge index which is favourable if the reject is returned to a sedimentation basin. The emission of nitrous gas (N_2O) is very low. The installation makes it possible to use space efficiently, since polishing, phosphorus removal and denitrification can take place in the same unit. Already the phosphorus removal process reduces the need for process volume by 80 % compared to a conventional process with flocculation and sedimentation basins.

KEYWORDS

Biological filter, contact filtration, denitrification, methanol, nutrient removal, sand filtration, wastewater.

INTRODUCTION

For many years filter technology has been used in water and wastewater treatment for the removal of suspended solids, reduction of the phosphorus content and for other biological reactions. This paper evaluates the conditions for combined suspended solids, phosphorus and nitrogen removal in one filter unit.

Many Swedish wastewater treatment plants have to be upgraded to meet more stringent requirements both for nitrogen and phosphorus removal in the future. Although pre-denitrification is the most widespread method, in some cases it can be economically advantageous to use post-denitrification with sand filter as the last step in wastewater treatment systems.

DynaSand filters have proven to be effective not only for removal of suspended solids but also for reduction of the phosphorus content. It is possible to reduce effluent total phosphorus concentrations to 0.1–0.2 mg/l. Earlier pilot plant investigations made in the USA (Koopman et al., 1990) and in Sweden (Andersson et al., 1991) showed that DynaSand could be used for wastewater denitrification. Full-scale experiments with a continuous up-flow sand filter, DynaSand-filter, have been carried out at the Loudden sewage treatment plant in Stockholm for more than two years.

Stoichiometry and reaction kinetics

The performance of sand filters for denitrification can be predicted based on stoichiometric and kinetic models. Hultman and co-workers (1992) compiled stoichiometric reactions in denitrification with methanol as a carbon source in sand filters. It was found suitable to express the electron acceptors oxygen, nitrate, and nitrite in oxygen units, as earlier done by McCarty and co-workers (1969), as the sum C_T by use of the expression:

$$C_T = \text{dissolved oxygen, mg/l} + 2.86(\text{nitrate-nitrogen, mg/l}) + 1.71(\text{nitrite-nitrogen, mg/l}) \quad (1)$$

Much information is available concerning the kinetics of denitrification in fixed film reactors. Early studies were made by Harremoës (1976, 1978). Under certain conditions the denitrification rate r_c may be expressed as a half order reaction with respect to the nitrate concentration c, i.e.:

$$r_c = dc/dt = - k_{1/2}\sqrt{c} \quad (2)$$

This rate equation may be integrated to:

$$\sqrt{c} - \sqrt{c_o} = - 1/2\ k_{1/2}\Theta \quad (3)$$

in which c_o = influent nitrate-nitrogen concentration
Θ = retention time in the filter
$k_{1/2}$ = half order reaction coefficient

In measurement of the nitrate concentration at different heights in the filter it may be convenient to write equation 3 as:

$$\sqrt{c} - \sqrt{c_o} = - 1/2\ k_{1/2}\ h/q_A \quad (4)$$

in which h = bed height
q_A = surface load

Instead of the nitrate concentration c, the sum C_T might be used:

$$\sqrt{C_T} - \sqrt{C_{T,o}} = - 1/2\ k\ h/q_A \quad (5)$$

or $$\sqrt{C_T/C_{T,o}} = 1 - a\ h/\sqrt{C_{T,o}} \quad (6)$$

in which k = parameter depending on operational conditions
a = $k/2q_A$
$C_{T,o}$= influent value of C_T

In experiments with sand filters at stationary conditions a straight line would be expected between $\sqrt{C_T/C_{T,o}}$ and $h/\sqrt{C_{T,o}}$ if the removal of C_T follows a half order reaction. The value of the parameter a can then be expressed as a function of factors influencing filter performance.

MATERIALS AND METHODS

Description of DynaSand filter

DynaSand filter is a continuously working sand filter in which the filtration process is carried out by use of up–flow through a bed of sand. A view of the filter is shown in Fig. 1. Water is introduced into the filter through the feed tube with the distributor. Filtrate exits via an overflow weir at the top of the unit. The sand bed is drawn slowly downward into the suction of an air lift pump, that extends from the bottom of the filter to its top. Because of the turbulent environment already in the air lift pump,particulate matter is removed from the sand grains. A sand washer is located at the top of the air lift . The sand falls through the washer where the waste particles are removed by a counter–current flow of a small fraction of the filtrate. The reject weir is set slightly below that of the effluent weir and this causes a steady stream of filtrate to flow upward through the sand washer. The cleaned sand is returned to the top of the bed. The reject water with the waste particles is discharged from the filter over the separate weir.

A DynaSand filter with a cross–sectional area of 4.7 m^2 and a maximum bed height of 6 m was utilized for full–scale experiments. For the most part, 3.5 m or 4.6 m bed heights were used. The bed consists of sand 1.2–2 mm in grain size.

System layout

Biologically treated and settled effluent from the Loudden wastewater treatment plant (sometimes mixed with primary settled wastewater) was introduced into the filter, where denitrification, phosphorus precipitation and filtration took place. The Loudden treatment plant is operated with ferrous sulphate as the precipitation agent and with the activated sludge process for biological treatment. The effluent was completely nitrified except for the winter period in which only partial nitrification was obtained. The system layout for the experiments at the Loudden wastewater treatment plant is presented in Fig. 2. Methanol was added as a carbon source to wastewater before the filter. A control loop for the addition of methanol was installed. As the filter received the effluent from the secondary settling tank, the concentrations of phosphorus were low, 0.2 mg/l and 0.5 mg/l for soluble phosphorus and total phosphorus respectively. To simulate the conditions at other sewage treatment plants with higher values for effluent phosphorus concentrations, phosphoric acid was added to the filter influent. Ferric chloride was used to precipitate the phosphorus. The addition of H_3PO_4 has raised the phosphorus content to values between 0.8 and 1.5 mg/l. Precipitation with $FeCl_3$ gave values of about 3 – 4 g Fe/g soluble P which corresponds to the value of 2.5 g Fe/m^3 of water. Precipitation and flocculation take place in the bottom part of the filter and afterwards the formed flocs are removed during the upward flow of the water through the bed. In the first experiments primary settled wastewater, mixed with secondary settled wastewater, was used as filter influent. In these cases the influent contained higher concentrations of suspended solids and total phosphorus and more $FeCl_3$ had to be added.

Analytical procedures

Samples were taken in the influent, effluent, and at five levels in the filter (0.8, 1.3, 1.8, 2.8, 3.8 m) and analysed for several parameters including ammonium, nitrate, nitrite, total nitrogen, phosphorus (unfiltrated and filtrated), pH, oxygen, COD (unfiltrated and filtrated), iron, alkalinity, suspended solids and volatile suspended solids. By this sampling technique it was possible to follow the removal efficiency and rate at different parts in the filter. Oxygen, pH, flow, pressure, turnover time of the sand, sludge volume index for reject water and doses of chemicals were measured directly at the time of sampling. All parameters were analysed according to the Swedish Standards. Nitrogen fractions were analysed by Aquatec analyser.

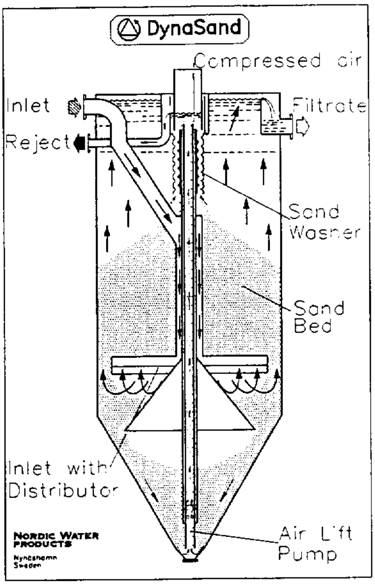

Fig. 1. DynaSand filter

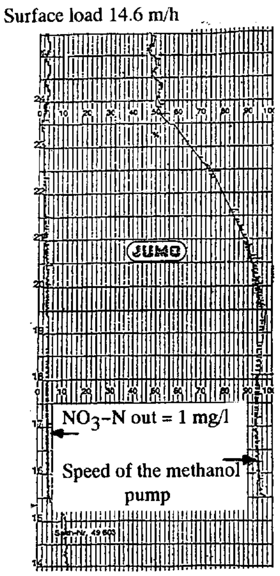

Fig. 3. Chart for the methanol addition

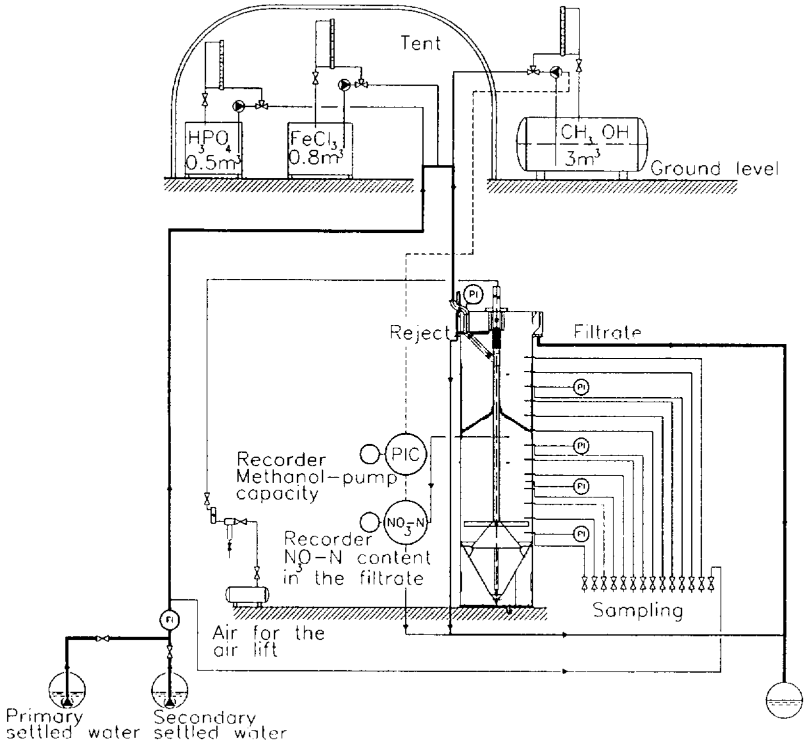

Fig. 2 Full scale experiment with DynaSand filter

Control loop for the addition of methanol

Since filters are used as the last step in a wastewater treatment process, the possibility to control the addition of external carbon source is very important. If too much carbon source is added it will result in an increased concentration of organic matter in the effluent. If too little is added the denitrification process is limited. The system installed at Loudden was equipped with a control loop for methanol addition. Since the detention time in a DynaSand filter is only about 15 minutes and the changes of influent nitrate concentration in wastewater introduced into the filter are much longer, such a control loop operated well. The methanol dosage was controlled by the continuous measurement of nitrate in the effluent by a dr Lange meter. Set–points for the effluent were varied between 1 and 3 mg NO_3–N/l. A sample from the upper part of the filter is injected to a dr Lange meter for the nitrate content measurement. The signal from the measuring device is sent to a controller on which a set point can be selected. The difference between this signal and the set point is converted into a signal to the metering pump. The signals are recorded (Fig. 3.). The signal from the controller is proportional to the speed of the pump for methanol dosage. If the nitrate concentration in the wastewater decreases, less methanol is dosed. The figure shows that the speed of the methanol pump decreases due to a lower influent nitrate concentration and that the effluent nitrate concentration is kept constant at about 1 mg N/l.

RESULTS AND DISCUSSION

Operational performance

Many factors were shown to influence the performance of the filter, such as the influent concentration of nitrate, oxygen, and phosphorus, pH, temperature, hydraulic loading and the dosage of methanol. No operational disturbances were obtained due to the formation of bubbles of nitrogen gas.

Experiments were performed to demonstrate the possibilities for the filter to simultaneously remove nitrate and phosphorus. Typical results are shown in Fig. 4. and 5. The nitrate concentration is decreased from 7.3–20 mg N/l down to 0.5–2.2 mg N/l at the same time as the total phosphorus concentration is decreased from 0.6–5 mg P/l down to 0.1–0.5 mg P/l. In Sweden the effluent requirements are normally 0.5 mg P/l for total phosphorus. For large treatment plants or in sensitive areas 0.3 mg/l may be prescribed. These stringent requirements can be achieved as seen in Fig. 6. based on experimental results from 28 January to 14 April 1993.

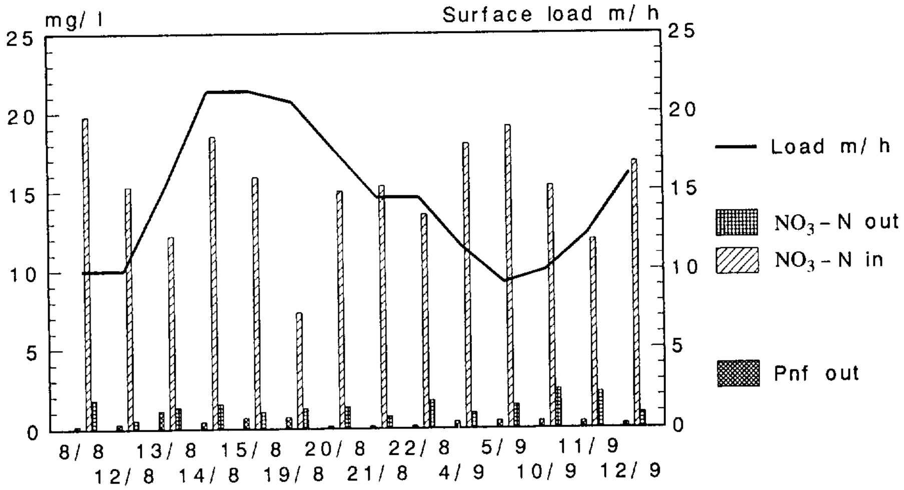

Fig. 4. Denitrification and phosphorus reduction. 8/8–12/9 1991.

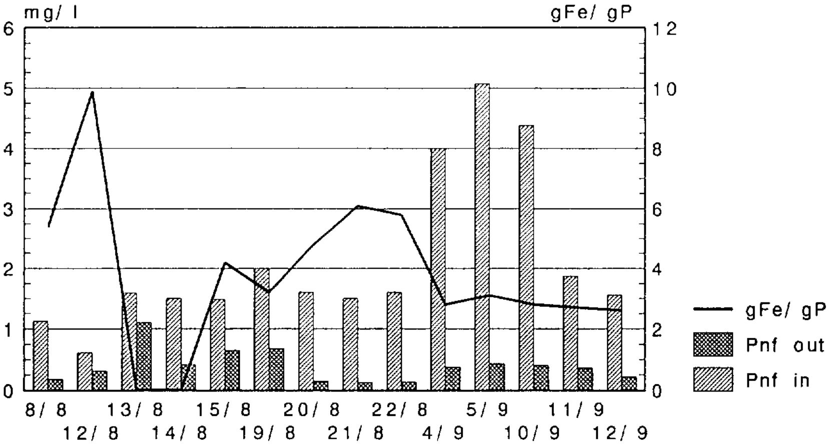

Fig. 5. Total phosphorus reduction, 8/8–12/9 1991

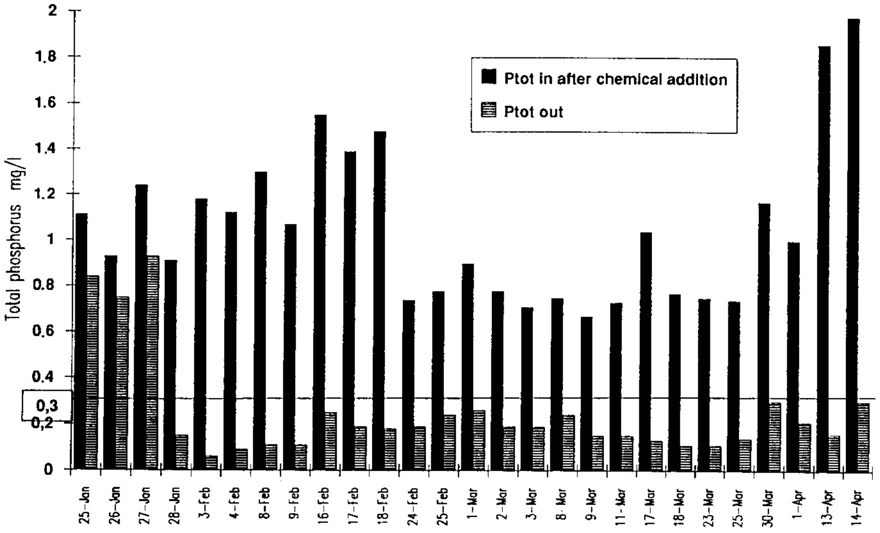

Fig. 6. Influent and effluent phosphorus values, 25/1 – 14/4 1993.

The sludge that was formed in the filter normally had a sludge index of about 50–60 ml/g and had, thus, good sedimentation properties. The emission of nitrous gas (N_2O) was very low based on a recently performed study in Sweden on the emission of nitrous gas from full-scale treatment plants (Björlenius, 1993).

Stoichiometry

Stoichiometric relationships were studied for data obtained in September 1991 when several studies were made on the performance of the filter at different levels. The following relationships were found with a correlation coefficient of 0.97:

$$\text{Removed COD concentration (mg/l)} = 1.32C_T + 0.75$$

$$\text{Alkalinity increase (mg } HCO_3\text{/l)} = 4.18\text{(removed nitrate and nitrite nitrogen, mg/l)} + 1.7$$

These results are in agreement with literature data and were mainly used to verify that experimental, sampling and analytical procedures were well controlled.

Reaction kinetics

The use of formula 6 in evaluation of filter performance was tested in experiments with measurements of the profile of oxygen, nitrate, and nitrite. In most cases a good agreement was obtained. Typical results are shown in Fig. 7. However, several examples were also obtained where the relationship deviated from a half order reaction. This was probably due to rate limitations by methanol.

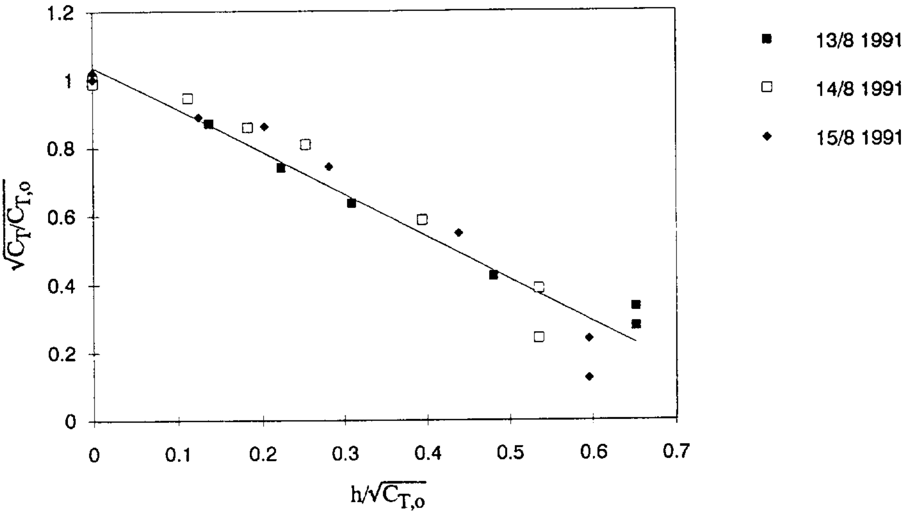

Fig. 7. Evaluation of the filter by use of formula 6.

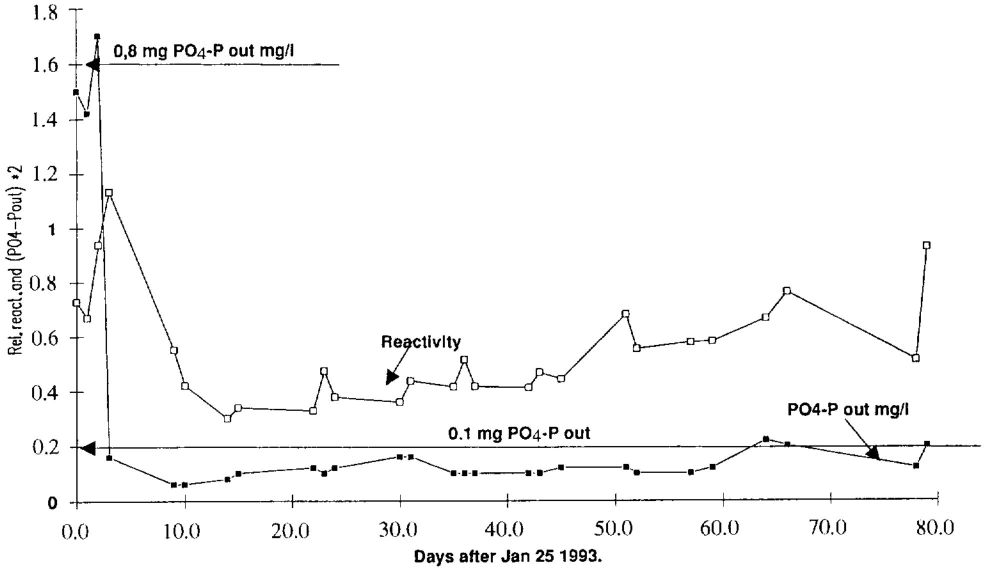

Fig. 8. Relative reactivity versus soluble phosphorus concentration in the effluent, 25/1 – 14/4 1993.

Several parameters influence the denitrification rate in the filter. To compare treatment results it is desirable to normalize reaction rates to certain reference conditions. It will then be possible to study the influence of the phosphorus concentration on the denitrification rate. The problem has been studied in the following manner. Before January 25 1993 the filter was flooded with phosphorus and a relative reactivity for that period was on average 1 (Fig. 8.). On January 28, ferric chloride was added and the effluent phosphate value decreased to 0.03 mg P/l. The relative reactivity started to decrease but it did not reach its bottom value until 11 days later. From day 15 the operational conditions were changed to increase the effluent phosphate concentration. The relative reactivity increased as the phosphate concentration increased. When the effluent phosphate value reached 0.1 mg P/l the relative reactivity had been restored to about 1. The results indicate that there is no need for a higher effluent phosphate concentration than 0.1 mg P/l. As full denitrification reactivity can be obtained at a phosphate concentration of only 0.1 mg P/l, it will be possible to denitrify and fulfil the Swedish requirements for phosphorus at the same time.

CONCLUSIONS

The overall conclusion reached during this study is that the continuous sand filter could be used for simultaneous removal of suspended solids, phosphorus and nitrate. Addition of methanol for denitrification could be controlled by measurements of nitrate in the effluent from the filter. No operational disturbances resulted from the formation of bubbles of nitrogen gas. The removal rate of nitrate could normally be described by a half order reaction. Phosphorus may limit the denitrification rate for concentrations below about 0.1 mg/l soluble phosphorus in the effluent from the filter.

ACKNOWLEDGEMENT

This research was funded by Nordic Water Products AB as a cooperative project between Nordic Water AB, Stockholm Water Ltd and the Department of Water Resources Engineering, Royal Institute of Technology.

REFERENCES

Andersson, B., Aspegren, H., Berg, L. and Gustelius, A. (1991). Efterdenitrifikation i sandfilter. Vatten, 47, 1, pp. 14–23.

Björlenius, B. (1993). Lustgasutsläpp från kommunala reningsverk (report in preparation).

Harremoës, P. (1976). The significance of pore diffusion to filter denitrification. Journal WPCF, 48, 2, pp. 377–388.

Harremoës, P. (1978). Biofilm kinetics. Chapter 4 in: Water Pollution Microbiology, Mitchells, R. (Ed)., 2, John Wiley & Sons, New York, pp. 71–109.

Hultman, B., Jönsson, K. and Plaza, E. (1992): DynaSand-filter – Erfarenheter från Louddens reningsverk. Nordisk konference om nitrogenfjernelse i kommunale renseanlaeg. Nordiske seminar og arbejdsrapporter, 1992:601, Vol. 1, pp. 104–123.

Koopman, B., Stevens, C.M. and Wonderlick, C.A. (1990). Denitrification in a moving bed upflow sand filter. Research Journal WPCF, 62, 3, pp. 239–245.

McCarty, P.L., Beck, L. and Amant, P.S. (1969). Biological denitrification of wastewaters by addition of organic materials. Proc. 24th Ind. Waste Conf., Purdue Univ., pp. 1271–1285.