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Simultaneous nitrification–denitrification in slow sand filters

George Nakhla [a,*], Shaukat Farooq [b]

[a] *Department of Chemical and Biochemical Engineering, University of Western Ontario,*
London, Ont., Canada N6A 5B9
[b] *Gulf Organization for Industrial Consulting, P.O. Box 5114, Doha, Qatar*

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Abstract

While the ability of slow sand filters to remove total suspended solids (SS), turbidity, and organics from wastewaters is well known, this study has demonstrated that they can also achieve simultaneous nitrification–denitrification, producing effluent total Kjedahl nitrogen (TKN) and total nitrogen (TN) concentrations as low as 0.6 and 1.5 mg/l, respectively, utilizing particulate and slowly biodegradable COD in the process. The impact of filtration rates in the range of 0.15–0.38 m/h, filter depth of 0.5–1.5 m, and sand size 0.3–0.5 mm on nitrogen removal processes at temperatures of 10–39 °C was assessed. Nitrification efficiency, denitrification efficiency, and total nitrogen removal efficiency correlated well with filtration rate and sand size only, with all three parameters inversely proportional to the square root of the aforementioned two process variables. Nitrification exhibited the most sensitivity to filtration rate and sand size. The filters produced effluent with turbidities of 0.1–0.5 NTU, SS concentrations of 3–6 mg/l in the fine sand and 6–9 mg/l in the coarse sand. Effluent BOD_5 and COD concentrations were mostly in the 0.8–2.6 and 15–34 mg/l range, respectively.

Keywords: Granular media filtration; Sand filter; Tertiary wastewater treatment; Nitrification; Denitrification; Nitrogen removal

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1. Introduction

The use of slow sand filtration in drinking water treatment for removal of pathogenic organisms is ubiquitous and has been well documented in the literature for more than three decades [1,2]. More recent attention has focused on the use of slow sand filters for tertiary wastewater treatment [3,4]. Farooq and Al-Yousef [5] conducted a pilot study using slow

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[*] Corresponding author. Tel.: +1-519-661-2131; fax: +1-519-661-3498.
E-mail address: gnakhla@eng.uwoca (G. Nakhla).

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sand filtration with effective sand sizes of 0.31 and 0.56 mm for the treatment of secondary chlorinated effluents, and achieved 79–92% BOD_5 removal and 50–67% COD removal as well as 90% reduction of total bacterial counts.

In contrast to rapid sand filters which have been used traditionally in municipal wastewater treatment for removal of turbidity and suspended solids [6,7], and less frequently for post-denitrification [8], slow sand filters are biologically active filters encompassing a much more diverse and complex microbial population similar to that found in an activated sludge system and trickling filters biofilm [9]. Intermittent sand filters have been used to upgrade lagoon systems to provide nitrification in the US [10]. More recently, intermittent sand filtration or "New Hamburg" process has been implemented at two wastewater treatment plants in Ontario, Canada [11]. These filters, operating at annual surface loadings of 153–195 $m^3/(m^2$ year), and instantaneous loadings of 3.24 $m^3/(m^2$ day), were reported to achieve BOD_5 and TSS concentrations of <5 mg/l, and total ammonia nitrogen of <4 mg/l. The distribution of nitrifiers in low-loaded (1.1 m/day) slow sand filters has been characterized by Baghat et al. [12], who observed that the ammonia-oxidizers (*Nitrosomonas*) were not only more abundant than nitrite-oxidizers (*Nitrobacter*), but also better distributed throughout the filter depth.

It is apparent that most of the research work on the application of slow sand filtration for wastewater treatment, has emphasized removal of pathogens, turbidity, SS, and organics, with less interest in nitrogen removal, although, nitrification has been studied [10–12]. The process of simultaneous nitrification–denitrification (SND), i.e. without alternating anoxic oxic phases in time or space has recently elicited significant interest. It has been shown that some full-scale extended aeration plants in Italy have achieved SND with proper control of oxidation–reduction potential [13,14]. Pochana and Keller [15] reported that the three main factors affecting SND are soluble COD, dissolved oxygen concentration (<0.8 mg/l), and floc size. Since the factors affecting SND are all likely to vary along the filter depth, slow sand filters have the potential to achieve SND. The objective of this study is to present the findings of a 2-year pilot study of slow sand filtration, and the impact of filter loading rate, filter depth, and sand size on the removal efficiency of TKN and TN.

2. Methodology

2.1. System description

The filtration plant was located on the premises of Al-Khobar Wastewater Treatment Plant in the Eastern Province of Saudi Arabia on a 15 m × 15 m plot bordering the plant's secondary clarifiers to facilitate the conveyance of unchlorinated effluent to the sand filters. Three identical filter modules (F1, F2, and F3) 2 m internal diameters, 3.65 m high were constructed of 15 cm thick reinforced concrete and symmetrically placed on a truncated 9.2 m equilateral triangular RC base. The details of the filter bed are presented in Fig. 1. A 15 cm high circular weir was constructed 15 cm away from the inner wall and filter top to minimize disturbance and erosion of the sand bed. Three manometers, installed at depths of 2.23, 2.64, and 3.56 m from the top were used to measure headless. The underdrain of the filter was comprised of 20 cm $(W) \times 20$ cm $(H) \times 40$ cm (L) hollow concrete blocks,

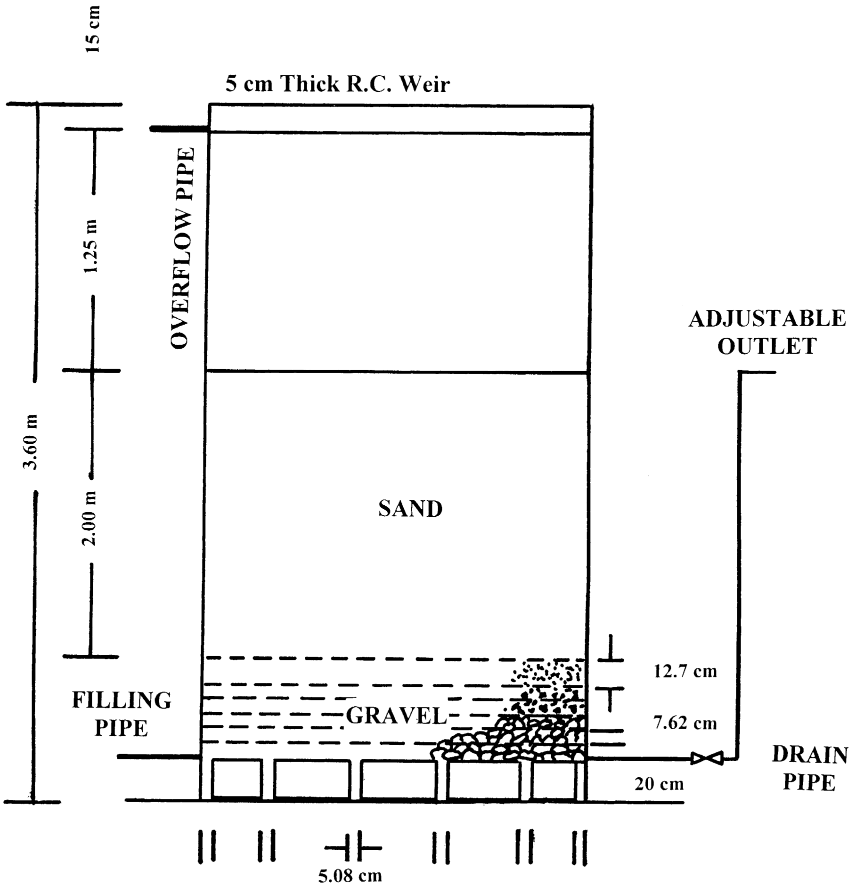

Fig. 1. Details of sand filters.

cemented to the floor, 5 cm apart from each other, with the entire pore volume interconnected to support the overlying 50 cm of reversely graded gravel in sizes ranging from 0.32 to 26.3 cm. A 5 cm effluent collection pipe placed 20 cm above the filter floor and supported on the concrete blocks extended to the center of the filter. A fixed overflow pipe controlled the water level in the filter, while the effluent pipe was connected to a T with valves on both sides to facilitate drainage of the filter as well as flow monitoring. To preclude the development of negative pressure within the sand bed, the tip of the 2 in. flexible outlet pipe from each filter, discharging freely into a common effluent tank, was located above the sand surface.

Two of the filters were filled with sand with an effective diameter of 0.5 mm and a uniformity coefficient (UC) of 1.6 while the third filter employed a 0.3 mm effective diameter sand with a UC of 2.2. Each filter module was equipped with a 1-hp, 60 Hz, single-phase pump that drew unchlorinated secondary effluent from the collection sump of the secondary clarification system. The filters were operated over a broad range of flow from 8 to 20 l/min corresponding to filtration rates of 0.15–0.38 m/h, and three depths of 1.5, 0.8, and 0.5 m.

Table 1
Operational conditions for sand filters

Filter	Flow (l/min)	Bed depth (cm)	Sand size (mm)	Total days of operation	Total days of suspension
F1	8	150	0.5	177	32
F1	10	150	0.5	35	1
F1	10	80	0.5	99	2
F1	10	50	0.5	76	2
F2	16	150	0.3	191	39
F2	20	150	0.3	21	1
F2	20	80	0.3	99	3
F2	20	50	0.3	79	3
F2	10	50	0.3	18	0
F3	16	150	0.5	191	55
F3	20	150	0.5	60	1
F3	20	80	0.5	60	2
F3	20	50	0.5	79	6
F3	10	50	0.5	18	0

Filters F1 and F3 employed coarse sand with F3 operating at twice the loadings of F1, while F2 employed the fine sand and was running at the same loading of F3. The experimental program was designed primarily to assess the impact of filtration rate, sand size, and filter depth on the performance of sand filters, and ran well over 18 months following the completion of construction. The details of the various operational periods are presented in Table 1. All three filters were commissioned simultaneously. The number of days during which the operation of the sand filter was suspended to address mechanical problems, i.e. feed pump failures during a given run is also included in Table 1. It is noted that with the exception of problems at the onset of commissioning resulting in prolonged interruptions of 32–55 days for the three, all other remaining runs totaling 11 ran smoothly with total downtimes of about 2–4% of the run duration. Since these interruptions were almost short of about 1 day, during which time the filters remained submerged, the impact of these interruptions on data quality is minimal.

2.2. Secondary effluent characteristics

The municipal wastewater treatment facility was essentially an oxidation ditch, carrousel-type, activated sludge system designed for a flow of 133,000 m^3/day with the chlorinated secondary effluent discharged to the Arabian Gulf. The characteristics of the unchlorinated secondary effluent are presented in Table 2. The plant achieved the required criteria and provided excellent removals of BOD_5, SS, TN, with total phosphorous concentrations generally around 1 mg/l. It is interesting to note that the plant achieved simultaneous nitrification–denitrification, as evidenced by the low total Kjedahl nitrogen, nitrate and nitrite concentrations in the effluent.

2.3. Analytical methods

While the emphasis of the work was on microbiological parameters, the sand filter influent and effluents were routinely monitored for BOD_5, COD, TSS, TKN, nitrates–nitrogen, and

Table 2
Secondary unchlorinated effluent characteristics

Parameter	Range	Average
Temperature (°C)	10–39	28.2
Conductivity (μmho/cm)	2800–3600	3447
pH	7.3–7.7	7.5
Alkalinity (mg/l as $CaCO_3$)	95–160	125
Dissolved oxygen (mg/l)	5–7.1	6.1
Turbidity (NTU)	0.2–0.95	0.7
SS (mg/l)	8–88	14
BOD_5 (mg/l)	2.8–6.1	4.8
COD (mg/l)	32–58	41
TOC (mg/l)	11.7–16.8	14.1
TKN (mg/l)	0–6.2	3.2
Organic N (mg/l)	0–6.2	2.7
NO_3–N (mg/l)	0.05–1.3	0.4
NO_2–N (mg/l)	0–1.15	0.56
Total phosphorous (mg/l)	0–2	1.2
Orthophosphates (mg/l)	0–1.6	0.6
Chlorides (mg/l)	424–1119	713
Sulfates (mg/l)	227–590	285
Total coliform (number/100 ml)	3100–1700000	369000
Fecal coliform (number/100 ml)	0–940000	153000
Standard plate count (number/ml)	3200–820000	238000
Coliphage (PFU/100 ml)	100–6200	577

nitrites–nitrogen, which were analyzed using the procedures set forth in Standard Methods for the Examination of Water and Wastewater [16], Methods 219, 220, 209, 420A, 418C, and 419, respectively.

3. Results and discussions

3.1. Suspended solids and organics removal

Due to the very low influent turbidity and substantial available head, filter runs were solely dictated by the sustainability of desired filtration rates, irrespective of headloss. As apparent form Table 1, sustained runs with minimum interruptions were achieved. The typical pattern for removal of SS across the filters is depicted in Fig. 2 for F1 employing the coarse sand at a depth of 1.5 m and a filtration rate of 0.19 m/h (10 l/min) and F2 and F3, at 1.5 m depths and filtration rate of 0.38 m/h (20 l/min). The influent and effluent SS concentrations varied from 10 to 12 and 3 to 6 mg/l, respectively, corresponding to an overall average removal efficiency of 63.9%. Simultaneously F3 achieved only 21.6% SS removal efficiency, with effluent SS concentrations in the 7–9 mg/l range at the same conditions of F2 while F1 achieved overall SS reduction efficiency of 28.5% at half the hydraulic loading of F3. Effluent turbidity from all three filters was mostly in the range of 0.1–0.3 NTU. Throughout the testing period, influent SS concentrations ranged from 8 to 22 mg/l;

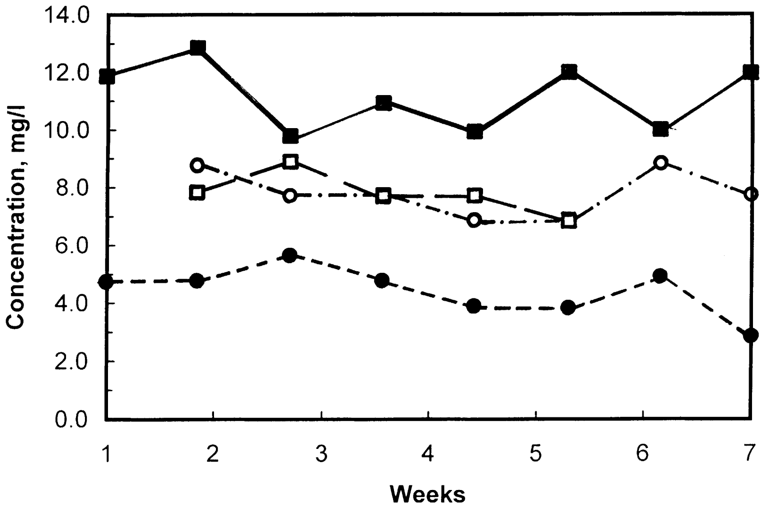

Fig. 2. Influent (■) and effluent SS variation in filters F1 (□), F2 (●), F3 (○) at a depth of 1.5 m.

coarse sand filters achieved 21.8–43.4% SS removal efficiencies while the fine sand filter accomplished 49.6–71% SS removal efficiencies. Influent turbidity ranged from 0.2 to 0.95 NTU, 33–56% of which was removed in the coarse sand filters and 40–62% in the fine sand filter.

The reductions in BOD_5 and COD across the coarse sand filter F1 at a depth of 1.5 m and a filtration rate of 0.19 m/h (10 l/min) is presented in Fig. 3. BOD_5 removal efficiencies ranged from 58.4 to 78.5%, averaging 65.4%, while COD removal efficiencies varied from 16.6 to 46.2% with an average of 34.9%. Effluent BOD_5 and COD concentrations ranged

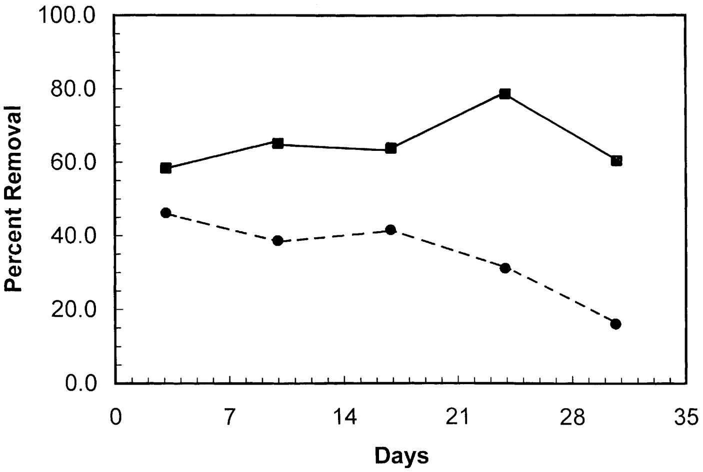

Fig. 3. Temporal variation of BOD_5 (■: avg. infl. = 5.1 mg/l) and COD (●: avg. inf. = 44.2 mg/l).

from 1 to 2 and 27 to 30 mg/l, respectively. The higher BOD_5 removal relative to COD removal is to be expected since the COD that escapes the extended aeration treatment, is mostly slowly or non-biodegradable. The organics removal efficiencies observed in this study compare well with those reported for a coarse sand filter (0.5 mm diameter) at a depth of 1.1 m and hydraulic loading rate of 0.16 m/h of 84.7% BOD_5 reduction and 43.9% COD reduction [5]. Once again, throughout this study, the fine sand outperformed the coarse sand achieving overall BOD_5 and COD removals of 76.5–83.4 and 33.4–40.4%, respectively compared to 33.4–65.4 and 11.7–35% at comparable filtration rates. BOD_5 removal was found to decrease with increased flow rate in the range of 0.15–0.38 m/h, larger sand size, and increased filter depth in the range of 0.5–1.5 m. The reduction in organics removal efficiency with filter depth is rather interesting as generally at a given filtration rate, hydraulic retention time increases with the increase in filter depth, thus, indicating that BOD_5 removal is limited by dissolved oxygen limitations in the deep beds.

It is interesting to note that the slow sand filters removed 2.1–5.2 mg BOD_5/l and 5.4–17.3 mg COD/l producing effluent concentrations of 0.8–2.6 and 15–34 mg/l, respectively, while effluent SS ranged from 3 to 12 mg/l with corresponding removals of 2.3–10 mg/l. In order to determine the impact of sand size on organics removals, the difference in average removals (on a concentration basis) of TSS and COD between F2 and F3 were calculated for each of the five operational conditions. The relationship between the aforementioned differential COD and TSS removals is depicted in Fig. 4, which clearly shows that 2.04 mg COD were removed per mg TSS. Considering that the volatile fraction of SS in the secondary effluent is 0.6–0.65 [17], and using a COD equivalent of 1.42 g COD/(g VSS) [18a], approximately 0.85–0.92 mg COD/(mg TSS) would be removed in association with TSS straining. Accordingly, the particulate COD removed in association with the straining of SS is only 2–9 mg/l. Consequently, an additional 3.4–8.3 mg/l of COD was removed by the slow sand filters. It must be asserted that while an argument against the significance of these values based on the analytical accuracy of the test methods can be postulated, such argument is emphatically refuted by the consistency of the observed differences in the 17 runs conducted. Since this COD escaped extensive biological treatment in the extended aeration system, it is deemed as either non-biodegradable or very slowly biodegradable. Therefore, the removal of this COD in slow sand filters is particularly important, given

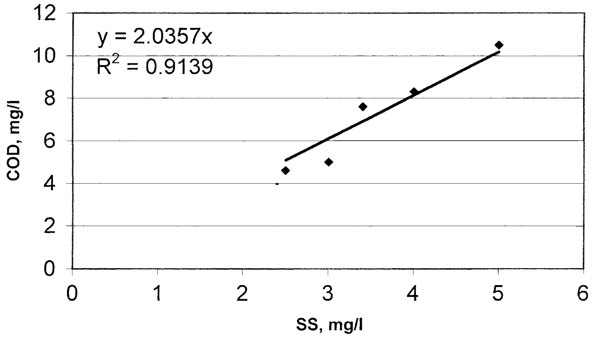

Fig. 4. Relationship between COD and TSS removals.

the detention times varied from as low as 1.3–8 h, and clearly reflects the efficiency of the diverse microbial culture in the system.

3.2. Nitrification and denitrification

The measurement of various forms of nitrogen in the filters influent and effluents was primarily intended to assess the hypothesis that nitrification and denitrification occurred simultaneously in the slow sand filters. Accordingly, four parameters, namely nitrification efficiency (NE), nitrate and nitrite removal efficiency (NNRE), denitrification efficiency (DE), and total nitrogen removal efficiency (TNE) were determined for the various filter runs. NE was defined as the concentration of TKN removed as a percent of the influent TKN (Eq. (1)), and NNRE was defined similarly. Denitrification efficiency (Eq. (2)) was defined as the sum of TKN, nitrates, and nitrites in the reduced divided by the sum of TKN oxidized (i.e. influent–effluent) and influent nitrates plus nitrites. Total nitrogen removal efficiency (Eq. (3)) was defined as amount of total nitrogen removed (calculated as sum of TKN, nitrates, and nitrites) removed as a percent of the influent TN calculated similarly. Since the influent and effluent wastewater flows to the filers are identical, concentrations rather than mass flow rates can be used to assess nitrogen removal processes within the sand filters. Following below is a mathematical representation of the various nitrogen removal processes:

$$\text{nitrification efficiency} = ((\mathrm{TKN})_{\mathrm{in}} - (\mathrm{TKN})_{\mathrm{out}})\frac{100\%}{(\mathrm{TKN})_{\mathrm{in}}} \tag{1}$$

$$\text{denitrification efficiency} \\ = \frac{((\mathrm{TKN}+\mathrm{NO_3}+\mathrm{NO_2})_{\mathrm{in}} - (\mathrm{TKN}+\mathrm{NO_3}+\mathrm{NO_2})_{\mathrm{out}})100}{(\mathrm{TKN}+\mathrm{NO_3}+\mathrm{NO_2})_{\mathrm{in}} - (\mathrm{TKN})_{\mathrm{out}}} \tag{2}$$

$$\text{total nitrogen removal efficiency} \\ = \frac{((\mathrm{TKN}+\mathrm{NO_3}+\mathrm{NO_2})_{\mathrm{in}} - (\mathrm{TKN}+\mathrm{NO_3}+\mathrm{NO_2})_{\mathrm{out}})100}{(\mathrm{TKN}+\mathrm{NO_3}+\mathrm{NO_2})_{\mathrm{in}}} \tag{3}$$

The variations of NE, DE, TNE, and NNRE for the coarse sand filter at a depth of 80 cm and a filtration rate of 0.18 m/h (10 l/min) with influent TKN and TN concentrations of 3.6 and 4.6 mg/l, respectively are depicted in Fig. 5. It is apparent from Fig. 5, that of the four aforementioned parameters, only DE was stable ranging from 72.9 to 81.5%. NE, TNE, and NNRE fluctuated between 47.2 and 83.4, 41.8 and 67.5, and 39 and 66%, respectively. With the average influent TN and TKN concentrations of 4.6 and 3.6 mg/l, effluent TN varied from 1.5 to 2.75 mg/l while effluent TKN ranged from 0.6 to 1.2 mg/l. Nitrogen removal efficiencies in the fine sand filter at a depth of 80 cm and a filtration rate of 0.38 m/h (20 l/min) for influent TN and TKN concentrations of 4.4 and 3.6 mg/l, respectively, are presented in Fig. 6. Upon comparison with the coarse sand data, the fine sand filter achieved not only much higher NE, DE, and TNE than the coarse sand at the same depth and double the hydraulic loading, but also its performance was more stable. Once again, DE was better

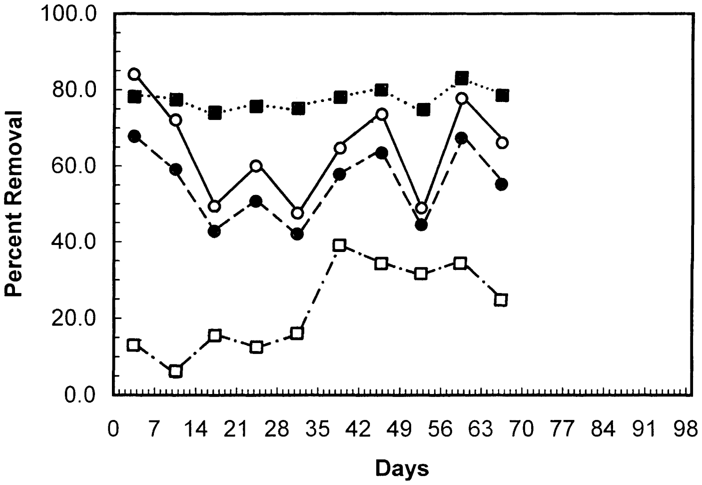

Fig. 5. Temporal variation of nitrification (□), denitrification (●), total nitrogen removal efficiency (○), and $NO_3 + NO_2$ reduction efficiency (■) in F1.

than NE ranging from 75.8 to 85.4% as compared with 69.2–78.2%. TNE ranged from 60 to 67% corresponding to effluent concentrations of 1.45–1.76 mg/l.

Table 3 lists the NE, NNRE, and TNE for the various filter runs. The consistent occurrence of simultaneous nitrification–denitrification (SND) processes, irrespective of filter depth and flow rate within the ranges of parameters employed in this study, is indeed remarkable and

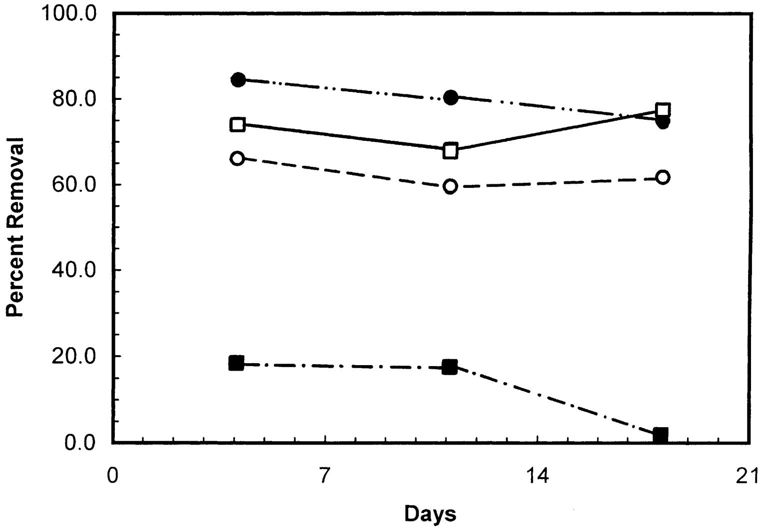

Fig. 6. Temporal variation of nitrification (○), denitrification (■), total nitrogen removal efficiency (●), and $NO_3 + NO_2$ reduction efficiency (□) in F2.

Table 3
Nitrogen removal efficiencies at various operational conditions

Filter	Flow (l/min)	Sand depth (cm)	Sand size (mm)	TKN removal (%)	$NO_3 + NO_2$ removal (%)	Total nitrogen removal (%)
F1	8	150	0.5	78.2	25.5	67.5
F1	10	150	0.5	65.9	20.3	55.1
F1	10	80	0.5	63.8	23.4	54.9
F1	10	50	0.5	61.4	22.5	52.0
F2	16	150	0.3	65.4	30.8	60.2
F2	20	150	0.3	74.2	12.3	63.4
F2	20	80	0.3	70.2	17.6	56.0
F2	20	50	0.3	58.0	18.4	48.5
F2	10	50	0.3	64.8	26.2	54.8
F3	16	150	0.5	64.2	25.5	48.3
F3	20	150	0.5	54.9	7.9	45.9
F3	20	80	0.5	59.4	27.2	51.1
F3	20	50	0.5	42.4	10.5	34.7
F3	10	50	0.5	58.7	23.0	50.1

novel, given that the evidence that sand filters can nitrify has only been presented recently [12] while no evidence of denitrification without external carbon addition is available in the literature. By comparison of the data for F2 and F3 continuously operated at identical filtration rates and filter depth, but employing different sand sizes, it is conspicuous that the fine sand outperformed the coarse sand with respect to nitrification, denitrification, and total nitrogen removal. The higher overall biological activity including nitrogen and organics removal efficiencies in the fine sand can only be attributed to the higher specific surface area and consequently the higher biomass densities. This finding emphatically refutes the traditional thinking that the *schmutzdecke* at the top of the sand media is the only biologically active layer in a sand filter. Furthermore, the rapid stability of biological processes following depth reduction and scraping of the top layer, provides further credibility to the in-depth biological activity of a slow sand filter.

Using the typical influent TKN and TN concentrations of 3–3.9 and 3.9–4.9 mg/l, respectively, and the total NE and TNE listed in Table 3, effluent TKN and TN concentrations ranged from 0.6 to 1.75 and 1.5 to 2.7 mg/l, respectively. Accordingly the slow sand filters removed approximately 2 mg/l of TKN and 2.3 mg/l of TN. The estimated nitrogen content of the VSS removed based on a 60% volatile fraction of SS and 12% by weight nitrogen [18b] is only 0.16–0.7 mg/l with an average of 0.4 mg/l. Based on the COD requirements for denitrification of 3.5–4.5 mg COD/(mg TN) [15], the estimated COD consumption by denitrification is thus 8–10.6 mg/l, which is much higher than the COD removed (not associated with VSS retention) of 2–9 mg/l, estimated earlier. More importantly, the residual COD in the filter influent is not readily biodegradable and accordingly may hinder denitrification. Furthermore, hydraulic retention times in the filters varied form 1.3 h at a filter depth of 0.5 m and a filtration rate of 0.38 m/h to 10 h at a filter depth of 1.5 m and a filtration rate of 0.15 m/h. It is, therefore, evident that the slowly biodegradable soluble COD was inadequate to meet the denitrification requirements, and accordingly it is postulated that soluble organic products derived from biomass decay must have supplemented the carbon available for the process. In fact, the total COD removal of 5.4–17.3 mg/l, with an average of 11 mg/l is in closer agreement with the theoretical requirements of 8–13 mg/l.

3.3. Statistical correlation of nitrogen removal processes with process parameters

The impact of filtration rate on NE, DE, and TNE was assessed by correlating the performance of filters F1 and F3 at a bed depth of 1.5 m. At this depth, four filtration rates were employed, 0.15 and 0.19 m/h in F1 versus 0.3 and 0.38 m/h in F3, and thus, the data could be statistically analyzed using both linear and non-linear models. At bed depths of 0.8 and 0.5 m, the filers were operated at 0.19 and 0.38 m/h only and thus, the data would be insufficient for statistical analysis. Similarly, in order to assess the impact of sand size, performance of filters F2 and F3 operated at identical flow rates and depths was compared. The effect of sand depth on nitrogen removal processes was evaluated using the data for F1 and F3 at the three depths investigated in this study. A summary of the pertinent relations is presented in Table 4. It is apparent that NE, DE, and TNE correlated well with filtration rate and sand size, as reflected by the high values of R^2 (the correlation coefficient). The poor correlation of various nitrogen removal processes with depths is evident, thus, implying that the most cost-effective depth for nitrogen removal is the 0.5 m.

It is apparent from Table 4 that NE, DE, and TNE were all inversely proportional to the square root of the both filtration rate, and sand size. Furthermore, nitrification exhibited the most sensitivity to process variables, i.e. filtration rate and sand size, with denitrification showing the least sensitivity as reflected by the coefficients of the equations. This finding is rather interesting, since it would be expected that the high dissolved oxygen (DO) transfer into the sand bed with increasing filtration rates should enhance nitrification not hinder it. Thus, the inverse relationship between filtration rate and nitrification can only be explained by kinetic limitations rather than DO limitations as a result of the decrease in contact times ensuing from higher filtration rates. This is further substantiated by the inverse correlation of nitrification with sand size, implying that the higher attached biomass in the case the fine sand due to a higher specific surface area was indeed advantageous to nitrification. On the other hand, denitrification being a process that occurs at very low DO levels, it is plausible that it would be hampered by high filtration rates and concomitant dissolved oxygen transfer rates.

Table 4
Correlation of various nitrogen removal processes with slow sand filtration parameters

Nitrogen removal process efficiency (%)	Process variable	Equation	Correlation coefficient (R^2)
Nitrification	Flow (Q, l/min)	$-22.5Q^{0.5} - 911.6 + 1007.6Q^{0.02}$	0.72
Denitrification	Flow (Q)	$-4.39Q^{0.5} + 93.8$	0.66
Total nitrogen removal	Flow (Q)	$-9.61Q^{0.5} + 91.9$	0.67
Nitrification	Sand size (S, mm)	$-89.5S^{0.5} + 125.1$	0.66
Denitrification	Sand size (S, mm)	$-38S^{0.5} + 102.7$	0.59
Total nitrogen removal	Sand size (S, mm)	$-82.9S^{0.5} + 111.2$	0.65
Nitrification	Bed depth (D, m)	$-0.003D^2 + 63.0$	0.26
Denitrification	Bed depth (D, m)	$-144D^{0.5} + 86.5$	0.34

4. Summary and conclusions

Based on the findings of this study, it can be concluded that slow sand filtration can be used for tertiary wastewater treatment not only for further removals of SS, turbidity, and microbiological contaminants, but also for nitrogen removal at low concentrations of approximately 5 mg N/l. The results of this 2-year pilot-testing program confirmed that simultaneous nitrification–denitrification processes occur within the filter bed. At influent TKN and TN concentrations of 3–3.9 and 3.9–4.9 mg/l, respectively, the slow sand filters affected 42.4–78.4% nitrification, and 45–67.5% total nitrogen removal efficiencies, producing effluent TKN and TN concentrations in the range 0.6–1.75 and 1.5–2.7 mg/l, respectively. Statistical analysis of the data indicated that nitrification efficiency, denitrification efficiency, and total nitrogen removal efficiency correlated well with filtration rates and sand size, while not being impacted by bed depth in the 0.5–1.5 m range. The aforementioned three parameters were inversely proportional to the square root of filtration rate and sand size, with nitrification being the most sensitive and denitrification the least sensitive.

The coarse sand (0.5 mm diameter) affected a 21.8–43.4% reduction in TSS vis-à-vis 49.6–71% in the fine sand (0.3 mm diameter). Coarse and fine sand filter effluent TSS concentrations ranged from 6–9 and 3–6 mg/l, respectively. Effluent turbidity from all three filters was 0.1–0.5 NTU. Filtration rates and filter depth did not significantly impact TSS and turbidity removals.

Average BOD_5 and COD removal efficiencies in the fine sand ranged from 76.5 to 83.4% and 33.4 to 40.4%, respectively, as compared with 33.4–65.4 and 11.7–35% in the coarse sand. Of the 5.4–17.3 mg/l of COD removed, approximately 40–45% was due to entrainment of volatile suspended solids. Furthermore COD requirements for denitrification was about 8–11 mg/l, thus, implying that the sand filter utilized slowly biodegradable organics and soluble products derived from biomass decay for denitrification.

Effluent quality from the slow sand filters with BOD_5, COD, TSS, TKN, and TN concentrations of 0.8–2.6, 15–34, 3–6, 0.6–1.75, and 1.5–2.7 mg/l at the low bed depth of 0.5 m and high filtration rate of 0.38 m/h clearly demonstrates that the slow sand filter can be effectively used for tertiary wastewater treatment for simultaneous removal of organics and nitrogen. This is of particular importance to developing countries that do not have the resources to readily avail themselves of cutting-edge mechanical tertiary treatment systems, and/or undertake significant modifications of existing processes, as it demonstrates that a primitive passive technology such as slow sand filtration following the widely used extended aeration can achieve superior effluent quality.

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