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The impact of fractionation of hydraulic load on oxidation performances of sand filters

Mahmoud Bali and Moncef Gueddari

ABSTRACT

Infiltration–percolation is an extensive treatment technique aimed at eliminating organic matter, oxidizing nitrogen, and removing pathogens. The main purpose of this work is to evaluate the impact of fractionation of hydraulic load on oxidation performances of unsaturated sand filters. Experimental results showed that oxidation of organic matter and ammonium nitrogen has mainly occurred in the upper layers of the filter bed. They also showed that treatment efficiency increased with the increase of the thickness of the filtering mass and the fractionation of applied hydraulic load. The experiments pointed out the influence of the fractionation of daily load on oxidation capacity of the intermittent sand filter. Results showed that increasing the fractionation improves the purification capacity of the treatment process. The simulations showed that biomass growth is very sensitive to the fractionation of hydraulic load, and that the increase of the number of feeding–drainage cycles per day leads to accumulate purifying biomass in the upper layers of unsaturated filters.

Key words | fractionation, hydraulic load, impact, infiltration–percolation, oxidation, performances

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INTRODUCTION

As a result of rapid population growth coupled with urbanization and increased living standards, the demand for water is constantly increasing in many parts of the world (Nadav *et al.* 2012; Mesut & Orhan 2013). Climate change and its influences on the quantity and quality of water resources further complicate the problem of sustainable water supply. Hence, reuse of treated municipal wastewaters is increasingly becoming popular in arid and semi-arid regions of the world (Nadav *et al.* 2012).

Advanced treatment technologies, such as ion exchange, reverse osmosis, activated carbon, etc., can be implemented to improve the quality of secondary wastewater effluents. Yet, the use of these advanced technologies is quite limited because of high capital and operational costs (Mesut & Orhan 2013). Alternative wastewater treatment methods, such as infiltration–percolation, are typically more appropriate thanks to lower costs and numerous other benefits. Infiltration–percolation process could be considered as the oldest method for wastewater treatment, which ensures good sanitary risk depletion (Brissaud *et al.* 1991).

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Infiltration of wastewater through unsaturated sand beds is an urban treatment process aimed at eliminating organic pollution, oxidizing nitrogen, and removing pathogens. This process can achieve high pathogen and colloid removal efficiencies (Auset *et al.* 2005).

The technique of infiltration–percolation has been widely applied for the on-site treatment and the disposal of septic tank effluents, to treat primary effluents of small communities. It is also used to polish secondary effluents of larger treatment plants before the reclaimed water is reused or disposed of in sensitive environments (Brissaud & Lesavre 1993; Salgot *et al.* 1996). This technique has been developed as tertiary treatment of secondary effluents in several Mediterranean countries (Auset *et al.* 2002). Properly treated, wastewater effluents can be reused for different purposes (groundwater recharge, irrigation, etc.) as an alternative resource (Chennaoui *et al.* 2014). They provide a source of water that could significantly curtail exploitation of valuable natural water resources.

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Sand filters remove contaminants in wastewater through physical, chemical, and biological treatment processes. Although the physical and chemical processes play an important role in the removal of many particles, the biological processes play the most important role in sand filters (EPA 1999). Sand beds act as aerobic fixed biomass reactors, as far as the oxygen required to oxidize the biodegradable pollutants, transported by the wastewater effluents, is available in the air phase of the porous medium (Bancolé *et al.* 2003). Oxygen consumption is balanced by the renewal of the air phase of the filter with atmospheric fresh air (Schmitt 1989). Oxygen renewal, as a prominent phenomenon for aerobic bacterial activity, deeply impacts vertical flow sand filter treatment efficiency (Petitjean *et al.* 2012). Intermittent infiltration allows maximizing the renewal of the air phase of the porous medium (Boller *et al.* 1993). Alternation of operation and drying periods is the most practical way to manage clogging at the surface and in the core of filtrating beds (Brissaud *et al.* 2003). It allows the sustainability of the treatment process to be maintained. The main purpose of this study is to evaluate the impact of fractionation of applied hydraulic load on oxidation performances of sand filters.

MATERIALS AND METHODS

The results provided in this paper were obtained from experiments conducted in a 100 m^2 filter bed located at Dissa agriculture area in the north of Gabès city (south-east of Tunisia). The sand filter is a trapezoidal basin of 2.0 m height filled with 30 cm of coarse gravel and 1.5 m of sand. The mean grain size of sand (d_{50}) is 0.26 mm and the uniformity coefficient of the particle-size distribution (d_{60}/d_{10}) is 1.93. A polyethylene pipe was used, drilled with 0.5 cm holes to drain filtered water out. The experimental arrangement is depicted in Figure 1. The infiltration–percolation basin was fed with activated sludge effluents from Gabès treatment plant. Secondary wastewater effluents were applied according to a 4 day operating–3 day drying schedule. Wastewater effluent was spread uniformly over the surface area through a distribution system of perforated pipes (3 mm diameter holes with a density of 20 holes per meter).

In order to evaluate the influence of fractionation of daily hydraulic load on treatment performances of the infiltration–percolation process, a load of 0.40 $m^3\,m^{-2}$ was fractioned into two or three applications per day. Three

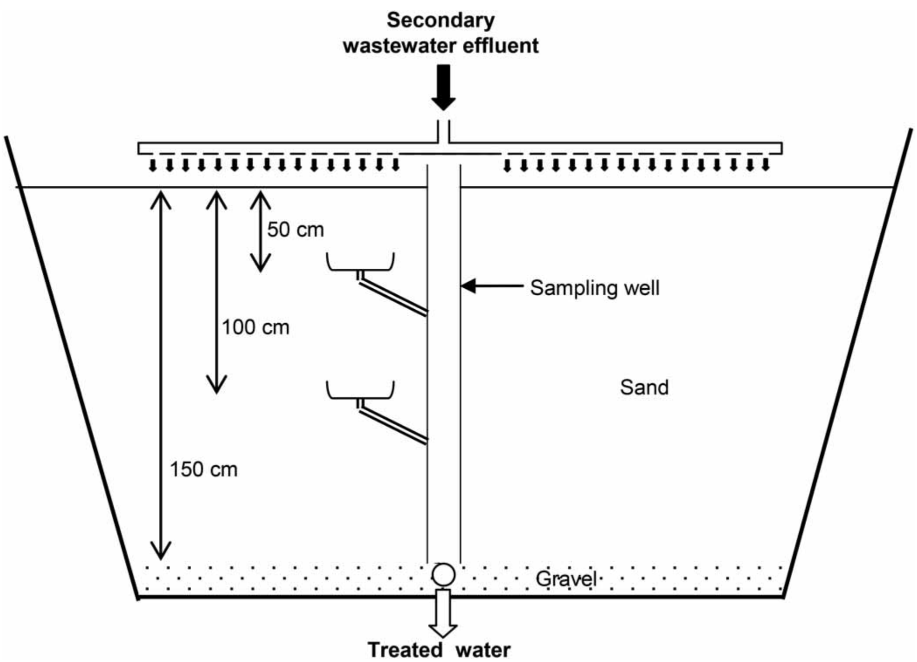

Figure 1 | Schematic drawing of the infiltration–percolation basin (not to scale).

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experiments, F, G, and H, were investigated. During these experiments, the daily number of feeding–drainage cycles, *f* (fractionation factor), was respectively, 1, 2, and 3. The daily hydraulic load and the feeding rate (40 m^3/hour) did not change during the study, but three feeding regimes were used. In fact, during experiment F, the wastewater effluent was applied in one feeding sequence per day for a 60 minute duration. During experiment G, the wastewater was dosed two times/day for a 30 minute duration. During experiment H, the wastewater effluent was applied in three doses/day for 20 minute/dose. Feeding sequences were spaced to allow sufficient time for drainage and reaeration of the sand filter. Secondary effluents and percolating water sampled at 0.5, 1, and 1.5 m depth were analyzed, according to AFNOR standard methods, for chemical oxygen demand (COD), ammonium nitrogen (NH_4-N), total Kjeldahl nitrogen (TKN), and nitrates (NO_3-N). Biomass growth in the sand filter was simulated through the mathematical model described by Bancolé *et al.* (2003). This model allows the simulation of the biomass profiles as function of the filter depth and the fractionation of hydraulic load.

RESULTS AND DISCUSSION

Oxidation performances

The oxidation performances were evaluated through the experiments carried out on the infiltration–percolation basin. Figure 2 depicts the variation in COD content during the experiments F, G, and H as a function of time and bed depth. During experiment F, the daily hydraulic load was 0.4 m^3 m^{-2}, applied in a single feeding ($f = 1$). The secondary effluent COD content was 118.6 mg O_2/L. The residual mean COD content in the percolating water was about 23.5 mg O_2/L, corresponding to a reduction of 80%. The average removal rates of 55.7% and 71% were observed, respectively, at 0.5 m and 1 m depth of the sand filter. Experimental results showed that the oxidation of organic matter

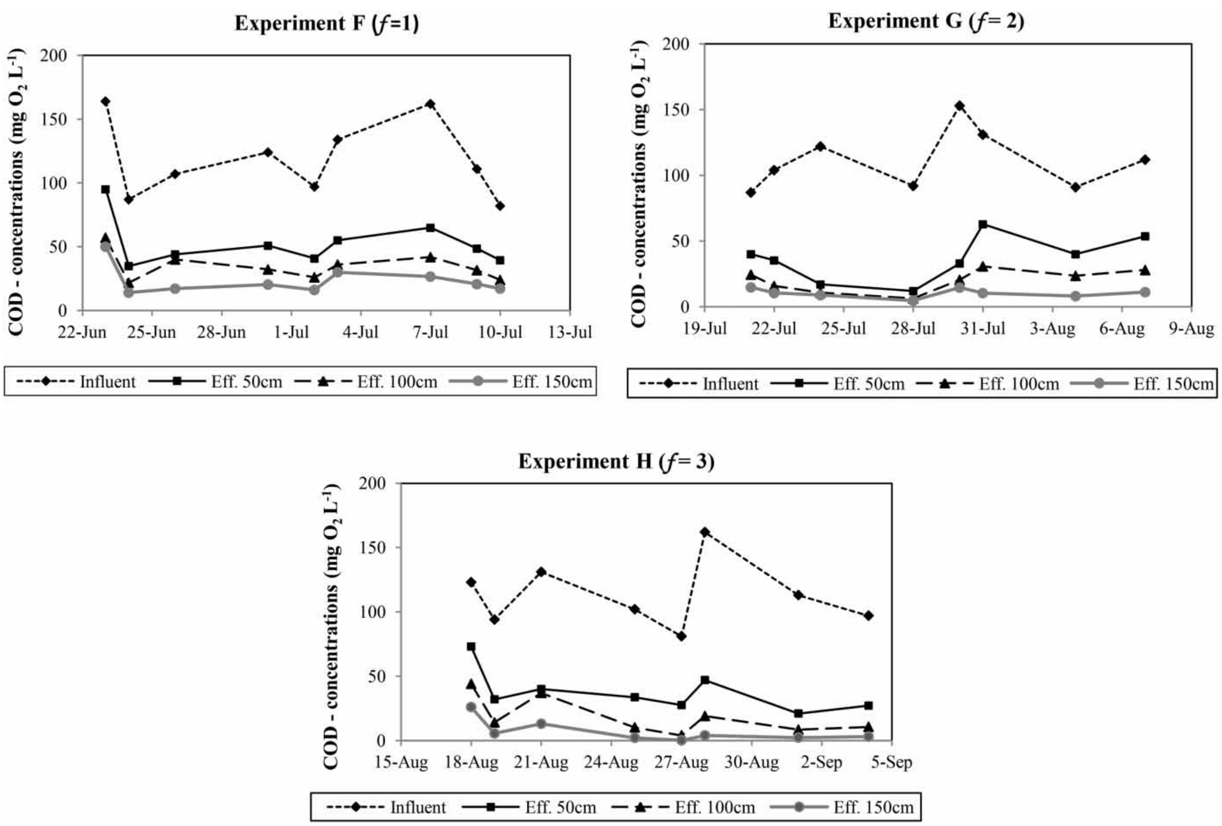

Figure 2 | COD concentrations at 50, 100, and 150 cm filter depths during experiments F, G, and H.

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takes place mainly in the upper layers of the filter. They also showed that the treatment efficiency increases with the increase of the thickness of the filtering mass.

Throughout experiment G, the same hydraulic load was fractionated into two applications ($f = 2$). The average COD content in the secondary effluent was 111.5 mg O_2/L. The residual content was 36.7 mg O_2/L and 20 mg O_2/L, respectively, at 0.5 m and 1 m depth of the sand bed, corresponding to removal efficiency of about 67% and 82%, respectively. Analysis of the samples collected at the bottom of the infiltration basin showed a high elimination of organic matter; the removal rate was 90.6%. This rate is higher than that observed in the previous experiment. This result indicates that the removal efficiency of organic matter increases with the fractionation of the applied hydraulic load. The variation of the treatment performance with the filter thickness and the fractionation of hydraulic load could be explained by the distribution of water residence time in the porous medium. Indeed, when the effluent passes quickly through the filter bed, pollution does not have enough time to be suitably oxidized. Whereas when the infiltration speeds are slower, pollution remains trapped in the filter which favors its degradation. Brissaud *et al.* (1999) demonstrated that the lower the fractionation and the filter thickness, the shorter the water residence time becomes. Achieving total oxidation requires a minimum water residence time and sufficient amount of oxygen in the unsaturated filter. During experiment H, the hydraulic load was fractionated into three applications per day ($f = 3$). The monitoring of COD showed the good performance of the infiltration–percolation process in the elimination of carbonaceous pollution. The abatement rates sometimes reached values near 100% (Figure 2). Secondary effluent COD content was 112.9 mg O_2/L. The average outlet was about 7 mg O_2/L at 1.5 m bed depth, corresponding to a reduction rate of 93.8%. This rate is higher than those observed in previous experiments (F and G). This indicates that the removal efficiency of organic matter increases with the fractionation of the applied hydraulic load.

Regarding the elimination of nitrogenous pollution, Figure 3 illustrates the variation of ammonium nitrogen content during the three experiments, as a function of time and depth of the sand filter. During experiment F, the average NH_4-N content in the secondary effluent was 39.2 mg/L. From the beginning of the experiment, it was noticed that there was a significant retention of this parameter in the filter bed. This shows that the filter had sufficient amounts of oxygen ensuring a good oxidation of the pollution. NH_4-N removal efficiency was 75.3%, 81.6%, and 86.2%, respectively, at 0.5, 1, and 1.5 m depth of the sand filter. This indicates that the surface layers of the filter play an essential role in nitrogen oxidation.

The NO_3-N concentration was significantly increased in the filtered water (Figure 4). The mean NO_3-N content was, respectively, 2.3 mg/L and 42.5 mg/L in the applied effluent and percolating water at 1.5 m depth. Nitrification has mainly occurred in the upper layers of the filter bed where nitrifying biomass and oxygen were concentrated. During experiment G, the average removal efficiency of ammonium nitrogen was 67.3%, 84.8%, and 95.8%, respectively, at 0.5 m, 1 m, and 1.5 m depth of the sand filter (Figure 3). These yields are higher than those observed at the same depths during experiment F. This shows that the fractionation of hydraulic load improves the oxidation of nitrogenous pollution. The impact of fractionation of the daily hydraulic load into three applications per day is appreciable. In fact, the average removal rate of ammonium nitrogen was about 97% at 1.5 m filter depth. Comparing these results with those of previous experiments, we can deduce that increasing the fractionation of daily load enhances nitrogen oxidation. Indeed, when the hydraulic load is low, the water retention time in the filter is quite long; consequently, it allows a better degradation of pollution. Similar results reported by Bancolé (2001) showed that fractionation of the applied hydraulic load significantly improves the treatment performances of the infiltration–percolation process. Nitrification has occurred during the first days of operation period and has quickly reached its maximum (Figure 4). The average NO_3-N concentration was 41.7 mg/L at 1.5 m filter depth.

Oxidation capacity

The main purpose of the experiments F, G, and H was to show the influence of fractionation of applied hydraulic load on the treatment performances of infiltration–percolation process. Results showed that the feeding regime affects the treatment efficiency of the sand filter. Figure 5 illustrates the variation of the oxidation capacity (ω),

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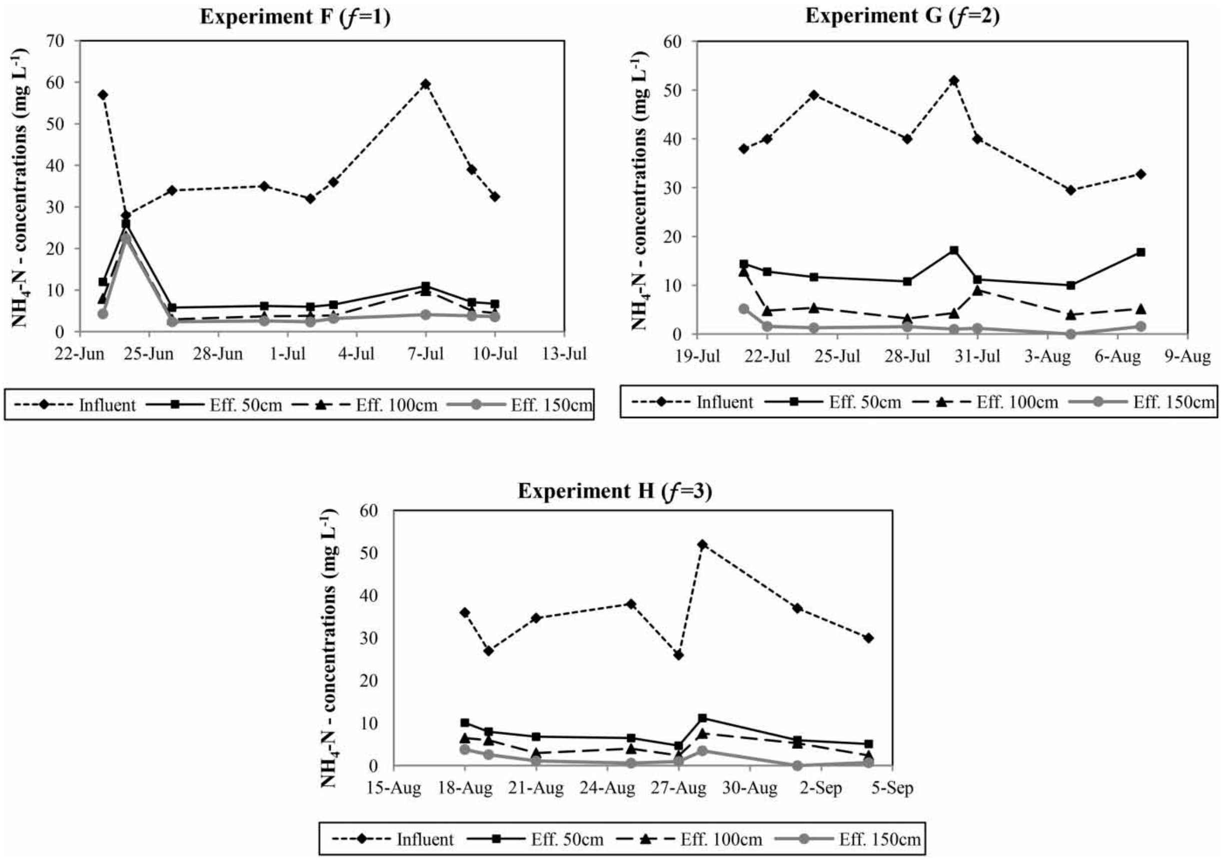

Figure 3 | NH_4-N concentrations at 50, 100, and 150 cm filter depths during experiments F, G, and H.

corresponding to the difference between the total oxygen demand (TOD) of the applied influent and of the percolated water (Schmitt 1989), as function of the fractionation and the thickness of the filter bed. The TOD is expressed by the following equation (Makni 1995):

$$TOD\ (mg\ O_2/L) = COD + 4.57\ TKN \qquad (1)$$

Experimental results showed that oxidation capacity increases with the increase of the thickness of the sand filter. For instance, with a single daily feeding ($f = 1$), ω was 235 mg O_2/L at 50 cm below the infiltration surface, while it was, respectively, 270 mg O_2/L and 282 mg O_2/L at 100 and 150 cm bed depth. With three daily applications, the oxidation capacity was about 320 mg O_2/L at 150 cm depth, which is greater than those observed with $f = 1$ and $f = 2$. This improvement in the purification performance can be explained by the distribution of water residence time in the porous medium. Increasing the fractionation causes a decrease of the water infiltration velocities, and, therefore, improves treatment performances. Similar results reported by Schmitt (1989) showed that the oxidation capacity increases with the fractionation of the applied hydraulic load.

Biomass growth

The biological degradation of organic matter and nitrogen takes place in the biofilm. Simulations showed that biomass growth is very sensitive to the fractionation of applied hydraulic load (Figure 6). With three applications per day, the biomass contents are higher than those obtained with one ($f = 1$) or two ($f = 2$) application(s). This could be explained by the fact that the circulations of wastewater within the porous medium are slow and that the exchanges with the immobile phase are more important, thus, the biomass grows better and the oxidation is, therefore, improved. Stevik *et al.* (2004) demonstrated that high flow rate increases the average water suction in the filter which results in greater transport through

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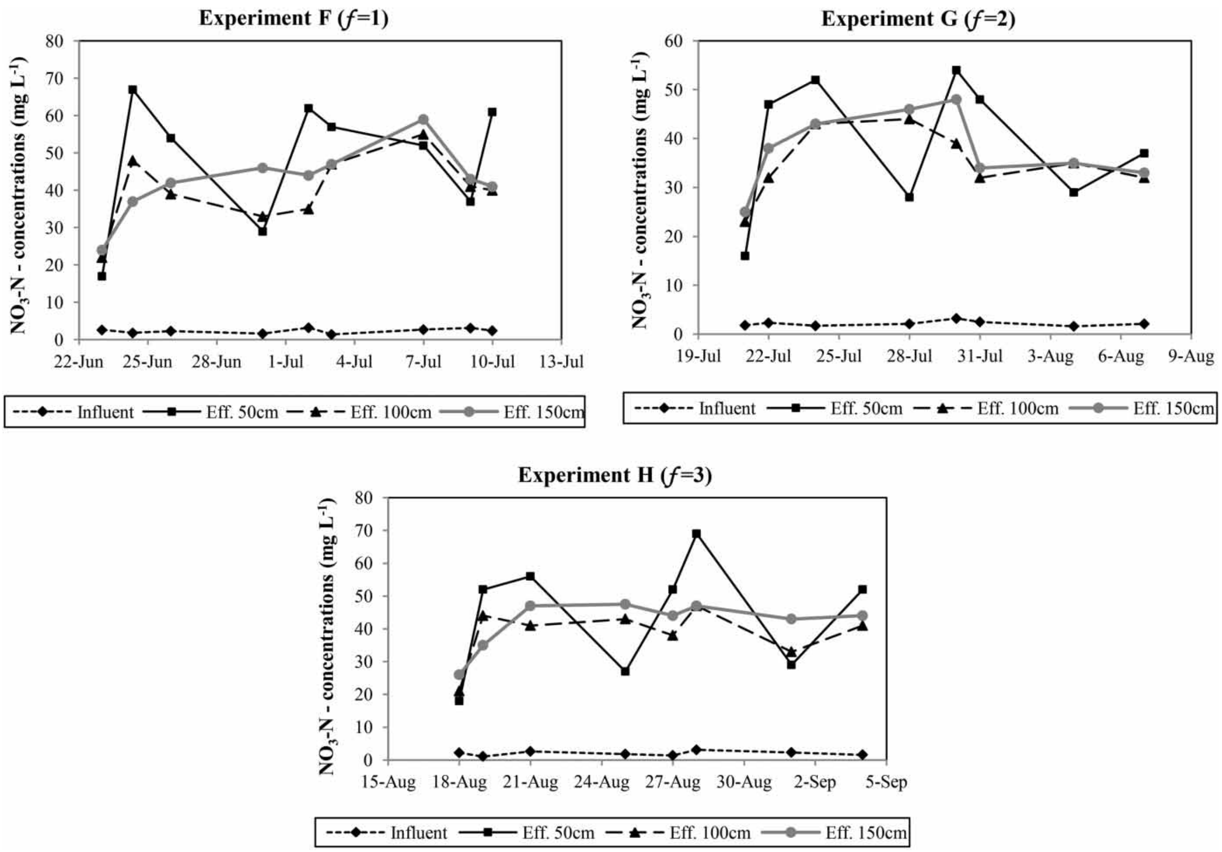

Figure 4 | NO_3-N concentrations at 50, 100, and 150 cm filter depths during experiments F, G, and H.

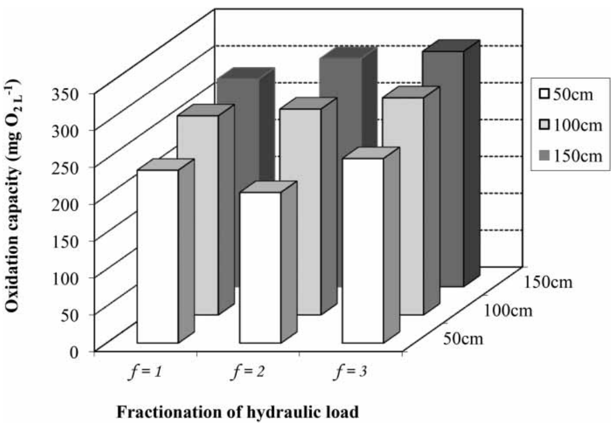

Figure 5 | Influence of fractionation and filter depth on oxidation capacity.

larger pores and, consequently, decreases the effect of bacterial biomass developed in the porous medium.

The biofilm has essentially developed in the upper 30 cm of the sand bed. The increase of the number of feeding–drainage cycles per day leads to accumulation biomass in the upper layers of the unsaturated filter. Similar results reported by Ben Rajeb *et al.* (2009) indicated that the microbial biomass increases with operating time and is mainly located in superficial layers of the filter. According to Petitjean *et al.* (2012), bacterial biomass in vertical flow sand filters is mainly impacted by the operating mode. The authors showed strong interplay between oxygen renewal and bacterial consumption in the case of sequential batch feeding with transient flooding of filter surface. As the biomass develops, the hydraulic conductivity decreases, consequently, reduces percolation velocities, and increases water residence time within the porous medium. Thus, oxidation performances were improved when the fractionation of hydraulic load increased. The residence time or contact period between the pollutant matter and the purifying biomass is the principal parameter that influences the biodegradation. Bancolé *et al.* (2003) demonstrated that increasing the fractionation of daily load improves the filtered water quality but, at the same time, has a major adverse effect: the internal clogging which threatens

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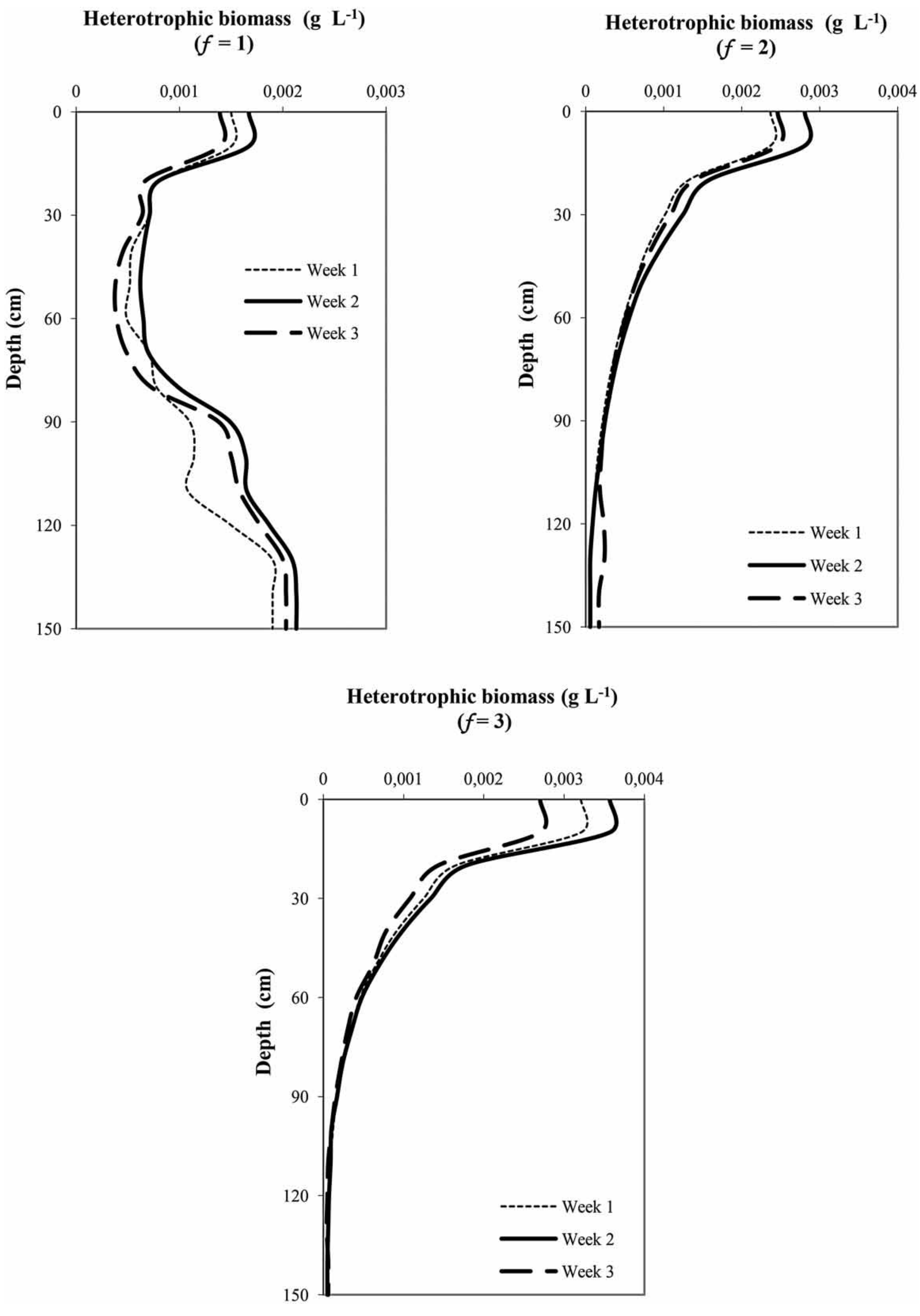

Figure 6 | Biomass growth during experiments F ($f = 1$), G ($f = 2$), and H ($f = 3$).

the process sustainability. Bori Akadar *et al.* (2014) indicated that biomass growth should be monitored to prevent clogging of sand infiltration processes. Simulations also showed that the biomass contents calculated at the third week are lower than those determined during the second week of operation. This can be explained by the regression of microbial biofilm

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through endogenous respiration. Therefore, drying phases (3 days in this case) allow regression of the biomass. These phases favor sustainability of the infiltration–percolation process, reducing the risk of internal clogging due to the development of biomass. Auset *et al.* (2002) indicated that a drying period allows a periodic elimination of accumulated biomass due to endogenous respiration, thus avoiding a possible clogging of the filter. Operation–drying alternation entails a periodic fluctuation of the ecosystem state.

CONCLUSIONS

The experimental study has shown the influence of the bed depth and the fractionation of hydraulic load on oxidation performances of intermittent sand filter. Results indicated that oxidation efficiency of organic matter and ammonium nitrogen increases significantly with the depth of filtering medium and the fractionation of hydraulic load. Water residence time appears to be a key factor of oxidation performances of infiltration–percolation process. Simulations showed that biomass growth appears to be highly dependent on the number of daily feeding–drainage cycles. The increase of the fractionation of the applied load leads to accumulation of biomass in the upper layers of the sand filter. The knowledge of oxidation capacity and biomass growth is essential to secure the design and operation of intermittent sand filters and to guarantee the sustainability of the process in the long term.

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