INCORPORATION OF HYBRID BIOFILTERS IN WATER-SENSITIVE URBAN DESIGN

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Abstract. This paper presents a research study aimed at the development of a hybrid biofilter that can serve for two different applications. This is a unique approach due to the prolonged dry period in Israel covering 7-8 months of the year. The tactic suggested herein is to use the same system for stormwater harvesting/treatment during winter, and for bioremediation of nitrate-contaminated groundwater during summer. Crude cotton and *Eucalyptus* wood-chips served as alternative carbon sources for denitrification, and both proved to support efficient reduction of nitrate with minimal release of nitrite and organic matter. During the stage of stormwater treatment, two types of biofilter-columns (120 & 70 cm long) were tested, with a minimal saturation zone and no addition of organic carbon. Complete nitrification could be achieved, even under high instantaneous hydraulic loads for both column types. Vegetation on top of the biofilters contributed to improved removal of the nitrate formed, by plant assimilation.

Introduction

Intensive urbanization is a global trend which cause deterioration of quality of life in the city, and increase water demand and pollution problems. The enlarged paved and constructed areas reduce open spaces which are needed for rainwater infiltration. Therefore, storms cause major damages to infrastructure and to pollution of water resources. One of the concepts which has been developed in recent years is the “Water Sensitive Urban Design” (WSUD). This approach incorporates technological solutions to reduce storms damages, and to prevent soil

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degradation and water pollution. Moreover, it can potentially lead to the recovery of significant amounts of water that would have been lost in the sea, through harvesting the urban stormwater and directing it into the aquifer through engineered structures termed bioretention systems or biofilters. This concept has also added values such as creation of aesthetic green landscapes, and moderation of microclimate effects (Wong, 2006). Biofilters are based on solid engineering design concepts incorporating drainage arrangements in the catchment area served. A typical layout is shown in Fig.1

Fig. 1. Typical layout of a biofilter system

The application of biofiltration systems for stormwater harvesting is suited for areas with rainfall spread over the entire year. In this regard, much effort has been invested by research groups at Monash University in Melbourne, Australia, to investigate the hydrological and engineering aspects of these constructed catchment systems. Some of their studies yielded beneficial information regarding the capabilities of biofilters to remove various contaminants such as suspended solids (Read *et al.*, 2008), heavy metals (Hatt *et al.*, 2011), pathogenic bacteria (Chandrasena *et al.*, 2012), and nutrients (Zinger *et al.*, 2013). However, the use of biofilters in Israel is problematic due to the prolonged dry climate period covering 7–8 months of the year. Thus, a conventional biofilter for harvesting and treatment of stormwater can be active only during the short wet period of the year. Since the biofilter is a biological system incorporating activity of both plants and bacteria, continuous wetting of the system is required during the dry period to preserve the biomass. Therefore, a unique version of the biofilter should be used. The approach suggested to be applied in Israel is to use a hybrid biofilter for both stormwater harvesting/treatment during winter, and for remediation of nitrate-contaminated groundwater during summer, as shown in Fig. 2.

Groundwater contamination by nitrates is a global problem in many locations, mainly due to intensive agriculture, and to irrigation with effluents containing high levels of nutrients. Technologies for the remediation of nitrate-contaminated groundwater include processes such as membrane separation or ion exchange (Shrimali & Singh, 2001), and biological processes. In biological treatment to reduce nitrate and/or nitrite, a carbon source (electron donor) should be added to enable efficient denitrification. For this purpose, many carbon compounds have been proposed and tested (Hamlin *et al.*, 2008; Ashok & Hait, 2015).

Fig. 2. The concept of a hybrid biofilter application in Israel

In our study based on former experience (Aloni & Brenner, 2017), crude cotton wool was used in biofilter columns and compared to *Eucalyptus* wood-chips which are commonly applied in such systems. Cotton contains almost pure cellulose fibers and is considered as a sustainable source since it is very common in agriculture, and its cost is low.

1. Materials and methods

2.1 - Stage I: Denitrification experiments in biofilters

For this experimental stage two columns were established according to the Australian design concept (Zinger *et al.*, 2013), shown in Fig. 3. Each column built of PVC has height of 120 cm, diameter of 23.5 cm, and spaced with 5 ports for sampling. The bottom layer of the column is filled with 3-5 mm basalt stones (10 cm height) in order to establish a solid mechanical support for the layers above.

These were composed of quartz sand in three layers: bottom 2.5-3.5 mm (7 cm height), middle 0.8-1.5 mm (8 cm height), and a top layer of 0.4-0.6 mm (45 cm height). Each column has a drainage outlet at the bottom connected to a solid pipe up the column which can control various levels of column saturation (to form an anoxic zone for denitrification). For these experiments the height of the saturation zone was 70 cm. On top of the column, a 54 cm transparent Perspex column could be connected to support growing plants. The top 30 cm of the smallest sand layer was mixed with two types of solid carbon sources. Two columns were tested: one with cotton and the other with *Eucalyptus* wood-chips. Both sources were mixed with pea-straw (mass ratio 3:1). On top of the columns *Vetiver* plants were planted in order to test the effect of vegetation.

Fig. 3. Structure of the biofilter columns used in the study

Above the saturated zone, 30 cm of the filter included only quartz sand (0.4-0.6 mm). This layer served for consumption of oxygen in order to reduce its concentration before entering the saturated zone (to prevent aerobic degradation of the carbon source). Two 250 liter tanks were filled with a nitrate solution (KNO_3) to form concentration of 100 mg/L in tap water. This solution served as the feed for

the columns, pumped continuously by *Masterflex L/S compact drive* peristaltic pumps. The hydraulic load applied was 36 mm/h (38 L/d per column).

2.2 - Stage II: Operation of biofilter-columns for the simulation of stormwater treatment

For this purpose, seven additional columns were constructed and operated. Due to the low nitrogen content of typical Israeli stormwater (less than 5 mgN/L), the biofilters were designed to be capable of removing TKN by aerobic nitrification. It is believed that it is not crucial to reduce the resulting nitrate (<5 mgN/L) by incorporation of denitrification in the biofilter design, since this level is far below the natural background of groundwater, and below drinking water standards and effluent disposal limitations. It is therefore not essential to apply a large (deep) saturated zone within the biofilter enriched with carbon source, since leaching of TOC (carbon source hydrolysis) is more problematic than the release of low-levels nitrate. As demonstrated in previous study (Aloni and Brenner, 2017), excess carbon leaching (being itself a problem) might cause sulfate reduction and formation of sulfides in groundwater.

Based on these assumptions, the columns were designed to have a minimal bottom saturated zone of 10 cm only (to maintain continuous humidity within the biofilter for the plants), and no use of organic carbon source in all columns. Another difference from the Australian practice was the construction of 5 of the 7 columns used to simulate stormwater treatment (winter phase) in a shorter height of 70 cm only. This was done in order to test potential Israeli applications which might be limited by a shallow infrastructure of water and sewage pipes. Two other columns had the same structure as the columns served for the simulation of denitrification in stage I (see Fig. 3).

The experiments were done using a synthetic mixture for the simulation of a typical Israeli stormwater. We used data collected in a large urban area, incorporating 25 sub-basins which include residential area, industrial zone, and paved roads. The synthetic solution which served for the experiments was prepared by mixing DDW (80%) and tap water (20%). Various salts were added to form typical concentrations of organic matter (TOC 5 mg/L), Ammonia (5 mgN/L), phosphate (2 mgP/L), sodium (20 mg/L), chloride (20 mg/L), pH 7, alkalinity (30 mg/l as CaCO₃), and electrical conductivity (150 µs/cm). Humic-acid was selected to present the natural organic matter characterizing surface water. It is a relatively a non-biodegradable organic substance, but it tends to adsorb to soil. No suspended solids and metals were added at this stage. The main initial purpose was to follow the transformations of organic matter and nutrients (nitrogen and phosphorus forms) within the columns.

For these experiments, three types of plants were used: *Agapanthus*, *Tolbaghia*, and *Vetiver*. Layout of the experimental array is shown in Fig. 4. Three

columns were operated with no plants (two long columns and one of the short columns) in order to examine bacterial activity within the column with no plant effect. One of the long column was seeded with biomass from a near-by WWTP.

Fig. 4. Layout of the experimental array for the simulation of stormwater treatment

2. Results and discussion

3.1 - Testing denitrification in biofilters

As explained before, two columns were operated to simulate bioremediation of nitrate-contaminated groundwater (initial concentration 100 mg/L), under continuous flow, hydraulic load of 36 mm/h, and use of *Vetiver* plants on top of the columns.

Fig. 5. Nitrate outlet concentrations in the cotton and wood-chips biofilters

This stage was applied for 100 days. During this stage, *Vetiver* plants after acclimation of several weeks in external vessels, were added on top of the columns. These plants proved to be resistant to hot weather and could flourish well under continuous wetting. The plants adjusted and developed very well, but no change in process performance was observed compared to previous studies with no plants (data not shown). Chronological changes of nitrate concentrations in columns outlets are shown in Fig. 5 demonstrating similar performance for the two carbon sources that were tested.

The synthetic solution that served for the denitrification experiments did not contain nitrite. Nitrite is actually an intermediate compound formed frequently during denitrification. It might accumulate due to some factors such as C/N ratio, hydraulic load, and oxygen inhibition. These parameters are more difficult to control in a deep biofilter than in a conventional reactor. As happened in a previous study (Aloni & Brenner, 2017) nitrite might accumulate under certain conditions, when high levels of nitrate are treated. Moreover, nitrite is much more problematic than nitrate concerning human health effects.

Fig. 6. Nitrite outlet concentrations in the cotton and wood-chips biofilters

Therefore, it was crucial to monitor nitrite formation during all experiments related to denitrification of high-nitrate concentrations. Fig. 6 shows very low levels of nitrite during the experiment, indicating partial removal of nitrate (Fig. 5), but complete reduction of nitrite.

The synthetic solution which served for the experiments did not included any source of organic matter. The source of remaining TOC in the biofilter outlet stems from hydrolysis of the carbon sources put within the columns. Fig. 7 shows the levels of TOC released during the study. It can be concluded that proper design of

C/N ratio, appropriate carbon distribution within the biofilter, and controlled hydraulic load, can result in partial but sufficient nitrate reduction (as required) with a minimal release of residual TOC.

3.2 - Simulation of stormwater treatment

As described before, 7 biofilter-columns were constructed to simulate stormwater treatment (5 short columns, 3 of them planted with *Agapanthus*, *Tulbaghia*, and *Vetiver*; 2 long columns similar to those tested in stage I). The columns were operated in a batch mode based on manual instantaneous irrigation, which was gradually increased in volume and decreased in frequency.

Fig. 7. TOC outlet concentrations in the cotton and wood-chips biofilters

Results of five subsequent periods, are described herein. They include: daily feed of 1 liter; 2 liters twice a week; 5 liters once a week; 10 liters once a week, and 15 liters once a week. This strategy was selected to gradually load the columns in order to reach a critical burden resulting in columns failure (breakthrough of pollutants). It is also aimed at comparing two types of columns (long and short), and for testing the no-saturation & no-addition of carbon source concept and its effect on nutrients transformations (based on the assumptions presented before).

Fig. 8 demonstrates high efficient removal of ammonia, probably due to bacterial nitrification, since this behavior is achieved in columns with and without vegetation.

The large aerobic zone applied, enabled complete nitrification even with the highest hydraulic load (15 liters instantaneous irrigation). All columns produced effluents with ammonia concentration lower than 0.4 mgN/L (feed concentration was approximately 5 mgN/L). This process results in the formation of nitrate, as shown in Fig. 9. The theoretical nitrate concentration is expected to be 5 mgN/L. The column seeded with bacteria show higher concentrations with a gradual

decrease with time, probably due to bacteria decay. The four columns with vegetation demonstrate lower outlet nitrate concentrations compared to the non-vegetated columns. It is clearly shown that the plants contribute to the removal of nitrate by assimilation. No nitrite accumulation was observed (data not shown).

Fig. 8. Fate of ammonia during simulation of stormwater treatment

Removal of phosphate was relatively high under low hydraulic loads, probably due to sorption to soil and to plant assimilation. Under high organic loads there was a breakthrough causing release of residual phosphate (data not shown).

Fig. 9. Fate of nitrate during simulation of stormwater treatment

During the experiments water loss was observed in all columns (difference between inlet and outlet water volumes). It reached levels of 10-15% (data not shown). This phenomenon actually contributes to the increase of contaminants concentrations in biofilter outlet. It is therefore more accurate to calculate removal efficiency on the basis of contaminants load and not on the basis of their concentrations. Contaminant load is calculated by multiplying water volume and contaminant concentration.

3. Summary and conclusions

Operation of biofilters during a long period to simulate treatment of stormwater and bioremediation of nitrate-contaminated groundwater, proved the feasibility of the concept offered. The main conclusions derived for the mode of bioremediation of nitrate-contaminated groundwater are:

- Use of cotton as an alternative solid carbon source in place of the traditional wood-chips was found to be feasible and yielded efficient removal of nitrate.
- Under continuous flow and controlled hydraulic load, nitrite formation was negligible and TOC levels remained very low.
- Complete removal of nitrates is not recommended, in order to avoid TOC leaching, and to prevent development of anaerobic environment which might cause sulfate reduction and formation of sulfide.

The main conclusions for the stormwater treatment mode are:

- The problematic nitrogen forms that should be removed from typical stormwater are organic nitrogen and ammonia. These could be easily removed by bacterial nitrification. In this regard, both short and long columns achieved complete nitrification to levels below 0.4 mgN/L for the whole range of hydraulic loads applied.
- Since nitrate levels resulting from nitrification are very low, there is no necessity to apply denitrification. Thus, there is no need to add carbon source and to apply a saturated zone. This will enable to design simple and less costly biofilters, and to prevent problems of TOC leaching into groundwater.
- Biofilters with plants achieved higher removal of total N and P, probably due to plant assimilation.

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