Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.926838

55 (2015) 1413–1421
July

Taylor & Francis
Taylor & Francis Group

Effect of primary effluent coagulation on performance of laboratory-scale managed aquifer recharge system

Chol D.T. Abel[a,*], Roman C. Vortisch[b], Joseph P. Ntelya[a], Saroj K. Sharma[a], Maria D. Kennedy[a,c]

[a]*UNESCO-IHE Institute for Water Education, P.O. Box 3015, 2601 DA Delft, The Netherlands, Tel. +31 152151896; Fax: +31 152122921; emails: c.abel@unesco-ihe.org, cholabel@gmail.com (C.D.T. Abel), Tel. +31 152151896; email: ntelyajoseph@yahoo.com (J.P. Ntelya), Tel. +31 152151772; email: s.sharma@unesco-ihe.org (S.K. Sharma), Tel. +31 152151774; email: m.kennedy@unesco-ihe.org (M.D. Kennedy)*
[b]*Department of Hydrosciences, Dresden University of Technology, Helmholtzstraße 10, 01069 Dresden, Germany, Tel. +49 35146333382; email: roman.vortisch@gmail.com*
[c]*Department of Water Management, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands*

Received 24 January 2014; Accepted 14 May 2014

ABSTRACT

Aluminum and iron salts are widely used as coagulants in water and wastewater treatment. Two identical soil columns were fed with coagulated and non-coagulated primary effluent (PE) to investigate effect of coagulation on removal of suspended solids, bulk organic matter, nitrogen, and pathogens indicators during managed aquifer recharge. Aluminum sulfate and iron chloride were used as coagulants. Experimental results showed considerable suspended solids removal of >65% by both coagulants at optimum doses. However, the overall suspended solids removal by infiltration and coagulation–infiltration was ~90%. Likewise, removal of phosphorus by coagulation was 80%, whereas total removal by coagulation–infiltration was >98% compared with ~30% by infiltration only. Coagulation of primary removed 16–22% of dissolved organic carbon whereas total removal of ~70% by coagulation–infiltration accounted to 1.4 orders of magnitude higher than infiltration only. Furthermore, removal of pathogens indicators increased considerably from 2.5 $\log_{10}$ units during infiltration only to 3.8 $\log_{10}$ units during coagulation–infiltration for *Escherichia coli*. Similarly, *total coliforms* removal increased from 2.6 to >4 $\log_{10}$ units. These results imply that coagulation of PE using both aluminum sulfate and iron chloride essentially gives similar contaminants removal. Removal of suspended solids improves operation of soil aquifer treatment site by reducing surface clogging while reduction of phosphorus through coagulation also improved removal of pathogenic micro-organisms.

Keywords: Coagulation; Managed aquifer recharge; Optimum dose; Primary effluent; Suspended solids

1. Introduction

Wastewater reclamation through managed aquifer recharge (MAR) systems like soil aquifer treatment (SAT) is becoming increasingly attractive in water-scarce regions due to lower capital investment, energy requirements, and operator expertise requirements [1,2]. SAT improves water quality during percolation through the unsaturated zone [3] before it receives

---

*Corresponding author.

1944-3994/1944-3986 © 2014 Balaban Desalination Publications. All rights reserved.

additional purification during its lateral movement in the saturated zone [4]. Additionally, SAT has been used to provide additional treatment for primary, secondary, and tertiary effluents from wastewater treatment plants (WWTPs) for reuse [1,4,5]. SAT using primary effluent (PE) could be an attractive option for developing countries where wastewater is discharged to receiving water bodies with minimal or no treatment [6]. Nevertheless, wastewater effluent (i.e. SAT) contains high concentrations of suspended solids, colloidal particles, and nutrients that interact with soil and cause physical, biological, and chemical clogging of the infiltrating surface [7]. Therefore, a proper pre-treatment of PE prior to its application to SAT is likely to reduce the formation of the surface clogging and enhance SAT performance [1]. Coagulation–flocculation followed by sedimentation is one of the treatment processes employed to reduce suspended and colloidal particles in water/wastewater.

Aluminum and iron salts are the commonly used inorganic coagulants [8]. Aluminum and iron salts dissociate when added to water and immediately form trivalent ions of Al^{3+} and Fe^{3+} [9]. While alum coagulation is normally effective within pH range between 6.5 and 7.5, coagulation with iron salts is effective in a pH range between 4 and 11 [10].

Despite the successful use of aluminum sulfate and iron chloride in water and wastewater treatment processes that apply coagulation, the use of both coagulants for pre-treatment of PE and subsequent use in SAT has not been well explored. Therefore, the purpose of this study was to investigate the effect of PE coagulation using aluminum sulfate and iron chloride on SAT performance with respect to SS, dissolved organic carbon (DOC), NH_4–N, PO_4–P, and pathogens indicators removal.

2. Materials and methods

2.1. Source and characteristics of PE

The PE used in this study was sampled from an activated sludge WWTP Harnaschpolder, situated in The Hague area, the Netherlands. PE was stored in a cooling room in the laboratory at 4°C upon collection and used within 3 d after collection. The PE samples were then removed from the cooling room and aerated at room temperature for 4 h to increase dissolved oxygen (DO) concentration before experimentation. The PE was then allowed to settle after which the supernatant was siphoned and filtered through 63 μm microsieve prior to application to the column. Detailed water quality characteristics of the PE used in the study are presented Table 1.

Table 1
Characteristics of PE

Parameter	Unit	Average concentration
DOC (before aeration)	mg/L	49.4 ± 3.9
DOC (after aeration)	mg/L	41.5 ± 6.8
pH	–	7.4 ± 0.2
Temperature	°C	20.5 ± 0.7
DO (PE upon collection)	mg/L	0.5 ± 0.1
DO (after aeration)	mg/L	7.1 ± 0.8
EC	μs/cm	1407.2 ± 116.3
BOD_5	mg/L	145 ± 7.1
COD	mg/L	448 ± 10.4
SS	mg/L	180 ± 12.7
Turbidity	NTU	139.8 ± 24.2
NO_3–N	mg/L	2.2 ± 0.2
NH_4–N	mg/L	46.5 ± 7.5
PO_4–P	mg/L	10.5 ± 2.3
Alkalinity	mg/L as HCO_3^-	483.1 ± 7.3

2.2. Jar test

Analytical grades hydrated iron (ferric) chloride ($FeCl_3{\cdot}6H_2O$) and aluminum sulfate ($Al_2(SO_4)_3{\cdot}18H_2O$) from Merck KgaA, Germany were used as the source of iron and aluminum ions utilized for coagulation of PE used in the experiments. A jar test apparatus (VELP SCIENTIFICA JLT6, Italy) with multiple stirrers operated at the same speed was used for simulating rapid and slow mixing. Rapid mixing of PE in 1 L beaker was performed by conducting coagulation at 100 rpm (mean velocity gradient $61.9\,s^{-1}$) and 150 rpm (mean velocity gradient $113.7\,s^{-1}$) at 1.5 and 1 min, respectively. Iron chloride and aluminum sulfate were added few milliliters below the PE surface at the center of the beakers and varied at 0, 1.93, 3.86, 5.79, 7.72, 9.65, 19.3, 28.95, 38.60, 48.25, and 57.9 mg Fe^{3+}/L for iron chloride and 0, 0.47, 0.93, 1.86, 2.79, 3.72, 4.65, 6.51, 9.30, 11.16, 13.95, and 18.6 mg Al^{3+}/L for aluminum sulfate. Slow mixing was then carried out at 20 rpm for 20 min followed by a sedimentation phase of 30 min during which the flocs formed in the solution were left to settle. About 100 mL sample volume was siphoned from the supernatant of each beaker.

2.3. Experimental setup

Laboratory tests were performed on two identical uPVC columns roughened from inside to minimize preferential and column interface flow. The columns were wet-packed in layers by allowing silica sand grains (grain size 0.8–1.25 mm, uniformity coefficient (Cu) = 1.4) to settle in de-ionized water while slightly tapping on the surface of the column using a mallet rubber hammer to ensure homogeneous media packing in the column. Each column was 4.2 m high with an internal diameter of 57 mm. The media was sieved through 2 mm mesh screen followed by cone and splitting to obtain a representative sample as detailed in [11]. A ponding headspace of 20 cm was provided on the top of each column and influent samples were taken from a port situated in this length to account for any PE quality change in the connection tubes between the feed tank and the column headspace. Sampling ports (SPs) were fitted at an interval of 10 cm in the upper 50 cm of the medium after which subsequent SPs were deployed at 50 cm intervals. The bottom (20 cm) of the column was filled with gravel with grain size ranging from 2 to 10 mm as a support layer. A variable-speed peristaltic pump was used to continuously deliver the PE to the top of the columns at hydraulic loading rate (HLR) of 1.25 m/d at room temperature. Hydraulic residence time of 3.2 d was obtained under continuous PE loading (wetting) at this HLR.

Biofilms formation on the media and subsequent biostability of the soil columns was monitored for 120 d by analyzing DOC of influent and effluent samples filtered through cellulose filter with nominal size of 0.45 µm (Whatman, Germany) after which DOC removal was calculated. The columns were assumed to be ripened (biostablilized) when a difference of <±1% DOC removal was obtained between each successive pair of samples. Ripening process was repeatedly carried out when operating conditions of the system were changed to ensure that the micro-organisms have adapted to the new environmental conditions. Samples from the ripened columns (PE + $\mathrm{SAT_{Al}}$ and PE + $\mathrm{SAT_{Fe}}$) were analyzed for SS, DOC, nitrogen, phosphorus, and pathogens indicators. PE coagulated with aluminum sulfate and iron chloride was then infiltrated into columns. While the first column received PE coagulated with aluminum sulfate (PE + COAG $\mathrm{Al^{3+}}$ + SAT), the second column was fed with PE pretreated using iron chloride (PE + COAG $\mathrm{Fe^{3+}}$ + SAT).

During infiltration of both coagulated and non-coagulated PE, the infiltration rate decreased due to formation of a clogging layer at the surface of the media which was frequently flushed with new PE gently added to the inner surface of the column and removed by syringe. This process was performed once the infiltration rate dropped by 50%. Details of soil column used in the study are presented in [12].

2.4. Analytical methods

Aromatic unsaturated bonding structures in organic compounds causes ultraviolet (UV) light absorption over the range of 200–300 nm [13]. DOC and UV absorbance at wavelength of 254 nm ($\mathrm{UVA_{254}}$) of all pre-filtered samples collected from the WWTP and column were determined within 3 d [14,15]. Specific ultraviolet light absorbance (SUVA) was calculated to explore the contribution of aromatic structures of DOC of the samples using their $\mathrm{UVA_{254}}$ measurements and corresponding DOC values ($\mathrm{UVA_{254}} \times 100/\mathrm{DOC}$).

Ammonium–nitrogen ($\mathrm{NH_4}$–N), nitrate–nitrogen ($\mathrm{NO_3}$–N), and phosphorus ($\mathrm{PO_4}$–P) were determined using colorimetric automated techniques using a spectrophotometer according to [16]. Standard calibration line (in 5 concentration range) was prepared for $\mathrm{NH_4}$–N, $\mathrm{NO_3}$–N, and $\mathrm{PO_4}$–P to calculate their concentrations in various water samples. Determination of SS was performed by drying a 47 mm diameter regenerated cellulose filter with nominal size of 0.4–1 µm (Whatman, Germany) in a furnace at 520˚C for 3 h. The filter was weighed before and after filtering a well-mixed 50 mL of PE and dried at 105˚C for at least 2 h until a constant weight was obtained. SS was then calculated as the difference in the filter weight relative to sample volume used.

Plate count method was used to enumerate pathogens indicators (*Escherichia coli* and *total coliforms*) in unfiltered PE samples according to the methods detailed in [17].

3. Results and discussion

3.1. Coagulation procedure and optimization

During the preliminary experiments, coagulation of PE was performed at different rapid mixing intensities and time to determine the appropriate mixing intensity, time, and optimum coagulant concentrations (OCCs) for aluminum sulfate and iron chloride. OCCs for both iron chloride and aluminum sulfate were the concentrations beyond which no further substantial reduction of residual turbidity and SS was achieved. As presented in Fig. 1 and Table 2, no further appreciable reduction of turbidity and suspended solids was achieved beyond aluminum sulfate dosage of 9.3 mg $\mathrm{Al^{3+}}$/L for both 100 and 150 rpm mixing intensities. Removals of 91% turbidity and 77.5% SS were achieved at mixing intensity of 150 rpm compared to 83.3 and 64.1% at 100 rpm. However, PE coagulation using iron chloride and mixing intensities of 100 and 150 rpm revealed no major change in turbidity removal beyond 88.3 and 86.3% at coagulants doses of 28.95 and 19.3 mg $\mathrm{Fe^{3+}}$/L. SS removals of 74.1 and 71.6% were attained under similar doses and mixing intensities.

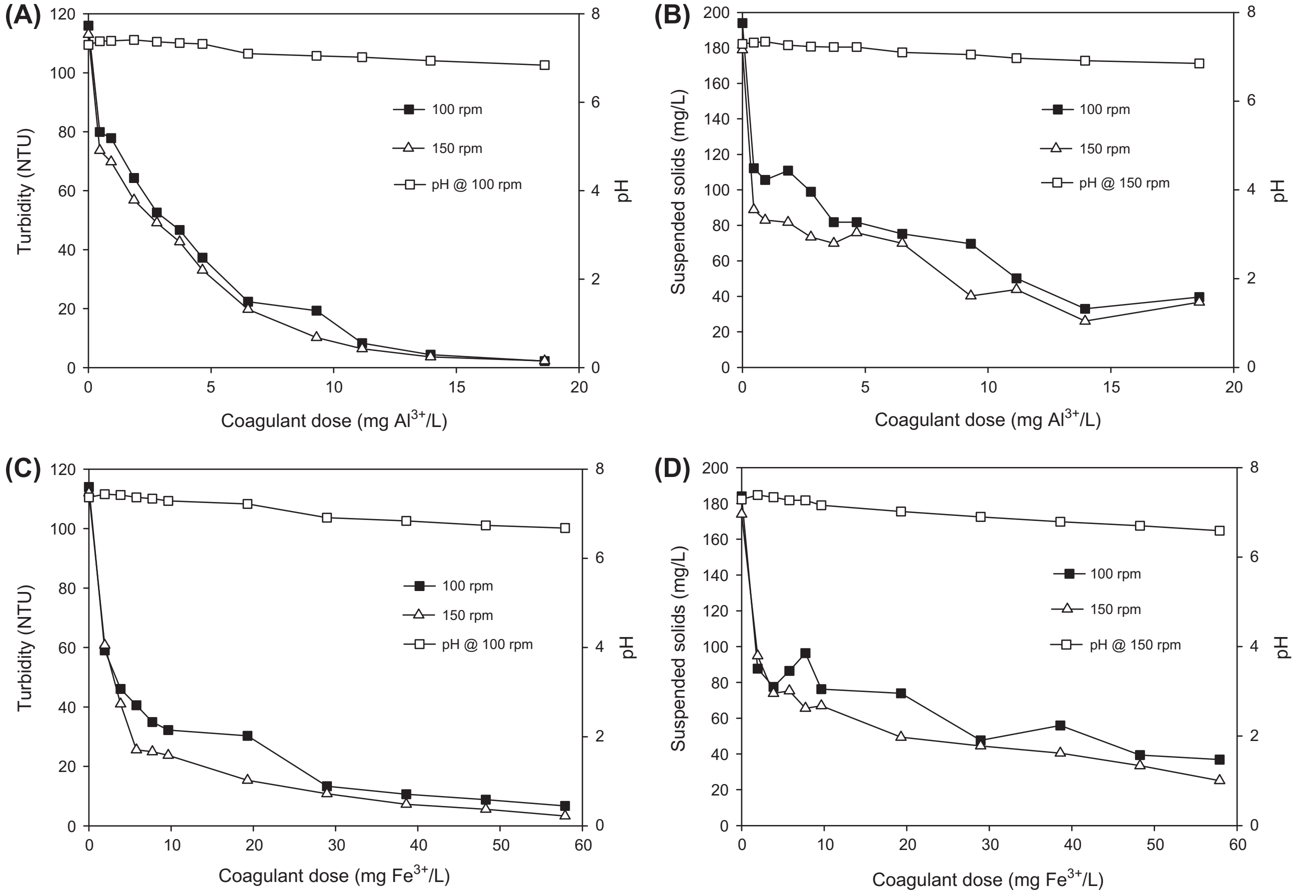

Fig. 1. Effect of rapid mixing of PE in 1 L beaker on residual turbidity and suspended solids using aluminum sulfate (A and B) and ferric chloride (C and D).

Table 2

Effect of PE coagulation using different coagulants at different rapid mixing intensities on removal of turbidity and suspended solids

Coagulant	Mixing intensity (rpm)	Coagulant dosage (mg/L)	Turbidity removal (%)	Suspended solids removal (%)	pH
Aluminum sulfate	100	9.3	83.3	64.1	7.05
	150	9.3	91.0	77.5	7.05
Ferric chloride	100	28.95	88.3	74.1	7.01
	150	19.3	86.3	71.6	7.12

Among the two rapid mixing intensities examined, 150 rpm demonstrated higher turbidity and SS removal compared to 100 rpm. It was also noticed that no substantial turbidity and SS removal observed beyond coagulant doses higher than 9.3 mg Al^{3+}/L for aluminum sulfate and 19.3 mg Fe^{3+}/L for ferric chloride.

Thus, it was concluded that rapid mixing intensity of 150 rpm and OCCs of 9.3 mg Al^{3+}/L and 19.3 mg Fe^{3+}/L should be adopted for coagulation of the PE used prior to infiltration.

3.2. Suspended solids

Removal of SS is an essential feature of wastewater coagulation [18]. SS was monitored by tracking the quality of infiltrated coagulated and non-coagulated PE along the soil column. It was observed that most

SS removal from non-coagulated PE (influent: 170.3 ± 3.7 mg/L) occurred in the upmost part of the column. Coagulation of PE (influent: 185.0 ± 4.2 mg/L) using OCC of 9.3 mg Al^{3+}/L from aluminum sulfate and OCC of 19.3 mg Fe^{3+}/L from iron chloride removed 65.1 ± 0.4 and 68.7 ± 0.8%, respectively. However, similar total SS removals of 90.4 ± 0.7, 89.6 ± 0.7, 89.9 ± 0.5, and 90.9 ± 0.1% were achieved in PE + SAT_{Al}, PE + SAT_{Fe}, PE + COAG Al^{3+} + SAT, and PE + COAG Fe^{3+} + SAT, respectively. These results suggest that despite substantial initial SS removal by coagulation process, there was notable contribution to the total SS removal as compared to infiltration only. Most of SS was removed in the upmost 1 m of the column during infiltration of non-coagulated PE. However, coagulation process led to notable reduction of clogging layer development at the surface of the media and consequently stabilized the infiltration rate. This process prolonged the frequency at which the media surface was gently flushed with influent water from one week to four weeks. Furthermore, equal SS removals following PE coagulation with both coagulants implies that the cost of each coagulant coupled with the volume of sludge generated would dominate which coagulant should be adopted for pretreatment of PE prior to infiltration.

3.3. Bulk organic matter

Aluminum sulfate and iron chloride act to destabilize and remove colloidal and DOCs through production of cationic hydrolysis products [19]. For both coagulants, DOC content of 44.4 ± 3.4 mg/L was removed at optimum coagulant doses by 16.3 ± 1.1% with aluminum sulfate and 22.2 ± 0.5% with iron chloride. These observed differences are consistent with the findings of other researchers that higher DOC removals are achieved with iron chloride as compared to aluminum sulfate [20,21] which is attributable to formation of bigger and stronger flocs by iron chloride [22,23] that facilitate DOC charge neutralization, adsorption, and entrapment into insoluble aggregates [24]. Furthermore, when the coagulated PE was infiltrated into soil columns total DOC removals of 68.1 ± 2.5 and 70.4 ± 0.3% were attained in PE + COAG Al^{3+} + SAT and PE + COAG Fe^{3+} + SAT, respectively. These results show no considerable difference in using either of the coagulants to pre-treat PE. However, DOC removal was relatively higher than that achieved during infiltration of non-coagulated PE, where 47.6 ± 1.5 and 49.3 ± 0.4% of initial DOC concentration (35.7 ± 1.0 mg/L) was removed in PE + SAT_{Al} and PE + SAT_{Fe}, respectively. These results show that wastewater coagulation prior to biological treatment (i.e. infiltration) enhances DOC biodegradability during biological treatment [25]. Fig. 2 presents DOC concentration profiles along soil columns fed with PE.

SUVA is used to indicate aromatic compounds in the DOC and chemical nature of the DOC [26]. SUVA values changed during infiltration of both coagulated and non-coagulated PE. Coagulation process using aluminum sulfate and iron chloride reduced SUVA of PE slightly from 1.9 ± 0.1 L/mg m to respective values of 1.7 ± 0.1 and 1.5 ± 0.1 L/mg m suggesting removal of aromatic fractions of DOC. On the contrary, SUVA values of the coagulated PE upon infiltration increased considerably in the first 1 m of the column followed by decrease in the subsequent 3 m. SUVA values along PE + COAG Al^{3+} + SAT profile increased from an influent value of 1.8 ± 0.1 to 3.6 ± 0.2 L/mg m in the first 1 m of the column, then slightly decreased to 2.4 ± 0.1 L/mg m at the effluent. Similar trends were observed along PE + COAG Fe^{3+} + SAT profile where SUVA increased from 1.5 ± 0.1 to 3.4 ± 0.1 L/mg m in the upmost 1 m before decreased to 2.5 ± 0.2 L/mg m at the effluent. On the other hand, SUVA of the non-coagulated PE increased from an influent value of 1.7 ± 0.1 to 3.0 ± 0.2 L/mg m in the upmost 1 m of the column after which a steady decrease was observed along the remaining 3 m depth of the column, resulting in an effluent SUVA value of 2.3 ± 0.0 L/mg m. Increase in SUVA values in the first 1 m of the column is attributed to removal of aliphatic DOC fractions through biodegradation, whereas decrease in SUVA values suggests removal of aromatic DOC fractions in the subsequent 3 m of the column through adsorption.

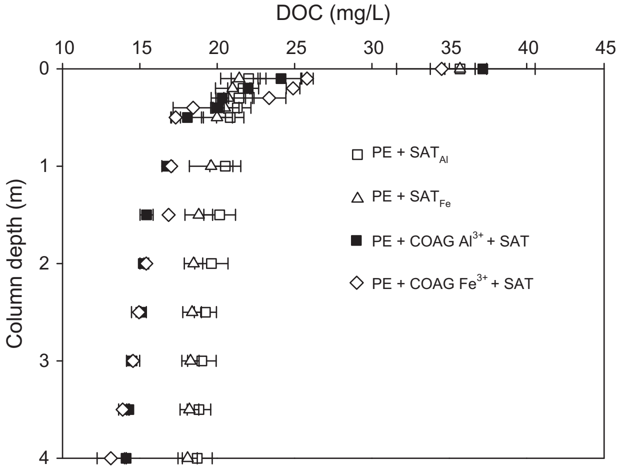

Fig. 2. Average DOC concentration as a function of column depth (influent: PE, media size: 0.8–1.25 mm, HLR = 1.25 m/d).

3.4. Nitrogen

Coagulation of PE prior to infiltration resulted in initial NH_4–N reduction of 6.6 ± 1.3 and 7.2 ± 0.2% by aluminum sulfate and iron chloride, respectively. However, coagulation and infiltration combined led to a total NH_4–N reduction of 60.9 ± 2.6 and 64.7 ± 1.9% in PE + COAG Al^{3+} + SAT and PE + COAG Fe^{3+} + SAT, respectively. Infiltration of non-coagulated PE removed 21.4 ± 0.9 and 22.9 ± 2.4% of its NH_4–N content of 48.9 ± 3.9 mg N/L in PE + SAT_{Al} and PE + SAT_{Fe}, respectively. It was noticed that most of NH_4–N reduction occurred in the top 1 m through nitrification process as evidenced by the corresponding increase in NO_3–N concentrations at this depth. Further NH_4–N reduction observed along the column was attributed to adsorption of NH_4–N to the media [27]. On the other hand, NO_3–N content of non-coagulated PE were 1.0 ± 0.2, 5.4 ± 0.3, and 2.4 ± 0.3 mg N/L at influent, <1 and 4 m, respectively. At the same depths, coagulated PE exhibited 1.2 ± 0.1, 14.2 ± 1.6, and 7.2 ± 0.7 mg N/L NO_3–N concentrations. A steady decrease of NO_3–N was observed in the last 3 m of the column suggesting dominance of denitrification process as evidenced by low NO_3–N concentration exiting the column. Removal of NO_3–N by denitrification process in MAR systems prevents pollution of groundwater [27]. DO concentration rapidly decreased from 7.8 ± 0.3 mg/L to as low as 0.6 ± 0.1 mg/L in the first 1 m of the column suggesting utilization of DO by micro-organisms to mediate biological reduction of DOC and NH_4–N. Fig. 3 illustrates change in (A) NH_4–N concentrations along columns profiles and (B) corresponding changes in NO_3–N concentrations.

3.5. Phosphorus

Substantial removal of PO_4–P from PE was achieved through coagulation. Aluminum sulfate removed 79.1 ± 1.2% of influent PO_4–P of 12.6 ± 0.1 mg/L, whereas iron chloride removed 80.3 ± 0.5%. Infiltration of the coagulated PE diminished the remaining PO_4–P content leading to a total removal of 98.4 ± 0.2 and 98.1 ± 0.3% in PE + COAG Al^{3+} + SAT and PE + COAG Fe^{3+} + SAT, respectively. However, infiltration of non-coagulated PE removed 30.6 ± 0.7% of influent PO_4–P of 10.1 ± 0.6 mg/L, whereas iron chloride removed 29.4 ± 2.0%. PO_4–P is mainly sorbed or precipitated in filter media [28]. The main removal mechanism for PO_4–P during infiltration is predominantly adsorption, which diminishes once the sorption capacity of the media is exhausted due to continuous application of PO_4–P [27]. This limitation has presumably caused the relative low PO_4–P removal from the non-coagulated PE. Furthermore, the presence of natural organic matter (NOM) originating from surface water used as drinking water source had led to competition between the NOM and PO_4–P for adsorption sites, especially at pH above 7 (7.4 ± 0.2) [29]. Fig. 4 shows change in PO_4–P concentrations of coagulated and non-coagulated PE along soil columns profiles.

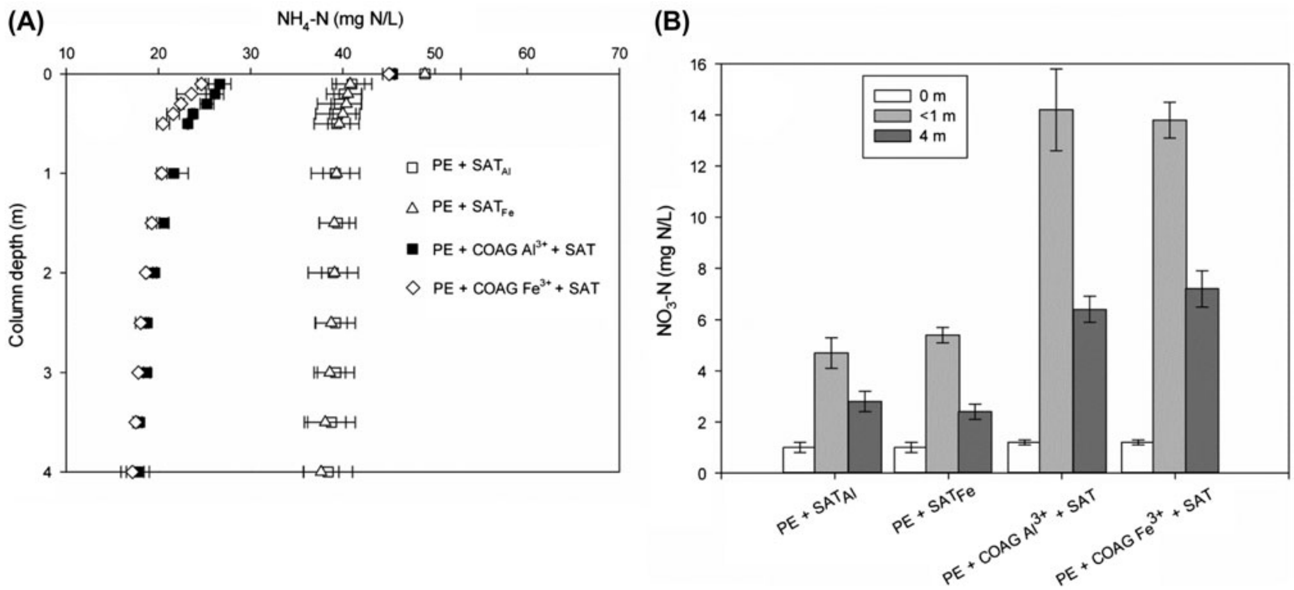

Fig. 3. Average (A) NH_4–N and (B) NO_3–N concentrations profiles along the soil column operated at alternate wetting/drying cycles (influent: PE, media size: 0.8–1.25 mm, HLR = 1.25 m/d).

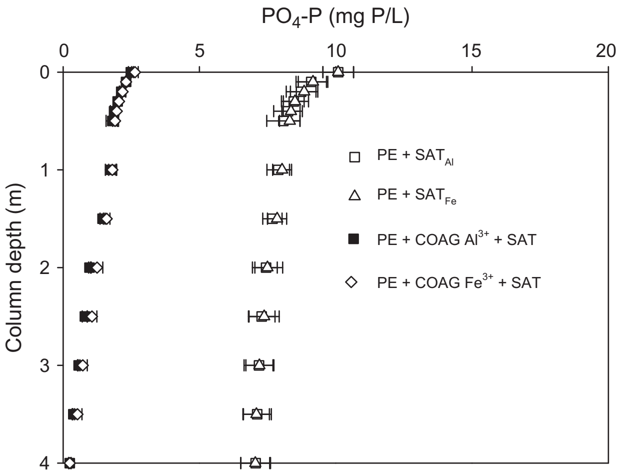

Fig. 4. Average PO_4–P concentration along the column depth (influent: PE, media size: 0.8–1.25 mm, HLR = 1.25 m/d).

Table 3
Effect of PE coagulation and infiltration in soil columns (influent: PE, media size: 0.8–1.25 mm, HLR: 1.25 m/d)

	Pathogens indicator removal (log_{10} units)	
Operating condition	*E. coli*	*Total coliforms*
PE + SAT_{Al}	2.5 ± 0.2	2.7 ± 0.3
PE + SAT_{Fe}	2.5 ± 0.1	2.6 ± 0.3
PE + COAG Al^{3+} + SAT	3.8 ± 0.0	4.4 ± 0.0
PE + COAG Fe^{3+} + SAT	3.8 ± 0.0	4.3 ± 0.0

3.6. E. coli *and* total coliforms

The effect of coagulation followed by infiltration on removal of *E. coli* and *total coliforms* from PE was examined using two coagulants. The mean concentrations of indicator pathogens in PE treated with coagulation was $6.6 \times 10^6 \pm 0.6 \times 10^6$ CFU/100 mL for *E. coli* and $25.1 \times 10^6 \pm 0.9 \times 10^6$ CFU/100 mL for *total coliforms*. Coagulation of PE using aluminum sulfate removed 0.6 ± 0.2 log_{10} units of *E. coli* compared to 0.6 ± 0.1 log_{10} units of *total coliforms*. However, coagulation process using iron chloride removed 0.9 ± 0.3 and 0.6 ± 0.0 log_{10} units of *E. coli* and *total coliforms*, respectively.

From Table 3, it can be seen that infiltration of non-coagulated PE removed 2.5 ± 0.2 log_{10} units of *E. coli* and 2.7 ± 0.3 log_{10} units of *total coliforms* in PE + SAT_{Al} compared to 2.5 ± 0.1 log_{10} units of *E. coli* and 2.6 ± 0.3 log_{10} units of *total coliforms* in PE + SAT_{Fe}.

E. coli and *total coliforms* removal in PE + COAG Al^{3+} + SAT accounted to 3.8 ± 0.0 and 4.4 ± 0.0 log_{10} units, respectively. Similar removal was achieved when PE was coagulated with iron chloride then infiltrated into PE + COAG Fe^{3+} + SAT resulting in *E. coli* and *total coliforms* removal of 3.8 ± 0.0 and 4.3 ± 0.0 log_{10} units, respectively. Attenuation of pathogens during infiltration is achieved through inactivation, straining, and attachment to aquifer materials [30]. High removals for both *E. coli* and *total coliforms* by coagulation coupled with infiltration might be attributed to removal of PO_4–P by coagulation which reduced competition between pathogens indicators and PO_4–P for adsorption sites in the media along the column profile.

The above results show that PE coagulation prior to infiltration is a viable pre-treatment option for MAR as it reduces SS content of PE substantially and consequently lead to longer run time for infiltration basins. Besides, introduction of coagulation improved the overall DOC, NH_4–N and pathogens removal regardless of the coagulant type. Summary of various contaminants removal is presented in Table 4.

4. Conclusions

Coagulation process using aluminum sulfate and iron chloride reduced the initial SS load of PE prior to application to the soil column by >65%. This considerable SS removal has a positive effect on SAT site

Table 4
Summary of contaminants removal during infiltration of coagulated and non-coagulated PE in soil columns (media size: 0.8–1.25 mm, HLR: 1.25 m/d)

	Contaminant removal					
Operating conditions	SS (%)	DOC (%)	NH_4–N (%)	PO_4–P (%)	*E. coli* (log_{10} units)	*Total coliforms* (log_{10} units)
PE + SAT_{Al}	90.4 ± 0.7	47.6 ± 1.5	21.4 ± 0.9	30.6 ± 0.7	2.5 ± 0.2	2.7 ± 0.3
PE + SAT_{Fe}	89.6 ± 0.7	49.3 ± 0.4	22.9 ± 2.4	29.4 ± 2.0	2.5 ± 0.1	2.6 ± 0.3
PE + COAG Al^{3+} + SAT	89.9 ± 0.5	68.1 ± 2.5	60.9 ± 2.6	98.4 ± 0.2	3.8 ± 0.0	4.4 ± 0.0
PE + COAG Fe^{3+} + SAT	90.9 ± 0.1	70.4 ± 0.3	64.7 ± 1.9	98.1 ± 0.3	3.8 ± 0.0	4.3 ± 0.0

performance in terms of surface clogging leading to longer run time before drying and scraping/raking. Nevertheless, there was no major effect on the overall SS removal following infiltration of the coagulated PE which leveled at ~90%, similar to SS removal obtained from infiltration of non-coagulated PE.

Coagulation of PE using aluminum sulfate and iron chloride resulted in DOC removal of 16.3 ± 1.1 and 22.2 ± 0.5%, respectively. Infiltration of the coagulated PE led to a profound DOC removal which was 1.4 orders of magnitude higher than infiltration only for both coagulants.

Substantial PO_4–P removal above 80% was achieved by coagulation of PE using aluminum sulfate and iron chloride. Furthermore, infiltration of the coagulated PE led to a total PO_4–P removal >98% compared to ~30% by infiltration only.

Removal of *E. coli* and *total coliforms* by coagulation was less than $1\log_{10}$ units. However, infiltration of coagulated PE led to removal of 3.8 and $>4\log_{10}$ units for both pathogens indicators compared to $\sim 2.5\log_{10}$ units for non-coagulated PE. This ascribed to the fact that PO_4–P competes with pathogens indicators for adsorption sites in non-coagulated PE. This competition was substantially reduced by removal of PO_4–P through coagulation which in turn led to relatively high bacteria removal.

Acknowledgments

This work was conducted under the financial support of UNESCO-IHE Partnership Research Fund (UPaRF) under the framework of NATSYS project. We extend our gratitude to UNESCO-IHE laboratory staff for their analytical support.

References

[1] S.K. Sharma, M. Hussen, G.L. Amy, Soil aquifer treatment using advanced primary effluent, Water Sci. Technol. 64(3) (2011) 640–646.

[2] M. Viswanathan, M. Alsenafy, T. Rashid, E. Alawadi, K. Alfahad, Improvement of tertiary wastewater quality by soil aquifer treatment, Water Sci. Technol. 40(7) (1999) 159–163.

[3] D. Quanrud, S. Carroll, C. Gerba, R. Arnold, Virus removal during simulated soil-aquifer treatment, Water Res. 37(4) (2003) 753–762.

[4] P. Nema, C. Ojha, A. Kumar, P. Khanna, Techno-economic evaluation of soil-aquifer treatment using primary effluent at Ahmedabad, India, Water Res. 35(9) (2001) 2179–2190.

[5] R.W. Crites, S.C. Reed, E.J. Middlebrooks, Natural Wastewater Treatment Systems, CRC Press, Boca Raton, FL, 2006, pp. 413–426.

[6] L. Wilson, G. Amy, C. Gerba, H. Gordon, B. Johnson, J. Miller, Water quality changes during soil aquifer treatment of tertiary effluent, Water Environ. Res. 67 (3) (1995) 371–376.

[7] H. Bouwer, Artificial recharge of groundwater: Hydrogeology and engineering, Hydrogeol. J. 10(1) (2002) 121–142.

[8] J. Duan, J. Gregory, Coagulation by hydrolysing metal salts, Adv. Colloid Interface Sci. 100–102 (2003) 475–502.

[9] J. Bratby, Coagulation and Flocculation in Water and Wastewater Treatment, 2nd ed., IWA Publishing, London, 2006.

[10] J.M. Ebeling, P.L. Sibrell, S.R. Ogden, S.T. Summerfelt, Evaluation of chemical coagulation–flocculation aids for the removal of suspended solids and phosphorus from intensive recirculating aquaculture effluent discharge, Aquacult. Eng. 29(1–2) (2003) 23–42.

[11] B. Schumacher, K. Shines, J. Burton, M. Papp, A comparison of soil sample homogenization techniques, in: M.S. Simmons (Ed.), Hazardous Waste Measurements, Lewis Publishers, Chelsea, MI, 1991, pp. 53–68.

[12] C.D.T. Abel, S.K. Sharma, S.A. Mersha, M.D. Kennedy, Influence of intermittent infiltration of primary effluent on removal of suspended solids, bulk organic matter, nitrogen and pathogens indicators in a simulated managed aquifer recharge system, Ecol. Eng. 64 (2014) 100–107.

[13] J. Michail, E. Idelovitch, Gross organic measurements for monitoring of wastewater treatment and reuse, Chem. Water Reuse 1 (1981) 35–64.

[14] C.D.T. Abel, S.K. Sharma, E. Buçpapaj, M.D. Kennedy, Impact of hydraulic loading rate and media type on removal of bulk organic matter and nitrogen from primary effluent in a laboratory-scale soil aquifer treatment system, Water Sci. Technol. 68(1) (2013) 217–226.

[15] S.K. Maeng, S.K. Sharma, C.D.T. Abel, A. Magic-Knezev, G.L. Amy, Role of biodegradation in the removal of pharmaceutically active compounds with different bulk organic matter characteristics through managed aquifer recharge: Batch and column studies, Water Res. 45(16) (2011) 4722–4736.

[16] A.D. Eaton, L.S. Clesceri, E.W. Rice, A.E. Greenberg, Standard Methods for the Examination of Water and Wastewater, 21st ed., American Public Health Association, American Water Works Association, and Water Environment Federation, Washington, DC, 2005.

[17] C.D.T. Abel, S.K. Sharma, Y.N. Malolo, S.K. Maeng, M.D. Kennedy, G.L. Amy, Attenuation of bulk organic matter, nutrients (N and P), and pathogen indicators during soil passage: Effect of temperature and redox conditions in simulated soil aquifer treatment (SAT), Water Air Soil Pollut. 223 (2012) 5205–5220.

[18] N. Almutairi, M. Hamoda, I. Al-Ghusain, Coagulant selection and sludge conditioning in a slaughterhouse wastewater treatment plant, Bioresour. Technol. 95(2) (2004) 115–119.

[19] E.L. Sharp, S.A. Parsons, B. Jefferson, The impact of seasonal variations in DOC arising from a moorland peat catchment on coagulation with iron and aluminium salts, Environ. Pollut. 140(3) (2006) 436–443.

[20] K. Bell-Ajy, M. Abbaszadegan, E. Ibrahim, D. Verges, M. LeChevallier, Conventional and optimized

coagulation for NOM removal, J. Am. Water Works Assoc. 92(10) (2000) 44–58.

[21] J.K. Edzwald, J.E. Tobiason, Enhanced coagulation: US requirements and a broader view, Water Sci. Technol. 40(9) (1999) 63–70.

[22] H. Ratnaweera, N. Hiller, U. Bunse, Comparison of the coagulation behavior of different Norwegian aquatic NOM sources, Environ. Int. 25(2–3) (1999) 347–355.

[23] R.J. Stephenson, S.J.B. Duff, Coagulation and precipitation of a mechanical pulping effluent—I. Removal of carbon, colour and turbidity, Water Res. 30(4) (1996) 781–792.

[24] P. Jarvis, B. Jefferson, S.A. Parsons, How the natural organic matter to coagulant ratio impacts on floc structural properties, Environ. Sci. Technol. 39(22) (2005) 8919–8924.

[25] O.S. Amuda, A. Alade, Coagulation/flocculation process in the treatment of abattoir wastewater, Desalination 196(1–3) (2006) 22–31.

[26] J.A. Leenheer, J.P. Croué, Peer reviewed: Characterizing aquatic dissolved organic matter, Environ. Sci. Technol. 37(1) (2003) 18A–26A.

[27] N.V. Paranychianakis, A.N. Angelakis, H. Leverenz, G. Tchobanoglous, Treatment of wastewater with slow rate systems: A review of treatment processes and plant functions, Crit. Rev. Environ. Sci. Technol. 36(3) (2006) 187–259.

[28] C. Vohla, R. Alas, K. Nurk, S. Baatz, Ü. Mander, Dynamics of phosphorus, nitrogen and carbon removal in a horizontal subsurface flow constructed wetland, Sci. Total Environ. 380(1–3) (2007) 66–74.

[29] A. El Samrani, B. Lartiges, E. Montargès-Pelletier, V. Kazpard, O. Barres, J. Ghanbaja, Clarification of municipal sewage with ferric chloride: The nature of coagulant species, Water Res. 38(3) (2007) 756–768.

[30] L. McDowell-Boyer, J. Hunt, N. Sitar, Particle transport through porous media, Water Resour. Res. 22(13) (1986) 1901–1921.