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Article

Improvement of Hydraulic and Water Quality Renovation Functions by Intermittent Aeration of Soil Treatment Areas in Onsite Wastewater Treatment Systems

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Abstract: We tested intermittent aeration of the soil treatment area (STA) of onsite wastewater treatment systems (OWTS) for its ability to restore and maintain STA hydraulic flow and improve the water quality functions of conventional OWTS. Evaluation was conducted on hydraulically-failed conventional OWTS at three state-owned medical group homes in Washington County, RI, USA. Testing was conducted in two phases, with Phase I (before intermittent soil aeration (ISA)) comprising the first 6 months of the study, and Phase II (during ISA) the remaining 7 months. Intermittent soil aeration restored STA hydraulic function in all three systems despite a marked reduction in the STA total infiltrative surface. Soil pore water was collected from 30 and 90 cm below the STA during both phases and analyzed for standard wastewater parameters. Although the STA infiltrative surface was reduced—and the contaminant load per unit of area increased—after installation of the ISA system, no differences were observed between phases in concentration of total N, NO_3, total P, or dissolved organic carbon (DOC). Apparent removal rates—which do not account for dilution or differences in infiltrative area—for

total N, total P, and DOC remained the same or improved during Phase II relative to the pre-operation phase. Furthermore, intermittent soil aeration enhanced actual removal rates —which do account for dilution and differences in infiltrative area. The effects of ISA on actual removal of contaminants from STE increased with increasing hydraulic load—a counterintuitive phenomenon, but one that has been previously observed in laboratory studies. The results of our study suggest that intermittent soil aeration can restore and maintain hydraulic flow in the STA and enhance carbon and nutrient removal in conventional OWTS.

Keywords: septic tank effluent; intermittent aeration; hydraulic function; water quality; SoilAir™

1. Introduction

Approximately 25% of the population of the USA relies on onsite wastewater treatment systems (OWTS) for dispersal and renovation of domestic wastewater, a number that has remained constant for the past 35 years [1]. Improperly functioning OWTS constitute public health and environmental hazards because of their potential to degrade ground, surface, and coastal water quality. Of special concern are elevated emissions of N, P , biodegradable organic C and pathogens, which can adversely impact the utilization of ground and surface water resources [2,3].

The ability of soil treatment areas (STA) in conventional OWTS to accept and renovate septic tank effluent (STE) is subject to fluctuations in dosing frequency, volume, and strength of wastewater. These systems are prone to hydraulic failure due to a number of factors, including lack of proper maintenance [4]. Improvements in the quality of wastewater as it passes through the STA vary considerably, particularly with respect to N removal, which can range from 0 to 30% [2,5].

Current advanced treatment technologies for improving water quality discharged from OWTS include those aimed specifically at removing nitrogen (e.g., recirculating media filters and activated sludge systems) or biochemical oxygen demand (BOD_5) and pathogens (e.g., single-pass sand and peat filters, UV/ozonation units) [2]. Although effective, these technologies can be expensive, require maintenance for proper functioning, and involve hiring a maintenance specialist, all of which can make them difficult to adopt by homeowners [6]. Alternatives for hydraulically failed systems, such as STA replacement to meet current regulations, can also be costly, and may only postpone subsequent hydraulic failure in the absence of routine inspection and maintenance.

In the present study we tested intermittent aeration of STAs for its ability to improve the hydraulic and water quality functions of existing OWTS. The tests were conducted at three medical group homes within the Narragansett Bay watershed in southern Rhode Island, USA. The technology, SoilAir™, involves intermittent aeration (ISA) of the soil treatment area, rather than aeration of septic tank effluent [7]. It has been shown to enhance infiltration of STE in numerous field tests, and was found to enhance the quality of water draining from STAs in pilot studies [8]. Over 1,000 field applications of this technology in commercial and household OWTS in eleven states in the USA and in Canada have shown that it can rejuvenate septic systems by restoring hydraulic function in a matter of days. In a

previous study, Potts *et al.* [8] evaluated the effects of intermittent soil aeration on removal of total N, biochemical oxygen demand (BOD_5) and fecal coliform bacteria from STE in sand-filled leachfield mesocosms relative to unaerated mesocosms. The results of this pilot-scale study indicated that intermittent soil aeration enhances removal of total N, fecal coliform bacteria, and BOD_5, with improvements in water quality generally increasing with hydraulic load.

2. Materials and Methods

2.1. Study Sites

Field evaluations of the performance of ISA technology were carried out at three sites in Washington County, Rhode Island, USA. All were medical group homes managed by the Rhode Island Department of Mental Health, Retardation and Hospitals (RIMHRH), with one site located in the town of South Kingstown and two in Charlestown (Table 1). Medical group homes were selected for the study because they typically have sustained wastewater flows that exceed design flow and thus can stress the STA. Site selection was restricted to those that were similar in use, type and structural condition of the OWTS, accessibility to OWTS components, and soil properties (Table 1). Sites that met these criteria were inspected for functionality and identified as failed or not failed, with failure defined as the STA not accepting STE. Managers of the selected group homes had the septic tanks pumped regularly to prevent STE back-up into the homes. All of the systems selected for our study relied on stone-lined trenches for STE dispersion and were experiencing hydraulic failure. For the purposes of our study, the STA was considered to include the trenches receiving STE and the soil surrounding these trenches.

Table 1. Location, soil series, and soil profile descriptions for study sites [9].

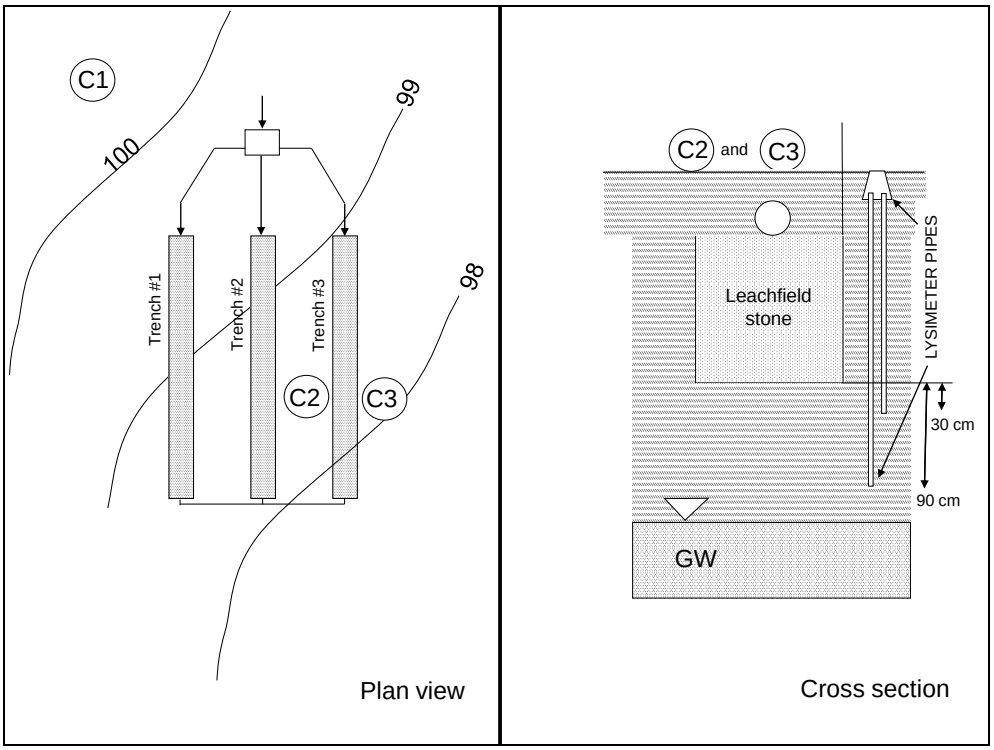
Site	Town	Soil series	Soil profile description
1	South Kingstown	Canton-Urban complex	Coarse loamy over sandy skeletal, mixed mesic Typic Dystrudepts. Upper solum fine sandy loam to gravelly fine sandy loam in the lower B horizons; massive, very friable. Substratum gravelly to very gravelly loamy sand to a depth of 60 inches or more.
2	Charlestown	Merrimac	Sandy, mixed, mesic Typic Dystrudepts. Weakly structured fine sandy loam in the A and upper B horizons and gravelly analogs in lower B. Substratum very gravelly sand; single grain; loose stratified; 40% gravel.
3	Charlestown	Canton-Charlton complex	Coarse loamy over sandy skeletal, mixed, mesic Typic Distrudepts. Upper solum fine sandy loam to gravelly fine sandy loam; massive, very friable. Substratum gravelly to very gravelly loamy sand extending to a depth of 60 inches or more; single grain friable to very friable.

Each septic tank was fitted with a plastic sampling pipe placed near the tank outlet and 45–60 cm below the water surface for sampling of STE. Three nests of ceramic suction cup lysimeters were installed at each site in February of 2006 (Figure 1). Cluster locations were as follows:

Cluster 1 (C1): Upgradient from STA
Cluster 2 (C2): Between leachfield trenches, within the STA
Cluster 3 (C3): Downgradient from STA (within 15–20 cm of outer wall of most downgradient trench)

Within each cluster, two lysimeters were installed with the bottom of the cups at a depth of 30 and 90 cm below infiltrative surface (designated C1-30, C1-90; C2-30, C2-90; C3-30, C3-90).

Figure 1. Plan view (left) and cross section (right) of placement of sampling clusters at the study sites. Drawings are not to scale.



2.2. Treatments

Two treatments are distinguished in the study: Phase I represents the period prior to operation of the ISA system, between March and August 2006; Phase II represents the period during which the ISA system was in operation, between September 2006 and April 2007.

2.3. Installation of Intermittent Soil Aeration System

ISA system components, time dosing pumps and associated controls were retrofitted onto Sites 1, 2 and 3 in mid-September, 2006 (Figure 2). In accordance with established installation protocols developed by Geomatrix, LLC (Old Saybrook, CT), the septic tank at every site was pumped prior to installation of the ISA system components and septic tank effluent pump (STEP) components. In addition, approximately 50%, 50% and 68% of the leachfield system capacity was isolated from the wastewater flow at Sites 1, 2 and 3, respectively, as part of the installation protocols by blocking the flow of STE to particular trenches at the distribution box (D-box) (Figure 2b).

Figure 2. (a) Air blower, filter and controller components of the intermittent soil aeration system; (b) septic tank effluent flow to a portion of the leachfield trenches was blocked at the distribution box to test the robustness of the technology; (c) septic tank effluent pump (STEP) system used in the study.

a **b** **c**

At each site a STEP system was installed in the second compartment of the most downstream septic tank (Figure 2c). Float switches were set to drop the effluent levels in the tank by no more than ~15 cm to provide for flow equalization capacity and to quantify flow. Air lines, consisting of 5 cm Schedule 40 polyvinyl chloride (PVC) pipe, were run from the blower (placed within a protective enclosure) and connected to the pipe between the septic tank and the STA (Figure 2a). Distribution boxes and inspection ports were sealed to prevent the short-circuiting of air. Electrical power and control cables were connected to the ISA system, STEP system and associated float switches. A telecommunications cable was connected between the device controls and the building to facilitate modem communication for remote telemetry of the systems. The microprocessor-based controllers were configured to operate both the blower and the timed-dose STEP system. The STEP system was programmed to be on for a set period of time, which correlated to the desired dose. The STEP dose interval was programmed to run every 6 h, unless a high or low-level float switch was triggered. In addition to controlling dosing, this allowed us to quantify the hydraulic load to the STA. The blower was programmed to remain inactive for approximately 1 h after a wastewater dose. After this time interval, the blower was programmed to run intermittently for a set period of time. The blower and STEP system were interlocked to prevent simultaneous operation, with priority given to the STEP system.

2.4. Sampling and Analyses

A hand pump was used to apply a vacuum (~80 kPa) to the suction cup lysimeters 24 h prior to sampling. Samples of soil pore water from suction cup lysimeters and STE samples were collected using a peristaltic pump fitted with silicon tubing, placed in autoclaved polyethylene screw-cap bottles, and stored in a cooler filled with ice packs immediately after collection.

STE samples were analyzed for dissolved oxygen (DO) immediately after collection in the field. The temperature and concentration of ferrous iron (Fe^{2+}) of samples of STE and of soil pore water samples from cup lysimeters were also determined immediately after collection. Prior to filtering, all samples were analyzed for pH immediately upon arrival at the laboratory. Unfiltered STE samples were analyzed for biochemical oxygen demand (BOD_5). A portion of all unfiltered samples was frozen for subsequent determination of total N (TN) and total P (TP) content. The remaining sample was

passed through a nylon membrane filter (0.45-μm pore-size, 47-mm dia.; Osmonics, Watertown, MA) and the filtrate stored in plastic, screw-cap vials at 4 ℃.

DO was measured using the azide modification of the Winkler titration method [10]. The concentration of Fe^{2+} in water was determined using EM Quant ® Iron (Fe^{2+}) test strips (EM Industries, Inc., Gibbstown, NJ). The pH of water samples was determined using a combination pH electrode and a model UB-10 pH meter (Denver Instruments, Denver, CO). The concentration of sulfate was measured using the barium chloride turbidimetric method [10]. Nitrate, ammonium, and phosphate concentrations of water samples were determined colorimetrically using an automated nutrient analyzer (model Flow Solution IV, Alpkem, College Station, TX). The total N and total P content of water samples were determined using the persulfate digestion method [10] followed by colorimetric analysis of nitrate and phosphate, respectively. Chloride was determined using the argentometric titration method [10]. BOD_5 was measured on undiluted, unamended samples by manometric respirometry using an OxiTop® BOD system (WTW, Fort Myers, FL) at 21 ± 1 ℃. The dissolved organic carbon (DOC) content of filtered samples was determined using a TOC-5000A Total Organic Carbon Analyzer (Shimadzu Instruments, Inc., Laurel, MD).

2.5. Calculation of Apparent and Actual Constituent Removal Rates

The mean concentration of N, P, chloride and DOC in samples from C1 (upgradient, or background) suction cup lysimeters (Figure 1) was subtracted from the mean concentration for samples from either C2 (within the STA) or C3 (downgradient from the STA) lysimeters at the same depth to correct for background effects. The apparent removal rate, R, for constituent X (%) was calculated using the equation:

$$R_X = 100 \times [(C_{X\text{-}STE} - C_{X\text{-}LYS})/C_{X\text{-}STE}] \quad (1)$$

where $C_{X\text{-}STE}$ is the concentration of constituent X in STE and $C_{X\text{-}LYS}$ is the background-corrected concentration of X in a soil pore water sample from a suction cup lysimeter, both expressed in mg/L.

The actual removal rate, Φ, for a constituent X (mg/m^2/d) in the STA was calculated using the equation:

$$\Phi_X = [((R_X - R_{Cl})/100) \times (V_{STE} \times C_{X\text{-}STE})]/A/t \quad (2)$$

where R_X is the apparent mean removal rate for constituent X (%), R_{Cl} is the observed mean removal rate for Cl^- (%), V_{STE} is the mean volume of septic tank effluent applied to the leachfield, $C_{X\text{-}STE}$ is the mean concentration of constituent X in septic tank effluent (mg/L), A is the estimated basal area of leachfield (m^2) (Table 2), and t is time (d). This analysis assumes that Cl^- acts as a conservative tracer of the movement of STE through the soil, with reduction in its concentration attributed exclusively to dilution. An apparent removal rate larger than that observed for chloride is assumed to represent loss processes other than dilution (e.g., biological uptake, abiotic sorption), whereas an apparent removal rate lower than observed for chloride is assumed to represent production processes (e.g., mineralization, desorption). Values of A prior to and after installation of the ISA system at Sites 1, 2 and 3 (Table 2) were estimated from design plans submitted to Rhode Island Department of Environmental Management as part of the original permitting process for septic system installation, and from knowledge of which trenches were isolated when the intermittent aeration system was installed. Values

of *V* represent the mean of automated measurements of the volume of STE dosed daily to the leachfield and were assumed to be the same prior to and during operation of the ISA system, since group home occupancies remained the same (Table 2).

Table 2. Estimates of bottom leachfield area (*A*), mean volume of septic tank effluent dosed daily to a leachfield (*V*), and hydraulic load in Sites 1, 2, and 3.

Site	Phase	A (m^2)	V (L)	Hydraulic load (L/m^2)
1	I	76.6	1440	18.8
	II	38.3	1440	37.6
2	I	24.5	1876	76.6
	II	12.3	1876	152.5
3	I	99.8	4686	47.0
	II	32.1	4686	146.0

2.6. Statistical Analyses

Student's *t* test ($P < 0.05$) was used to evaluate differences in water quality parameters between Phase I and Phase II.

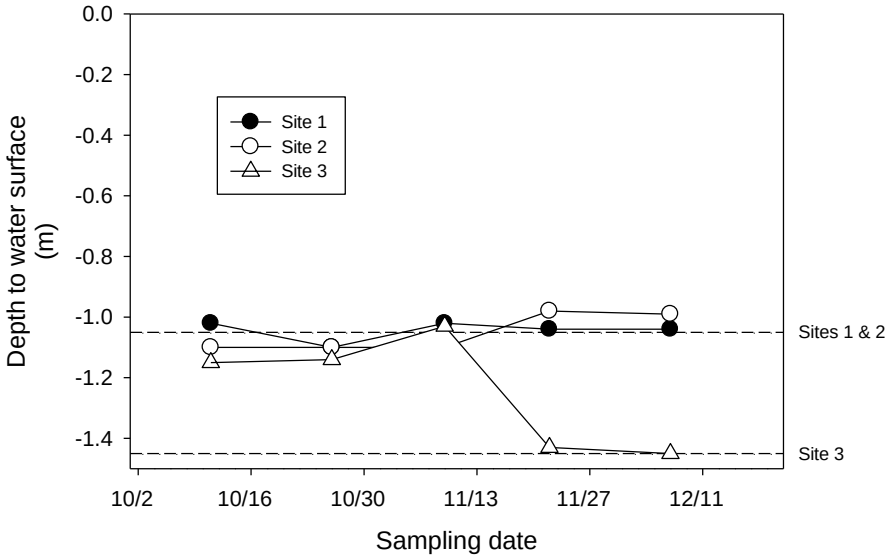
3. Results and Discussion

3.1. Hydraulic Function

All three systems were in hydraulic failure during Phase I, as indicated by STE levels that were considerably above the outlet pipe invert in the D-box and/or the STA not accepting effluent from the septic tank. Once ISA was in operation, measurements of depth to the water surface within the D-box suggest that the hydraulic load at all three sites infiltrated readily, as indicated by the relatively constant values of depth to water surface (Figure 3). Levels of STE were at the D-box outlet pipe inverts during Phase II in all cases. Depth values for Site 3 during the early part of Phase II were affected by an increased hydraulic load from a leaking toilet. Variations in depth to the water surface within a site are the result of differences in timing of measurements relative to dosing events.

Hydraulic failure, which was experienced at all three sites prior to implementation of ISA, results from a combination of factors, including hydraulic overload and/or longer periods of saturation resulting from overloading, which results in a biomat that is increasingly restrictive to STE infiltration. The biomat is thought to form from accumulation of suspended solids and organic debris released by microorganisms under anaerobic conditions, which results in a shift towards smaller pore sizes, restricting infiltration [2]. Fine mineral particles present in STE are trapped within this organic matrix, further restricting infiltration. The thickness of the biomat, and thus its infiltrative capacity, is the net result of microbial processes that produce organic polymers and those that consume it, with production favored under saturated, anaerobic conditions, and consumption favored under unsaturated, aerobic conditions. As such, intermittent aeration of the STA would be expected to enhance infiltration by promoting aerobic conditions that support microbial oxidation of organic polymers in the biomat.

Figure 3. Depth to water surface in the distribution box (D-box) at Sites 1, 2 and 3 during operation of the intermittent soil aeration system. Values indicate distance below the ground surface. Dashed line indicates depth to invert at each site. Depth values for Site 3 during the early part of Phase II were affected by an increased hydraulic load from a leaking toilet.



3.2. Water Quality

Levels of DO in STE were below detection limits at all three sites. Mean (n = 27) values of BOD_5 were 309, 365 and 202 mg/L for Sites 1, 2 and 3. These and other water quality parameter values for STE (Table 3) were in the range of those reported by others [11].

The pH of water below the infiltrative surface was not significantly different between Phase I and Phase II regardless of sampling depth or location at any of the test sites (Table 3). In those instances where Fe^{2+} was present prior to intermittent soil aeration (Phase I), the levels decreased while the ISA was operational, with statistically significant differences observed in most cases (Table 3). Levels of sulfate were not significantly different between Phase I and Phase II at any of the test sites, regardless of sampling depth or position (data not shown).

There was no statistically significant difference in concentration of total P (Table 3) and PO_4 (data not shown) in soil pore water before and during intermittent soil aeration. No significant differences in DOC concentration were observed between Phase I and Phase II at Site 1 or Site 3 (Table 3). By contrast, the concentration of DOC was significantly lower in water from 30 and 90 cm below the infiltrative surface at Site 2 during Phase II (Table 3).

The concentration of total N responded differently to intermittent soil aeration at the three sites. At Site 1 there was a significant increase in total N in soil pore water at 90 cm between Phase I and Phase II, from 12 to 24 and 9 to 20 mg N/L for C2 and C3, respectively (Table 3). These increases were observed despite the fact that the concentration of total N in STE inputs did not change (Table 3), although the load of N per unit area was higher as a result of increase hydraulic load. By contrast, there were no significant differences between Phase I and II in total N levels at 30 or 90 cm in either Site 2

or Site 3 (Table 3). Levels of NO_3 and NH_4 in soil pore water below the infiltrative surface were not significantly different between Phase I and Phase II regardless of sampling depth, position or test site. The relative distribution of inorganic N species differed among study sites during both phases of the experiment. Nitrate generally accounted for >90% of inorganic N at Sites 1 and 2, whereas at Site 3, NH_4 accounted for the bulk of the inorganic N in soil pore water. Previous studies of the composition of soil pore water below the infiltrative surface of conventional OWTS report that NO_3 accounts for 80 to 90% of inorganic N [12,13].

Table 3. Values (mean ± S.D.) of Cl^-, pH, Fe(II), total N, NO_3, total P and dissolved organic carbon (DOC) in STE and in soil pore water at Site 1, 2 and 3 prior to (Phase I) and during (Phase II) operation of intermittent aeration. $n \leq 12$ for Phase I; $n \leq 15$ for Phase II. Units are mg/L except for pH. Values in bold indicate significant difference between Phase I and Phase II.

Site	Parameter	Phase	STE	C2-30	C2-90	C3-30	C3-90
1	Cl^-	I	341 ±129	27 ±35	46 ±31	27 ±23	19 ±13
		II	323 ±128	39 ±45	135 ±40	96 ±93	115 ±77
	pH	I	6.7 ±0.2	6.2 ±0.5	6.2 ±0.5	6.2 ±0.6	6.2 ±0.6
		II	6.7 ±0.3	6.1 ±0.6	5.8 ±0.5	6.0 ±0.5	5.9 ±0.5
	Fe^{2+}	I	0 ±0	**1 ±1**	**1 ±0**	0 ±0	**1 ±0**
		II	0 ±0	**0 ±0**	**0 ±0**	0 ±0	**0 ±0**
	Total N	I	41 ±8	14 ±3	**12 ±7**	15 ±6	**9 ±1**
		II	47 ±7	14 ±9	**24 ±9**	20 ±13	**20 ±7**
	NH_4	I	23 ±7	3 ±3	1 ±1	1 ±1	1 ±1
		II	26 ±5	0 ±0	0 ±0	1 ±1	1 ±3
	NO_3	I	0 ±0	8 ±6	8 ±6	12 ±5	7 ±1
		II	1 ±1	8 ±7	12 ±6	9 ±8	11 ±7
	Total P	I	12 ±5	2 ±1	2 ±1	2 ±1	2 ±1
		II	13 ±2	3 ±2	3 ±1	3 ±2	4 ±2
	DOC	I	106 ±24	12 ±11	4 ±2	5 ±3	2 ±3
		II	118 ±20	3 ±3	2 ±5	2 ±3	6 ±5
2	Cl^-	I	49 ±20	42 ±6	41 ±5	2 ±2	14 ±14
		II	45 ±5	42 ±16	41 ±13	5 ±7	15 ±9
	pH	I	6.6 ±0.1	6.7 ±0.2	6.5 ±0.1	6.7 ±0.2	6.5 ±0.3
		II	6.6 ±0.2	6.5 ±0.2	6.5 ±0.2	6.9 ±0.1	6.5 ±0.5
	Fe^{2+}	I	0 ±0	9 ±1	0 ±0	0 ±0	0 ±0
		II	0 ±0	2 ±1	0 ±0	0 ±0	0 ±0
	Total N	I	41 ±7	37 ±8	30 ±6	14 ±9	21 ±9
		II	40 ±7	32 ±11	33 ±4	18 ±15	14 ±9
	NH_4	I	21 ±4	20 ±9	1 ±1	0 ±0	0 ±0
		II	22 ±4	20 ±8	1 ±1	0 ±0	0 ±0
	NO_3	I	0 ±0	9 ±4	22 ±7	9 ±7	12 ±6
		II	0 ±0	1 ±1	19 ±6	5 ±4	5 ±4
	Total P	I	9 ±4	7 ±4	2 ±1	2 ±1	2 ±1
		II	12 ±3	9 ±2	3 ±2	3 ±1	4 ±3
	DOC	I	105 ±23	63 ±11	**37 ±9**	**36 ±3**	**6 ±3**

Table 3. *Cont.*

Site	Parameter	Phase	STE	C2-30	C2-90	C3-30	C3-90
		II	100 ±16	67 ±6	**16 ±4**	**16 ±3**	**1 ±2**
3	Cl^-	I	42 ±11	27 ±13	44 ±10	41 ±6	44 ±11
		II	115 ±88	93 ±77	88 ±79	102 ±88	117 ±75
	pH	I	6.7 ±0.1	6.5 ±0.2	6.5 ±0.1	6.8 ±0.1	6.7 ±0.1
		II	6.8 ±0.3	6.6 ±0.2	6.6 ±0.2	6.8 ±0.2	6.7 ±0.2
	Fe^{2+}	I	0 ±0	15 ±7	17 ±9	4 ±2	7 ±5
		II	0 ±0	5 ±6	8 ±6	0 ±0	0 ±0
	Total N	I	38 ±7	20 ±3	26 ±4	32 ±3	30 ±5
		II	36 ±6	27 ±6	29 ±9	27 ±11	31 ±7
	NH_4	I	24 ±11	15 ±5	19 ±6	22 ±7	21 ±8
		II	19 ±6	18 ±5	20 ±8	18 ±8	19 ±9
	NO_3	I	0 ±0	0 ±0	0 ±0	0 ±1	0 ±0
		II	0 ±0	1 ±3	2 ±1	1 ±2	1 ±2
	Total P	I	6 ±2	3 ±1	4 ±1	5 ±1	5 ±2
		II	9 ±2	6 ±2	6 ±1	7 ±2	7 ±1
	DOC	I	77 ±13	42 ±6	56 ±10	58 ±6	57 ±7
		II	91 ±25	58 ±16	68 ±16	67 ±23	70 ±15

Previous mesocosm-scale evaluation of the effects of intermittent soil aeration of STAs on nitrogen transformations have shown high levels of NO_3 and nearly complete absence of NH_4 in water draining below 30 cm of sand or soil, in contrast to unaerated mesocosms [8,14,15]. Furthermore, drainage water from intermittently aerated mesocosms had a considerably lower pH than unaerated treatments [8,14,15]. We did not observe these effects in the present study. Mesocosms provide a much greater degree of control over variables such as penetration of air, homogeneity of soil properties, movement of STE through soil—and the reproducibility of these conditions—all of which can affect the dynamics of NH_4 and NO_3 production and consumption. The effects of ISA on nitrate dynamics may have taken place at shallow depths, such that the concentrations of NH_4 and NO_3 measured at 30 or 90 cm do not provide an accurate representation of inorganic N dynamics as a result of other production and consumption processes that can take place deeper within the soil profile, such as plant uptake, and microbial mineralization and/or immobilization. Using experimental mesocosms we have shown that total N removal appears to take place within the top 7.5 cm of aerated sand [15]. In addition, spatial and temporal variability may mask the effects of aeration on speciation of inorganic N below the STAs.

3.3. Apparent and Actual Removal of N, P and DOC

Intermittent soil aeration generally enhanced the apparent removal rates (R_x) of N, P and DOC at all three sites (Figure 4) despite marked reductions in nominal infiltration area (Table 2). In most instances, mean values of R_X for total N at 90 cm below the infiltrative surface were negligible or negative (higher N levels in soil pore water relative to STE inputs) during Phase I, and became positive (lower N levels in soil pore water relative to STE inputs) during Phase II (Figure 4). Intermittent soil aeration also increased apparent removal rates for total P, as indicated by higher values of R_X during Phase II (Figure 4). The exception was observed at Site 2, C2, where apparent removal rates were

negative during the ISA phase. Intermittent soil aeration had mixed effects on apparent rates of DOC removal (Figure 4). During Phase I there was a higher concentration of DOC in soil pore water relative to STE inputs, whereas during intermittent soil aeration apparent removal of DOC was observed. By contrast, at Sites 2 and 3 ISA resulted in lower apparent removal rates for DOC, stemming from a higher concentration of DOC in soil pore water than in STE inputs.

Apparent removal rates do not account for two potentially important factors that affect contaminant removal in the STA: (i) differences in size of STA utilized, and (ii) dilution by ground water, precipitation or snowmelt. In the present study, reductions in treatment area (Table 2), which would be expected to influence the effectiveness of these systems, were implemented to test the robustness of the ISA system with respect to its ability to restore hydraulic flow. Dilution of contaminants results in lower apparent concentrations, which overestimates the effectiveness of contaminant removal in the STA. Differences in Cl^- concentrations between STE and soil pore water suggest that dilution needs to be accounted for (Table 3). To address these two issues, we calculated an actual removal rate (mass removed/area/time) using Equation 2.

Actual removal rates for N during Phase I were relatively small, with both net production (negative values) and net removal (positive values) observed at a depth of 90 cm under the infiltrative surface (Figure 5). By contrast, actual removal rates for N at 90 cm below the leachfield during Phase II were consistently positive and up to two orders of magnitude higher at all sites (Figure 5). Intermittent soil aeration also resulted in higher actual P removal rates at all three sites, with values that were between 2 and 15 times higher than those observed during Phase I (Figure 5). Similarly, actual rates of DOC removal were 4 to 10 times higher during the ISA phase than during Phase I at all three sites (Figure 5).

Removal of total N in STA of conventional OWTS is generally low [16,17], owing to poor denitrification [17]. The results of our study show that apparent N removal rates in our systems prior to intermittent aeration ranged widely, from removal of up to 60% to increases in N concentration in soil pore water of 5 to 30% above the levels in STE inputs. Literature reports on apparent N removal rates for conventional systems vary considerably, from 21% [18], to 35% [12], to 50% [13]. These values are for systems receiving normal hydraulic loads, and are within the range of those observed by us prior to intermittent aeration in some instances. By contrast, the net increases in total N levels below the infiltrative surface relative to STE inputs during Phase I may be due to mineralization of nitrogenous exopolymers and dead microbial biomass accumulated within the STA, likely due to an increased hydraulic load.

The intermittent aeration of the STA (Phase II) resulted in an increase in both apparent and actual removal rates for N, P and C (Figures 4 and 5). Actual removal values for N, P, and C under field conditions during intermittent aeration (Phase II) were comparable to those observed for mesocosm scale experiments [8,14]. Furthermore, values of actual N removal rates during Phase II were comparable to those observed for wood-based denitrification reactors used to treat drainage water (950 to 2500 mg $N/m^2/day$) [19]. The positive effects of intermittent aeration are unlikely to be due to differences in temperature between Phase I and Phase II, inasmuch as mean temperature (as reflected in values for STE) was higher during Phase I (20.1 to 22.7 ^oC)) than during Phase II (16.8–17.4 ^oC). The rate of microbial processes, which are presumed to be involved in removal of N, P and C in these systems, is expected to decrease as temperature decreases [20].

Figure 4. Apparent removal rate for nitrogen, phosphorus and dissolved organic carbon at the three study sites prior to (Phase I) and during (Phase II) operation of intermittent soil aeration. Values are for lysimeters at 90 cm below the infiltrative surface placed between (C2) and downstream from (C3) leachfield trenches. Apparent removal rates were calculated according to Equation (1).

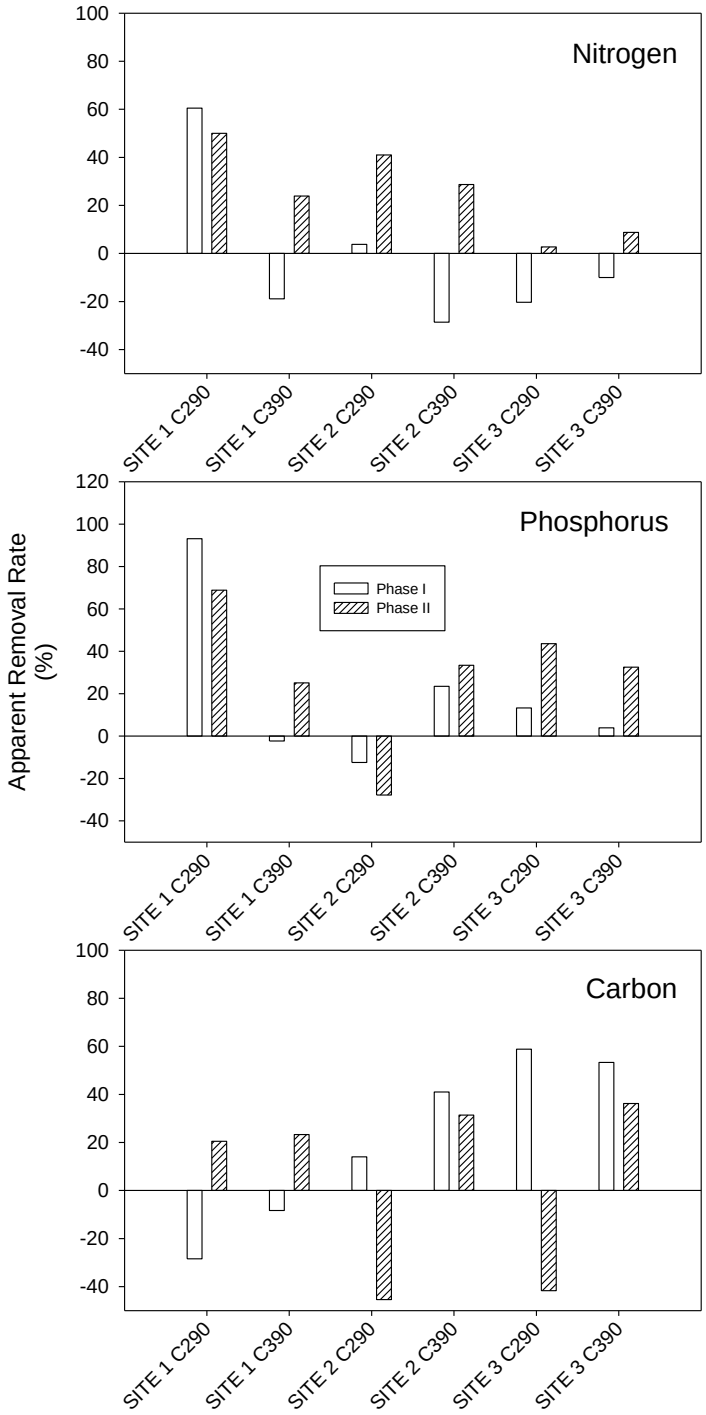
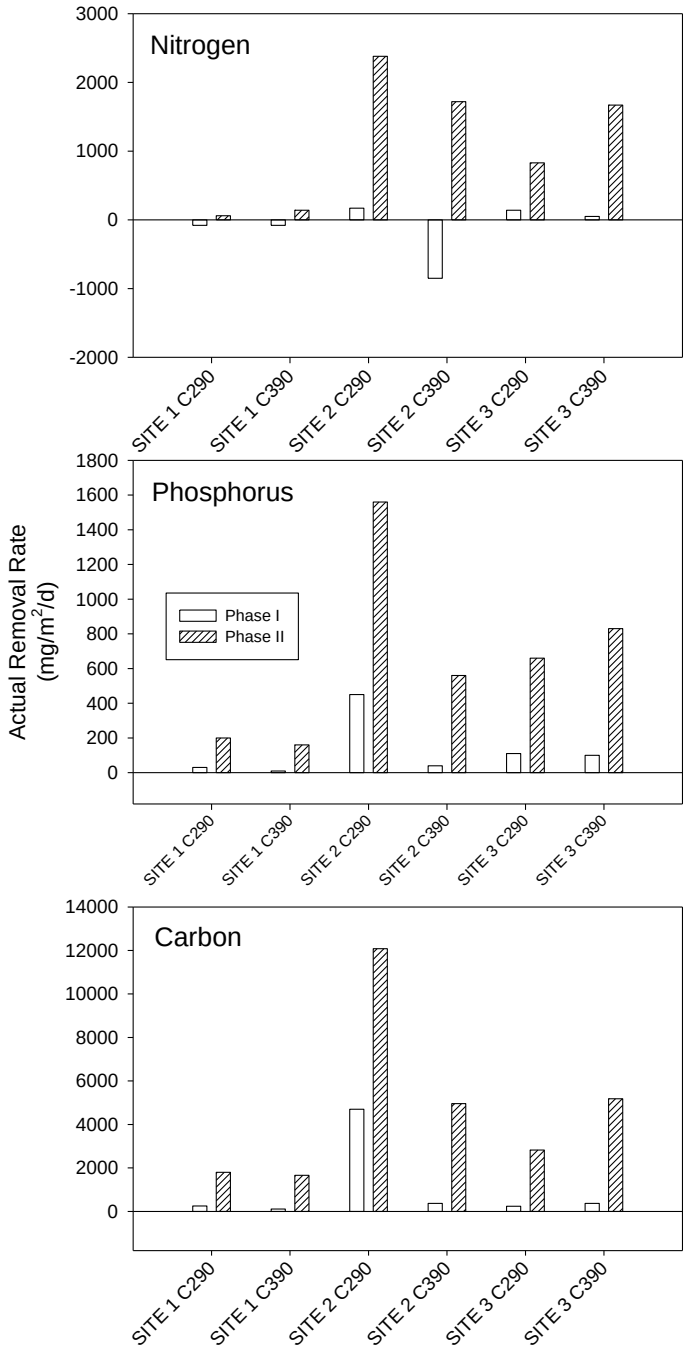


Figure 5. Actual removal rates for nitrogen, phosphorus and dissolved organic carbon at the three study sites prior to (Phase I) and during (Phase II) operation of intermittent soil aeration. Values are for lysimeters at 90 cm below the infiltrative surface placed between (C2) and downstream from (C3) leachfield trenches. Actual removal rates were calculated using Equation (2). Negative values indicate net constituent production.



3.4. Relationship between Hydraulic Load and Removal of N, P and DOC

Differences in the effects of ISA on actual removal rates of N, DOC and P among test sites (Figure 5) led us to examine the possibility that these effects are related to hydraulic load. In previous studies we

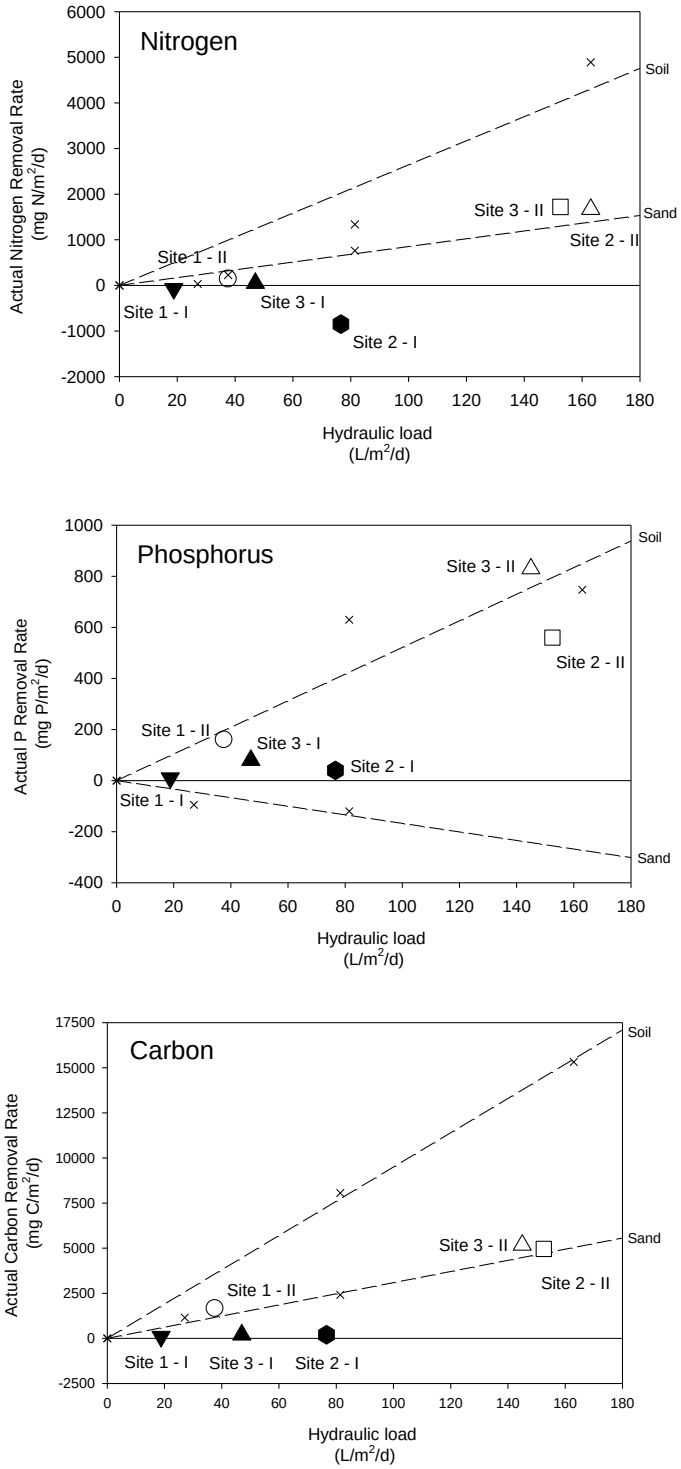
have observed that actual nitrogen removal from STE in intermittently aerated mesocosms increased with increasing hydraulic load [8,14]. The differences in hydraulic load at the three sites in the present study provided an opportunity to examine the applicability of pilot-scale results to field systems.

A plot of hydraulic load *vs.* actual N removal rate shows that prior to intermittent aeration, actual removal rates for N, P and C remained the same or decreased as a function of hydraulic load (Figure 6). By contrast, actual N removal rates increased with increasing hydraulic load at the field sites. Furthermore, the actual removal rates for N were similar to those for sand-filled mesocosms. Actual removal rates for DOC for the field sites exhibited a similar relationship with hydraulic load to that observed for nitrogen, with DOC removal rates increasing with hydraulic load, and field removal rates values that were close to those reported for sand mesocosms (Figure 6). Actual removal rates for P at the field sites also increased with hydraulic load; however, unlike N and C, these values were closer to those for soil-filled mesocosms (Figure 6). By contrast, actual removal rates for C and P during Phase I changed little with increasing hydraulic load, and rates of N removal appeared to decrease as hydraulic load increased (Figure 6).

In general, actual removal rates for N, P and C are expected to be inversely proportional to hydraulic loading rate because frequent saturation of the STA for long periods of time is expected to lead to anaerobic processes that are less efficient at C and nutrient removal [21]. In our study, actual removal rates under field conditions increased with increasing hydraulic load at all sites. The response of actual removal rates to hydraulic load in the present study suggests that removal mechanisms may be similar under field and laboratory conditions. We have previously suggested that enhanced N removal with intermittent aeration of the STA stems from a sequence in which aeration promotes ammonia oxidation to nitrate in soil, with the subsequent addition of STE to soils promoting removal of N via denitrification, by providing anaerobic conditions as well as organic C sources [8,14]. This is similar to the processes involved in N removal from wastewater using sequencing batch reactors (SBR) [22]. Recent studies of SBR have shown that simultaneous nitrification/denitrification can also take place in SBR [23]. Increases in removal of N with increased hydraulic load during the ISA phase in the present study suggest that N removal is enhanced by a longer period of anaerobic conditions and/or a larger volume of anaerobic soil. Because denitrification consumes organic C, intermittent aeration of STAs should also increase C removal, and this removal should increase with increasing hydraulic load, as was the case under both field and mesocosm conditions. Phosphate removal is also enhanced in SBR, apparently as a result of phosphate uptake by polyphosphate-accumulating microorganisms during the aerobic phase [24], which may explain enhanced P removal with increased hydraulic load.

Both C and N removal under field conditions were more similar to values observed for sand-filled mesocosms, whereas values for P removal were closer to those observed for soil-filled mesocosms (Figure 6). This difference may be explained by differences in removal mechanisms for these three constituents. Both C and N removal—assuming it takes place primarily via denitrification—involve gaseous losses (as CO_2, N_2, and N_2O) and do not require reaction with soil minerals. By contrast, net removal of P from STE likely involves the reaction of PO_4 (released during the anaerobic phase of enhanced biological phosphorus removal) with soil minerals, which were absent in the synthetic sand used in mesocosm studies [8].

Figure 6. Relationship between hydraulic load and actual removal rates for nitrogen, carbon and phosphorus at position C3 (downstream from leachfield trench; Figure 1) for the three field sites evaluated in the present study and for mesocosms containing 30 cm of sand [8] or soil [14]. Dashed lines represent linear regressions for soil and sand mesocosms data. Solid symbols represent values for Phase I (prior to intermittent soil aeration); open symbols represent values for Phase II (during intermittent soil aeration).



4. Conclusions

Our results suggest that intermittent aeration of STAs can enhance the hydraulic and water quality improvement functions of hydraulically-failed conventional OWTS. Intermittent soil aeration improves the infiltrative capacity of these systems, with normal hydraulic function observed despite reduction in infiltrative surface area and concomitant higher hydraulic load. Apparent removal rates for N, P, and DOC were comparable to or higher than those observed prior to intermittent aeration. Furthermore, these rates were achieved even though the potential infiltrative surface area was reduced between 33 and 50%. When differences in infiltrative surface area and dilution are taken into account, actual rates of removal for N, P, and DOC increase markedly in conventional STAs.

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