Supplementary material: Improvement of Onsite Wastewater Systems performance: Experimental and Numerical Investigation

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Table S1: Soil Bulk Densities

Media	Sand	Alluvial	Cedar Canyon	Loose Wood Chips	Dense Wood Chips	Biochar
Bulk Density (g/cm^3)	1.58	1.05	1.10	0.22	0.13	0.23

S1. Hydraulic Loading

Daily flow is an important parameter used for the design of OWTS and is normally based on an estimated per capita occupancy of a residence and some expected median per capita water use rate. While such a calculation may be sufficient in many situations, knowledge of actual flow is more useful. For the subsurface trench, hydraulic loading rates should not exceed 10% of the hydraulic conductivity (K_s) for a given soil textural class. Thus, a constant loading rate of 2 cm/day was used in this study. Microflow tubing of 2.4 mm x 0.92 mm was used to pump the wastewater from a tank to the top of each of the columns.

The wastewater would flow through a 6-inch Fernco Quick cap with a 0.5-inch hole located at the base of the column. Below this was a beaker for each of the columns where the wastewater would be collected. After 30 days allowing the soil columns to reach a steady-state nitrate concentration test would be done daily. The nitrate concentration tests were done with the DR300 Pocket Colorimeter made by Hach. To complete the tests a 10 mL sample would be collected directly from the soil column. Each column was tested and recorded each day from day 30 to day 100.

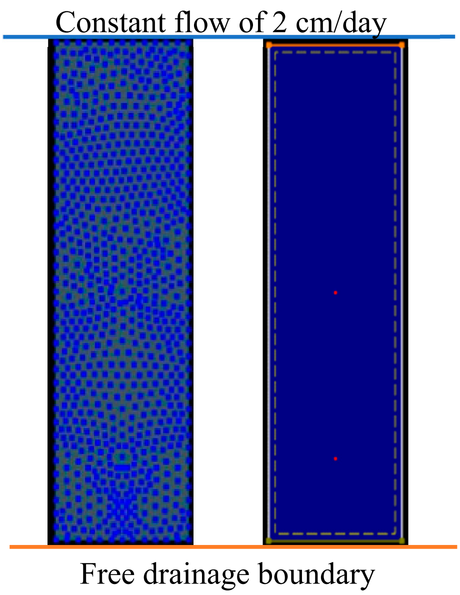


Figure S1: Modeled Columns Finite Element Mesh and boundary condition

S2. Creating Soil Characteristic Curves

The soil characteristic curve is a relationship between soil moisture and suction head. Equations S1and S2 shown below is the relationship between water content and the suction head parameters.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^m} \qquad S1$$

$$m = 1 - \frac{1}{n} \qquad S2$$

Where, θ is the instantaneous water content; θ_r is the residual water content; θ_s is the saturated water content; α is the inverse of the air entry value (1/cm); n is the pore size distribution index; h is the capillary pressure (cm)

The above equation relates water content (θ) and suction head (h). The suction head was measured at multiple moisture contents and used to determine other parameters such as α and n using solver by minimizing the least squared error between moisture content predicted using van Genuchten equation for a given suction head and measured moisture content at that suction head value. α and n are parameters that were then used in the HYDRUS 2D model. The test to determine suction head and water content values were done using a 4-inch proctor mold with the soil compacted to column compaction specifications. The compaction was done using two lifts for a total depth of 5 inch. The suction head was measured at different soil moisture. The moisture content gradually varied by draining the water after initial saturation. This draining could take several weeks depending on the type of soil. The soil was assumed saturated if after a day the ponded surface water did not change. With a saturated mold, the base was raised slightly exposing the soil to drain freely, shown in Figure S2. The water content sensor (WatchDog 1000 Series Micro Stations) and tensiometer (INFIELD7C) were then inserted 1 inch into the soil near each other, shown in S2. The water content and suction head measurements were taken periodically until no changes were observed after 2 days. The initial water content was assumed to be the saturated water content and the final water content was assumed to be the residual water content.

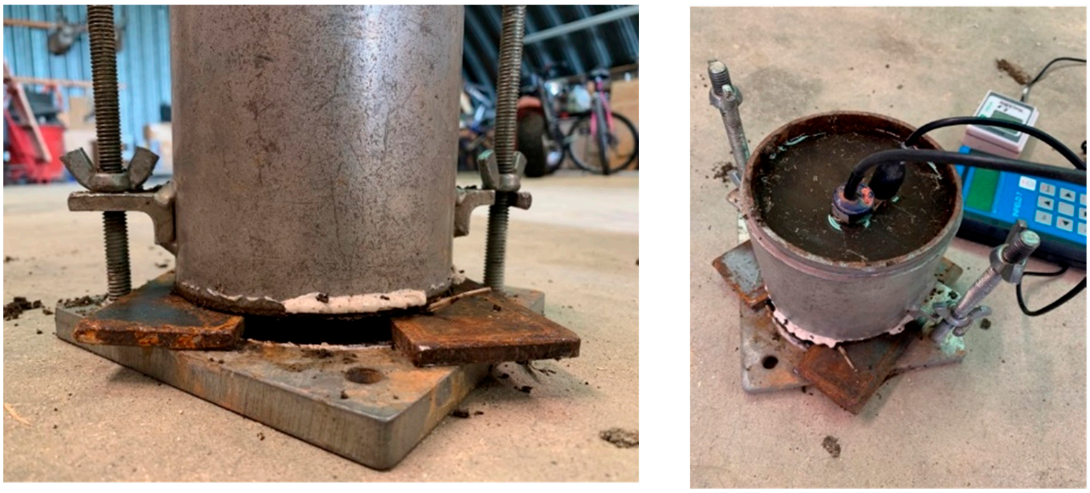


Figure S2: Experimental Setup

Alluvial Soil

Alluvial parameters were determined by comparing the soil moisture characteristic curves from the suction head and moisture content measurement from the lab to curves estimated based on the Van Genuchten equation. The soil characteristic curve test was done to determine the Van Genuchten parameters α and n. The raw data from the test is shown in Table S2. A plot of soil moisture characteristic curve of laboratory determined suction head and moisture content versus soil moisture characteristic curve estimated using van Genuchten equation relating suction head and moisture content is shown in Figure S2 below. To draw the soil moisture characteristic curve, the hydraulic parameters must be determined. The van Genuchten parameters include n, θ_r, θ_s, *and* K_{sat}. Saturated water content, θ_s was determined as 0.155 from the maximum water content from the test and a θ_r value of 0.099 was measured when the test was terminated. The Van Genuchten parameters α and n were determined by using Equations S1 & S2 and setting up a solver to find the least squared error between measured and predicted suction head. A scatter diagram comparing measured and modeled suction head data is shown in Figure S3. An R^2 of 0.87 was found as a correlation between measured and predicted. The van Genuchten parameters from the test were then used as a starting point in the inverse modeling procedure to calibrate the rest of the hydraulic parameters. Table S3 shows the calibrated hydraulic parameters for the alluvial soil.

Table S2: Alluvial Soil Characteristic Curve Data

WC	Suction Head (cm)	WC	LHS	RHS	Squared Error
13.90	4.08	0.14	0.71	0.89	0.030
13.90	8.16	0.14	0.71	0.79	0.006
13.90	9.18	0.14	0.71	0.77	0.003
13.90	9.18	0.14	0.71	0.77	0.003
13.90	10.20	0.14	0.71	0.75	0.002
13.90	11.22	0.14	0.71	0.74	0.001
13.20	28.55	0.13	0.59	0.57	0.000
13.20	39.77	0.13	0.59	0.52	0.005
13.20	38.75	0.13	0.59	0.52	0.005
13.20	45.89	0.13	0.59	0.49	0.009
13.20	52.01	0.13	0.59	0.47	0.013
13.20	55.06	0.13	0.59	0.47	0.015

12.90	67.30	0.13	0.54	0.44	0.010
12.90	76.48	0.13	0.54	0.42	0.014
12.90	80.56	0.13	0.54	0.41	0.015
12.90	84.64	0.13	0.54	0.41	0.017
12.60	94.83	0.13	0.48	0.39	0.008
12.60	107.07	0.13	0.48	0.38	0.011
12.20	123.39	0.12	0.41	0.36	0.003
11.20	142.76	0.11	0.23	0.34	0.012
10.90	155.00	0.11	0.18	0.33	0.024
10.60	166.21	0.11	0.13	0.32	0.040
10.20	187.63	0.10	0.05	0.31	0.067
9.90	191.71	0.10	0.00	0.31	0.096

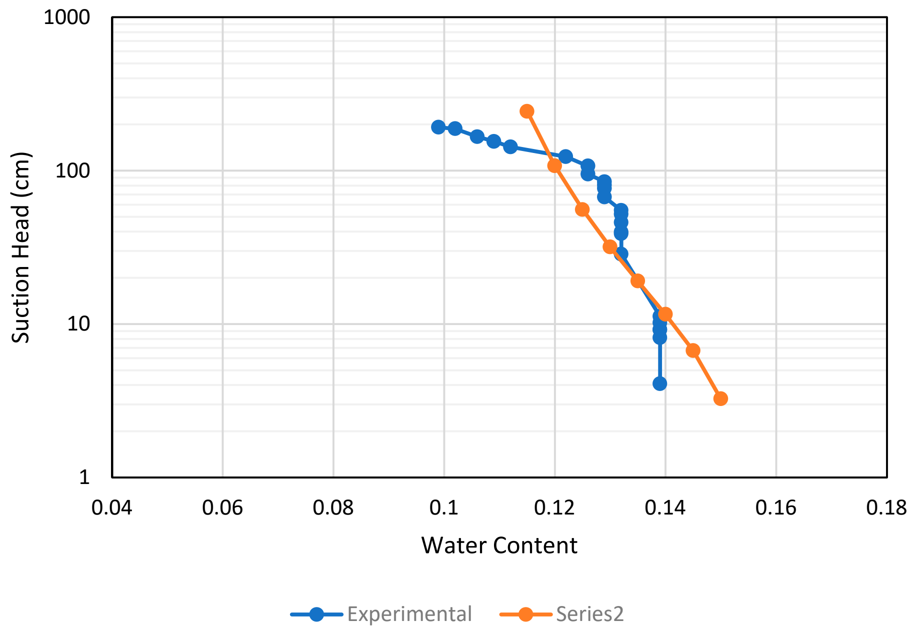


Figure S3: Experimental Column Setup

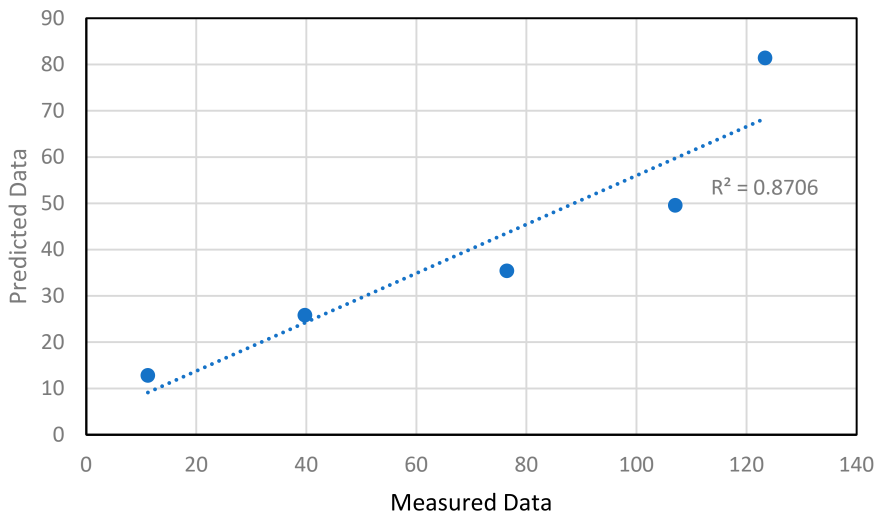


Figure S4: Experimental Column Setup

Table S3: Calibrated Hydraulic Parameters

Parameter	θr (cm³/ cm³)	θs (cm³/ cm³)	n	α (1/cm)	Ks (cm/day)
Value	.002	.470	1.34	.169	750

S3. Saturated Water Content Test:

For other media such as woodchips, the soil moisture characteristic curve would not work as the sensors failed to measure water content and suction head with such large void spaces. The porosity test was done using a 4-inch proctor mold with a sealed base. A depth of 5 inch was used for the compacted woodchips. The compaction was done to the specifications of the soil column densities. The compacted woodchips were then saturated by adding water until the 5-inch depth. The mold was allowed to sit for a day to allow the woodchips to fill the void spaces within each individual woodchip. Water was then added again until the 5-inch depth. The weight of the mold was measured before and after saturation. Equations S3 & S4 were used to find the saturated water content of the woodchips Figure S5 shows the experiment setup.

$$V_w = m_s - m_d \qquad S3$$

$$\theta_s = \frac{V_w}{V_t} \qquad S4$$

Where, θ_s the saturated water content; V_w is the water volume (cm^3); V_t is the total volume (cm^3); M_s is the saturated mass of the mold (gm); M_d is the dry mass of the mold (gm)

Figure S5: Experimental Setup

Loose Woodchips

The saturated water content for the loose woodchips was determined using the procedure in *Saturated Water Content Test*. Table S4 shown below has the measured and calculated values from the test. The measured values include Mold and Woodchips Mass and the Saturated Mold and Woodchips Mass. The volume of water and total porosity of the soil were found using Equations S3 & S4. The results from the test are shown in Table 4 shown below.

Table S4: Woodchip Saturated Water Content

Mold and Woodchips Mass (kg)	4.40
Saturated Mold and Woodchips Mass (kg)	4.95
Total Volume (cm3)	823.77
Volume water (cm3)	547
Porosity	0.66

The saturated water content was found through the test procedure explained in Saturated Water Content Test. This is supported by a study on hydraulic parameters of woodchips by Ehsan Ghane et al. (2016). The study also concluded that the residual water content of the woodchips was roughly 0.21 for a large variety of woodchips. The saturated and residual water content values were held constant while α, n, and K_s were optimized according to the inverse modeling procedure described in section 3.3.

S4. Parameterization of hydraulic parameters using an inverse modeling approach

Parameters that could not be determined using the experimental approaches described in the section above were determined using the inverse modeling approach. An inverse modeling module available within the HYDRUS 2D model was used. Average daily water content was obtained from the sensors placed at locations in the experimental columns was used for calibration. The calibration was done at each of the locations. The first 30 days of data were not included to allow time for experimental columns to reach a steady state. Table S5 shows the interface to choose which parameters to optimize within a range. The parameters to be optimized using inverse modeling can be specified by checking the box below each parameter. The model will run for a specified number of iterations before it converges. The observed and simulated values can then be plotted and the R^2 value between modeled and observed data can be determined. HYDRUS 2D will also give a range T-value with a 95% confidence for the upper and lower limit for the parameter.

Table S5: Parameters to optimize

	Qr [-]	Qs [-]	Alpha[1/cm]	n [-]	Ks [cm/day]	l [-]
Initial Estimate	0.02	0.47	0.16905	1.33658	750	0.5
Minimum Value	0.02	0.001	0.165	1.3	600	
Maximum Value	0.09	1	0.18	1.4	1000	
Fitted ?	☐	☐	☐	☐	☐	☐

S5. Parameter Sensitivity Analysis

To check the parameter sensitivity, columns with homogeneous media (sand, loose woodchips, and biochar) were considered. Therefore, the actual impact of parameters on nitrate/

flow transport will be displayed. Model calibrated parameter values were considered as the original values and a 25% increase/decrease (Table S6, S8, and S10) was considered for the parameter sensitivity analysis. However, the change in nitrate concentration at effluents was measured and represented as a change (%) with the change of parameter values.

Table S6: **Sand** Sensitivity Analysis Inputs

Parameter	Original Value	25% decrease	25% increase
θ_r (cm^3/cm^3)	0.0020	0.0015	0.0025
θ_s (cm^3/cm^3)	0.24	0.18	0.3
α (cm^{-1})	0.0698	0.0524	0.0873
n (-)	4.45	3.34	5.57
K_s (cm/day)	720	540	900
k (1/day)	0.258	0.194	0.322

Table S7: **Sand** Sensitivity Analysis Results

Parameter	25% decrease	25% increase
	Percent difference from original	Percent difference from original
θ_r (cm^3/cm^3)	0.27%	0.41%
θ_s (cm^3/cm^3)	20.10%	-12.11%
α (cm^{-1})	-9.79%	10.39%
n (-)	-3.74%	5.47%
K_s (cm/day)	1.11%	3.78%
k (1/day)	20.31%	-12.25%

Table S8: **Loose Woodchips** Sensitivity Analysis Inputs

Parameter	Original Value	25% decrease	25% increase

θ_r (cm³/cm³)	0.2100	0.1575	0.2625
θ_s (cm³/cm³)	0.664	0.498	0.83
α (cm⁻¹)	0.12062	0.090465	0.150775
n (-)	4.4698	3.35235	5.58725
K_s (cm/day)	114	85.5	142.5
k (1/day)	0.248	0.186	0.31

Table S9: **Loose Woodchips** Sensitivity Analysis Results

Parameter	25% decrease	25% increase
	Percent difference from original	Percent difference from original
θ_r (cm³/cm³)	0.27%	0.41%
θ_s (cm³/cm³)	20.10%	-12.11%
α (cm⁻¹)	-9.79%	10.39%
n (-)	-3.74%	5.47%
K_s (cm/day)	1.11%	3.78%
k (1/day)	20.31%	-12.25%

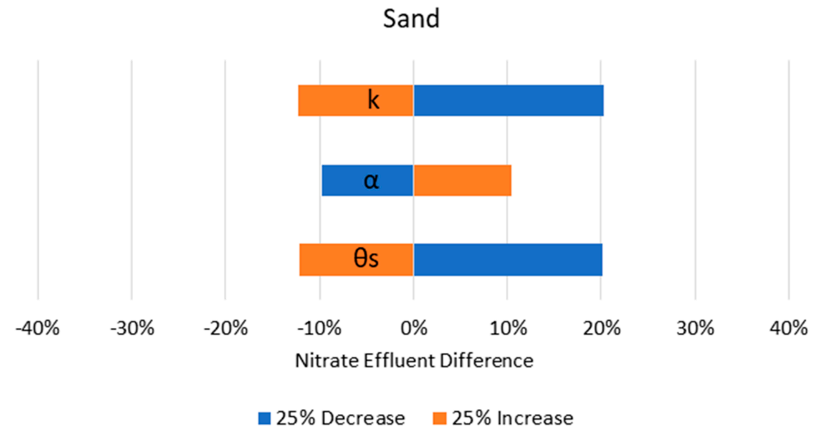
Table S10: **Biochar** Sensitivity Analysis Inputs

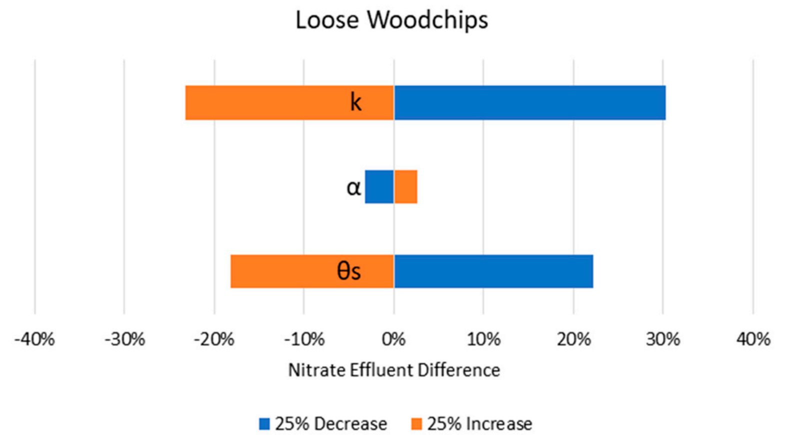
Parameter	Original Value	25% decrease	25% increase
θ_r (cm³/cm³)	0.001	0.00075	0.00125
θ_s (cm³/cm³)	0.64	0.48	0.8
α (cm⁻¹)	0.00001	0.0000075	0.0000125
n (-)	3.066	2.2995	3.8325
K_s (cm/day)	554.4	415.8	693
k (1/day)	0.032	0.024	0.04

Table S11: **Biochar** Sensitivity Analysis Results

Parameter	25% decrease	25% increase
	Percent difference from original	Percent difference from original
θ_r (cm³/cm³)	0.00%	0.00%

θ_s (cm³/cm³)	13.49%	-11.93%
α (cm⁻¹)	-0.60%	0.42%
n (-)	-0.12%	0.06%
K_s (cm/day)	-0.06%	0.00%
k (1/day)	13%	-12%





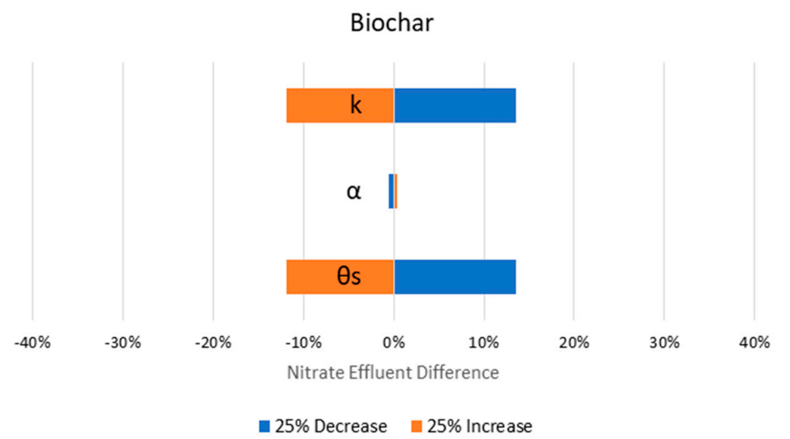


Figure S6: Sensitivity Analysis