Senior Design to Graduate Thesis: Designing and Evaluating a Bench-Scale Sand Filter for the Treatment of Residential Wastewater in Georgia

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Abstract – On-site sewage management systems provide treatment of wastewater on properties not served by municipal wastewater treatment. Conventional on-site systems use a septic tank to absorption field design. Alternative designs may be used where higher degrees of treatment are required due to sub-standard soils, high groundwater tables or limited plot areas. One such alternative is a post-septic tank sand filter system which further treats the wastewater before it is released to either a traditional absorption field or a drip-emitter system. The goal of this project was to design a bench-scale system for evaluating design standards for sand filters in Georgia. In the first phase of this project, a prototype bench-scale treatment system was designed and partially constructed by a Mercer University School of Engineering senior design team. In the second phase, one team member chose to complete construction of the system including advanced analysis of system components and re-design of system components as necessary for their graduate thesis project.

Keywords: On-site wastewater treatment, sand filter

INTRODUCTION

Residential wastewater is typically defined as water containing waste from domestic sources such as toilets, dishwashers, kitchen sinks, etc. [State of North Carolina Department of Environment, 5]. To prevent the pollution of natural water sources and maintain good public health, wastewater must be treated to a regulated degree before it can be returned to the environment and eventually reused. Most commonly, wastewater generated in an area is pumped to and treated at a central location, or public treatment plant. This energy and resource intensive management system involves a network of sewers and pump stations and carries a high cost that is shared by the large population served by the plant. Though the use of public treatment plants is very successful in large, densely populated areas, conveying wastewater from scattered rural areas to a central location is not efficient [USEPA, 7]. Decentralized management methods provide wastewater treatment for those small rural communities or individual sites, eliminating the need for excessive sewer conveyance to a central plant. Though often viewed as a temporary or insufficient substitute for the centralized option, these decentralized systems are designed for long-term reliable use [Office of Water, 3].

The most commonly used on-site sewage management system is the septic tank to absorption field configuration. In this system, the septic tank provides primary treatment of the wastewater allowing solids to separate from the water. Some solids settle to the bottom of the tank, while others float to the top and are separated from the effluent flow by a baffle. Effluent from the septic tank flows to an absorption field where it is distributed evenly to the soil. The effluent flows through the soil's unsaturated soil pores, where microorganisms in the soil feed on the waste and nutrients in the effluent before it reaches the groundwater table [NSF/ANSI, 2].

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Alternative on-site sewage management systems exist and may be used on sites where a conventional system is not feasible. These systems are typically desirable when a properties hydrogeology will not accommodate the design or installation of a traditional absorption field. One such alternative is the sand filter system. This system involves the addition of a sand filter after the septic tank [Office of Water, 3]. Naturally occurring microorganisms in the porous medium of the filter provide additional biological treatment of the effluent from the septic tank. The filter bed effluent is then directed to a subsurface application system. The selection and design of the subsurface application system is based on the treatment achieved by the sand filter [State of North Carolina Department of Environment, 5].

Because on-site systems are ultimately owned and maintained by the individual property owner, rules and regulations for the design and operation of these systems must be publicly available and thorough. This information is typically specific to the state in which the system is being installed [US EPA, 7]. In Georgia, the County Health Department permits construction of on-site sewage management systems. Currently, Georgia does not have design standards for on-site sewage management with sand filters [US EPA, 7]. The availability of design standards approved by the State of Georgia's Department of Community Health, Land Use Program would allow contractors as well as residents certified in the construction and operation of on-site sewage management systems to design and build sand filter systems for private use.

Students from Mercer University's School of Engineering (MUSE) responded to a proposal to evaluate existing standards for on-site sewage management with sand filters. Resulting information will aid Georgia's Land Use Program in the creation of design standards. This project began with a team of senior engineering students designing and building a prototype bench-scale sand filter system to be tested in the MUSE's Environmental Engineering Laboratory. The second phase of the project, conducted by a member of the team for graduate thesis work, consisted of more advanced analysis and redesign of some system components.

FIRST PHASE: SENIOR DESIGN

The senior design project client, Dr. Philip McCreanor of MUSE's Environmental Engineering Department, charged the senior design team with providing a means by which different filter sands could be evaluated for use in on-site wastewater sand filter systems. Georgia's Land Use Program expressed to the client an interest in experimental data on American Society for Testing and Materials (ASTM) C33 sand. The goals of the senior project were to design and construct a prototype bench-scale sand filter system, provide a sieve analysis of the sand used to fill the filter columns and test the porosity of the column sand.

Bench-Scale System Design and Construction

A prototype bench-scale sand filter system capable of loading multiple media at once or duplicating tests on one chosen medium was designed and partially constructed by the team. As requested by the Georgia Land Use Program, design of the bench-scale sand filter testing system was based on existing design standards from the states of North Carolina, Oregon and Washington.[Oregon Department of Environmental Quality, 4; State of North Carolina Department of Environment, 5; Washington State Department of Health, 9] Applicable sections of the United States Environmental Protection Agency's (US EPA) *Onsite Wastewater Treatment Design Manual* and traditional wastewater engineering concepts, were also considered in the team's design process [US EPA, 7]. The final design (Figure 1) consisted of four major elements: 1) wastewater storage and dosing unit, 2) septic tank, 3) flow division unit and 4) three independent sand filter columns.

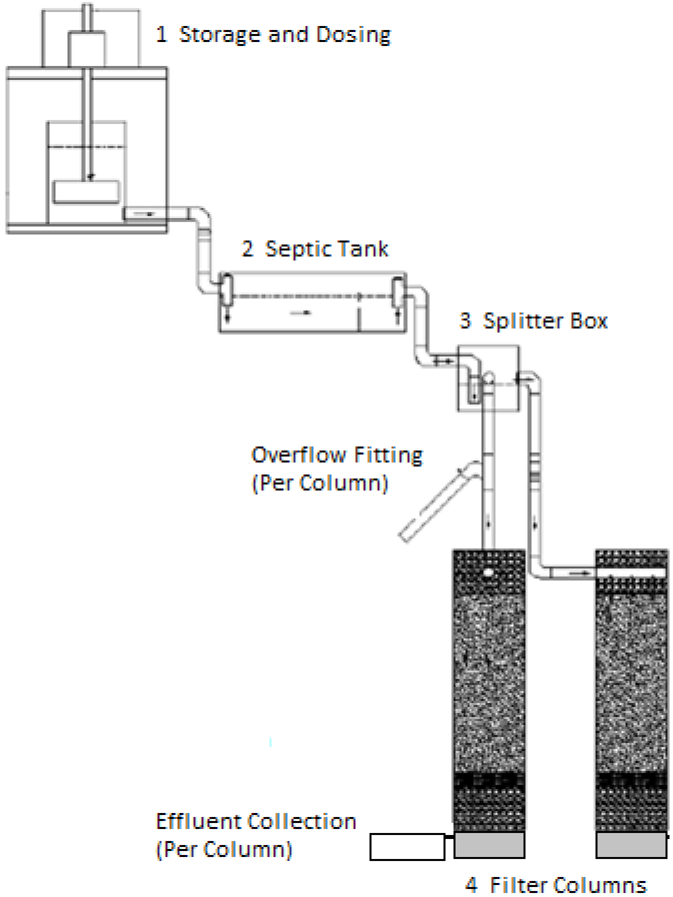

Figure 1. Prototype Bench-Scale Design by Senior Project Team.

Wastewater samples will be held in and distributed to the system by the storage and dosing structure. The storage tank was designed to be held in and cooled by a mini-refrigerator, and a rotating paddle was designed to stir the sample. The cooling and stirring of the stored sample will reduce storage related changes in sample characteristics. National Sanitation Foundation (NSF) International standards specify that the daily loading to experimental wastewater treatment systems be distributed as shown in Table 1 [NSF/ANSI, 2]. These loading requirements were addressed by designing a dosing system with an irrigation valve to be controlled by a datalogger. Release from the tank will be based on the time of day and on the level of wastewater in the tank. Once released from the storage structure, wastewater flows to the septic tank and through the remainder of the system by gravity.

Table 1. NSF International Loading Schedule for Testing of Wastewater Treatment Systems [NSF/ANSI, 2].

Time Frame	% of daily volumetric loading
6:00 a.m. to 9:00 a.m.	approximately 35
11:00 a.m. to 2:00 p.m.	approximately 25
5:00 p.m. to 8:00 p.m.	approximately 40

The septic tank, once initially filled, overflows with addition of flow from storage. This overflow then continues to the flow splitter structure below the septic tank where it is evenly divided into three effluent streams. These effluent streams are each applied to an individual sand filter column. The wastewater then flows through the pores of the sand in the filter columns and from the column structures to individual effluent collection systems.

Overflow control is included before each filter column to prevent the hydraulic failure of one column from impacting the flows to the other columns. Any backup flows from a column will be redirected through the overflow control structure to a separate collection vessel rather than building up in the splitter box and discharging to the other columns.

Column Design and Media

A maximum hydraulic loading rate of 40.8 lpd/m^2 (1.0 gpd/ft^2) to the filter column was used based on existing standards.[Washington State Department of Health, 9] A total system daily hydraulic load of 5.7 liters (1.5 gallons) was chosen based on sample storage volume limitations and sample collection frequency. The 5.7 liters (1.5 gallon) daily loading rate allows for three days' worth of application volume to be stored in an 18.9 liter (5-gallon) container. The 5.7 liters (1.5 gallons) of influent to the system is ultimately divided between the three filters yielding a flow of 1.9 lpd (0.5 gpd) to each filter. Based on this daily application volume and the maximum daily loading rate, the filters should have a surface area of 0.047 m^2 (0.5 ft^2). The sand filter columns were constructed using 0.25-m (10-inch) polyvinyl chloride (PVC) pipe, yielding an actual filter surface area of 0.051 m^2 (0.545 ft^2) and a hydraulic loading rate of 37.4 lpd/m^2 (0.917 gpd/ft^2), slightly less than the design loading rate.

The filter media columns were designed to be filled as shown in Figure 2. The pea-gravel-to-gravel combination at the bottom of the column prevents clogging of the effluent perforations.

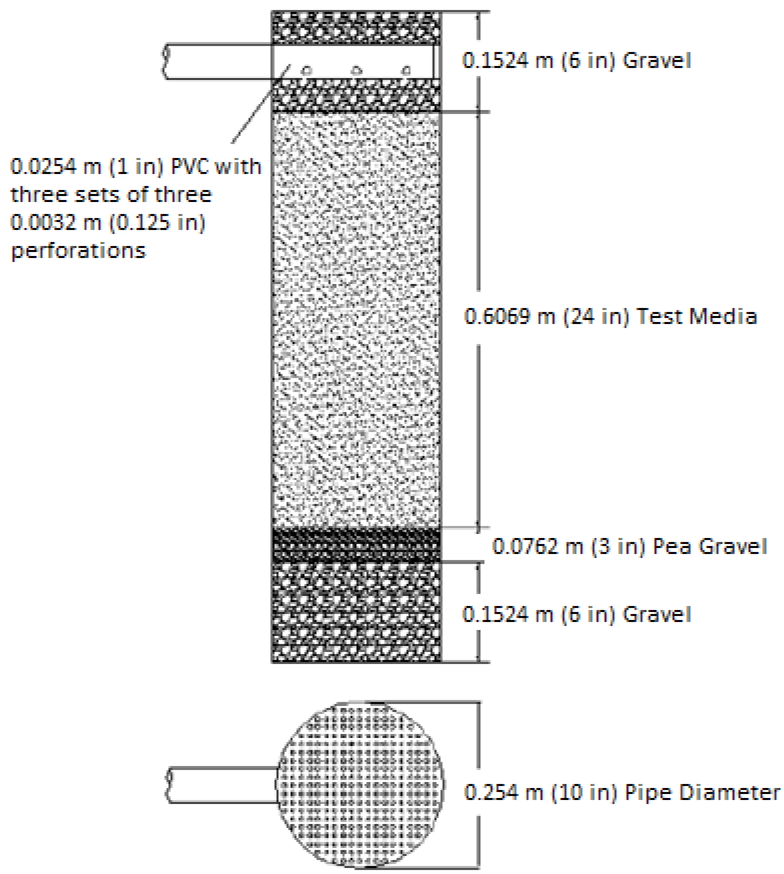

Figure 2. Cross-Section and Top Views of Filter Column with Media.

The design team completed the following tasks during the one-semester time frame allotted to the construction and testing phase of senior design:

- Constructed filter columns and filled with media layers,
- Constructed and tested septic tank,
- Constructed and tested splitter box,
- Connected septic tank to splitter box assembly and verified equal division of flows,
- Conducted a sieve analysis on the ASTM C33 sand filter media, and

- Tested the porosity of the media layers in the columns.

Sieve Analysis and Porosity Testing

ASTM C33 sand, a fine aggregate concrete sand that meets ASTM International gradation requirements, was to be the first media evaluated in the bench-scale sand filter testing system [Northeast Tri County Health District, 1]. This standard sand is commonly used as a concrete aggregate and is readily available and at a relatively low cost [Tchobanoglous, 6]. This sand is also specified by several states for use in sand filter systems. Its use in residential wastewater sand filter systems has been documented in other state's standards but should be tested and verified before being recommended for use in the Georgia [US EPA, 7]. ASTM is an international organization that develops sand composition standards as well as many other standards for materials, practices, etc. ASTM standard specifications for sands provide particle size distribution requirements which define the sand's makeup by varying grain sizes. The ASTM C33 specification requires 100% passing through a 9.5-mm (3/8-inch) sieve, and further gradation as shown in Table 2. The range of acceptable percent passing values can result in some variations in particle distributions between samples and, thus potentially coarser or finer ASTM C33 compositions [State of North Carolina, Department of Environment, 5].

Table 2. ASTM C33 Gradation Requirements [State of North Carolina, Department of Environment, 5]. and Sand Media Gradations in Each Column.

Sieve Size		% Passing			
		ASTM C-33	Column #1	Column #2	Column #3
3/8"	(9.5 mm)	100	100	100	100
#4	(4.75 mm)	95 to 100	97	96	97
#8	(2.36 mm)	80 to 100	90	90	90
#16	(1.18 mm)	50 to 85	77	77	76
#30	(0.60 mm)	25 to 85	44	44	44
#50	(0.30 mm)	5 to 30	27	27	26
#100	(0.15 mm)	0 to 10	5	5	5
#200	(0.075 mm)	0 to 3	Not measured		

Sieve analyses were conducted on the filter column sand to verify that the sand used met ASTM C33 specifications. As each filter column was filled, grab samples were taken. For every 5-cm (2 inches) of filter sand depth, 100 mL of sand were sampled and set aside. Ten samples were taken from each column, resulting in a total sample volume of 1 liter for each filter. The results of these sieve analyses, Table 2, indicate that the sand used meets the ASTM C-33 standard.

Each filter column was filled with specific depths of gravel, pea gravel, and ASTM C33 sand layers (Figure 2). The porosity of these layers was experimentally determined by filling each column from bottom to top with water. The volume of water required to fill the voids in each layer of material was recorded. The total volume of each layer was calculated based on the thickness of the layer and the surface area of the column. Porosity was calculated for each layer of media by dividing the fill water volume for the layer by the total layer volume. The porosities calculated for each layer in each column are presented in Table 3.

The entire bench-scale sand filter testing system could not be completed and tested in the one-semester allotted for this phase of senior design. Tasks to be completed to have a fully-operational system included:

- Construction of storage tank with cooling, mixing, and dosing components,
- Hydraulic connection of all system components, and

- Hydraulic testing of the completely assembled system.

Table 3. Porosity of the Media in the Filter Columns.

Layer	Porosity (%)		
	Column #1	Column #2	Column #3
Drain Gravel	40.1	39.5	39.2
Drain Pea Gravel	35.2	35.0	35.1
Filter Media (ASTM C-33 Sand	27.3	26.5	26.0

SECOND PHASE: GRADUATE THESIS WORK

A member of the senior design team chose to complete construction and evaluation of the bench-scale sand filter system for their graduate thesis project. The objectives to be accomplished during this phase include:

- Complete construction and testing of system components,
- Conduct saturated and unsaturated mass transport testing,
- Develop a model for mass transport and degradation through the column media, and
- Initiate the application of wastewater to the sand filter system.

Sample Storage and Dosing Unit

Testing of the storage and dosing system indicated that it would need to be redesigned. Specifically, there was insufficient head in the 18.9- liter (5-gallon) sample storage vessel to operate an irrigation valve. An automated ball-valve would work in this application but would not fit within the budget allotted to the project. It was decided that a 12-volt sump pump would be used to provide wastewater flows to the system. The pump would be controlled via a Campbell Scientific CR10X datalogger. Pump operation would be based on time of day and wastewater level in the tank. Mixing of the wastewater sample would be accomplished with a single-paddle mortar mixer with a low-viscosity paddle spinning at approximately 60 rpm to minimize aeration. The 18.9 liter (5-gallon) sample storage bucket would be placed in an ice water bath to chill the sample and reduce degradation of the sample. This sample storage configuration will be much more convenient to refill as it will be at floor-level rather than on an elevated platform. This design will be subjected to a two-week evaluation. During this evaluation, one-gallon samples will be collected on a daily basis and tested for chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5), total solids, and suspended solids. The storage tank will be replenished with fresh wastewater every fourth day. This testing will provide information on the degradation of the wastewater applied to the bench-scale sand filter testing system.

Mass Transport Through Saturated Media

The movement of solutes dissolved in water through a porous media is known as mass transport. Several different modes of transport affect the overall movement of mass through a porous media. The concentration gradient causes diffusion of matter from areas of high concentrations to areas of lower concentration. Advection and dispersion of matter are affected by the overall flow of water through the media and by the macroscopic behavior of water in pores, respectively. Modeling mass transport behaviors through a particular filter media volume can aid in estimating treatment expectations and predicting media behavior [State of North Carolina Department of Environment, 5; Vandevivere, 8].

Mass transport through a vertical column of media can be experimentally analyzed by introducing a set volume and concentration of a tracer to a steady flow of water through the column. The effluent from the end of the column is monitored for the initial appearance of the tracer and the change in concentration of the tracer over time. A plot of the ratio of effluent concentration to initial injection concentration (C/C_0) with respect to time, a breakthrough curve, illustrates the transport behavior of the tracer as it moves through the column. Mass transfer through the filter columns was investigated for saturated flow using a conservative solute, potassium chloride (KCl). This information can be used to estimate mass transport parameters for the column.

The movement of liquid and mass through the saturated media was studied by first filling each filter column from bottom to top with clean tap water. Clear tubing was attached to the column's effluent port and extended up past the top of the column. Two storage containers were set up above the influent port of the column. One container was used to supply tap water to the column while the other container was used to apply the slug of potassium chloride (KCl) tracer. Each container was fitted with an overflow system to ensure that a constant head of liquid was kept on the column and a shut off valve to start and stop flow from the container. A 175 g/L KCl solution was diluted to produce a consistent tracer solution concentration of 9.21 g/L of KCl. The average conductivity of the mixed tracer solutions was 14.93 μS/cm. The filter column was equipped with an effluent chamber to catch effluent and provide a vessel in which to measure conductivity of the effluent. Effluent conductivity was measured every five seconds using a conductivity probe monitored by a Campbell Scientific CR10X datalogger.

The tracer studies were conducted at average volumetric flow rates, Darcian velocities, and seepage velocities of 49.4 cm^3/s, 0.1 cm/s, and 0.39 cm/s, respectively. Several individual tracer slugs approximately 50 seconds in duration were applied to each column. Each tracer test produced a unique breakthrough curves. When a series of tests were performed on a single column, the effluent was allowed to return to its initial conductivity before another tracer slug was applied. Data was collected and arranged to produce a series of breakthrough curves for each column (Figures 3, 4, and 5). This data will be used to estimate the longitudinal hydrodynamic dispersion coefficient for each column which will then be used in the modeling of unsaturated flow and transport.

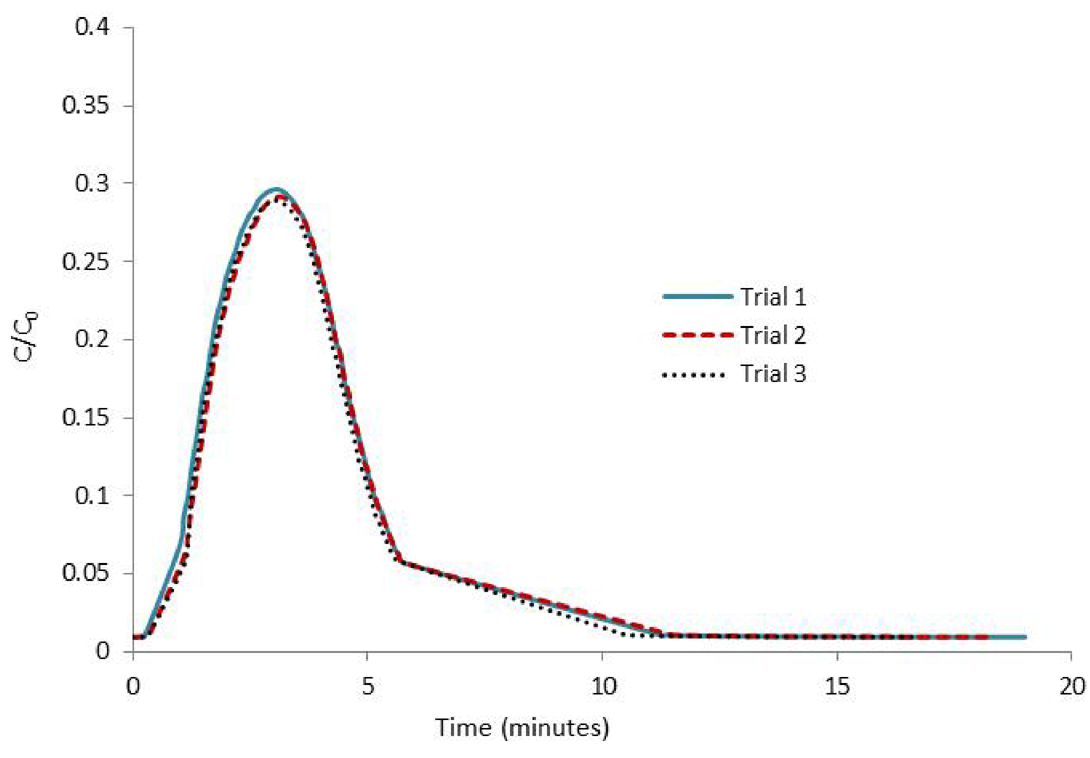

Figure 3. Column #1 Saturated Flow Tracer Study Breakthrough Curves.

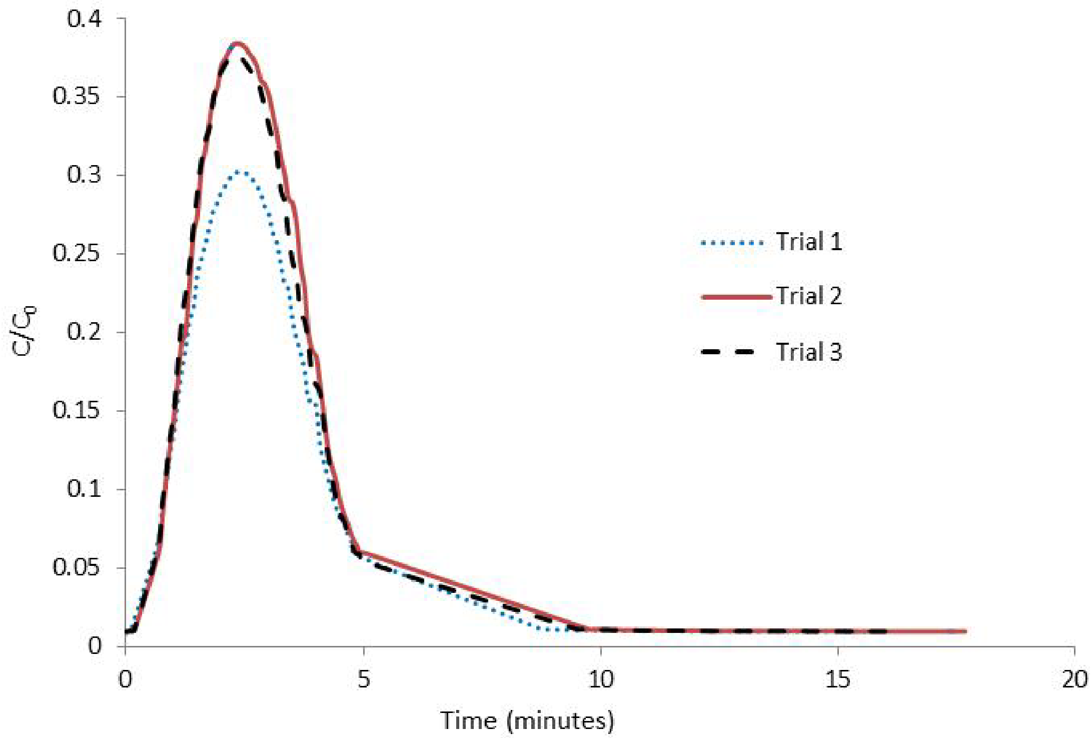

Figure 4. Column #2 Saturated Flow Tracer Study Breakthrough Curves.

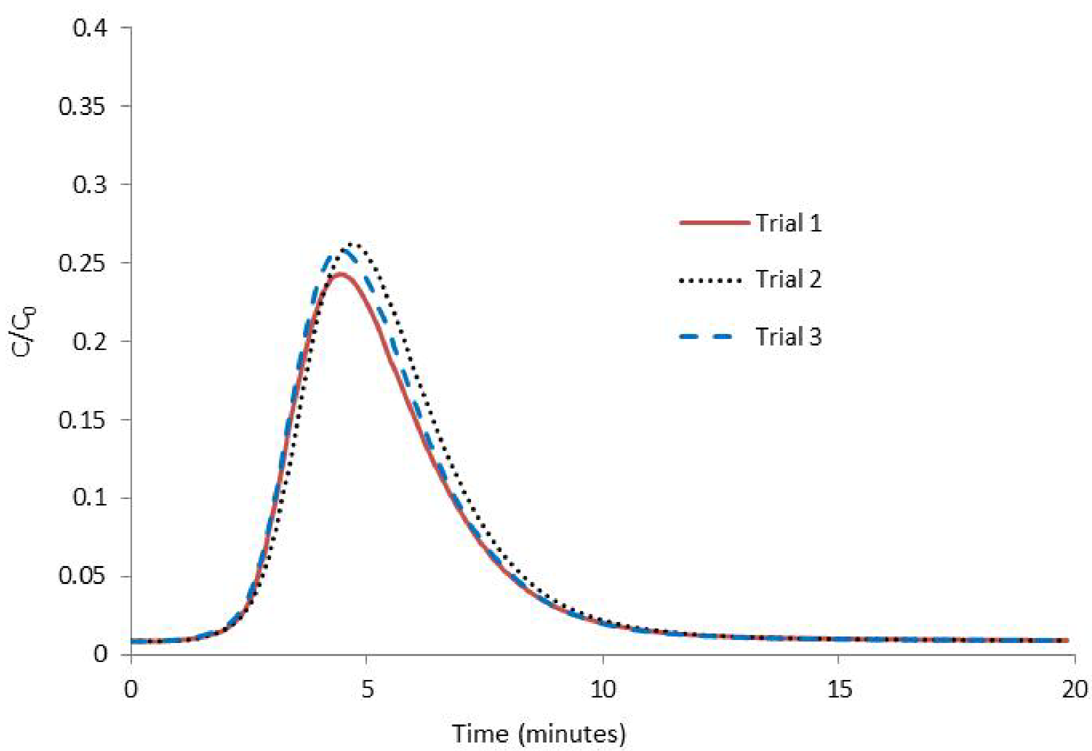

Figure 5. Column #3 Saturated Flow Tracer Study Breakthrough Curves.

FUTURE PROJECT WORK

The following laboratory tasks remain for completion of thesis related activities:

- Conduct unsaturated flow study of a tracer applied to the columns per NSF International dosing criteria (Table 1),
- Complete testing of sump-pump based sample storage and dosing unit,
- Install sample storage and dosing unit and septic tank into the bench-scale sand filter testing system,
- Conduct a tracer study on the completed system to determine overall residence time in the system,
- Initiate operation of the system with wastewater.

Modeling and simulation work for the thesis will include using a saturated flow model to determine the longitudinal hydrodynamic dispersion coefficient and development of a one-dimensional unsaturated flow fate and transport model. The transport component of this model will be verified using the unsaturated flow tracer study.

A future student will operate the system using wastewater as the influent. This student will also conduct work on the fate component of the one-dimensional fate and transport model developed in this study.

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