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# **HILLSBOROUGH FILTER PILOT DEMONSTRATION FINAL REPORT**

**TALIAFERRO STORMWATER RESEARCH FACILITY  
HILLSBOROUGH COUNTY, FLORIDA  
SWFWMD PERMIT NO. 44024189.002**

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**July 11, 2006**

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## Executive Summary

A zeolite filter pilot plant was operated over a 216 day period to evaluate its ability to enhance nitrogen removal from stormwater. When operated at a steady filtration rate of 192 gal/ft<sup>2</sup>-day, the zeolite filter was highly effective at removing ammonia, producing an effluent ammonia nitrogen concentration of 0.07 mg/L, and removing 93% of ammonia and 32% of total inorganic nitrogen. A variety of non-steady state experiments demonstrated that the zeolite filter performance was superior to a parallel sand filter under the varying conditions that are common to stormwater management systems. A storm event was simulated by applying a sudden increase in flowrate to the zeolite filter that was over 30 times greater than normal. The zeolite filter maintained a 90% or greater concentration reduction throughout the simulated storm, removed more than 99% of the applied ammonia mass, and provided superior performance to that of a parallel sand filter control. To assess ammonia removal following an extended inter-event period, the zeolite filter received no flow for 40 days and then received a storm event loading. The zeolite filter retained virtually all added ammonia mass, while ammonia nitrogen levels in the sand filter effluent were above 7 mg/L. The zeolite filter was also operated under low dissolved oxygen conditions and provided ammonia retention superior to sand. Two denitrification filters were evaluated for removal of nitrate and nitrite from zeolite filter effluent. A sulfur/limestone filter and a barley straw filter both reduced total oxidized nitrogen by 95% or more and produced effluent levels of 0.1 mg/L or less.

Based on the results of this study, development of a coupled zeolite filter/denitrification filter process is recommended for complete removal of inorganic nitrogen from stormwater. Bench or pilot scale evaluation should be conducted, under steady flow and event loading operation. Particle removal technologies should be evaluated for pre-treatment, such as coagulation and direct filtration. Additional stormwater constituents including divalent metals should be evaluated.

It is also recommended that a field demonstration project be conducted to use the zeolite filter to upgrade discharge from a wet detention pond. This study would integrate many of the findings in this report and provide field experience to address nitrogen removals in transient and interevent periods, clogging and suspended solids issues, and maintenance requirements. Enhanced particle removal processes could be considered along with the wet detention pond/zeolite filter combination.

It is recommended that zeolite media be evaluated in a variety of other stormwater management applications. These include upflow filters, sidebank and bottom filters, and pumpback recycle systems for continuous pond treatment. The zeolite filter may also be effective for “at source” or “on-site” stormwater controls. Examples are direct treatment of roof runoff, integration of zeolite treatment filters with green roof water cycling, or direct incorporation of zeolites into green roof planting media.

An economic analysis is presented that provides a first approximation of the cost to apply the zeolite filter technology in an urban watershed.



## Background

The establishment of total maximum daily loads (TMDLs) for Florida's receiving waters has challenged many municipalities to reduce nitrogen loadings from stormwater sources. Stormwater is a key contributor to nitrogen loading to the Tampa Bay Estuary, and the development of innovative BMPs is of particular interest in protecting surface water quality within the Tampa Bay Watershed.

Hillsborough County has established the *Taliaferro Stormwater Research Facility* (TSRF) to evaluate innovative stormwater BMPs. The Taliaferro Stormwater Research Facility (TSRF) is a 5.6-acre tract of land that lies within Hillsborough County's Curiosity Creek Watershed. The Taliaferro sub-basin within the Curiosity Creek Watershed has historically experienced significant flooding, but this flood prone area has been transformed by Hillsborough County into a research site that consists of interconnected stormwater ponds, constructed wetlands, and adjacent land areas draining into the ponds and wetlands. The Taliaferro site connects to the Curiosity Creek watershed through a culvert that passes underneath I-275 and a canal on the west side of I-275 that leads to Curiosity Creek; discharge is ultimately to the Tampa Bay Estuary.

**Stormwater Nitrogen:** Stormwater treatment BMPs have had variable and limited success in treating nitrogen, particularly for the soluble forms. The *Hillsborough Filter* is an innovative Best Management Practice (BMP) that targets the removal of soluble inorganic nitrogen from urban stormwater, using zeolite and other media to enhance the removal of soluble nitrogen species. The speciation of nitrogen affects its amenability to removal in various unit operations and processes.

The total nitrogen content of stormwater is composed of four forms:

$$\text{Total N} = \text{Organic-N} + \text{NH}_3\text{-N} + \text{NO}_2\text{-N} + \text{NO}_3\text{-N}$$

The oxidized nitrogen forms of significance are nitrate and nitrite. Often, the nitrite-N concentration is relatively minor, and the total oxidized nitrogen (TON) is reported:

$$\text{TON} = \text{NO}_3\text{-N} + \text{NO}_2\text{-N}$$

Total inorganic nitrogen (TIN) is:

$$\text{TIN} = \text{NH}_3\text{-N} + \text{NO}_2\text{-N} + \text{NO}_3\text{-N}$$

An additional differentiation of total nitrogen is based on filtration:

$$\text{Total N} = \text{Non-filterable N} + \text{Filterable N}$$

Non-filterable N is also termed "particulate N" or "suspended N", and can be physically removed by media filtration. Filterable N is termed "dissolved N" or "soluble N", and

will pass through media filters unless it is chemically sorbed to the filter media. Organic nitrogen can occur as particulate or dissolved. Inorganic nitrogen occurs generally in dissolved fraction, but sorption can result in the association of inorganic N with the particulate phase, for ammonia in particular. Non-filterable nitrogen is sometimes termed particulate nitrogen, and can settle out in a quiescent basin (settleable) or remain suspended (non-settleable). Filterable nitrogen is sometimes termed soluble nitrogen, and consists of colloidal and truly soluble nitrogen forms.

A challenge of nitrogen removal is to reduce nitrogen to the low concentrations that are consistent with water quality goals. Both influent stormwater and rainwater contain significant fractions of nitrogen in organic, ammonia, and nitrate forms, and the nitrogen speciation in stormwater ponds is highly variable (Rushton et al,1997). In-pond primary production can convert inorganic N into PON in the form of algae or floating macrophytes such as duckweed. Ponds with longer retention time may have a tendency to be dominated by PON and DON, with low levels ammonia, nitrite, and nitrate. This is the case at the Taliaferro Stormwater Research Facility, the host site for the research project described in this proposal. Stormwater inflow could change pond nitrogen speciation dramatically, as older water parcels are replaced by new, less processed stormwater. Sustainable stormwater management may place more emphasis on decentralized and multi-layered approaches, with treatment features closer to the source. Examples would be small ponds followed by filters, which could retain and treat nitrogen at lot size scale, or even directly treat roof runoff. Such systems would serve as high rate wet weather treatment (detention times of 15 to 60 min.) and experience “flashier” behavior than larger regional ponds, and could receive nitrogen species concentrations similar to rainfall. Rushton reported rainfall levels of 0.2 to 0.4 mg/L each for organic nitrogen, ammonia, and nitrate in the Tampa area (Rushton et al, 1997).

*Ammonia* is a significant component in stormwater. In a study of stormwater quality from a single family residential watershed in Central Florida, the mean ammonia concentration in 35 discrete composite stormwater samples was 1.37 mg/L; an average of 35.2% of the total nitrogen was as ammonia (Harper et al., 1999). This same study found that ammonia accounted for an average of 29.8 % of the 1.51 mg/L total nitrogen in bulk precipitation. In another study, Event Mean Concentrations (EMCs) ranged from 0.17 to 3.52 mg/L in runoff from a citrus grove in Central Florida (Reposa and Pandit, 1994). Ammonia is also produced within stormwater management systems by ammonification of organic nitrogen, and negative removal efficiencies have been reported in several types of stormwater BMPs. For example, increases in ammonia have been reported across a sand filter system following a dry detention pond (Harper et al., 1999), in a wet pond and pond/effluent filtration systems treating urban stormwater (Rushton et al., 2004; Teague and Rushton, 2005), for a wet pond followed by a sand filter (Gowan and Watkins,1997), in an urban wet pond (Smith et al., 2005), and in the Multi Chamber Treatment Train (Pitt, et al., 1999). *Nitrate* and *nitrite* are highly mobile and produced by ammonia oxidation (nitrification). Denitrification can be used to remove nitrate and nitrite in pond water by providing electron donors and somewhat reducing conditions. Ongoing studies at the Taliaferro

Stormwater Research Facility have demonstrated that oxidized nitrogen can be removed in nitrifying treatment filters with zeolite and sand media, as well as with filters containing an elemental sulfur/limestone mixture and ground barley straw. These results suggest that coupled nitrification and denitrification filters are a viable option for stormwater treatment.

*Dissolved organic nitrogen* appears to be a generally significant component of urban stormwater and may emerge as a factor that has great scientific and regulatory implications. Seitzinger and Sanders reported that a significant fraction of DON loaded in rivers to two east coast estuaries was biodegradable, that bioavailable DON was a significant portion of the “biologically available nitrogen budget” of estuarine ecosystems. These authors did not indicate to what extent the DON loadings are caused by human activity, but state that “organic nitrogen inputs may contribute more to estuarine and shelf eutrophication than was previously suspected.” A recent report by the American Society of Civil Engineers and the Environmental Protection Agency reviewed stormwater databases and published studies on BMP performance from around the United States (ASCE/EPA, 2002). The authors of the report derived a treatment limit, termed the “irreducible concentration,” which is the lowest discharge concentration which can be achieved by urban BMPs. The ASCE/EPA report suggests that the “irreducible concentrations” of total and organic nitrogen in urban stormwater are 1.9 and 1.2 mg/L, respectively. A similar concept has been established for treatment wetlands, where the suggested irreducible concentrations for both total and organic nitrogen are 1.50 mg/L (Kadlec and Knight, 1996). Studies with storm pond water from the Taliaferro Stormwater Research Facility in Hillsborough County, Florida, have shown that Taliaferro storm pond water contains 0.6 to 0.9 mg/L of organic nitrogen in the colloidal/dissolved form (passes through a 0.45  $\mu$ m filter), and this material is relatively recalcitrant in filtration treatment. Previous investigators have reported the existence of a dissolved organic nitrogen fraction that was relatively unchanged through wet detention pond treatment (Gain, 1996). The implications of the “irreducible fraction” of stormwater nitrogen are significant for setting of Total Maximum Daily Loads of nitrogen to receiving waters, to stormwater treatment discharge permits, and to receiving water quality.

Biochemical reactions transform nitrogen and further affect removal in unit operations. A summary of nitrogen transformations is presented in Table 1. The important inorganic nitrogen reactions are nitrification and denitrification. In nitrification, inorganic nitrogen as ammonia is nitrified to nitrate, an aerobic process (requiring oxygen). In denitrification, inorganic nitrogen as nitrate is denitrified to  $N_2$ , which requires an electron donor or carbon source and often occurs most favorably under anoxic (low oxygen) environments. Nitrite ( $NO_2$ ) is an important nitrification intermediate and component of rainwater, and is not shown here for simplicity). Ammonia and nitrate can both be present in the stormwater stream, or can be released within stormwater management systems by solubilization and ammonification of organic nitrogen and nitrification of ammonia. Both ammonia and nitrate can be assimilated by algae and emergent, submerged, and floating macrophytes; the organic nitrogen formed can then be recycled through solubilization and ammonification. To

remove inorganic nitrogen from a stormwater stream at a given location, nitrification must first be employed where ammonia is present, followed by denitrification.

**Table 1. Biochemical Reactions Affecting Nitrogen in Stormwater Treatment**

<b><u>Solubilization</u></b>	
Particulate Organic N	→ Soluble Organic N
<b><u>Ammonification</u></b>	
Soluble Organic N	→ NH <sub>4</sub> <sup>+</sup>
<b><u>Nitrification</u></b>	
NH <sub>4</sub> <sup>+</sup> + 2 O <sub>2</sub>	→ NO <sub>3</sub> <sup>-</sup> + H <sub>2</sub> O + 2 H <sup>+</sup>
NH <sub>4</sub> <sup>+</sup> + 1.5 O <sub>2</sub>	→ NO <sub>2</sub> <sup>-</sup> + H <sub>2</sub> O + 2 H <sup>+</sup>
<b><u>Denitrification</u></b>	
NO <sub>3</sub> <sup>-</sup> + 0.833 CH <sub>3</sub> OH + H <sup>+</sup>	→ 0.5 N <sub>2</sub> + 0.833 CO <sub>2</sub> + 2.17 H <sub>2</sub> O
NO <sub>3</sub> <sup>-</sup> + 2.5 H <sub>2</sub> + H <sup>+</sup>	→ 0.5 N <sub>2</sub> + 3 H <sub>2</sub> O
<b><u>Nitrification/ Anaerobic Ammonium Oxidation/Denitrification</u></b>	
5 NH <sub>4</sub> <sup>+</sup> + 3 NO <sub>3</sub> <sup>-</sup>	→ 4 N <sub>2</sub> + 9 H <sub>2</sub> O + 2 H <sup>+</sup>
8 NH <sub>4</sub> <sup>+</sup> + 6 O <sub>2</sub>	→ 4 N <sub>2</sub> + 12 H <sub>2</sub> O + 8 H <sup>+</sup>
<b><u>Synthesis</u></b>	
NH <sub>3</sub> <sup>+</sup>	→ C <sub>5</sub> H <sub>7</sub> O <sub>2</sub> N (cells; particulate organic N)
NO <sub>3</sub> <sup>-</sup>	→ C <sub>5</sub> H <sub>7</sub> O <sub>2</sub> N (cells; particulate organic N)

**Process Concept** Natural zeolites are crystalline, hydrated aluminosilicates having infinite, three dimensional atomic structures (Mumpton, 1999; GSA Resources Inc. (2006). They are low cost materials that appear to be excellent candidates for stormwater treatment filters. Zeolite media have two key properties that can be utilized in stormwater treatment filters. First, they act as ion exchangers for cations, including ammonia nitrogen. The second feature of natural zeolites is that they provide an excellent support for the establishment of microbial biofilms that can transform nitrogen. Previous reports have described bench scale studies using zeolites to enhance biological nitrogen removal from wastewaters (Celik, et al., 2001; Cooney et al., 1999; Rosic et al., 2002; Baykal, 1998). Previous laboratory studies have suggested that zeolite filters can be effective for stormwater ammonia removal as well (Smith, 2004; Smith et al., 2003).

A salient characteristic of stormwater treatment systems is the need to treat unsteady flows and loadings. For this reason, biological unit processes have been considered to have a limited effectiveness for stormwater treatment (Sansalone, 2005). The use of a zeolite ion exchange media will retain ammonia within the filter and prevent

breakthrough, especially under high hydraulic and mass loading. The ion exchange properties of the zeolite will function to store soluble nitrogen and make it available for subsequent desorption and microbial utilization. Ammonia nitrogen that is bound to the zeolite within the stormwater filter can be transformed through nitrification by attached microbial biofilms. Nitrification would destroy ammonia and result in biological regeneration of the zeolite ion exchange capacity. The zeolite amended stormwater filter would establish a cycle of: stormwater flow and ammonia loading onto the zeolite filter, during which ammonia is retained by ion exchange onto the zeolite, followed by biological regeneration of the zeolite by nitrification. The prevention of ammonia nitrogen breakthrough during high hydraulic and ammonia mass loadings, and its subsequent biological destruction, will retard the transport of ammonia out of the filter. The net effect will be to decrease the mass of ammonia nitrogen in the filter effluent. Since nitrification will produce nitrate (or nitrite), additional processes are needed for nitrate reduction to effect complete removal of inorganic nitrogen.

Candidate zeolites include clinoptilolites and chabazites. A list of several commercially available zeolite materials and their properties is presented in Table 2. Zeolites are available in either powder or granular form. They have a high surface area for binding of ammonium, typical packed bed porosity of 30 to 50%, and are stable across a wide range of pH. The ion exchange capacity is of high significance and is 1.65 to 2.5 meq/gram for the zeolites listed in Table 2. This high ion exchange capacity, and their porosity and stability, make natural zeolites excellent candidates for media in the *Hillsborough Filter*.

The Hillsborough Filter could be deployed in a variety of contexts as a stormwater BMP. One example is within a stormwater treatment train (Figure 1), where the filter is preceded by a pre-sedimentation basin and followed by a denitrification filter or wetland. The zeolite filter could be used to treat discharge from wet detention ponds, in which the wet detention pond would provide the pre-treatment functions of flowrate equalization and reduction of total suspended solids (TSS) through sedimentation. Another potential is deployment in smaller “on-site” systems located closer to source areas, such as the individual lots. An example is direct treatment of runoff from green or non-green roofs, where runoff would have characteristics closer to rainwater and would not require pre-treatment for TSS removal.

Table 2. Properties of GSA Zeolite Materials<sup>1</sup>

	<b>Cabsorb ZS500H</b>	<b>Cabsorb ZS403H</b>	<b>Cabsorb ZK406H</b>
<b>Zeolite Type</b>	Chabazite	Clinoptilolite	Clinoptilolite
<b>Form</b>	Powder or granules	Granules	Granules or powder
<b>Color</b>	Dark Brown Brightness 40	Grey	White (85 O.R.)
<b>Ring member</b>	8		
<b>Crystal Size</b>	< 1 micron		
<b>Crystallinity</b>	90%		
<b>Density (g/cc)</b>	1.73		
<b>Pore Size (Angstrom)</b>	4.1 by 3.7		
<b>Pore Diameter (Angstroms)</b>	4.3	4	4
<b>Pore Volume</b>	0.468 cc/g	15%	15%
<b>Surface area (m<sup>2</sup>/g)</b>	520.95	40	40
<b>Crystal void volume (cc/cc)</b>	0.47		
<b>Bulk density (kg/m<sup>3</sup>)</b>		760-1283	783-1054
<b>Packing density (kg/m<sup>3</sup>)</b>	513		
<b>Solid density (kg/m<sup>3</sup>)</b>		1603	1390
<b>Alkali Stability (pH range)</b>		7 to 10	7 to 10
<b>Acid Stability (pH range)</b>		3 to 7	3 to 7
<b>Thermal Stability (°C)</b>		650	650
<b>Ion Exchange Capacity (meq/g)</b>	2.50	1.85	1.65
<b>MOH's Hardness</b>	4 to 5		
<b>Moisture as Packaged</b>	< 3% by wt.		
<b>pH of 1% Dispersion Stability</b>	8.5		
<b>Sorption Capacity</b>	> 15 wt % H <sub>2</sub> O at 10% R.H.		
<b>SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> Ratio</b>	Approx. 4:1		

<sup>1</sup> Provided by GSA Resources, Inc.

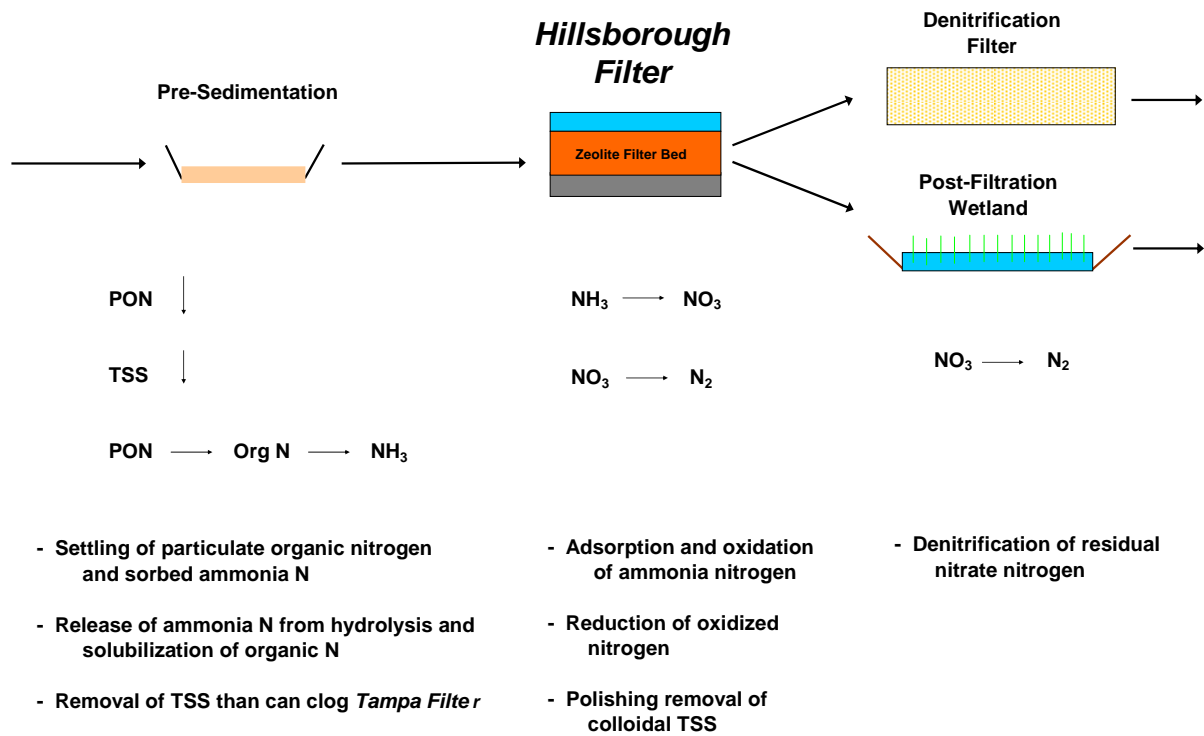


Figure 1. Zeolite filter in stormwater treatment train.

## Objectives

This study was focused on the exploration of a new technology for the enhancement of nitrogen removal in stormwater to supplement or enhance other commonly utilized BMPs in Florida. The *Hillsborough Filter* is a stormwater treatment filter design that uses natural zeolites (chabazites and clinoptilolites) as filtration media to enhance nitrogen removal from stormwater. The potential benefits of natural zeolite media will be demonstrated with a pilot scale installation at the Taliaferro site. A biologically active zeolite filter pilot system will be established and operated under various hydraulic and nitrogen loading regimes to evaluate its effectiveness as a nitrogen removal BMP. Water quality collection and monitoring will be performed to evaluate filter effectiveness in response to continuous, steady flowrates and nitrogen mass loadings, and its performance under imposed non-steady flowrates and influent nitrogen concentrations. The primary objective of the study is to document the overall effectiveness of the *Tampa Filter* BMPs in achieving nitrogen reduction in stormwater. The specific study objectives addressed were:

- *Evaluate the ability of the zeolite filter to remove dissolved inorganic nitrogen species and total nitrogen;*
- *Evaluate zeolite filter performance to simulated stormwater event flows and loadings;*
- *Evaluate filter performance over extended period of no flowrate;*
- *Evaluate post-zeolite denitrification media; and*
- *Estimate the overall efficiency and design requirements for a full scale system.*

## Materials and Methods

**Pilot Facility:** A schematic of the pilot filter installation at the Taliaferro Stormwater Research Facility is shown in Figure 2. Salient features of the pilot plant are described here. Pilot plant design and testing program were previously described in three technical memoranda which can be consulted for detailed information (Berryman & Henigar, Inc, 2004 a, 2004 b, 2004c). The field installation is shown in Figure 3. Photographic documentation of the pilot system is included in Appendix J.

Water was pumped from a sump which received water by gravity from several storm ponds. The pond pump supplied water through flowmeters. A chemical dosing tank and dosing pump provided ammonia dosing and in-line mixing. After the dosing point, two ball valves directed influent flow to either a 1500 gallon stormwater storage tank or through a bypass line directly to the influent standpipe. Where the stormwater storage



tank was used, tank discharge entered the same influent standpipe. Flow from the influent standpipe through the treatment system was by gravity flow. Water from the influent standpipe entered a two chamber baffle box, and baffle box effluent flow was split between two parallel media filters. Ball valves were used to equalize flows from the baffle box to the two parallel filters, or to direct all flow to one filter or the other.

Baffle box effluent entered the filter chambers at the top and flowed in a downward direction. A 12 inch gravel underdrain overlain by a geosynthetic fabric was used to support the filter media. The filters were rectangular with 30 ft<sup>2</sup> plan area (5 ft. wide, 6 ft. long). The depth of zeolite and sand media were 24 inches. A slotted drainpipe (1 inch high by 12 inch wide) was at the bottom of the underdrain and spanned the entire filter length and directed effluent through the filter containment wall into a standpipe in the clearwell chamber. Filter effluent exited the standpipe into the clearwell, and was pumped from the clearwell to Taliaferro Pond 5. The clearwell standpipe contained ball valves at approximately 7 inch increments, which enabled the filters to be operated at a selected media submergence depth, from fully saturated (standing water level above top of media) to fully unsaturated (standing water level below bottom of filter media).

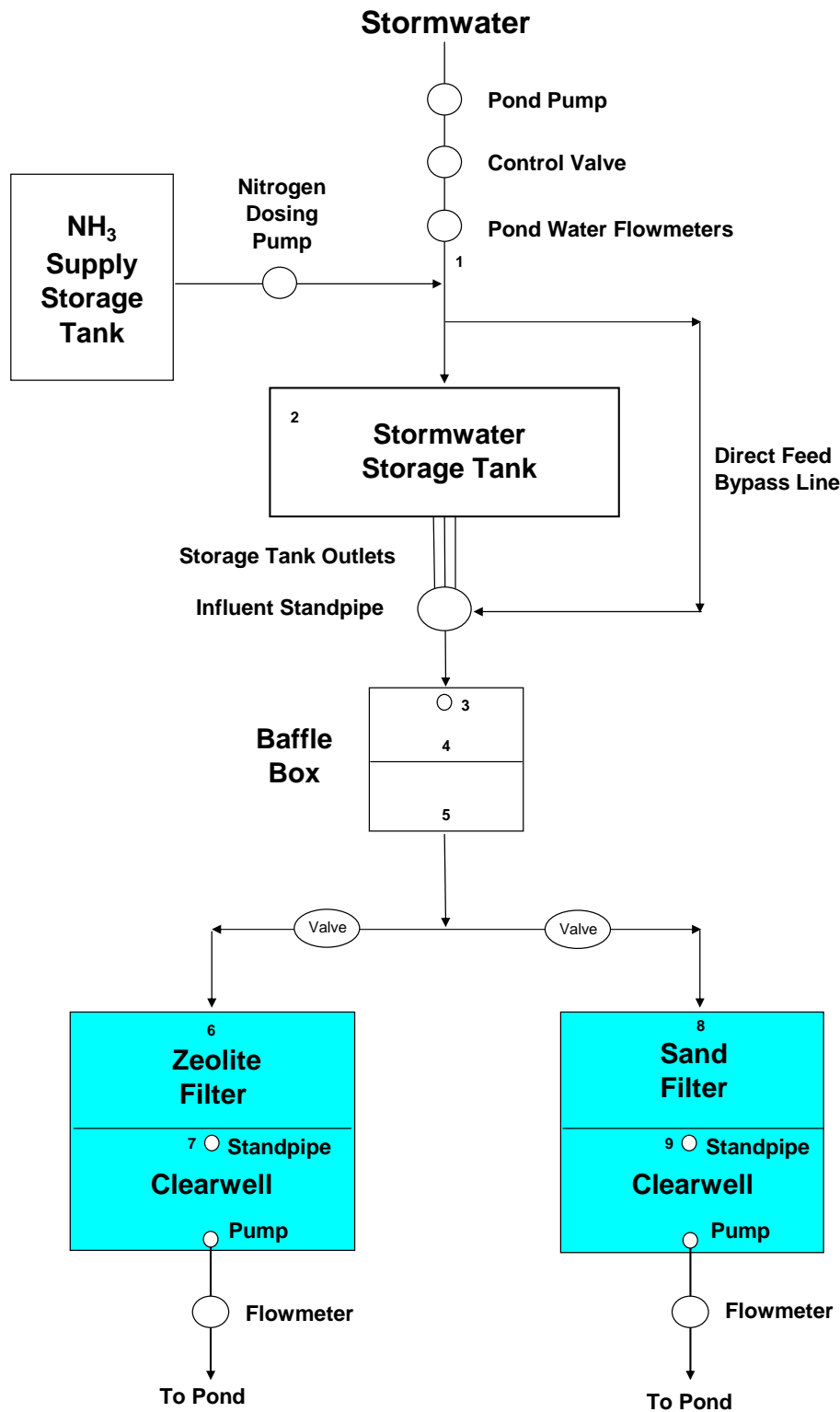


Figure 2. Design Schematic of Hillsborough Filter Pilot Demonstration, showing numbered monitoring locations.



**Figure 3. Hillsborough Filter Pilot System.**

Filter design provided for operation in either direct mode or batch mode. In *direct mode* operation, the stormwater storage tank was not used. Water supplied by the pond pump was directed through the flowmeter, dosed with  $\text{NH}_3$ , and flowed through the influent standpipe, baffle box and filters. Direct mode was used for continuous forward flow operation at constant flowrate and  $\text{NH}_3$  dosing, with equal flows to each filter. In *batch mode*, water supplied by the pond pump was directed into the 1500 gal. stormwater storage tank. The storage tank contents were released through three separately controlled discharge pipes located at different heights. Each discharge pipe contained an on/off valve and a ball valve. The on/off valves dictated when each of the different level pipes would contribute to the total tank discharge, while the ball valves controlled the magnitude of the flow through each pipe. From a starting full condition, the flowrate through each pipe declined as the water level in the storage tank declined. By adjusting the on/off valve timing and ball valve settings, simulated hydrographs could be created. Discharge from all three tank effluent lines entered the influent standpipe and proceeded through the baffle box and filters. Batch mode was used to simulate stormwater event based flows and loadings to each filter, at constant influent  $\text{NH}_3$  concentration.

The baffle box was a 600 gallon, two chambered pre-cast concrete tank. The filter chambers were 1500 gallon pre-cast concrete tanks with a baffle separation. The first (filter) chamber had interior dimensions of 5.0 ft by 6.0 ft, with a plan area of 30 ft<sup>2</sup>. The clearwell chamber has interior dimensions of 5.0 ft by 4.16 ft and a 20.8 ft<sup>2</sup> plan area. A cover was fabricated to completely prevent the ingress of rainfall.

The zeolite was 8 x 20 mesh Cabsorb ZS500H zeolite supplied by GSA Resources Inc. (Figure 4). ZS500H is a natural herschelite-sodium chabazite with a theoretical molecular formula of  $(\text{Na}_6\text{K}_6)(\text{Al}_{12}\text{Si}_{24}\text{O}_{72}) \cdot 27 \text{H}_2\text{O}$ . The experimentally measured Cation Exchange Capacity (CEC) of ZS500H is 2.50 meq/gram. The chabazite was chosen for pilot demonstration testing because of the higher adsorption capacity for ammonia ion versus other zeolites (Table 2). The 8 x 20 mesh size zeolite corresponds to a particle size range of 0.85 to 2.36 mm, and is larger than the size of sand media typically applied in stormwater treatment sand filters (such as the Delaware or Austin filters) and in slow sand filters (0.3 to 0.5 mm). The larger media size selection was based on several considerations. First, the goal of the Hillsborough Filter was nitrogen removal rather than particle filtration. While the *Hillsborough Filter* may be employed in multifaceted approaches, many *Hillsborough Filter* applications would contain some form of sedimentation pre-treatment or be applied for low TSS influent streams. The use of a larger particle size will also provide more storage capacity within the media for suspended or colloidal sediment that are removed and biomass that accumulates, making the *Hillsborough Filter* less subject to significant declines in hydraulic conductivity. This latter factor is quite significant because the goal is to have a long term, low maintenance deployment of a filter system that can capture and remove nitrogen components. The sand media was 1/8 x 16 filter sand, and was chosen to reasonably approximate the zeolite particle size. Zeolite and sand media physical tests are described in Appendix A.



**Figure 4. Zeolite ZS500H (1 large scale division = 1 cm).**

A geotextile fabric layer was mounted in a frame and placed over the filter media to capture suspended solids and prevent their entrance into the filter media (Appendix B). Mirafi Filterweave Woven Geotextile FW402 was placed under the media and above the gravel support. FW402 has a 0.425mm apparent opening size, 10% open flow area, and a flowrate of 145 gal/min ft<sup>2</sup> (ASTM D4491).

A Multi Level Sampling System (MLSS) was fabricated and deployed within the zeolite filter bed (Figure 5). The MLSS provided the capability to profile nitrogen species and other water quality parameters such as dissolved oxygen, pH, and turbidity. The MLSS is described in Appendix C.



Figure 5. Multi Level Sampling System placement in filter chamber.

**Denitrification Filters:** Two denitrification filter columns were installed at the Taliaferro field site to evaluate the ability to remove nitrate and nitrite from zeolite filter effluent (Figure 6). One filter contained elemental sulfur (75% by volume) as electron donor with limestone also added to supply alkalinity. Sulfur has previously been researched for denitrification of septic tank effluent (Zhang, et al, 1999). The second filter column contained barley straw media, which has previously been shown to reduce algal growth in wastewater treatment ponds (Zhou, et al, 1999). The two denitrification filters were operated in parallel on the same zeolite effluent for 41 days (Day 116 to 157). The physical properties of the filter columns are shown in Table 3. A preliminary bench scale evaluation of denitrification media was conducted before the field deployment and is presented in the following section.





Figure 6. Denitrification filters at Taliaferro site (elemental sulfur on left).

Table 3. Denitrification Filter Column Properties

<b>Empty Bed Volume, cm<sup>3</sup></b>	<b>980</b>
<b>Empty Bed Residence Time, min</b>	<b>56</b>
<b>Hydraulic Loading, gpm/ft<sup>2</sup></b>	<b>0.133</b>
<b>Average Influent NH<sub>3</sub>-N, mg/L</b>	<b>1.03</b>
<b>Average NH<sub>3</sub>-N Loading Rate, gram/m<sup>2</sup>-day</b>	<b>8.03</b>

**Bench Scale Testing:** A number of factors significant to pilot testing were evaluated in bench scale testing. The purpose was to develop data to support pilot testing. Bench scale results are described in a series of Appendices. To assess Taliaferro Pond water quality, nitrogen dosing, suspended solids content, alkalinity, a pond water sample was characterized for general water quality parameters and nitrogen content

(Appendix D). Bench filter columns were established and operated to assess nitrogen removal performance using the test zeolite and sand control were under steady flowrate and loading (Appendix E). A simulated stormwater event loading was also applied to the zeolite and sand columns (Appendix F). Batch leaching studies were performed to evaluate the potential of two organic materials to support denitrification by releasing chemical oxygen demand (Appendix G). Bench filter columns were established and operated to assess nitrogen removal performance using several potential denitrification media, including organic electron donor sources (heterotrophic denitrification) and autotrophic denitrification with inorganic electron donor sources (Appendix H).

**Analytical Methods:** Analyses for nitrogen, phosphorus, and total organic carbon were performed by a commercial laboratory, ELAB Inc. of Ormond Beach, FL, which is NELAC certified for methods listed in Table 4. For orthophosphorus, nitrate, and nitrite, the ion chromatographic method was routinely used. A small volume of sample, typically 50-100 uL, was introduced into an ion chromatograph. The anions of interest were separated and measured, using a system comprised of a guard column, separator column, suppressor device, and conductivity detector. The IC was a Dionex DX-120 with AS-14 Anion Column, AG-14 Guard Column, and 30uL Sample Loop for Major Anions. The MDL was determined statistically according the procedures dictated by US EPA and Florida DEP. The PQL (Practical Quantitation Limit) was based on the lowest calibration standard for the analyte. Ammonia was analyzed by automated colorimetry, in which alkaline phenol and hypochlorite were reacted with ammonia to form indophenol blue which is intensified with sodium nitroprusside. The blue color is proportional to the ammonia concentration. Total phosphorus was also analyzed by digestion followed by automated colorimetry. In the digestion, the sample was heated in the presence of sulfuric acid, potassium sulfate, and mercuric sulfate for two and one half hours. The residue was cooled, diluted to 25 ml and placed in an auto analyzer for determination of phosphorus by colorimetry. Ortho-phosphorus was analyzed by an automated colorimetric ascorbic acid method, in which ammonium molybdate and antimony potassium tartrate were added to the treated sample and reacted with orthophosphate in an acidic medium to form an antimony-phosphomolybdate complex. This complex was reduced to an intensely blue-colored complex by ascorbic acid. The concentration of the orthophosphate was measured by detecting the absorbance of the complex with a spectrophotometer. Total kjeldahl nitrogen (TKN) analyses employed semi-automated block digestion and colorimetry. A sample was heated in the presence of sulfuric acid, potassium sulfate, and mercuric sulfate for two and one half hours, converting nitrogen components of biological origin (e.g., amino acids, proteins, and peptides) to ammonia. The resulting residue was cooled, diluted to 25 ml and placed on the auto analyzer for ammonia determination by colorimetry. This digested sample could also be used for phosphorus determination. Total nitrogen was calculated by summation of TKN, nitrite, and nitrate, while organic nitrogen was calculated as the difference between TKN and  $\text{NH}_3\text{-N}$ .

Particle size separation was conducted for nitrogen size distribution using non-serial sieving and filtration. Sieving was conducted by gravity flow through nylon screens of

100, 55, and 25 um mesh size (Aquatic Eco-Systems, Inc). Filterable (soluble) and non-filterable (particulate) nitrogen were separated using in-line pressure filtration using 0.45um polyvinylidene fluoride hydrophilic membrane filters (Durapore HVLP 04700).

Temperature, pH, conductivity, dissolved oxygen, and turbidity were measured using a multi-parameter instrument (Troll 9000, In-Situ, Inc.). The instrument was calibrated and deployed according to the manufacturer's recommendations (In-Situ, Inc, 2004). A potentiometric glass pH electrode was used for pH measurement, an RDO Optical Fluorescence Sensor for dissolved oxygen, and a 9000 turbidity sensor with wiper for turbidity as NTU.

Additional supporting analyses were conducted for water quality characterization of pond and treated water and to support process analyses (Table 5). A DR5000 UV-VIS spectrophotometer (Hach DR5000) and Digital Reactor Block (Hach DRB200) were employed.

**Table 4. Analytical Methods by NELAC Certified Laboratory (ELAB, Inc.)**

<b>Parameter</b>	<b>Method</b>	<b>MDL<sup>1</sup></b>	<b>PQL<sup>2</sup></b>	<b>units</b>
TKN	EPA 351.2	0.095	0.50	mg/L
Ammonia	EPA 350.1	0.014	0.05	mg/L
Nitrate	EPA 300.0	0.0091	0.05	mg/L
Nitrate	EPA 353.2	0.005	0.05	mg/L
Nitrite	EPA 300.0	0.0091	0.05	mg/L
Nitrite	EPA 353.2	0.004	0.05	mg/L
Total Phosphorus	EPA 365.4	0.0064	0.10	mg/L
Ortho-Phosphate	EPA 300.0	0.021	0.10	mg/L
Ortho-Phosphate	EPA 365.1	0.015	0.10	mg/L
Total Organic Carbon	EPA 415.1	0.08	1.00	mg/L



**Table 5. Supporting Characterization and Analytical Methods.**

<b>Analyte</b>	<b>Procedure</b>	<b>Method</b>
Total suspended solids	Filtration through Whatman GF/C glass fiber filter (1.2 um nominal)	APHA 2540 D
Total alkalinity	Titration with 0.16N H <sub>2</sub> SO <sub>4</sub> to bromocresol green-methyl red endpoint	APHA 2320
Chemical oxygen demand	Sulfuric acid digestion with dichromate oxidation	Closed reflux microdigestion
Ammonia Nitrogen	Salicylate method	Hach 8155
Nitrite Nitrogen	Diazotization (colorimetric)	APHA 4500-NO <sub>2</sub> <sup>-</sup> B Hach 8507
(Nitrite + Nitrate) Nitrogen	Cadmium reduction; diazotization (colorimetric)	APHA 4500-NO <sub>3</sub> <sup>-</sup> E Hach 8192
Dissolved oxygen	Winkler titration, azide modification	APHA 4500-O C Hach 8215
UV-254 Adsorption	Adsorption at 254 nm	APHA 5910 B

## Results and Discussion

Pilot plant operation commenced on September 14, 2005 and ended on April 18 2006. A total of 1.46 million gallons of Taliaferro pond water was treated in the pilot system over the 216 day period of study. The testing program included an extended start-up period during which the pilot system was modified to increase dissolved oxygen concentrations in the pond water entering the treatment system. The pilot system was operated for a period at constant flowrate and loading, which provided comparative steady operation performance data for parallel zeolite and sand filters. During the steady operation period, detailed testing was performed to characterize solute profiles within the zeolite filter bed and the size distribution of nitrogen species. The filters were then subjected to a number of non-steady events. A step flowrate increase and a simulated storm event loading were conducted to assess filter performance in response to non-steady loadings. A specific test was conducted to delineate the effects of influent dissolved oxygen on ammonia removal, and another test was performed to assess the effect of an extended non-operational period on event loading performance. Two denitrification filter columns were installed at the pilot site to evaluate the removal of nitrate and nitrate from zeolite filter effluent.

**Operational History and Monitoring:** The operational sequence is summarized in Table 6. The periods of operation are discussed sequentially in the following sections. A flowrate of 4 gallon per minute was established as the baseline steady flowrate to each filter, and served as the operational default flowrate that was applied throughout the pilot testing. The resulting hydraulic loading rate of  $0.133 \text{ gpm/ft}^2$  ( $192 \text{ gal/ft}^2\text{-day}$ ) is somewhat higher than that of a slow sand filter (ASCE, 1991). To put this into perspective, a filter size of 24 by 24 ft (at  $0.133 \text{ gpm/ft}^2$ ) would be required for drawdown of a one acre pond with a 12 in. water quality volume depth over 72 hours. The time history of applied flowrate is shown in Figure 7. Influent and filter effluent ammonia concentrations are shown in Figure 8, while inorganic nitrogen species in zeolite and sand filter effluents are shown in Figures 9 and 10, respectively. The ammonia nitrogen removal efficiency for zeolite and sand filters is shown in Figure 11. In Table 7 are shown average operational parameters over the entire study, excluding periods in which non-steady state experiments were performed. The filters were initially operated in a fully submerged condition. The filters were initially fully submerged, but submergence depth was set at 18 inch on Day 2 and remained at that depth for the remainder of the study.

**Start Up (Day 0-19):** Forward flow was initiated on 9/14/2005 (Day 0). Ammonia-N dosing was started at Day 0. Monitoring was initiated during this period (Figure 12).

**Inoculation (Day 20):** Deliberate microbial inoculation was considered a possible accelerator of microbial reaction establishment. Each filter was inoculated with two different microbial inocula collected from the Howard Curran Advanced Wastewater Treatment Plant of the City of Tampa. The first was settled nitrifying mixed liquor from the aerobic, separate stage, nitrifying suspended growth activated sludge process. The second inocula was settled backwash water from the tertiary, methanol fed,

**Table 6. Operational Summary.**

<b>Days</b>	<b>Operational Period</b>	<b>Goal</b>	<b>Nominal Filtration Rate gal/ft<sup>2</sup>-min</b>
0-19	Start Up	Establish system	0.133
20	Inoculation	Initiate biochemical reaction	0.133
21-57	Steady Operation	Characterize steady operation	0.133
58-59	Aeration Modification	Increase influent dissolved oxygen	0.133
60-70	Steady Operation	Characterize steady operation	0.133
71-86	Zeolite Media Desorption	Desorb and denitrify NH <sub>3</sub> -N	0.212 <sup>1</sup>
87-92	Steady Operation	Characterize steady operation	0.133
93	Step Loading	Non-steady performance	0.133 – 0.494
94-114	Dry Period	Non-loading	0
115-138	Steady Operation	Characterize steady operation	0.133
139-140	Event Loading	Non-steady performance	0.133 – 4.37
141-155	Steady Operation	Characterize steady operation	0.133
156	Low DO Operation	Evaluate effect of low dissolved oxygen	0.133
157-175	Steady Operation	Characterize steady operation	0.133
176-215	Extended Dry Period	Non-loading	0
216	Event Loading	Non-steady performance after extended non-loading period	0.133 – 3.13

<sup>1</sup> Sand filter flow was zero from Day 79 to 86

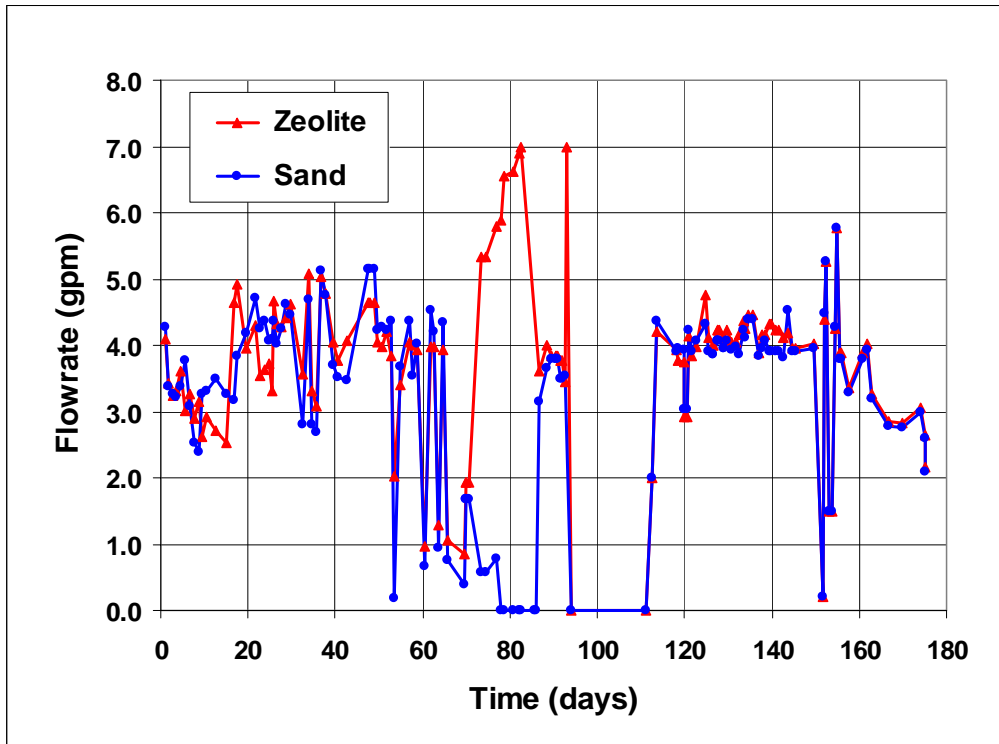


Figure 7. Applied flowrate to zeolite and sand filters

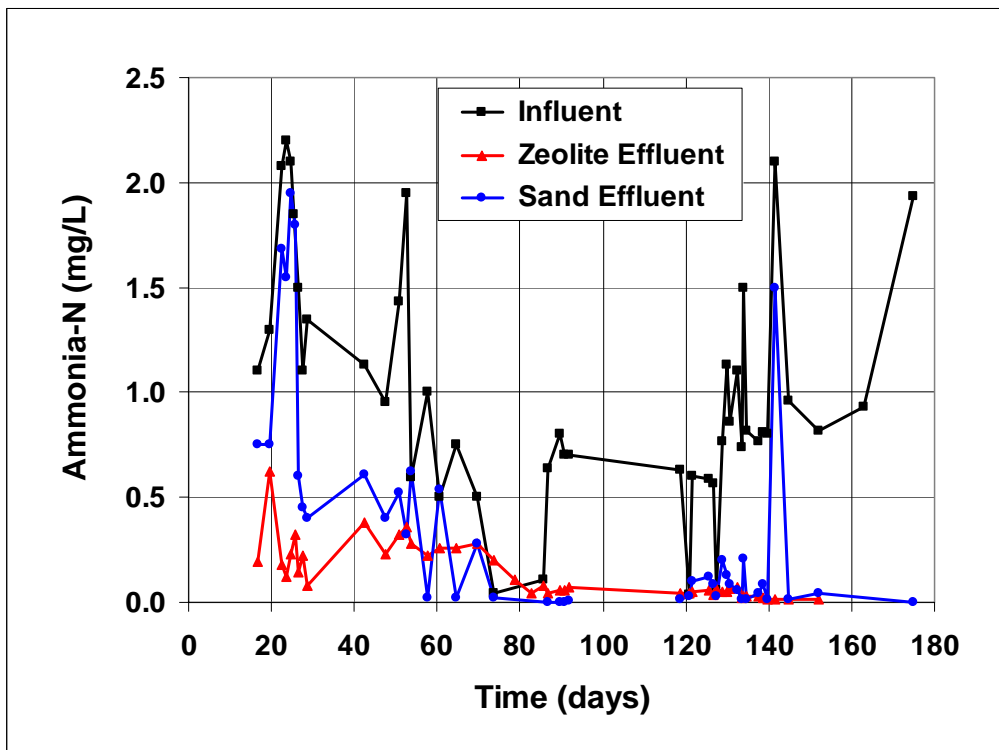


Figure 8. Ammonia nitrogen in filter influent and effluents.

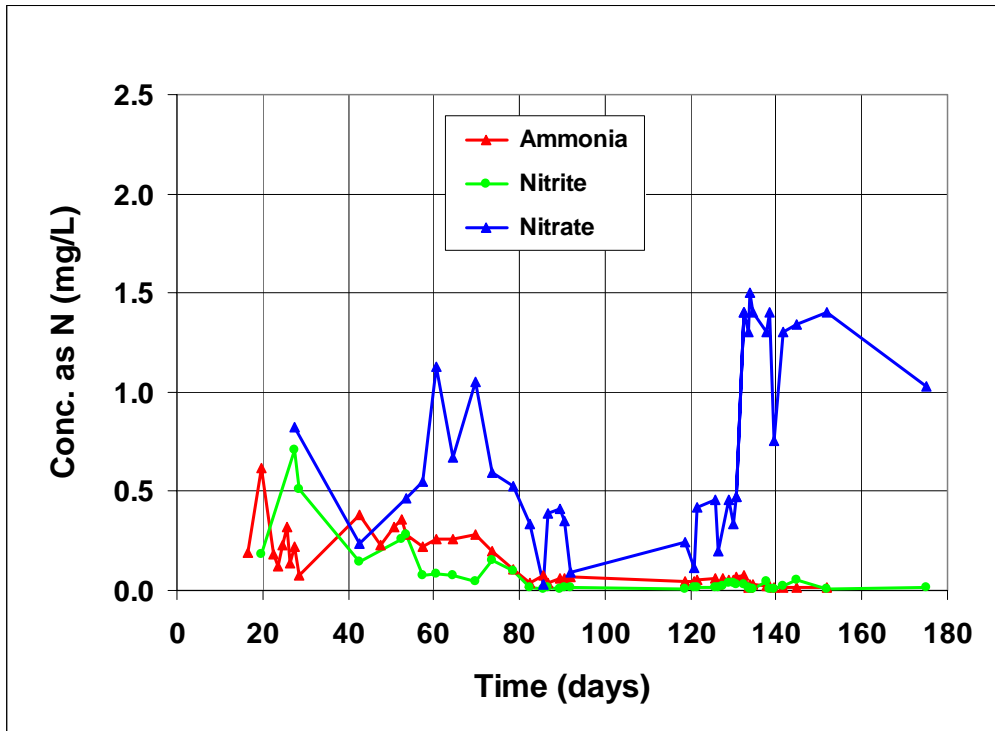


Figure 9. Inorganic nitrogen in zeolite filter effluent.

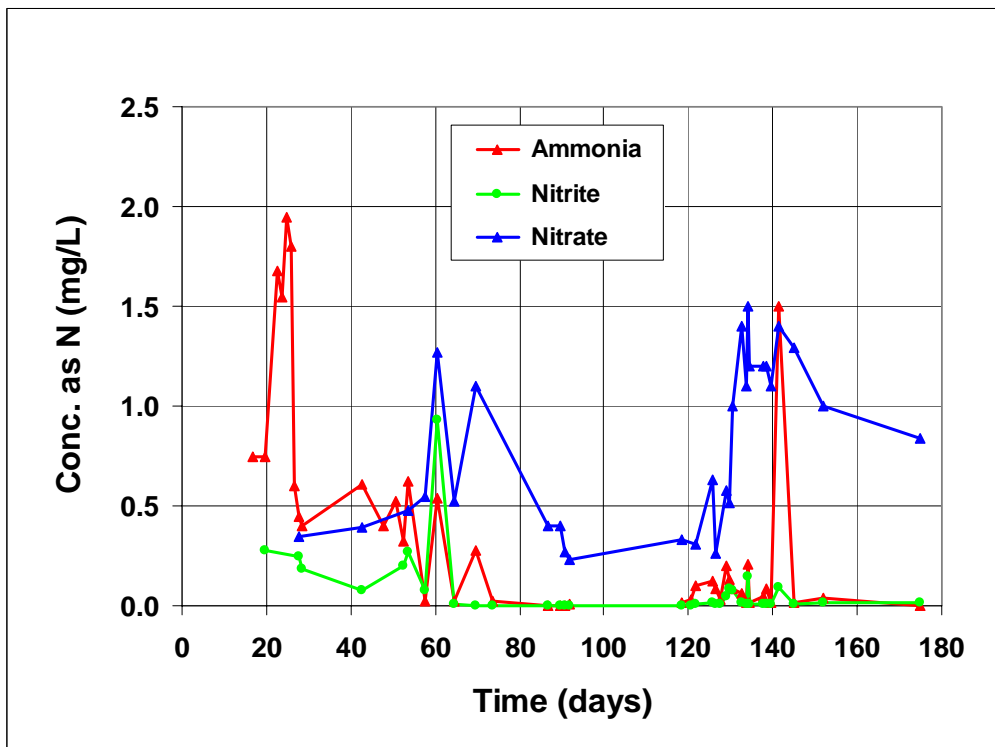


Figure 10. Inorganic nitrogen in sand filter effluent.

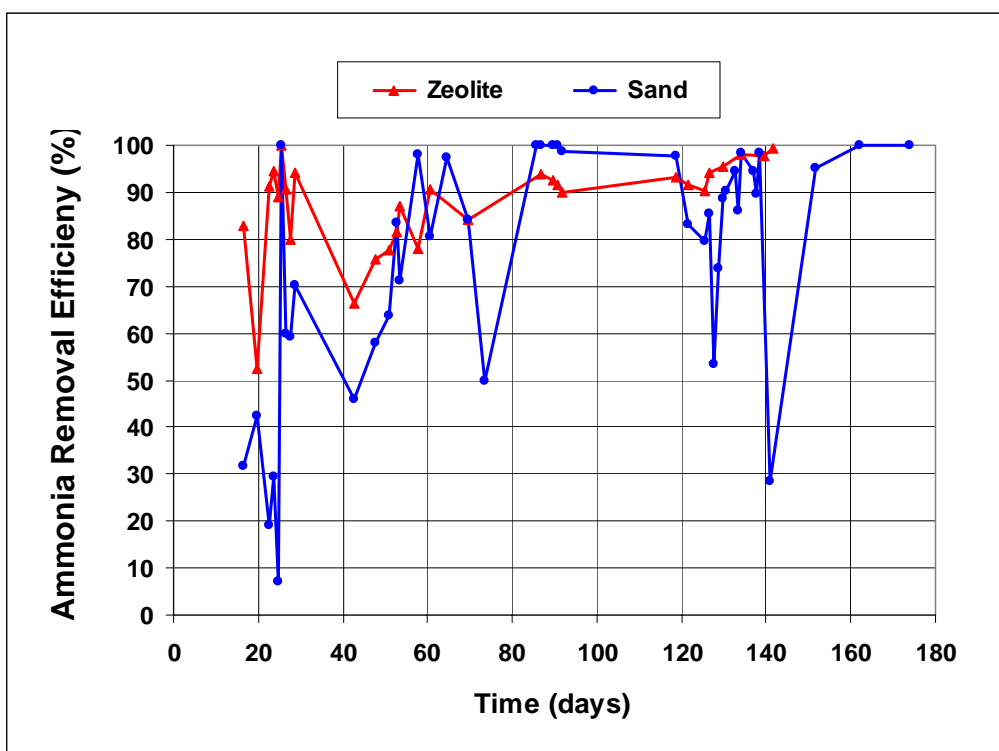


Figure 11. Ammonia removal efficiencies.

Table 7. Average operation parameters for non-perturbation periods.

Parameter	Zeolite	Sand
Influent NH <sub>3</sub> -N	1.0	1.0
Applied flowrate (gpm/ft <sup>2</sup> )	0.126	0.111
Effluent NH <sub>3</sub> -N, mg/L	0.13	0.37
Effluent NO <sub>2</sub> -N, mg/L	0.08	0.08
Effluent NO <sub>3</sub> -N, mg/L	0.73	0.79

anoxic denitrifying filters. Ten gallons of each inocula source were collected and 5 gallons of each were poured directly onto the surface of each filter. Forward flow was discontinued just before inoculation and restarted after 3 hours.

**Steady Operation (Day 21-57):** During this period, the pilot filters were operated at influent  $\text{NH}_3\text{-N}$  concentrations generally 1 mg/L and above (Figure 8).  $\text{NH}_3\text{-N}$  declined in the zeolite filter effluent after Day 20, whereas sand filter effluent was well above 1 mg/L. Zeolite filter effluent  $\text{NH}_3$  was less than sand effluent prior to inoculation, and declined after inoculation. From Day 20 to 26, influent  $\text{NH}_3\text{-N}$  was unintentionally increased to over 2 mg/L (Figure 8). Sand filter effluent  $\text{NH}_3$  followed the influent concentration and rose significantly from Day 20 to 26. Zeolite effluent  $\text{NH}_3$  concentration did not increase, but actually decreased. This suggests that zeolite media may have sorbed  $\text{NH}_3$  and maintained lower ammonia effluent concentrations. The lower  $\text{NH}_3$  concentrations in zeolite effluent versus sand can be attributed to the high ion exchange capacity of the zeolite, and to the high internal pore volume of chabazite that may favor nitrification establishment. Another possible explanation is production of  $\text{N}_2\text{O}$  by nitrifying organisms, a phenomena which may be increased when nitrifiers are grown under low DO conditions. Sand filter effluent  $\text{NH}_3\text{-N}$  declined significantly from Day 27 to 29, possibly due to nitrification establishment, but remained above zeolite effluent levels through Day 50.

Inorganic nitrogen through the treatment train on Day 43 is shown in Figure 12. At this time, the pondwater contained low levels of inorganic nitrogen, which was increased through dosing to the baffle box. Ammonia was significantly reduced in both zeolite and sand filters, and zeolite effluent levels were lower than sand for  $\text{NH}_3$ ,  $\text{NO}_2$ , and  $\text{NO}_3$ . The nitrogen concentrations were lower at 22 in. depth within the zeolite filter than in the effluent, suggesting that preferential flow paths within the zeolite bed were influencing filter performance.

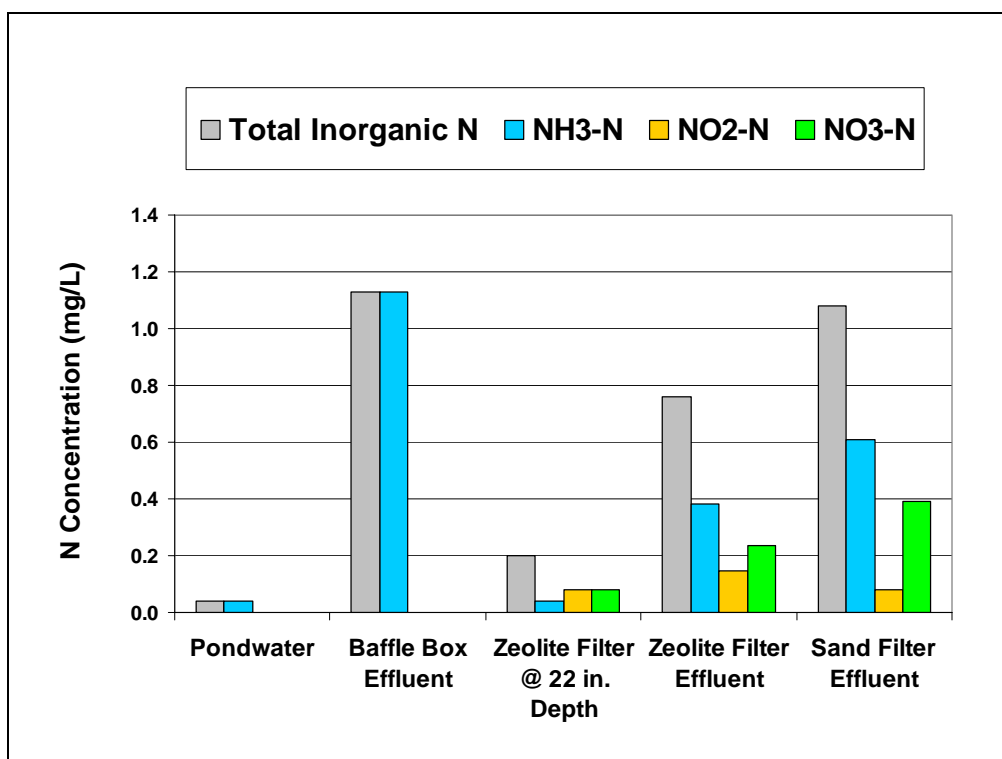


Figure 12. Inorganic nitrogen concentrations through treatment system (Day 43).

In the Taliaferro installation, pond water enters a sump, which in turn supplies a second sump. A pump in the second sump directs water to the pilot treatment system. Even though monitoring showed that pond water DO was 4 mg/L or greater, it was found that DO levels were 1 mg/L or less in pond sumps and baffle box influent and effluent. It was speculated that actual pond water entering the pipes was less than pond water column concentrations, or substantial oxygen demand was exerted by sediments accumulated at the sump bottoms. The unexpectedly low DO entering the pilot system resulted in filter effluent DO levels of less than 0.2 mg/L (Figure 13). Low DO levels were of concern because biological nitrification has a theoretical oxygen requirement of 4.57 grams  $O_2$ /gram  $NH_4^+-N$  (Table 1). To increase DO levels in the filters, the pilot system was modified by installing a sprinkler head aeration system in the sump from which the influent was drawn. After installation of the aeration system filter influent DO increased to 4 mg/L and greater (Figure 15).

**Steady Operation (Day 60-70):** During this period, the filters were operated with a steady flowrate and influent DO of 4 or greater, and influent  $NH_3-N$  was decreased to 0.5 to 1 mg/L (Figure 8). In both filters, effluent nitrate increased significantly, indicating that higher influent oxygen levels were enabling greater  $NH_3$  utilization by nitrification (Figures 9 and 10).  $NH_3-N$  declined in sand filter effluent through this period, but zeolite effluent remained at approximately 0.27 mg/L to Day 70 (Figure 8).

**Zeolite Media Desorption (Day 71-86):** The zeolite filter provided greater  $NH_3$  removals than the sand filter from Day 0 to 60. During this period, influent dissolved oxygen levels were stoichiometrically insufficient to support nitrification. It was hypothesized that the greater cumulative removal of  $NH_3$  by the zeolite filter was due to sorption, and had created a reservoir of  $NH_3$  mass that was adsorbed to the zeolite media. To test this hypothesis, ammonia supplementation to pond water was discontinued on Day 71 to 86 during which time influent  $NH_3-N$  was 0.11 mg/L or less (Figure 8). Sand effluent  $NH_3$  responded quickly and quite low after Day 70 (Figure 8). As a result of much lower influent  $NH_3$  concentrations, zeolite effluent  $NH_3$  began to decline after Day 70, and was higher than sand effluent during this period. To increase the rate of desorption, flowrate to the zeolite filter was increased to 5 to 7 gpm at Day 74. All inorganic nitrogen species declined in zeolite effluent (Figure 14). Desorption of  $NH_3$  and nitrification contributed to the decline of ammonia from zeolite effluent, with nitrate accounting for 60 to 90% of the nitrogen removed.

**Steady Operation (Day 87-92):** A flowrate of ca 4 gpm and influent  $NH_3-N$  of 0.7 mg/L were applied in preparation for a step flow experiment.

**Step Loading (Day 93):** A step flowrate increase experiment was conducted and is described in the Non-Steady Operation Performance section (below).

**Dry Period (Day 94-114):** Flow to the filters was discontinued during this period, simulating a 21 day non-flow (interevent) period.



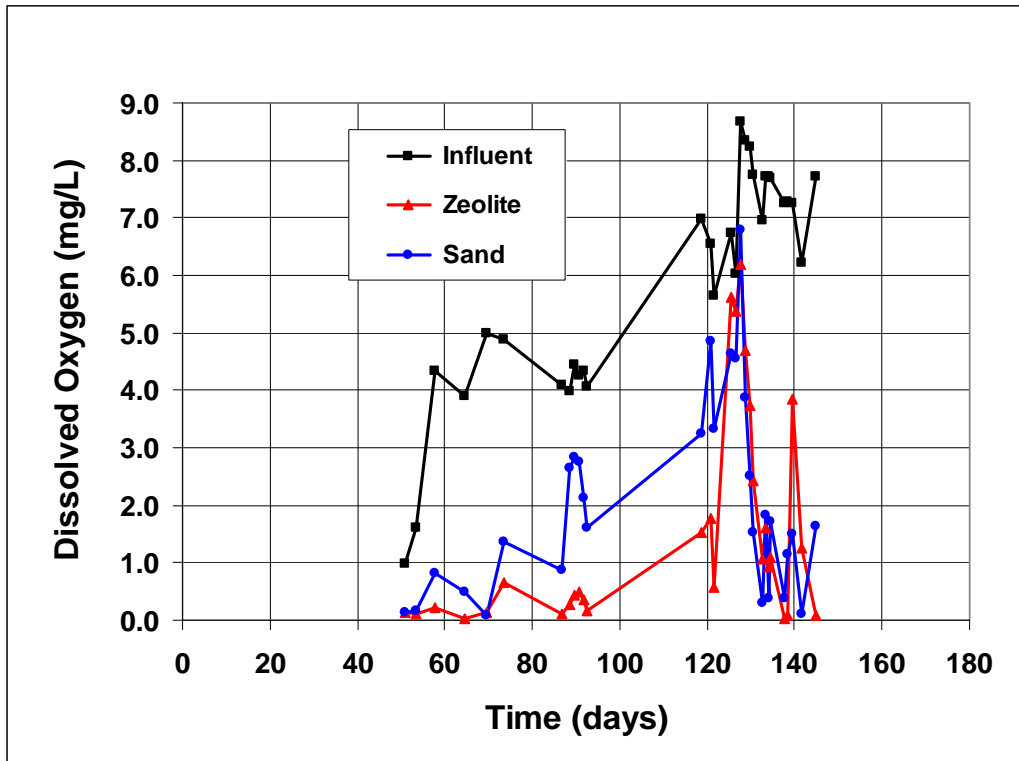


Figure 13. Dissolved oxygen in inorganic influent and filter effluents.

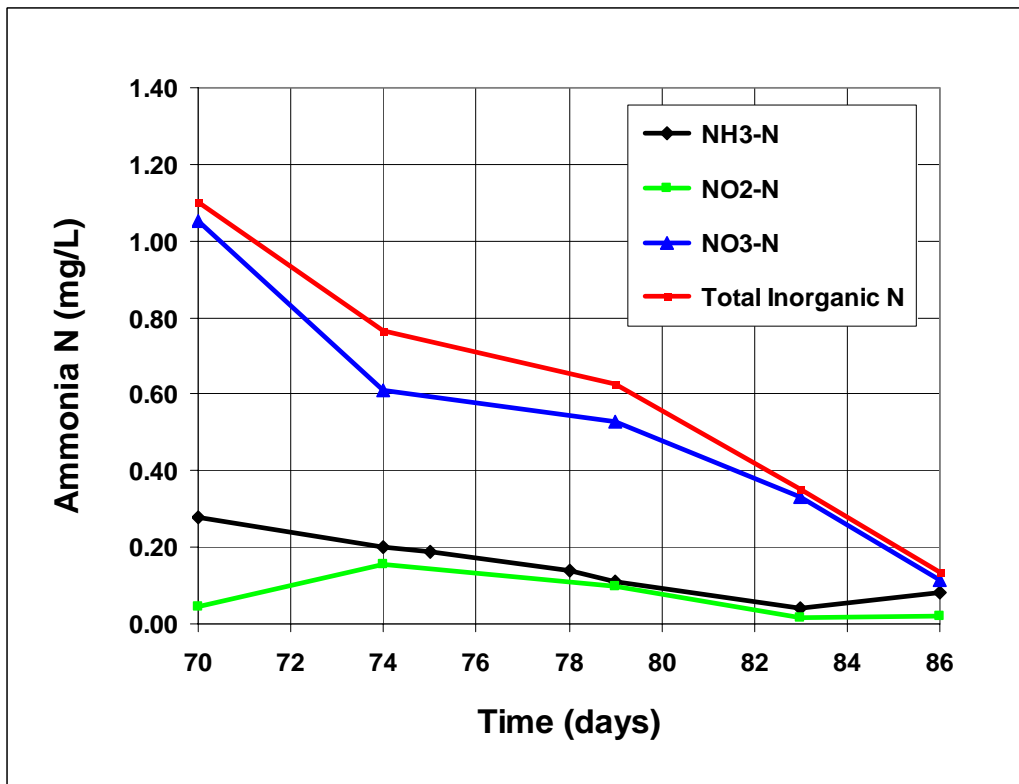


Figure 14. Ammonia desorption from zeolite filter media.

**Steady Operation (Day 115-138):** After a 21 day period in which they received no flow, filters were operated at 4 gpm with 0.7 to 1.2 mg/L influent  $\text{NH}_3\text{-N}$  (Figures 7 and 8). Monitoring data from a part of this period were used to benchmark steady operation performance, which is described in the Steady Operation Performance section (below).

**Event Loading (Day 139-140):** A simulated storm event loading experiment was conducted and is described below in the Non-Steady Operation Performance section.

**Steady Operation (Day 141-155):** Following the event loading experiment, the system was operated at 0.7 to 1.0 mg/L influent  $\text{NH}_3\text{-N}$ . Effluent  $\text{NH}_3\text{-N}$  levels were less than 0.1 mg/L in both zeolite and sand effluents during this period, and  $\text{NO}_3\text{-N}$  concentrations were 1 mg/L and above (Figures 9 and 10).

**Low DO Operation (Day 156):** An experiment was performed in which the influent aerator was turned off, and the filter response was monitored. Results are described in the Non-Steady Operation Performance section below.

**Steady Operation (Day 141-175):** Following the event loading experiment, the system was operated at 0.7 to 1.0 mg/L influent  $\text{NH}_3\text{-N}$ . Effluent  $\text{NH}_3\text{-N}$  levels were less than 0.1 mg/L in both zeolite and sand effluents during this period, and  $\text{NO}_3\text{-N}$  concentrations were 1 mg/L and above (Figures 9 and 10).

**Extended Dry Period (Day 176-215):** Flow to the filters was discontinued during this 39 day period, simulating an inter-event period. The purpose was to evaluate filter response to a storm event that would occur after an extended non-operational period.

**Event Loading (Day 216):** A simulated storm event loading experiment was conducted and is described below in the Non-Steady Operation Performance section.

**Steady Operation Performance:** Stormwater treatment filters would be expected to be subject to non-steady conditions including storm event loadings, extended inter-event periods with little or no flowrate, and variable influent nitrogen concentrations and speciation. Characterizing performance under steady operation conditions is useful as a point of departure for assessing the performance when non-steady flows and load are imposed. Nitrogen removal in the zeolite and sand filters during steady operation conditions was benchmarked, solute concentration profiles were measured in the zeolite media, and the nitrogen particle size distribution was measured in baffle box and filters.

**Nitrogen Removal:** A period of Day 118 to 132 provided steady conditions and was chosen to benchmarking steady operation. Ammonia reduction during the 15 day period is summarized in Table 8. Zeolite and sand filters were both effective at removing  $\text{NH}_3\text{-N}$ , although zeolite appeared to be slightly superior. Zeolite nitrate and nitrite levels were lower than in sand effluent (Table 9). Total inorganic nitrogen

**Table 8. NH<sub>3</sub> reduction in 15 day steady operational period (n=8).**

	<b>NH<sub>3</sub>-N, mg/L</b>	<b>% Reduction</b>
<b>Influent</b>	<b>0.781</b>	
<b>Zeolite Effluent</b>	<b>0.053</b>	<b>93.3</b>
<b>Sand Effluent</b>	<b>0.099</b>	<b>86.7</b>

**Table 9. Inorganic nitrogen in 15 day steady operational period (n=8).**

	<b>Influent</b>	<b>Zeolite Effluent</b>	<b>Sand Effluent</b>
<b>Total Inorganic N, mg/L</b>	<b>0.850</b>	<b>0.577</b>	<b>0.757</b>
<b>Ammonia-N, mg/L</b>	<b>0.781</b>	<b>0.053</b>	<b>0.099</b>
<b>Nitrite-N, mg/L</b>	<b>0.009</b>	<b>0.024</b>	<b>0.032</b>
<b>Nitrate-N, mg/L</b>	<b>0.060</b>	<b>0.500</b>	<b>0.627</b>

**Table 10. Dissolved oxygen in 15 day steady operational period (n=8).**

	<b>DO, mg/L</b>	<b>Δ DO / Δ NH<sub>3</sub>-N</b>
<b>Influent</b>	<b>7.2</b>	
<b>Zeolite filter</b>	<b>3.3</b>	<b>5.4</b>
<b>Sand filter</b>	<b>3.9</b>	<b>5.5</b>

removal was 32% in the zeolite filter versus 11% in the sand filter. It is hypothesized that the zeolite filter may be more effective than sand at capturing stormwater organic matter and providing electron donor for denitrification, and in creating niches within the filter bed that are conducive to denitrification reactions. In Table 10 are shown average effluent dissolved oxygen levels and the ration of oxygen reduction to ammonia nitrogen reduction in the zeolite and sand filters. The zeolite filter had lower average DO levels, which could reflect greater ammonia reduction or greater oxidation of organic materials in the pond water. The ration of DO decrease to NH<sub>3</sub>-N decrease

is similar in both filters and greater than the theoretical value for ammonia nitrification, suggesting that natural organic matter utilization occurred on both filters.

The concentrations and speciation of total nitrogen through the treatment system on Day 131 are shown in Figure 15. Influent total nitrogen was predominantly as organic and ammonia nitrogen. The major nitrogen transformation in both filters was decrease in ammonia with a roughly equal increase in nitrate and total nitrogen was not greatly reduced. A post-denitrification step would be needed for reduction in total nitrogen. Another significant feature is the limited decline in dissolved organic nitrogen in either zeolite or sand filters. The presence of dissolved organic nitrogen in stormwater is of great significant in determining the nitrogen endpoints that can be achieved in stormwater treatment systems.

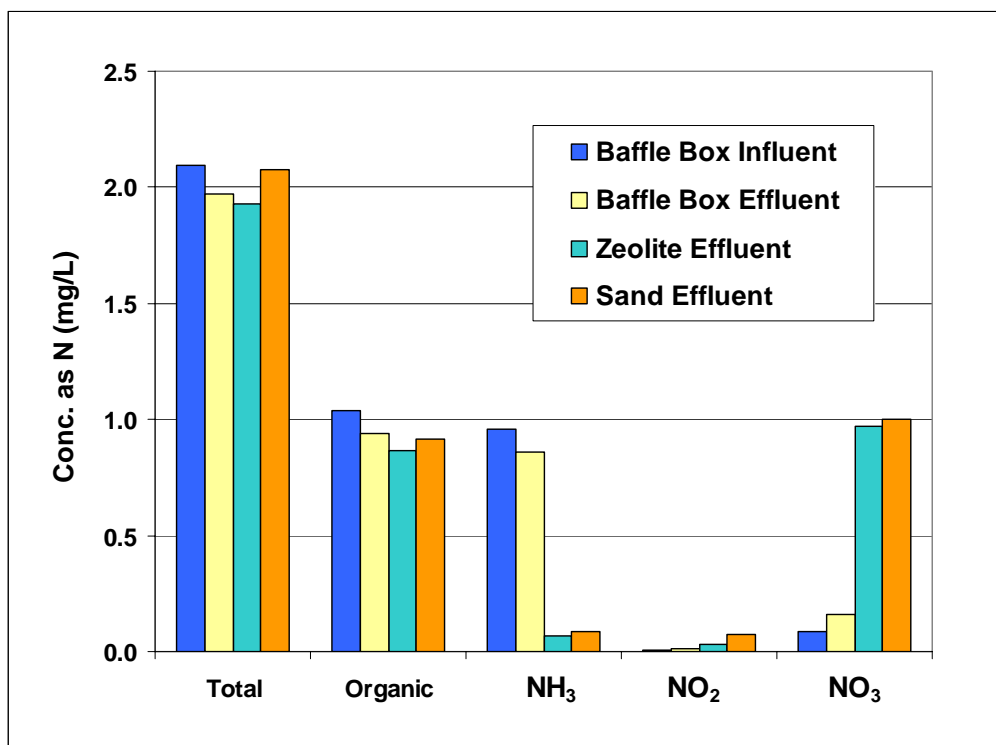


Figure 15. Nitrogen concentrations through treatment system (day 131).

**Organic Nitrogen Particle Size Distribution:** The size distribution of organic nitrogen in baffle box influent and effluent is shown in Figure 16. The baffle box effluent is pond water amended with NH<sub>3</sub>. The majority of organic nitrogen was not retained by a 0.45 um membrane filter, and was colloidal or truly dissolved organic nitrogen. Passage through the baffle box did not significantly change the concentration of organic nitrogen, since sedimentation would be ineffective for dissolved or colloidal constituents.

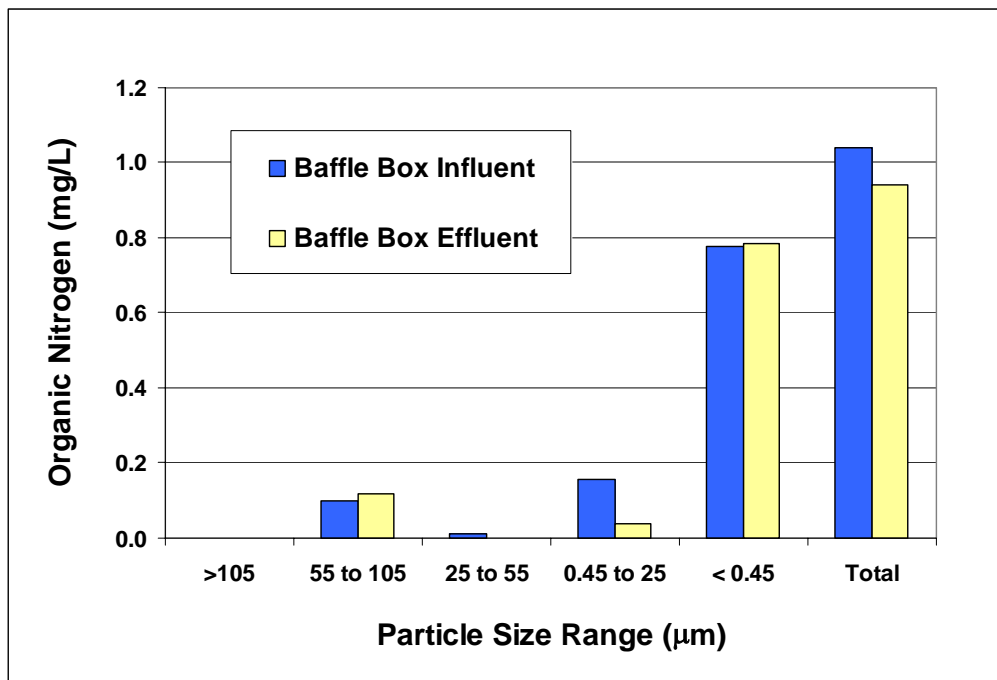


Figure 16. Particle size distribution of organic nitrogen (day 131).

**Zeolite Filter Solute Profiles:** The multi-level sampling system was used to collect and analyze samples at different depths in the zeolite filter bed. Total inorganic nitrogen and speciation are shown in Figure 17 for Day 54, when the zeolite filter effluent DO was less than 0.2 mg/L. Total inorganic nitrogen declined with depth, due to a decline in ammonia nitrogen. The influent DO of 1.6 mg/L on Day 54 would support a consumption of only 0.35 mg/L  $\text{NH}_3\text{-N}$  from nitrification to  $\text{NO}_3$ , but 0.47 mg/L  $\text{NH}_3\text{-N}$  decline from nitrification to  $\text{NO}_2$  (Table 1). These results suggest that a portion of ammonia was sorbed to the zeolite, without reaction, or possibly formation of  $\text{N}_2\text{O}$  by nitrifiers in the low DO environment in the media.

Solute profiles in the zeolite filter are shown in Figures 18 and 19 for Days 142 and 145, for which influent DO was 6 to 8 mg/L. The saturation depth of the zeolite filter was 6 inches. In both the Day 152 and 145 profiles, ammonia was substantially transformed by the first sample depth of 7 inch, which is only one inch below the saturation level at which the filter was operated. This suggests a highly active nitrifying population in the top one inch of the saturated zone. In both profiles, nitrate accumulation was substantial within the top one inch of water saturation. These profiles suggest zeolite filter designs with shallow bed depths may be effective if the magnitude of event loadings is limited. In both profiles, dissolved oxygen declined significantly. However, the differences in the profiles on Day 142 and 145 may be due to the influent concentrations of ammonia and oxygen. On Day 142, influent ammonia was twice as high as on Day 145, and influent DO was lower. These factors both favor the establishment of anoxic conditions. As expected, the DO regime in the filter was lower on Day 142 versus Day 145. Possibly as a result, nitrate levels on Day 142 declined significantly (Figure 18). There is also greater decrease in dissolved organic

carbon on Day 142. In both profiles, a slight increase in ammonia at lower depths suggests ammonification processes. These profiles provide insight into how oxygen levels can influence inorganic nitrogen transformations in the zeolite filter.

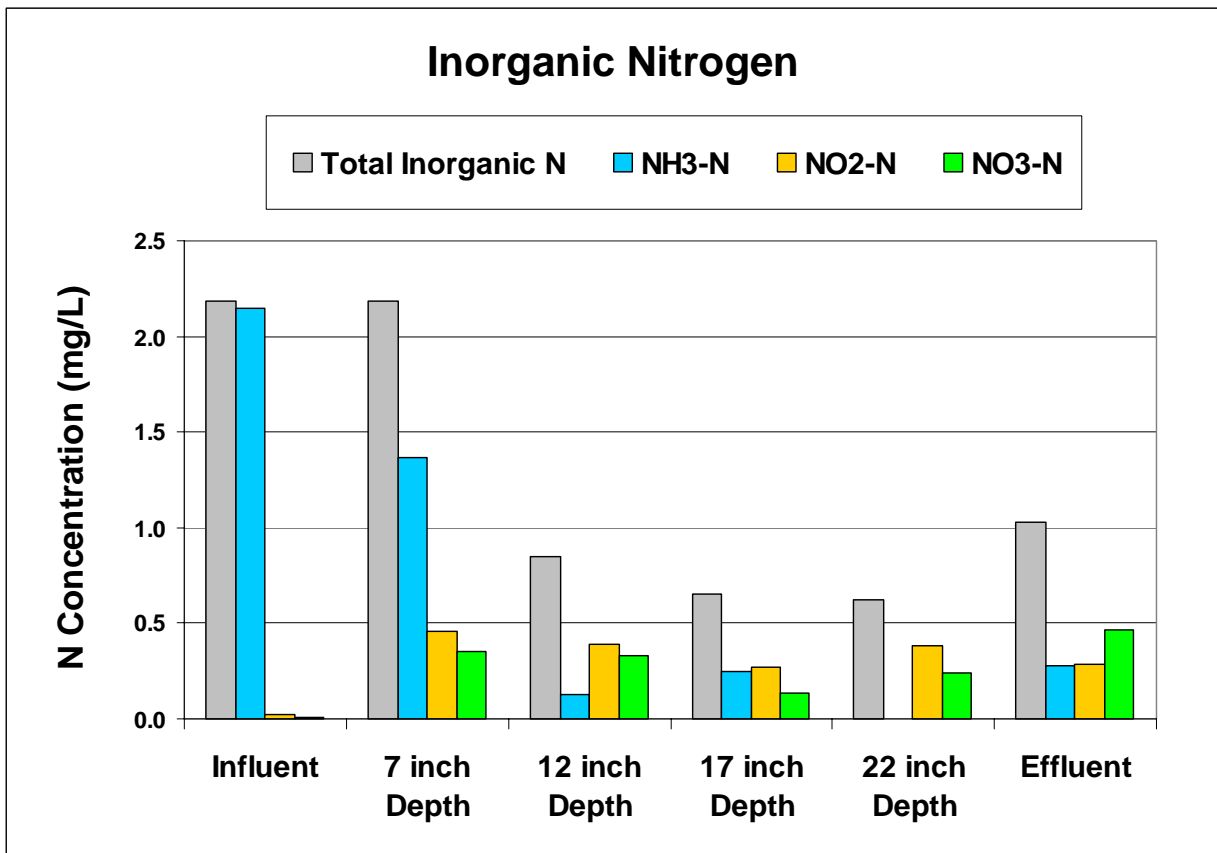


Figure 17. Nitrogen profiles through zeolite filter (Day 54).

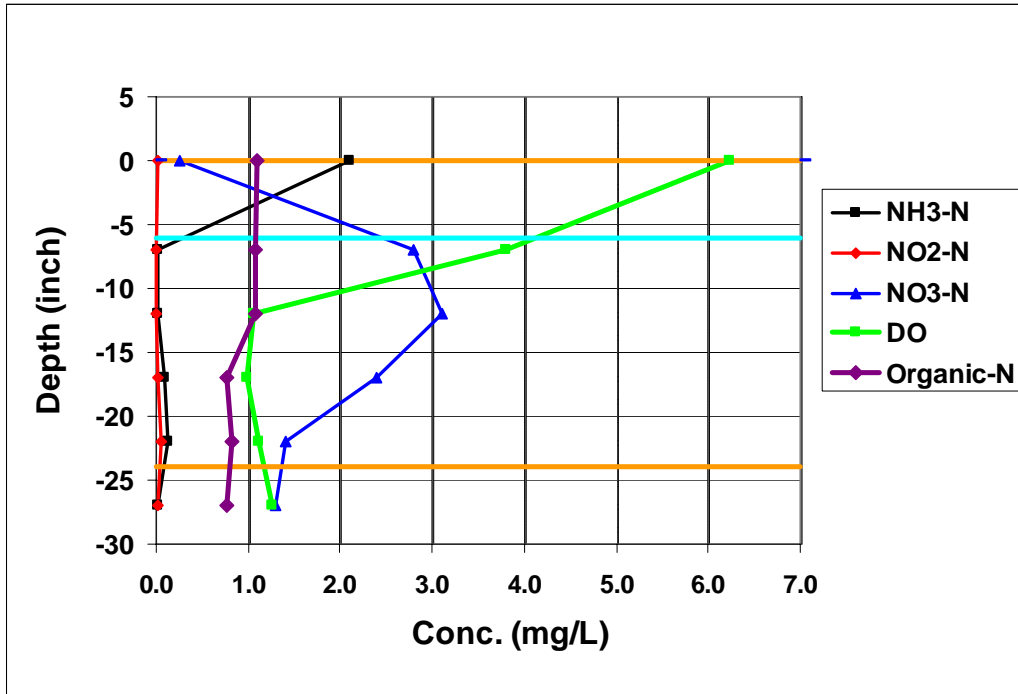


Figure 18. Solute profiles in zeolite filter bed (Day 142).

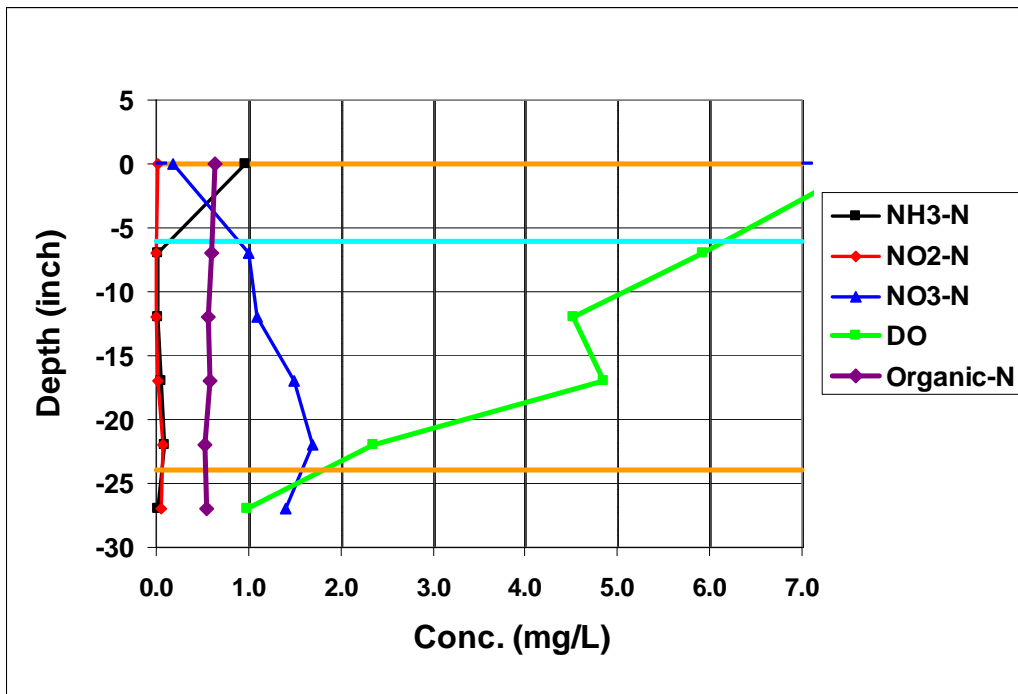


Figure 19. Solute profiles in zeolite filter bed (Day 145).

**Non-Steady Operation Performance:** A number of experiments were conducted to assess filter response to non-steady conditions that can occur in stormwater treatment trains.

**Step Flow Increase:** The first non-steady experiment (Day 93) was a step increase in the applied filtration rate for 60 minutes (Figure 20). The direct flow mode of operation was used, and applied flowrate was limited by the pump capacity. The magnitude of the step increase was relatively limited compared to what could be expected in stormwater events. Under this flow increase, effluent ammonia did not rise but nitrate increased (Figure 21). The increase in nitrate was accompanied by an increase in effluent dissolved oxygen (Figure 22). These results suggest that the fraction of influent ammonia undergoing nitrification was lowered by the increase in flowrate. The pH rose by 0.12 units during the perturbation, which is also consistent with reduced nitrification (Figure 23). Zeolite effluent turbidity rose to 0.8 during the perturbation (Figure 24).

The zeolite results can be compared with the sand filter results. The sand filter exhibited greater ammonia breakthrough, and nitrate nitrogen levels decreased (Figure 25). The later result is ostensibly due to lower rates of nitrification in the sand filter, and is consistent with the higher DO increase during the perturbation to the sand filter (Figure 26). The pH change was minor, but the effluent turbidity rise to 1.2 NTU was slightly higher than for zeolite.

The time course of zeolite and sand filter effluent ammonia are compared in Figure 29. As expected, zeolite was superior in preventing breakthrough of the increased ammonia loading during the perturbation. Also, nitrate levels in zeolite filter effluent increased, indicating that denitrification processes that follow zeolite filters could have to treat higher instantaneous nitrate loading in storm events. The results of the step flowrate perturbation were consistent with the hypothesized performance of zeolite filters, although the perturbation was of limited magnitude.

**Simulated Storm Event:** A simulated storm event loading was applied to each filter (Day 139-140) using the stormwater storage tank batch mode. The storage tank was filled to 1300 gallons, dosed with ammonia nitrogen, and released to the filter as a simulated hydrograph. The simulated inflow hydrograph is shown in Figure 30. A slow period of inflow was followed by a high flowrate that peaked at over 130 gpm, or over 30 times the nominal steady state. Influent nitrogen concentrations were constant during the experiment at 0.80, 0.01 and 0.16 mg/L of nitrogen as ammonia, nitrite, and nitrate, respectively.

The response of the zeolite filter is shown in Figures 31 through 34. The zeolite filter was very effective at preventing ammonia breakthrough, with a maximum  $\text{NH}_3\text{-N}$  concentration of only 0.08 mg/L (Figure 31). Effluent  $\text{NO}_3\text{-N}$  concentrations were approximately 1.5 mg/L at the start of the experiment, but were flushed out of the filter bed as water within the bed was flushed out with stormwater tank water.  $\text{NO}_3\text{-N}$  dropped to 0.6 mg/L and rebounded to 0.78 mg/L as the storm event continued.



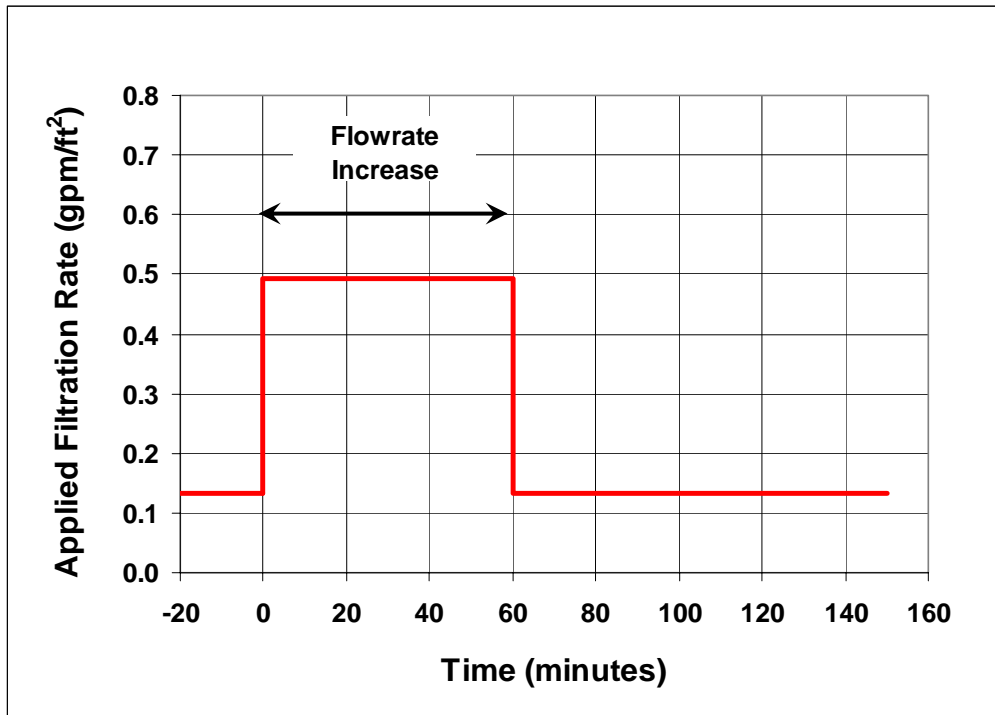


Figure 20. Applied step flowrate increase.

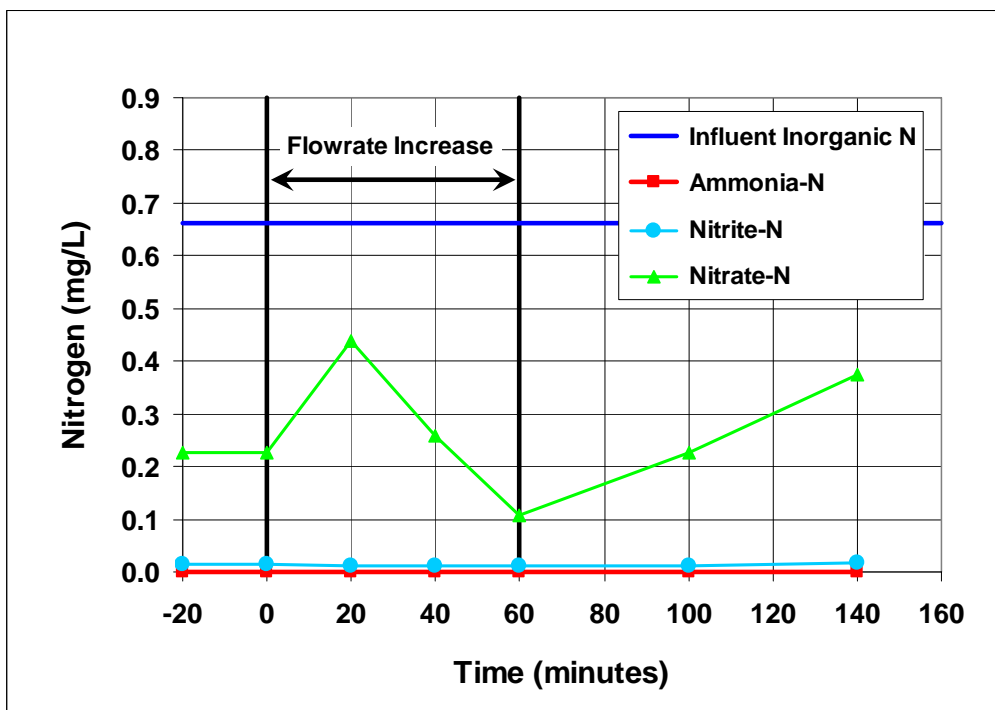


Figure 21. Zeolite filter effluent nitrogen in response to step flow increase.

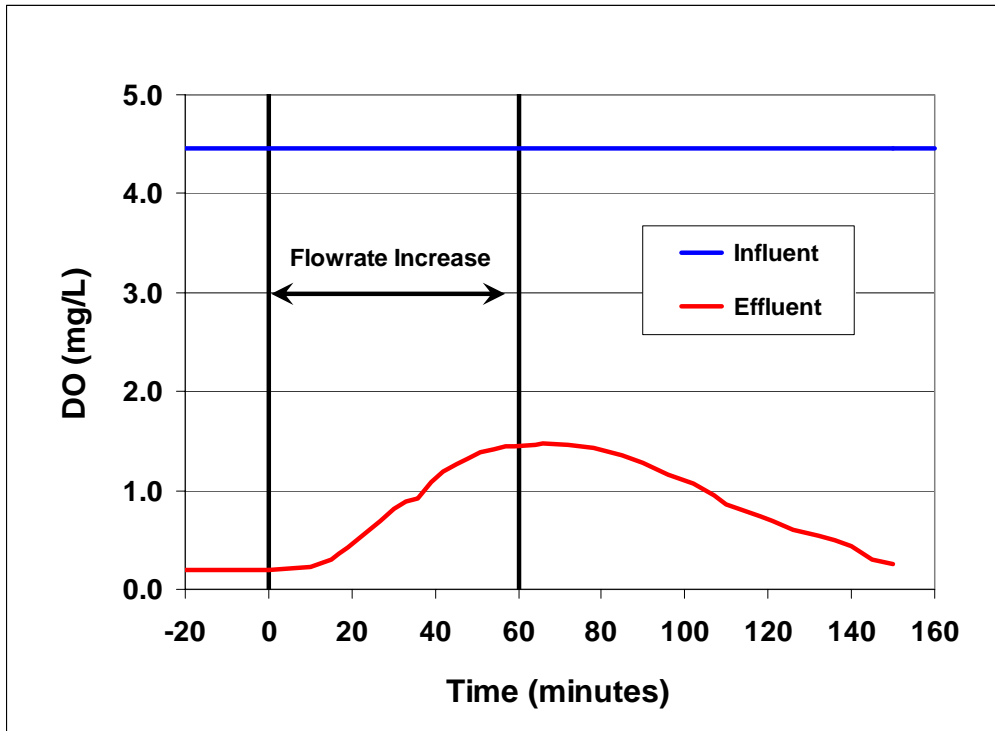


Figure 22. Zeolite filter effluent dissolved oxygen response to step flow increase.

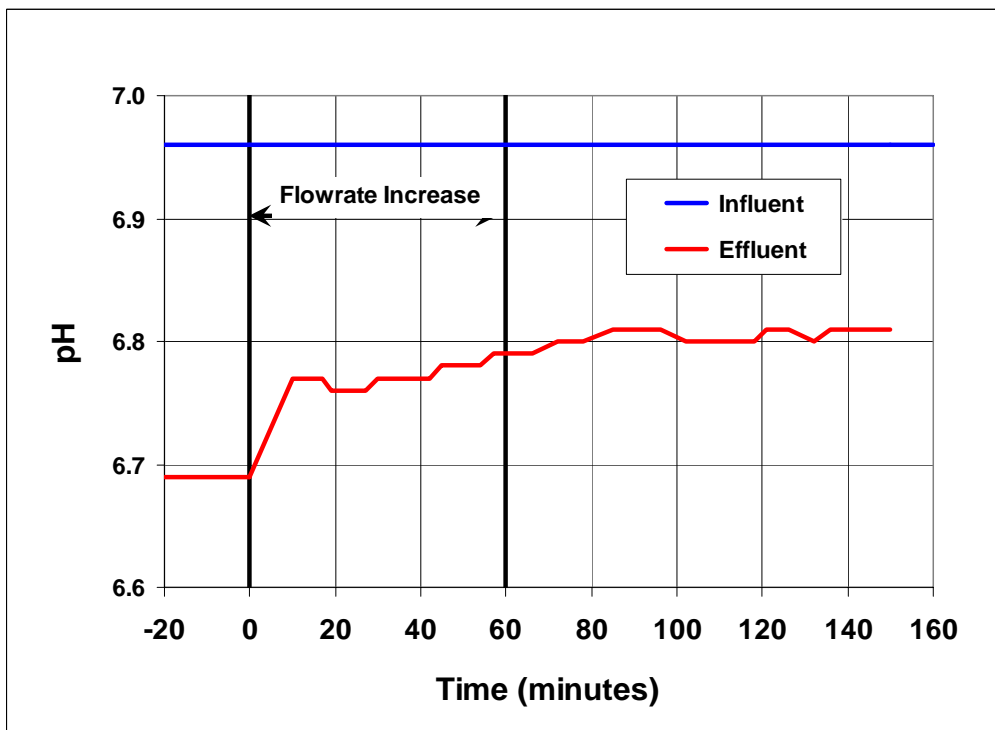


Figure 23. Zeolite filter effluent pH in response to step flow increase.

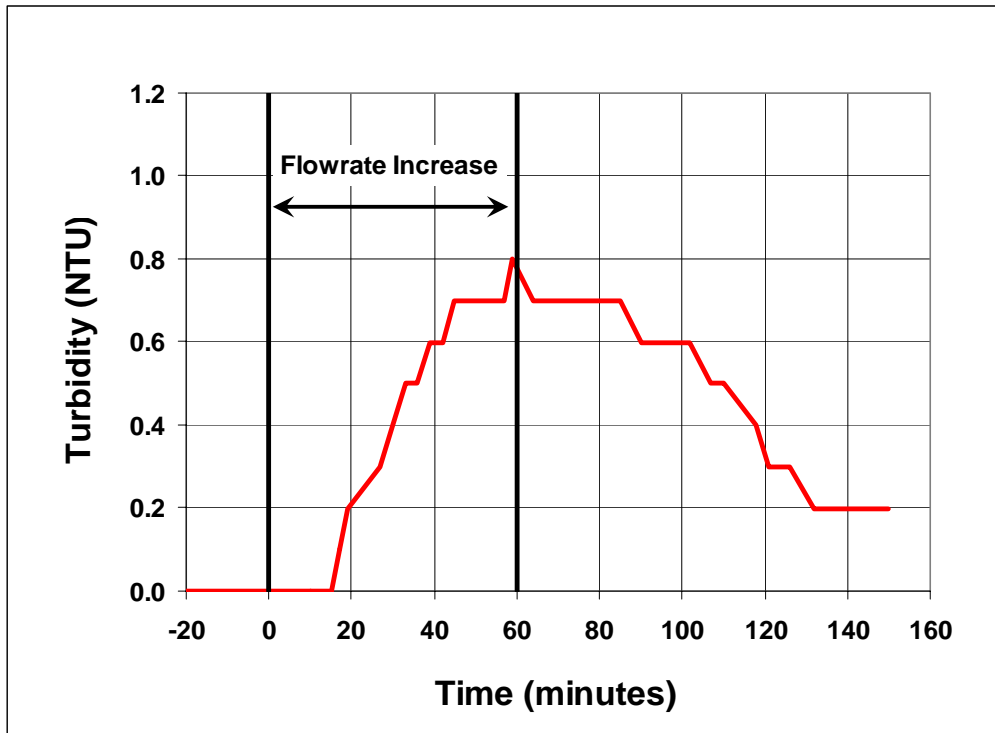


Figure 24. Zeolite filter effluent turbidity in response to step flow increase.

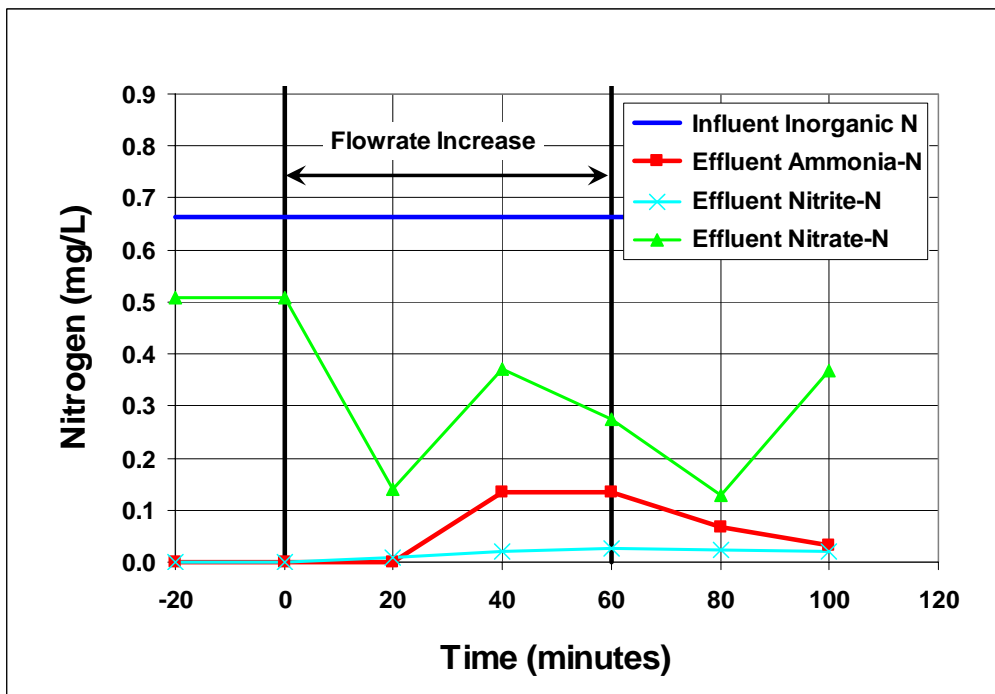


Figure 25. Sand filter effluent nitrogen in response to step flow increase.

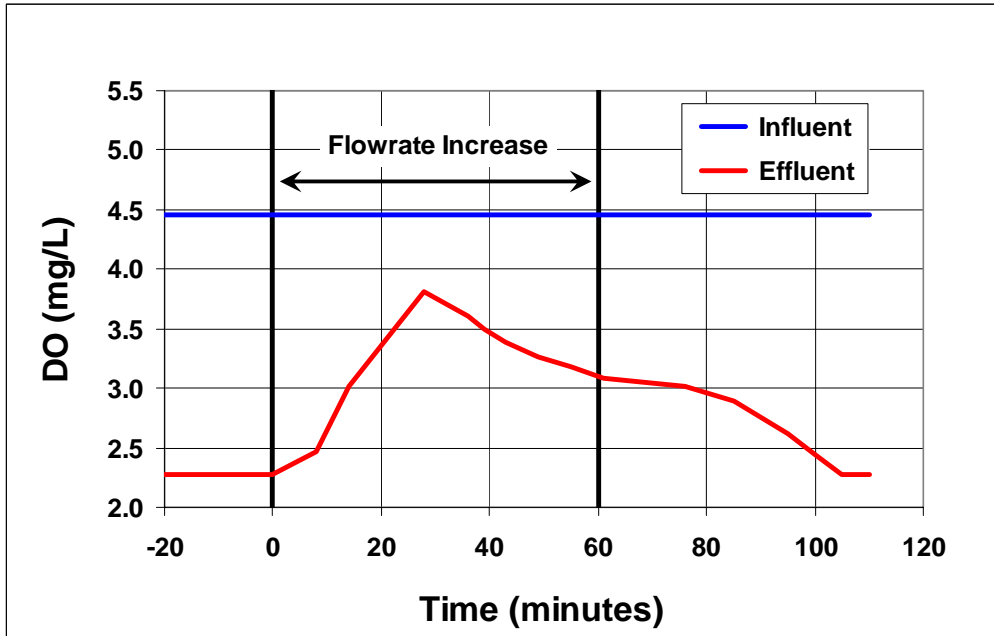


Figure 26. Sand filter effluent dissolved oxygen response to step flow increase.

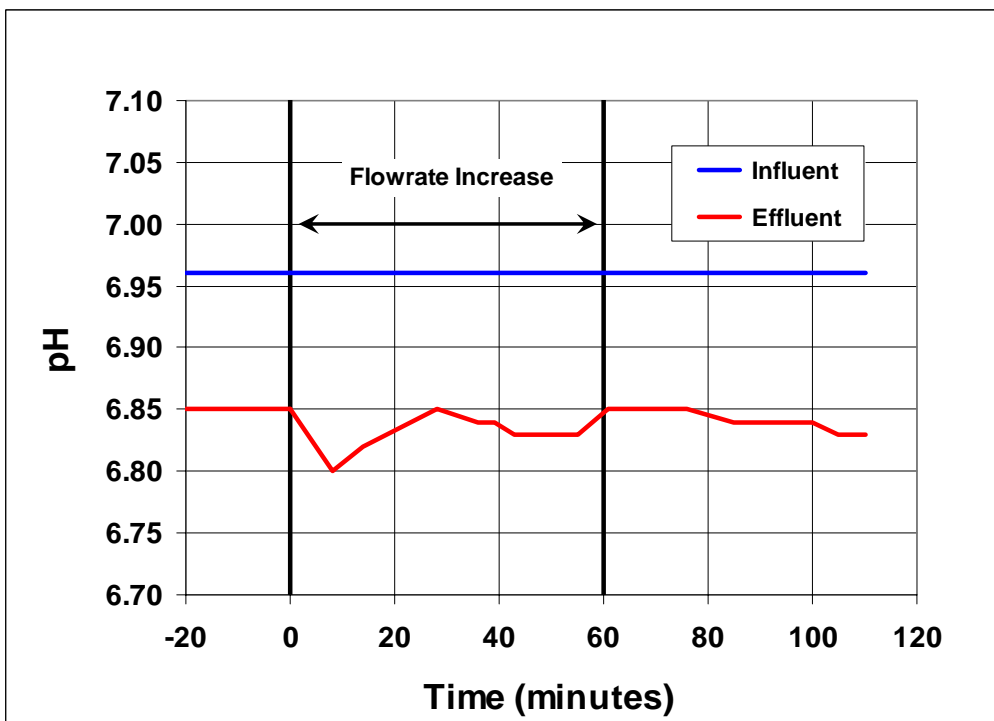


Figure 27. Sand filter effluent pH in response to step flow increase.

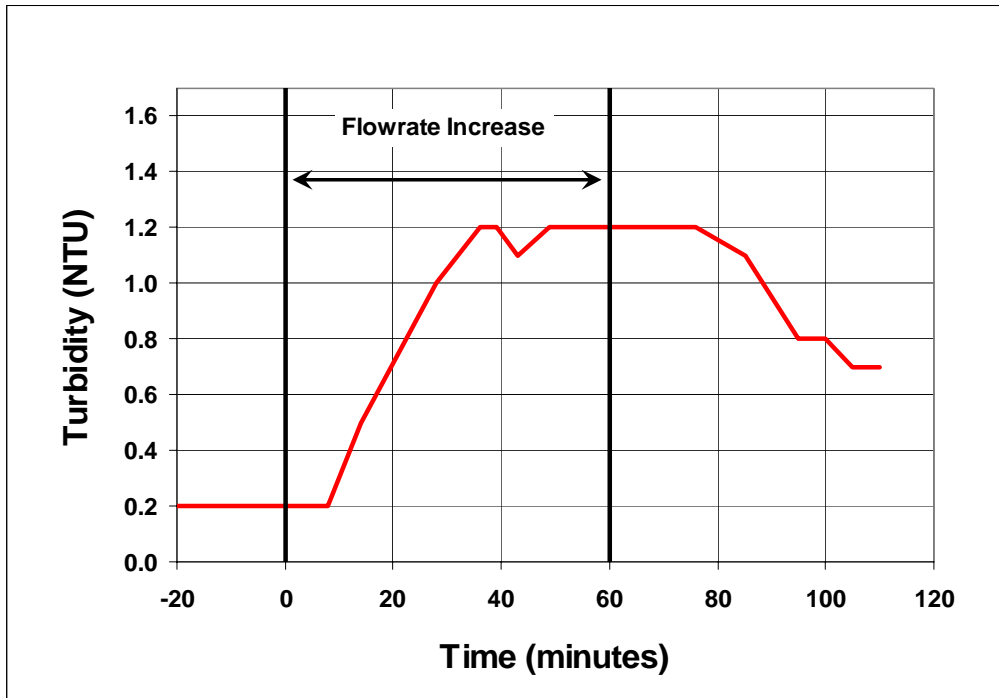


Figure 28. Sand filter effluent turbidity in response to step flow increase.

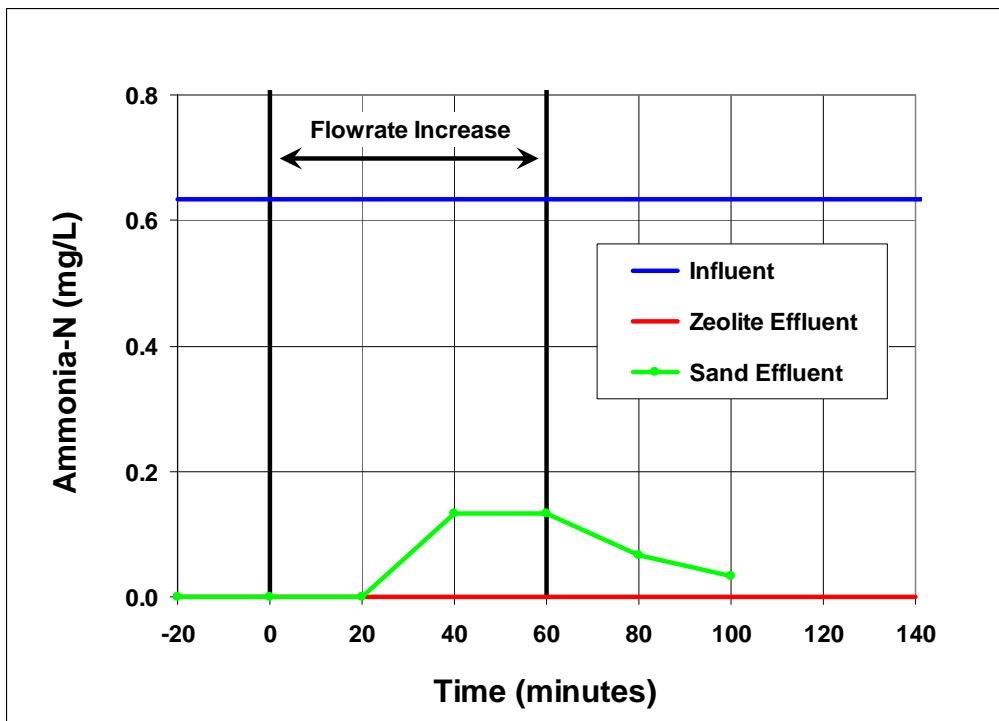


Figure 29. Comparison of effluent ammonia responses to step flowrate increase.

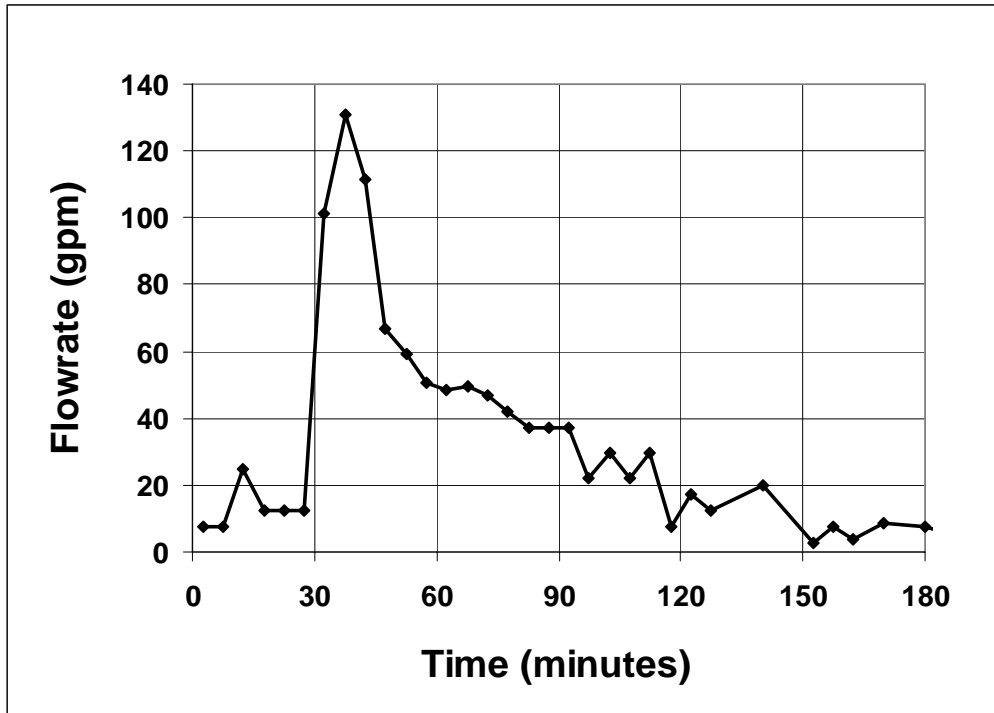


Figure 30. Zeolite filter inflow hydrograph.

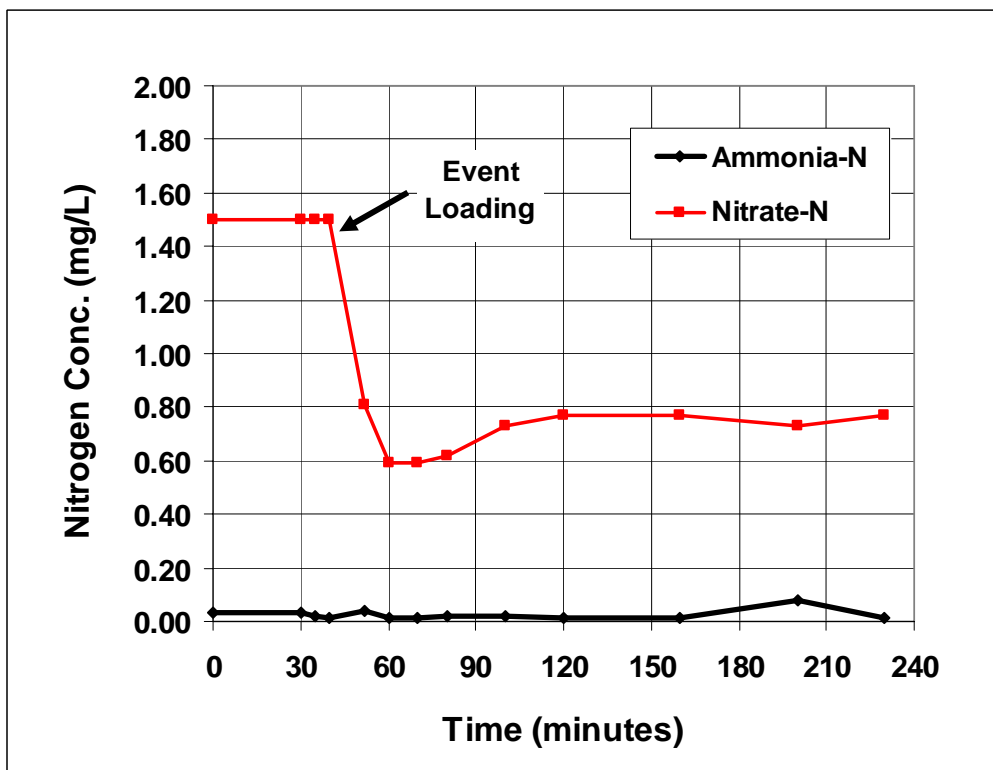


Figure 31. Zeolite filter ammonia and nitrate response to event loading.

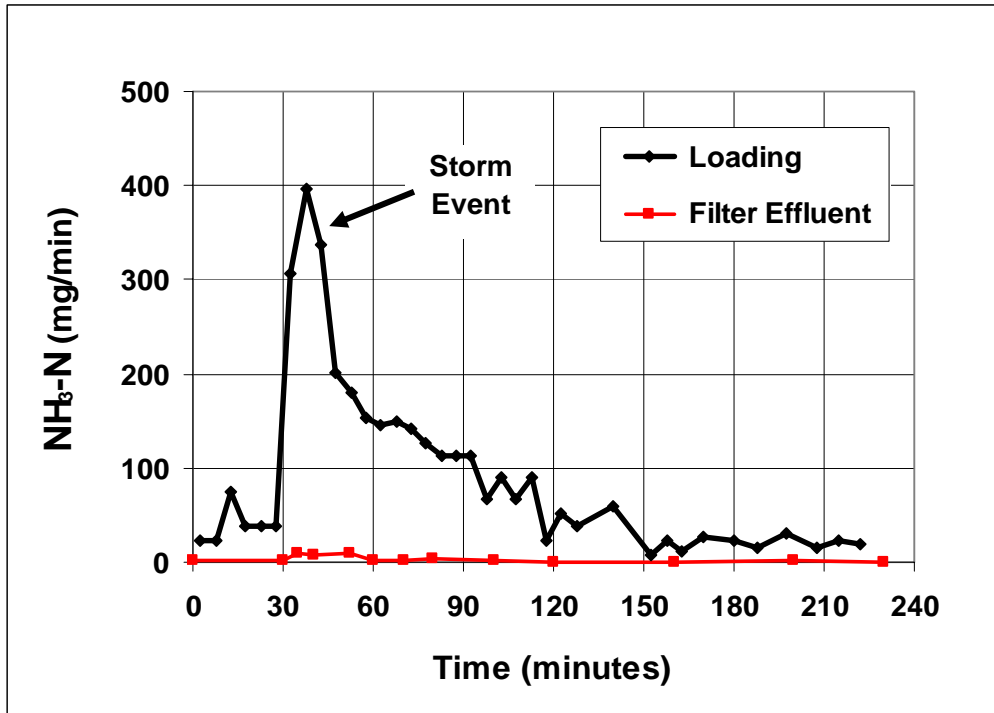


Figure 32. Ammonia loading and mass removal rate in zeolite filter.

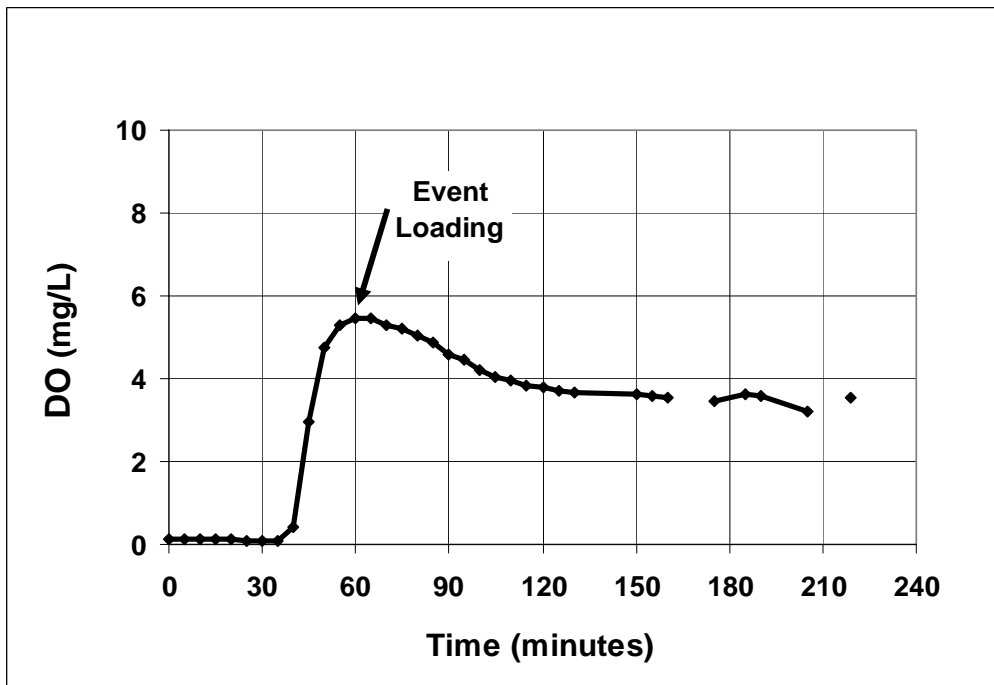


Figure 33. Zeolite filter effluent dissolved oxygen in transient.

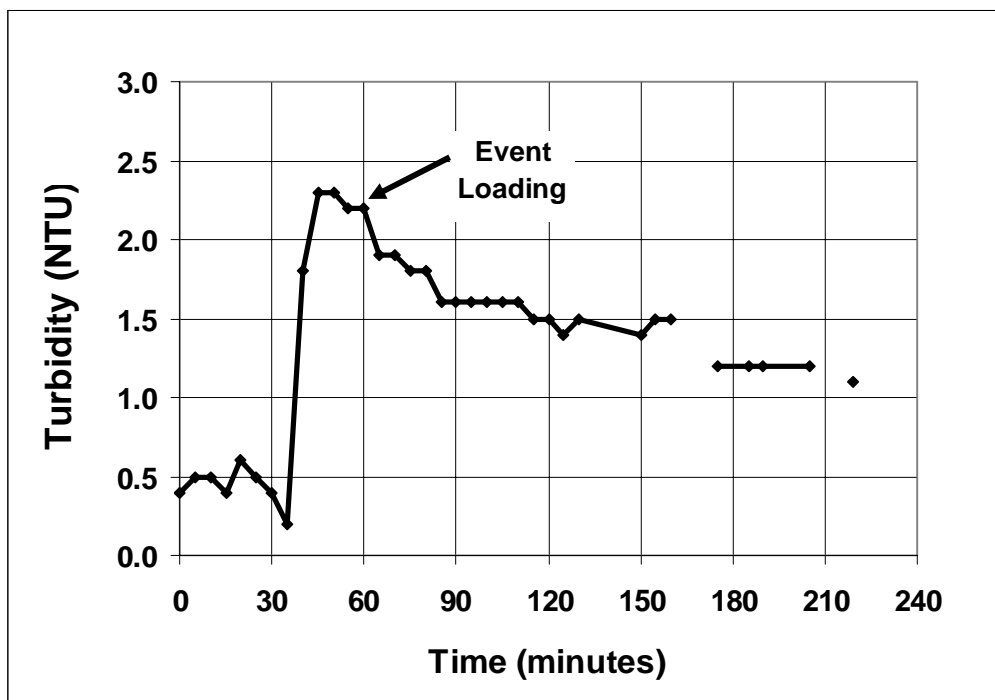


Figure 34. Zeolite filter effluent turbidity in transient.

The mass rates of  $\text{NH}_3\text{-N}$  applied to the zeolite filter and in filter effluent are shown in Figure 32. The zeolite filter received up to 400 mg/min  $\text{NH}_3\text{-N}$ , but the maximum effluent rate of 10 mg/min  $\text{NH}_3\text{-N}$  was only 2.5% of the maximum influent rate. The response of DO is shown in Figure 33, where DO rose from less than 0.5 mg/L in zeolite effluent to over 5 mg/L during perturbation. The increase in DO indicated that only a fraction of influent  $\text{NH}_3\text{-N}$  is being used for biological nitrification. The high ion exchange capacity enables the zeolite filter to contain the high rate of ammonia applied. Turbidity rose sharply during the event loading, indicating breakthrough of turbidity causing particles (Figure 34). This field experiment provided a strong field scale demonstration of the capability of the zeolite filter to contain instantaneous  $\text{NH}_3\text{-N}$  loadings that were high.

The sand filter was subjected to a simulated storm event perturbation as the zeolite filter, with a similar magnitude. The results are shown in Figures 35 through 39. The hydrograph was generally similar in shape, with a peak just after 30 minutes (Figure 35). Influent nitrogen concentrations were constant during the experiment at 0.78, 0.01 and 0.15 mg/L of nitrogen as ammonia, nitrite, and nitrate, respectively. During the perturbation,  $\text{NH}_3\text{-N}$  rose to 0.48 mg/L (Figure 36). Nitrate was initially flushed out but then rose to approximate the influent total inorganic nitrogen concentration of 0.95 mg/L. The mass rates of  $\text{NH}_3\text{-N}$  applied to the zeolite filter and in filter effluent are shown in Figure 37. The maximum effluent flux of 96 mg/min  $\text{NH}_3\text{-N}$  was 25% of the maximum influent flux. Approximately 20% of added ammonia mass was not captured by the sand filter in this experiment. DO rose to over 6 mg/L (Figure 38) and turbidity increased to 2.2 NTU (Figure 39).



The superior ability of the zeolite filter to contain ammonia breakthrough is attributed to the ion exchange afforded by zeolite. In the sand filter perturbation, ammonia declined as the flowrate declined and nitrate levels rose to approximately the level of influent inorganic nitrogen. This suggests that the nitrifying microbial population in the sand filter was active and able to rapidly metabolize higher N ammonia concentrations. The same was true in the zeolite filter. Prior to this perturbation, both filters had been continuously loading with ammonia and an active nitrifying population was expected. In real applications, such may not be the case, and microbial populations may have very low activity. In that case, a sand filter could have more difficulty in ammonia removal than zeolite, in which ion exchange can operate regardless of the activity of microbial populations. The differences in performance between zeolite and sand could be exacerbated in many stormwater applications. The turbidity rise in the two filters was similar, indicating that the two media had a similar ability of to retain turbidity causing particles.

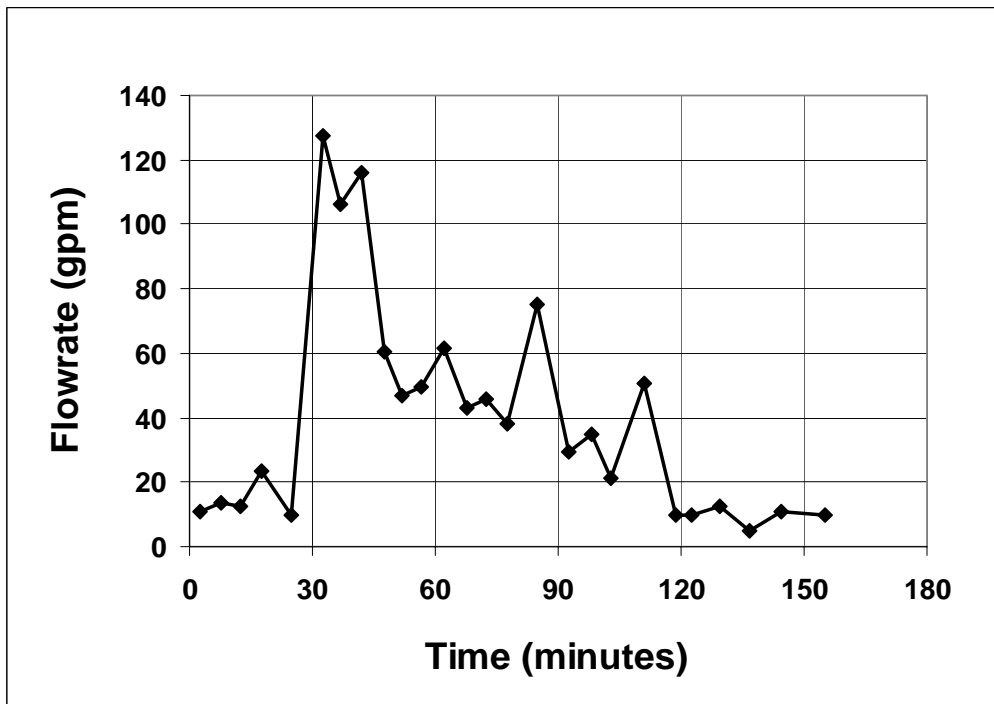


Figure 35. Sand filter inflow hydrograph.

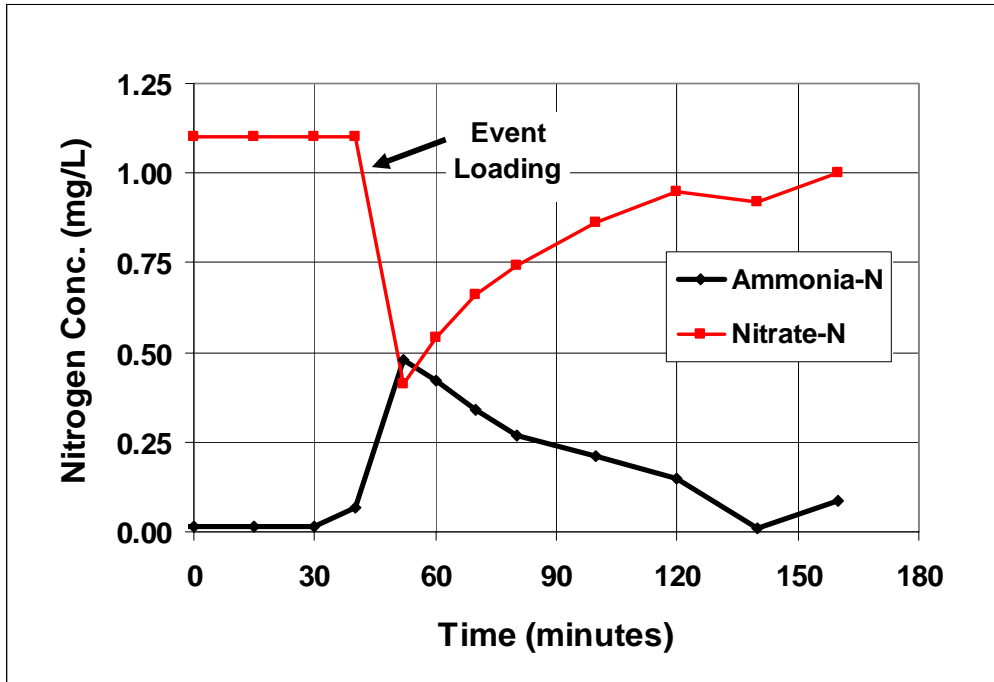


Figure 36. Sand filter ammonia and nitrate response to event loading.

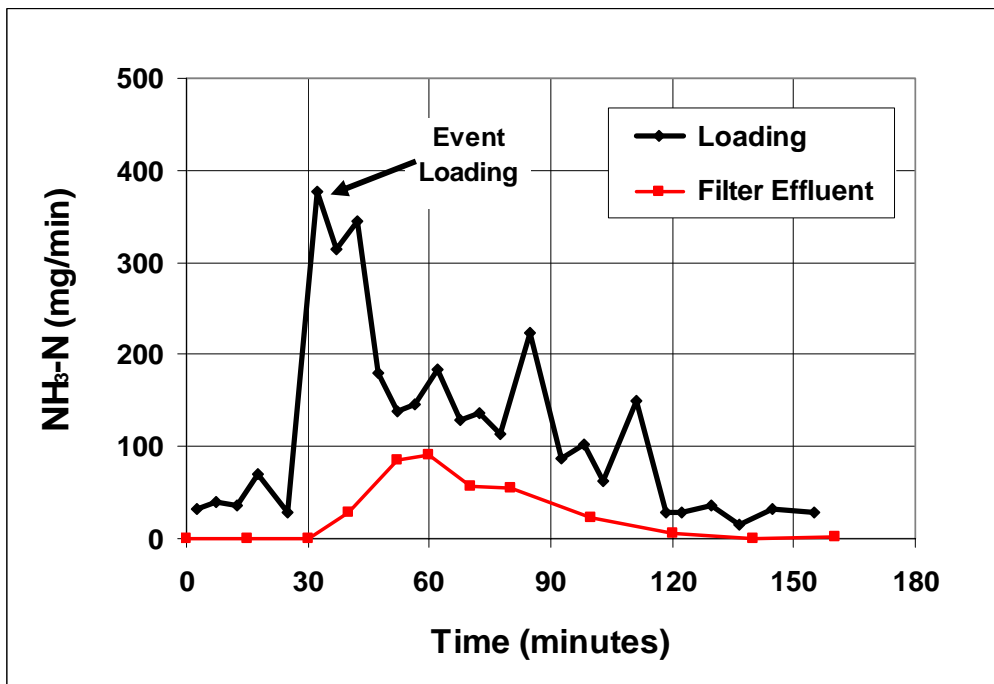


Figure 37. Ammonia loading and mass removal rate in sand filter.

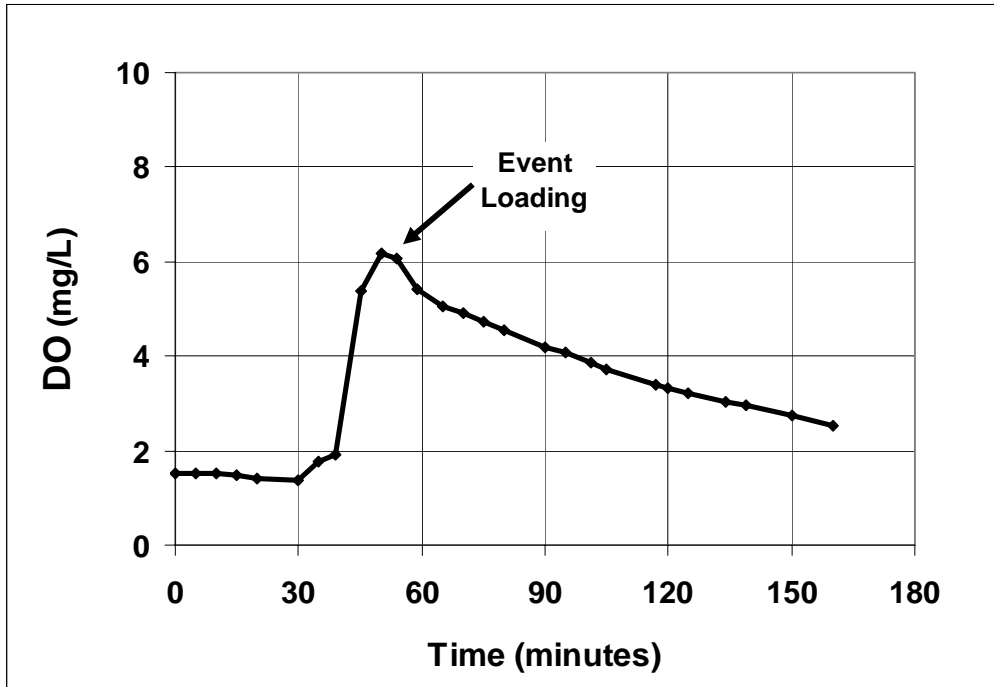


Figure 38. Sand filter effluent dissolved oxygen in transient.

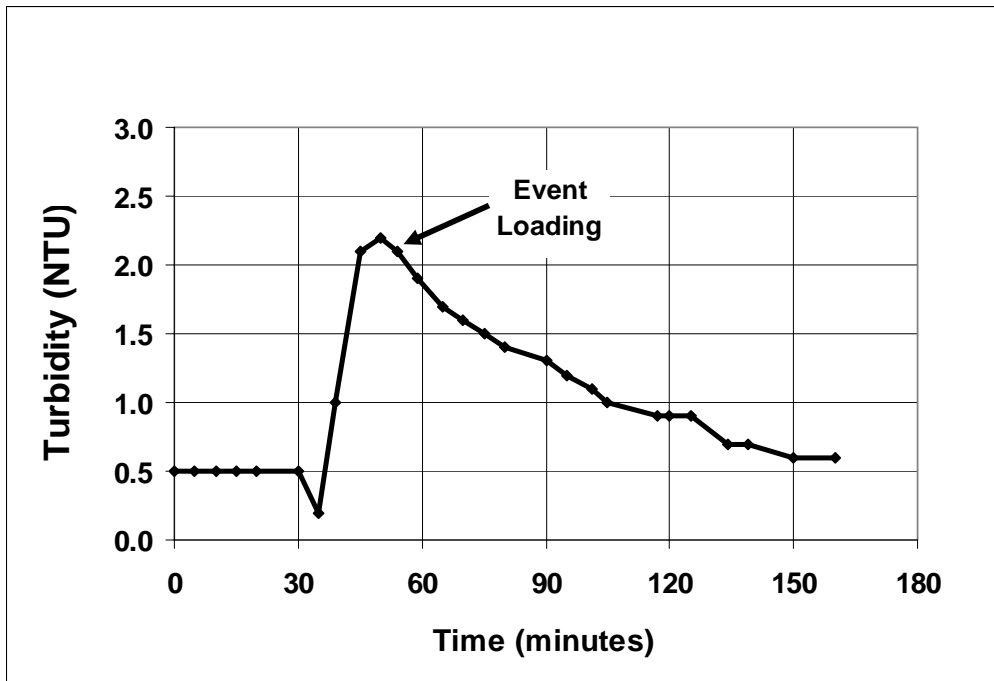


Figure 39. Sand filter effluent turbidity in transient.

**Effect of Dissolved Oxygen (Day 156):** This non-steady experiment was conducted to assess the response of zeolite and sand filters to low dissolved oxygen levels. Prior to the experiment, the filters were each receiving a 4 gpm flowrate and an influent  $\text{NH}_3\text{-N}$  concentration of 0.8 mg/L. The influent aeration system was functioning, resulting in an influent DO of 7.8 mg/L. The experiment was performed by first measuring the pre-perturbation steady performance levels of DO and inorganic nitrogen species. The aeration system was then turned off for 10.5 hours, but filter operation was otherwise unchanged.

During the time in which the aerator was off, influent DO fell from 7.8 to 5 mg/L and filter effluent DO fell from 0.6 mg/L to 0.1 mg/L (Figure 40). The increase in effluent ammonia was much more pronounced in the sand than in the zeolite filter (Figure 41). Inorganic nitrogen species in zeolite and sand effluents are shown in Figures 42 and 43, respectively. There is a decrease in nitrate in zeolite filter effluent, which suggests that nitrification has been affected by decreased DO. Decline in sand filter effluent nitrate is more pronounced as influent DO declines. The influent aeration system was turned on at 10.5 hours, and ammonia and nitrate levels reverted towards their pre-perturbation levels.

Dissolved oxygen is an important water quality parameter that affects the ability of treatment filters to remove ammonia. In these experiments, which were performed at the same time to parallel filters operated under the same conditions, the sand filter appeared more sensitive to lower influent DO than the zeolite filter. Ammonia release from the zeolite filter was much less pronounced. Zeolite may offer ammonia retention advantages in many stormwater treatment applications where low DO situations could be encountered.

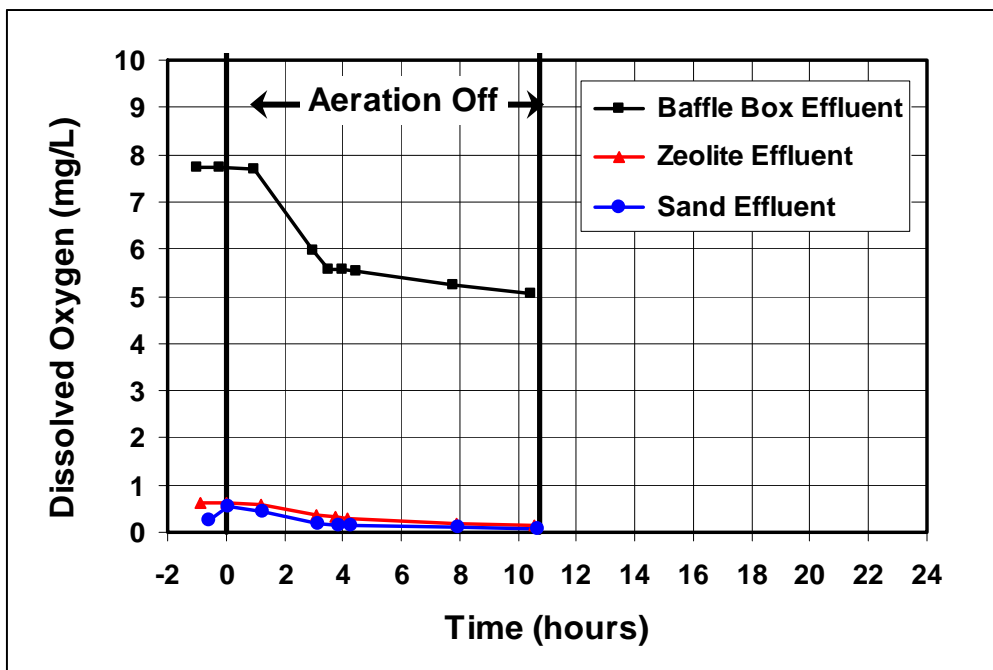


Figure 40. Dissolved oxygen in filter influent and effluents.

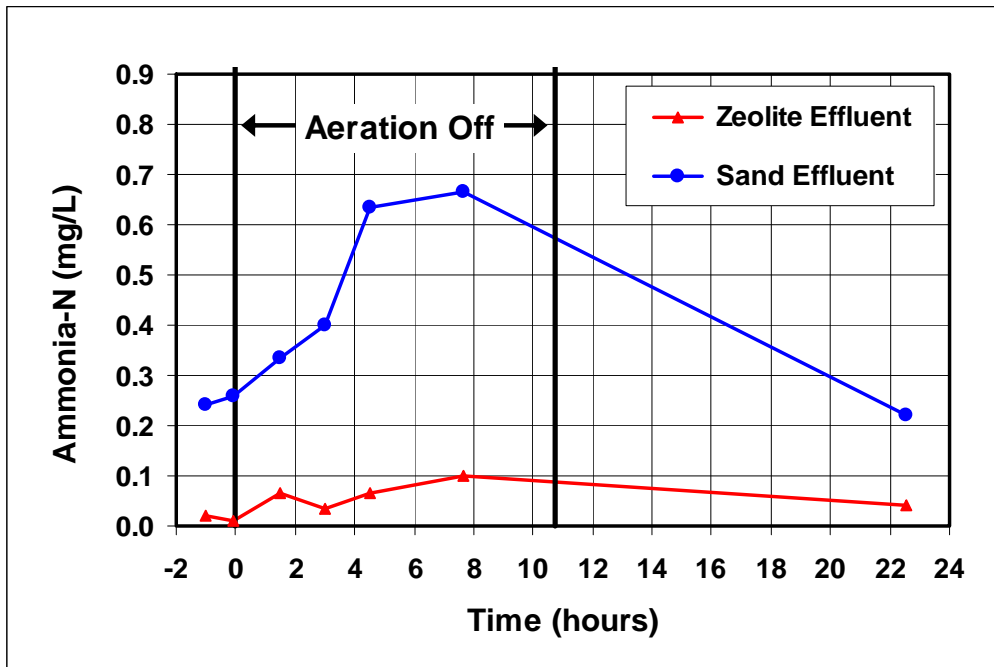


Figure 41. Filter effluent NH<sub>3</sub>-N response to decreased influent DO.

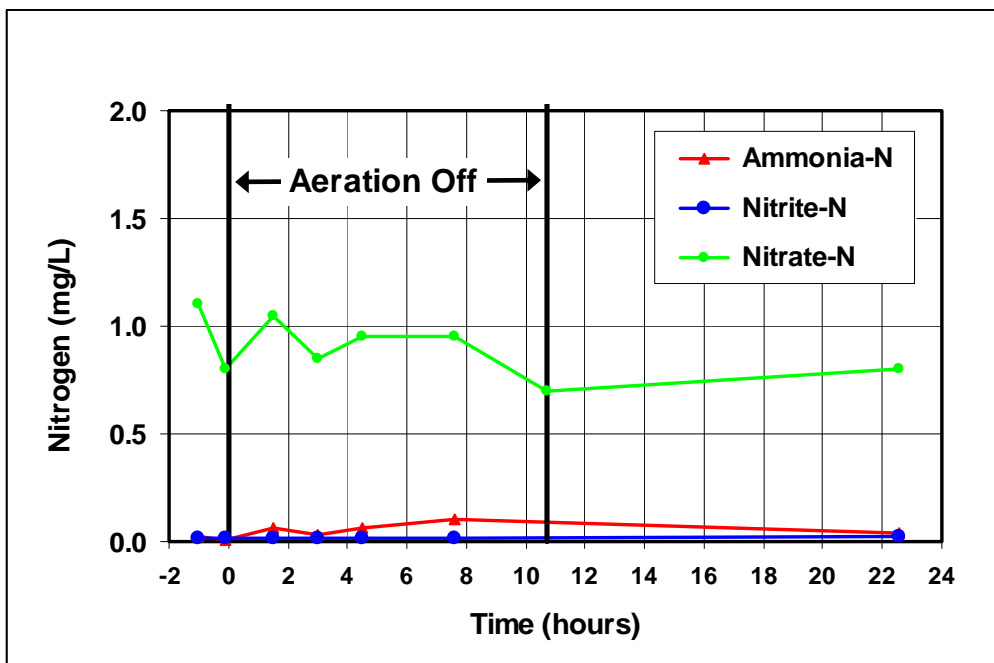


Figure 42. Zeolite filter response to decreased influent dissolved oxygen.

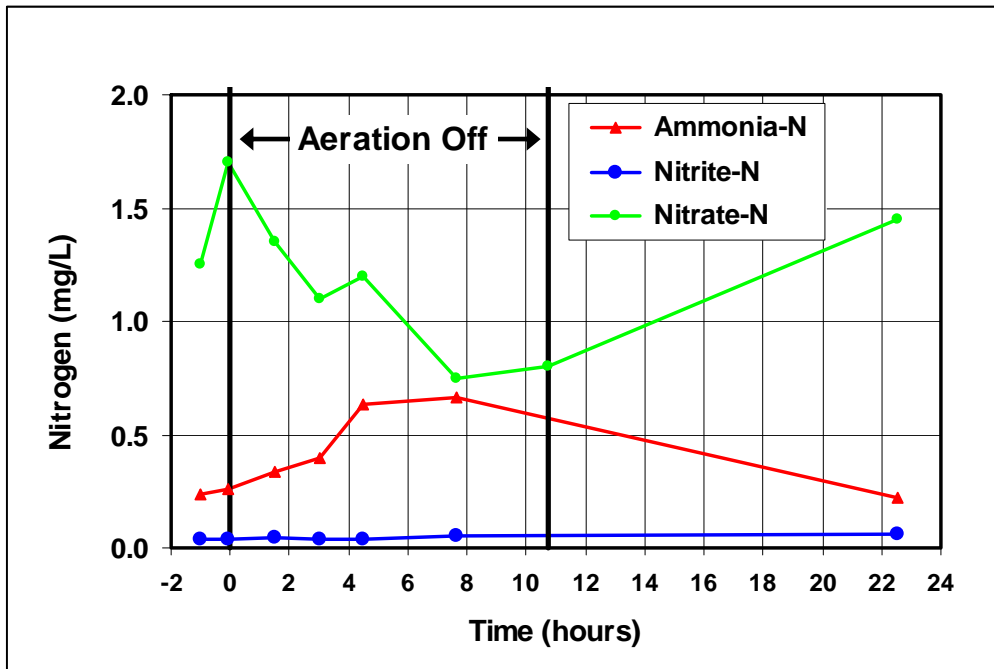


Figure 43. Sand filter response to decreased influent dissolved oxygen.

**Effect of Inter-event Period (Day 216):** The filters received no influent flow for 40 days (Day 176-215), after which they were then subjected to an event loading in the stormwater storage tank batch mode. The purpose of this experiment was to assess filter performance to a storm event after an extended time in which no added supply of substrate ( $\text{NH}_3\text{-N}$ ) was supplied to microorganisms, specifically nitrifying bacteria. Microorganisms which receive no substrate can lose their activity and be less effective as the length of time increases in which they receive no substrate. Dehydration of filter media can accelerate decline in activity. The pilot filters were both maintained at 18 inch saturation depth and were covered from the atmosphere for the 40 day inter-event period, and dehydration was not significant.

During the zeolite experiment, influent nitrogen concentrations were constant at 0.69, 0.01 and 0.06 mg/L of nitrogen as ammonia, nitrite, and nitrate, respectively. The influent hydrograph to the zeolite filter has a characteristic peak and a trailing slope (Figure 44). Effluent ammonia and nitrate levels are shown in Figure 45; effluent nitrite was negligible. After 40 days of non-operation, ammonia in the zeolite filter effluent was quite limited after 40 days of non-operation.  $\text{NO}_3\text{-N}$  rose to 5 mg/L during the perturbation. During the long inter-event period, nitrate may have accumulated in saturated filter pores and been flushed out by the storm event. Zeolite effluent DO was only 0.3 mg/L in the effluent standpipe and fell quickly to below 0.1 mg/L, where it remained through the storm event.

The influent nitrogen concentrations in the sand experiment were constant at 0.98, 0.01 and 0.03 mg/L of nitrogen as ammonia, nitrite, and nitrate, respectively. At 12 minutes after the start of perturbation, sand effluent  $\text{NH}_3\text{-N}$  was 7.8 mg/L, and fell as

the filter pore water was flushed out (Figure 48).  $\text{NO}_3\text{-N}$  rose to 1.5 mg/L. Dissolved oxygen in the effluent standpipe was 0.93 mg/L before perturbation, but fell close to zero very quickly with pore flushing (Figure 49). However, DO rose above zero after 25 minutes and reached levels greater than 1 mg/L.

These experiments suggest that microbial activity was still functional after the 40 day period of non-operation. Zeolite was much better at containing ammonia than sand, and nitrogen in zeolite effluent had predominantly already been converted to nitrate. The chabazite used in this study would have an important advantage over sand in a filter installation that is prone to dehydration. Chabazite ZS500H retains 17 to 20% of its weight as hygroscopically bound water at 10% relative humidity (Eyde, 2006). This imparts an effective, built in water storage reservoir that would assist in microbial survival in dry environments.

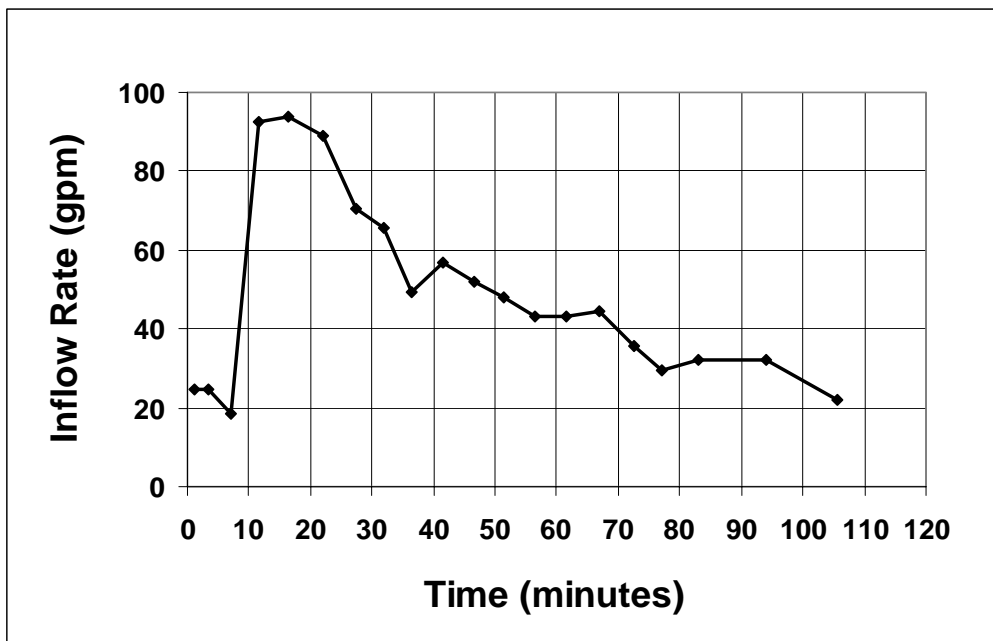


Figure 44. Zeolite filter influent hydrograph.

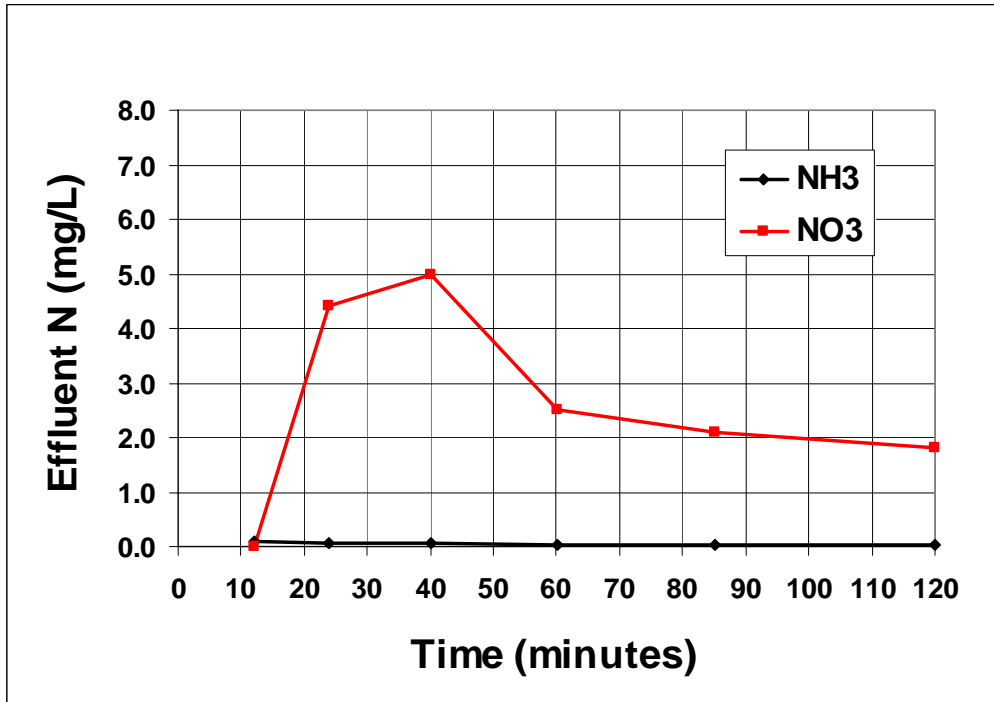


Figure 45. Zeolite filter effluent nitrogen.

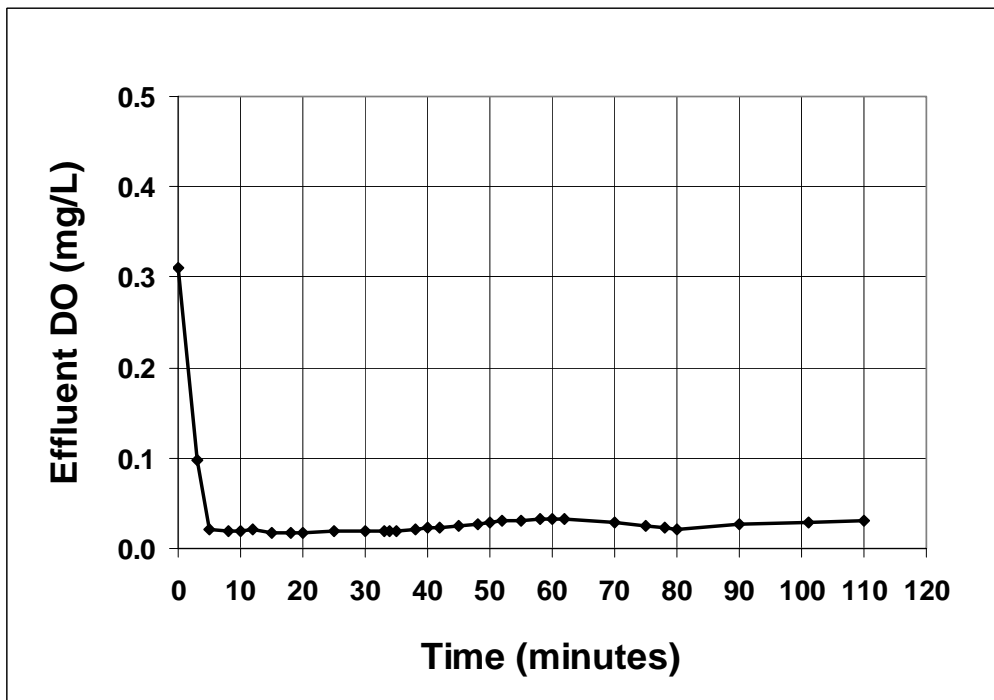


Figure 46. Zeolite filter effluent DO.



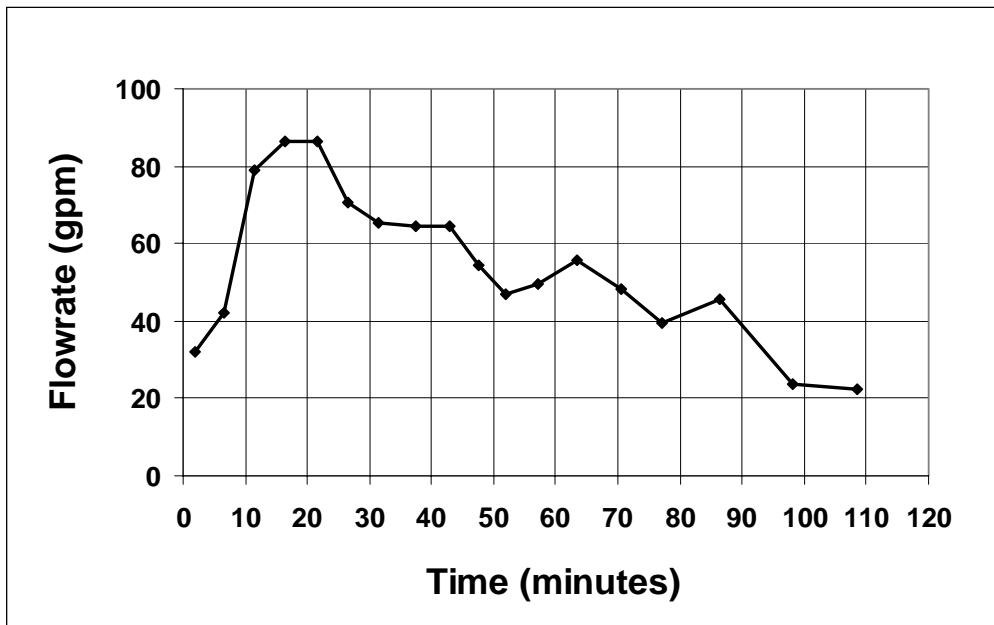


Figure 47. Sand filter influent hydrograph.

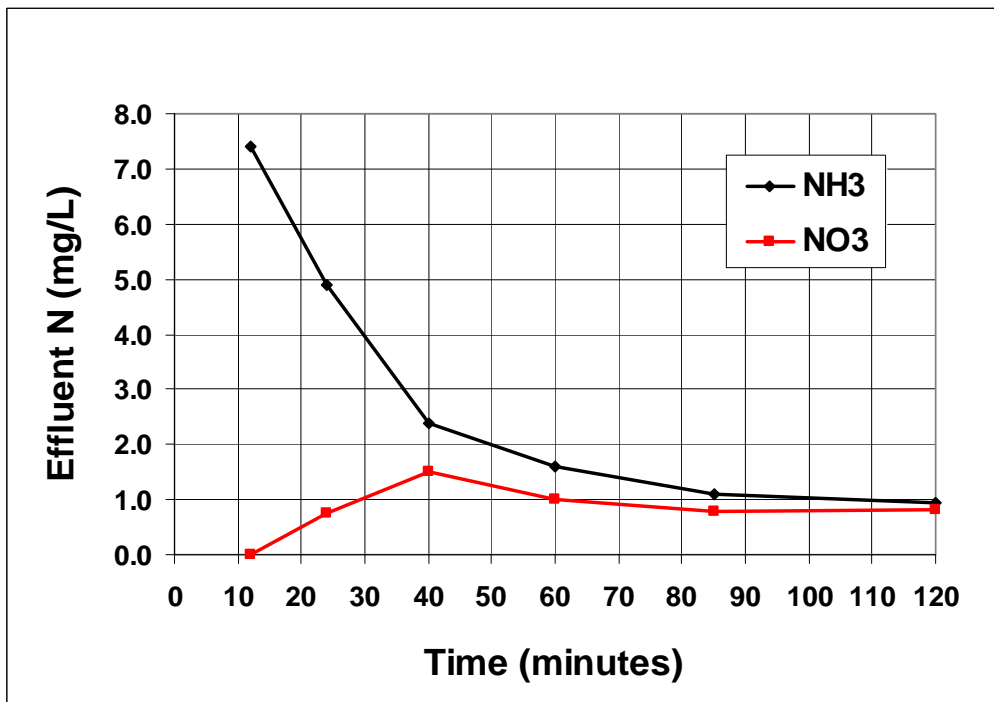


Figure 48. Sand filter effluent nitrogen.

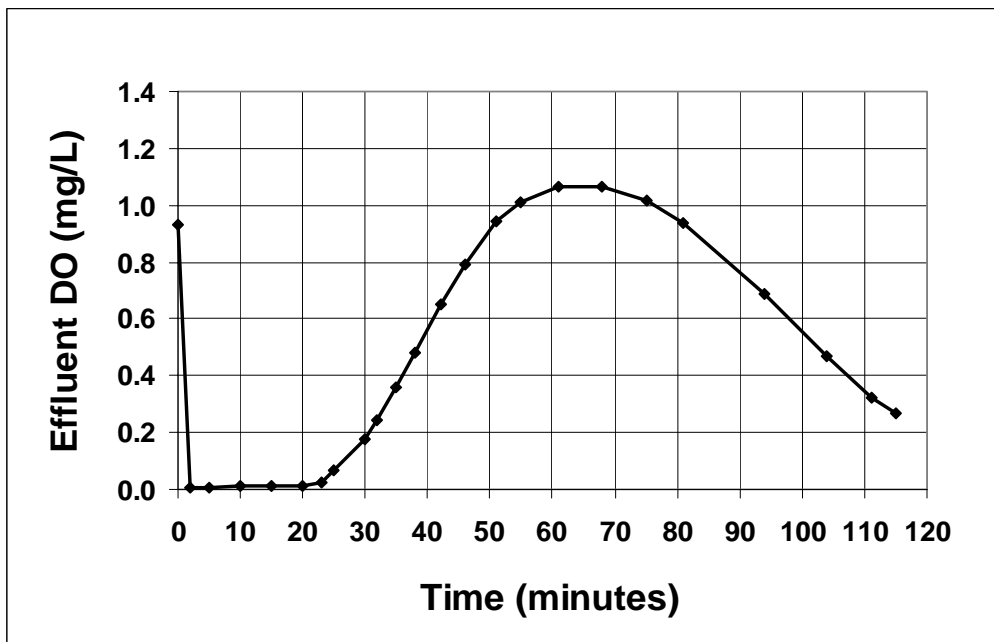


Figure 49. Sand filter effluent DO.

**Denitrification Filter Performance:** Two denitrification filter columns were operated on zeolite filter effluent for 41 days (Day 116 to 157). The filter media were sulfur/limestone (autotrophic denitrification) and barley straw (heterotrophic denitrification). The average oxidized nitrogen concentration influent concentration (zeolite filter effluent) over the monitoring period was 1.11 mg/L, with over 97% as nitrate. Zeolite effluent temperature and pH averaged 60.5 F and 7.0, respectively.

Total oxidized nitrogen in influent and effluents are shown in Figure 50. Performance improved after Day 137, and both filters achieved 95% and greater removal efficiency (Figure 51). Filter removal of total oxidized nitrogen increased as loading rate increased (Figure 52). The improved denitrification performance could be influenced by several factors, such as microbial population establishment and the water quality matrix. In Figure 53 are plotted the loading rate of total oxidized nitrogen, ( $\text{NO}_3 + \text{NO}_2$ )-N, and the effluent DO from the zeolite filter. Zeolite effluent DO was decreasing during the time in which high denitrification efficiencies were established in the filters. Denitrification is an anoxic process that can be affected by dissolved oxygen levels. Lower influent DO may have been required for denitrification to become established, or may have simply occurred at the same time that microbial denitrification was being established in the filters. The denitrification column experiments do not permit conclusions to be drawn about the inhibitory effect of DO.

The dissolved organic carbon (DOC) concentrations in denitrification filter influent and effluents are shown in Figure 54. DOC increased 2 to 10 mg/L across the barley filter, which is consistent with release of carbon from hydrolysis of a solid organic substrate. The zeolite filter effluent was clear with no obvious odor, but the barley filter contributed a noticeable amber coloration and a noticeable odor. The sulfur filter

effluent did not release DOC and the sulfur filter effluent did not exhibit noticeable color or odor.

Sulfur/limestone and barley straw both appear to have potential as denitrification media in post-zeolite stormwater filters. These media could be used in denitrification filters that are directly coupled to zeolite filters. Direct coupling could occur in a variety of physical configurations. One concept for direct coupling is an upflow denitrification filter in a second chamber that receives zeolite effluent from the bottom. This two chamber design would have the advantage of enabling the denitrification media (which is consumable) to be replaced independently of the zeolite media. The existing pilot filter could be readily modified to evaluate this design. Denitrification media issues to be evaluated are long term effectiveness in supporting denitrification, ability of filters to accept and treat event loadings, and effects on water quality such as release of carbon and other elements to the water being treated.

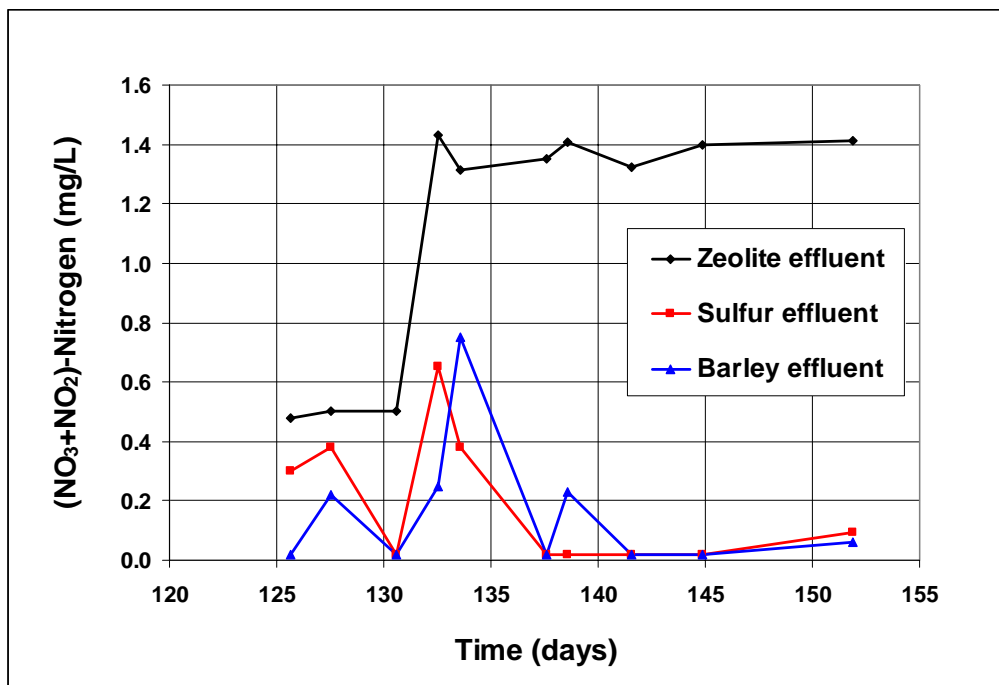


Figure 50. Total oxidized nitrogen in denitrification filters.

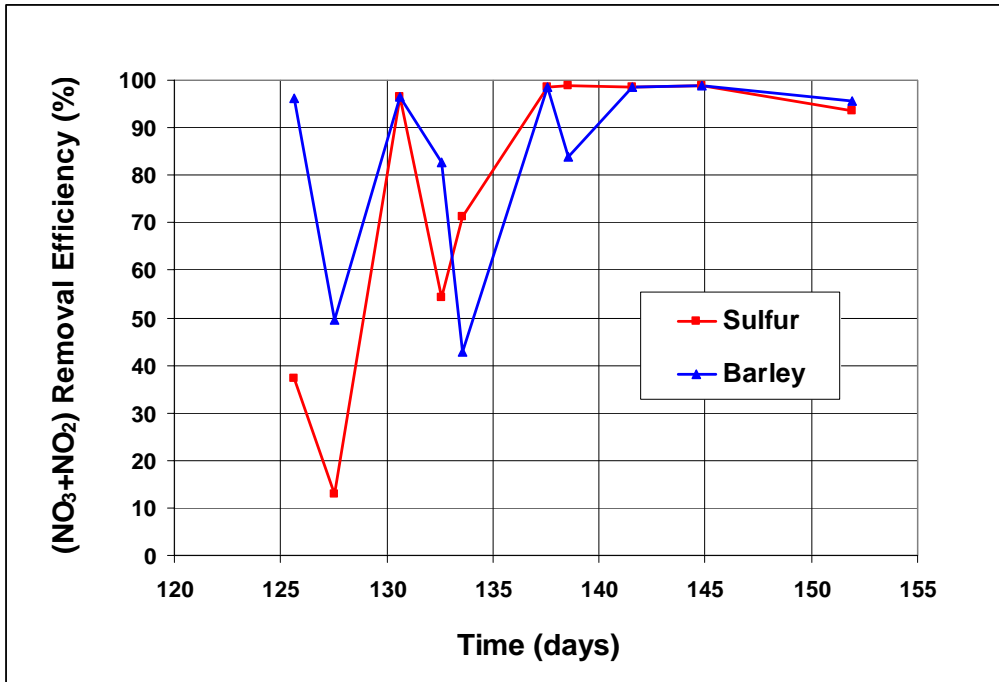


Figure 51. Total oxidized nitrogen removal efficiency in sulfur and barley filters.

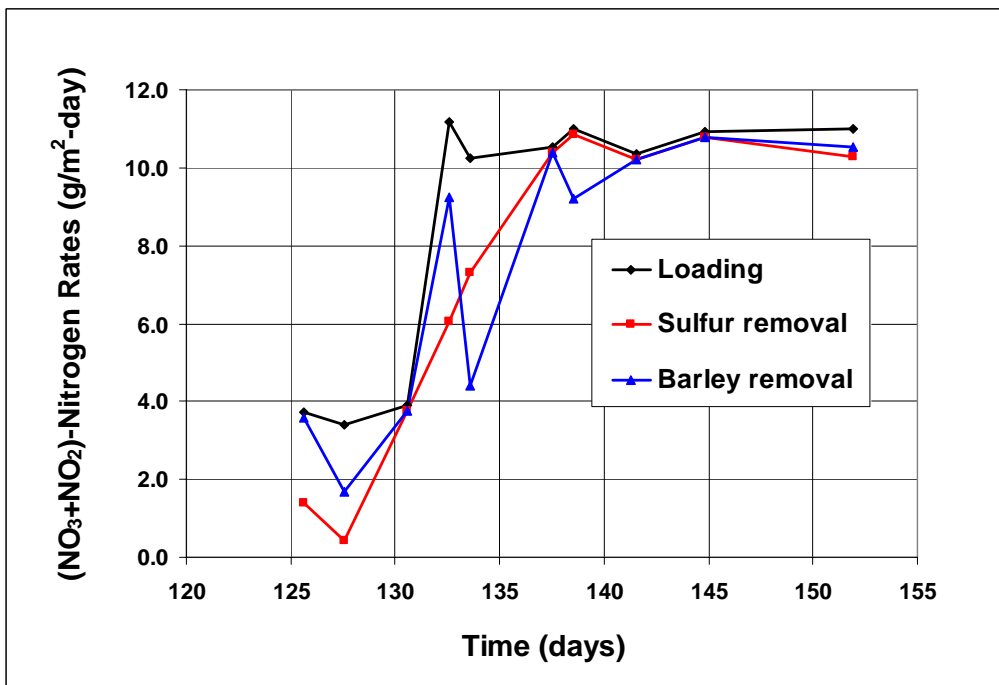


Figure 52. Total oxidized nitrogen loading and removal rates.

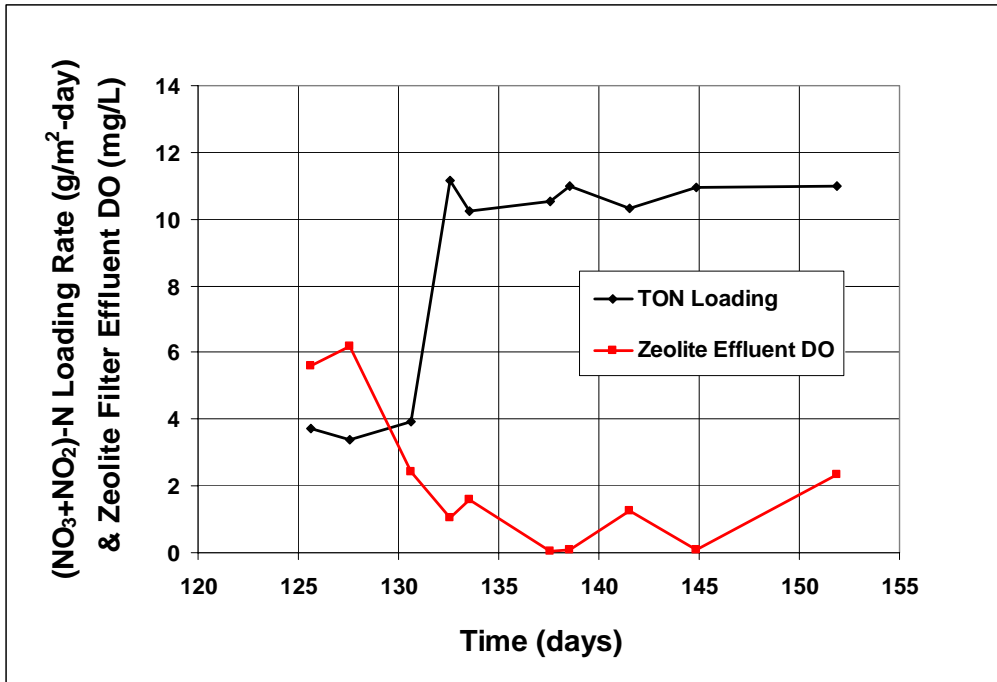


Figure 53. Total oxidized nitrogen loading rate to denitrification columns; zeolite filter effluent dissolved oxygen.

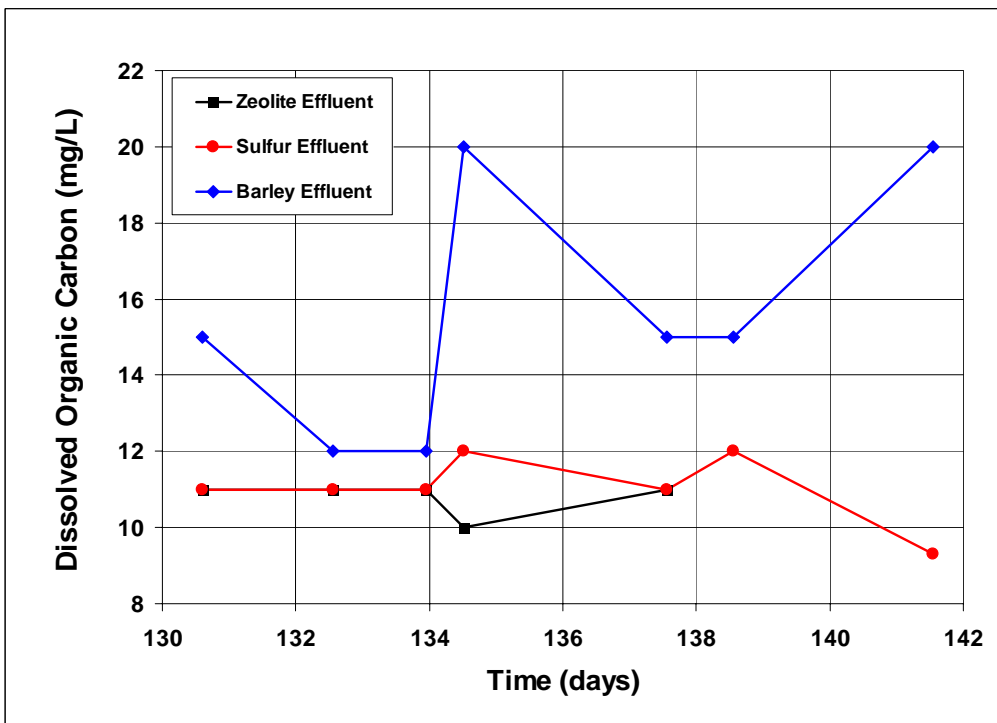


Figure 54. Dissolved organic carbon showing increase across barley filter.

## Conclusions

The following conclusions are drawn from this study.

- The zeolite filter removed 93% of ammonia and produced effluent  $\text{NH}_3\text{-N}$  of 0.05 mg/L when operated at a steady filtration rate of 0.133 gpm/ft<sup>2</sup> and influent  $\text{NH}_3\text{-N}$  concentration of 0.78 mg/L. For comparison, typical  $\text{NH}_3\text{-N}$  levels in wet pond discharges are 0.02 to 0.32 mg/L.
- Ammonia concentration was substantially reduced in the top inch of saturated zeolite media under steady operation at 0.133 gpm/ft<sup>2</sup>.
- Total inorganic nitrogen removal by the zeolite filter was 32% at a steady filtration rate of 0.133 gpm/ft<sup>2</sup> and influent  $\text{NH}_3\text{-N}$  concentration of 0.78 mg/L.
- The zeolite filter produced effluent  $\text{NO}_3\text{-N}$  of 0.52 mg/L when operated at a steady filtration rate of 0.133 gpm/ft<sup>2</sup> and influent  $\text{NH}_3\text{-N}$  concentration of 0.78 mg/L. For comparison, typical  $\text{NO}_3\text{-N}$  levels in wet pond discharges are 0.002 to 0.39 mg/L.
- Under steady operation at 0.133 gpm/ft<sup>2</sup>, nitrate removal occurred at zeolite depths of 7 inches and greater, and appeared to depend on dissolved oxygen levels within the filter bed.
- Denitrification filters using sulfur/limestone and barley straw media removed 95% or greater of total oxidized nitrogen from zeolite filter effluent and produced effluent levels of 0.1 mg/L or less. For comparison, typical total oxidized nitrogen levels in wet pond discharges are 0.002 to 0.39 mg/L.
- Over 78% of organic nitrogen in storm pond water was dissolved or colloidal organic nitrogen, defined using a 0.45  $\mu\text{m}$  membrane filter.
- Organic nitrogen removal in the zeolite filter was 25% or less.
- Baffle box pretreatment at the pilot site had little effect on dissolved organic nitrogen, ammonia, nitrite and nitrate concentrations.
- In a simulated storm event in which filtration rate increased to 4.4 gpm/ft<sup>2</sup>, the zeolite filter maintained a concentration reduction of 90% and greater throughout, and removed 99% of the applied ammonia mass.
- The zeolite filter was highly effective at preventing ammonia breakthrough in a simulated storm event that followed a 40 day non-loading period.
- The zeolite filter was more effective than sand in preventing ammonia breakthrough when influent dissolved oxygen concentration is low.

- Storm event loadings resulted in significant increases in nitrate-nitrogen in zeolite filter effluent, which would have to be contained if total nitrogen removal is the goal.

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## Recommendations

The zeolite filter performed very well in the pilot testing program, and additional studies are recommended to further develop the zeolite filter as a viable stormwater treatment technology.

It is recommended that a coupled filtration process be developed that combines the zeolite filter with a directly connected denitrification filter. This system could be evaluated using bench systems, or by modifying the Taliaferro pilot plant that was used in this study. The zeolite filter and denitrification filter would function as a coupled, integrated system, and dynamics of steady and non-steady response would be used to develop performance data and design criteria. For the coupled filter system, the scope of evaluation should be expanded to include other stormwater constituents. In addition to nitrogen, for example, zeolites are also capable of binding other cations, including the divalent metals that are often the most prominent contaminants of concern in urban stormwater. The possible release of organic and inorganic constituents from denitrification media should be evaluated. In addition, in order to increase removal of total nitrogen, the study should examine other processes that expand on the capabilities of the zeolite/denitrification filter. Removal of particulate and dissolved organic nitrogen is pre-treatment with coagulants, using pipe mixing systems for example, and either pre-sedimentation or a direct filtration mode.

It is recommended that studies be conducted to integrate the zeolite filter into treatment trains that accomplish overall nitrogen reduction. Studies should be conducted to couple the zeolite filter to treatment processes that remove particulate nitrogen. This study would serve to upgrade wet detention pond effluent. The existing wet detention ponds that are widely dispersed throughout Florida are a likely candidate with which to couple zeolite filters. Wet detention ponds are already existing pre-treatment systems for zeolite filters, which would provide both flow equalization and sedimentation. A well functioning wet detention pond would reduce susceptibility of the zeolite filter to hydraulic failure from excessive solids loading. The wet detention pond/zeolite filter would function as linked unit operations that dynamically respond to applied stormwater flows and loadings. The zeolite filter would be exposed to varying flows, changing influent quality, continuous and discontinuous operation, sudden storm event loadings, and long term inter-event periods. The results of such a study would integrate many of the findings in this report and provide field experience with many questions including transient and inter-event nitrogen removals, long term performance, clogging and suspended solids issues, and maintenance requirements. An additional evaluation feature is to consider enhanced particle removal processes along with the wet detention pond/zeolite filter combination. These could include use of coagulants to treat pond influent, or treatment of pond effluent followed by pre-sedimentation or in direct filtration mode.

It is recommended that zeolite media be evaluated in a variety of stormwater management applications. These include downflow filters such as used in the Taliaferro pilot study, upflow filters, and sidebank and bottom filters. A pumpback



system could be developed whereby water from a pond is continuously circulated through a zeolite filter during non-storm periods, in order to continuously reduce nitrogen levels in a pond or water body and to maintain the viability of microbial populations. The zeolite filter may be effective for at source, or “on-site” stormwater management. Examples are direct treatment of roof runoff, integration of zeolite treatment filters with green roof water cycling, or direct incorporation of zeolites into green roof planting media.

Dissolved organic nitrogen (DON) was found to be a significant component of the pond water applied to the zeolite filter, and the zeolite filter had limited removal effectiveness for DON. DON is the major component of what had been referred to as “irreducible” stormwater nitrogen. It is recommended that further studies be performed to characterize the nature and treatability of this important stormwater component. These could consist of the use of coagulants prior to zeolite in a direct filtration mode, for example. Understanding the fate and transport of DON in stormwater management systems and developing DON treatment options would appear to be of very high significance where Total Maximum Daily Loads to impaired water bodies and “no net increase” of stormwater constituent loadings from new development are issues to be contended with.

It was found that the dissolved oxygen regime significantly affected zeolite filter performance. Zeolite filter application must be cognizant of the influent dissolved oxygen levels and their variation in non-steady conditions. It is recommended in general that more attention be given to the dissolved oxygen regime in stormwater management systems, and to its effects on nitrogen transformations and removal. A variety of aeration devices could be integrated into stormwater management systems, such as passive oxygenating weirs that make optimal use of available head to increase oxygen transfer.

Different zeolite materials are available and should be explored. The chabazite used in this study was 8x20 mesh (0.841 to 2.36 mm), which is larger than typical filter sand. Inorganic nitrogen removal through ion exchange adsorption and biodegradation was the goal rather than particle filtration. The superior water retention capabilities may prove to have significant advantages for sustaining the viability of microbial populations through extended dry periods. A smaller particle size chabazite could be more effective for traditional particle removal processes, but could also be more susceptible to clogging. Different zeolites are available which have lower cost, smaller cation exchange capacities, and greater abrasion resistance; these may have cost and performance advantages in some applications.

## Economic Analysis

An economic analysis was conducted to provide a preliminary cost estimate for a Hillsborough Filter treating a two acre drainage area. The Hillsborough Filter would employ chabazite ZS500H media and a directly coupled upflow denitrification filter with sulfur media. Assumptions used in the cost analysis are listed in Table 11. The media costs are reasonably close to present values.

The total present worth of the Hillsborough Filter is \$50,171, of which \$25,203 is capital and \$24,968 is operations and maintenance. The corresponding annualized costs are shown in Table 12. This analysis does not include the cost of real estate and design. Replacement of zeolite media at 6 year intervals is 17% of the total annualized cost. Lower cost zeolite with similar properties as the chabazite used in the pilot testing are expected to be available in the future (Eyde, 2006). The cost of the Hillsborough Filter would be correspondingly reduced.

**Table 11. Assumptions and costs used in economic analysis.**

Drainage area	2 acres	<b>Drainage area</b>	<b>2 acres</b>
Imperviousness	50%	<b>Imperviousness</b>	<b>50%</b>
Water quality volume	0.5 in.	<b>Water quality volume</b>	<b>1.0 in.</b>
Drawdown time	24 hours	<b>Drawdown time</b>	<b>72 hours</b>
Filtration rate	0.133 gpm/ft <sup>2</sup>	<b>Filtration rate</b>	<b>0.133 gpm/ft<sup>2</sup></b>
Media depth	18 in.	<b>Media depth</b>	<b>18 in.</b>
Zeolite	39.91/ft <sup>3</sup>	<b>Zeolite</b>	<b>\$ 39.91/ft<sup>3</sup></b>
Sulfur	0.77/ft <sup>3</sup>	<b>Sulfur</b>	<b>\$ 0.77/ft<sup>3</sup></b>
Maintenance	4 times/year	<b>Maintenance</b>	<b>4 times/year</b>
Media replacement	6 years	<b>Media replacement</b>	<b>6 years</b>

**Table 12. Annualized Cost, 30 year life, 4% interest rate.**

<b>Installation</b>	<b>\$1,457.48</b>
<b>O and M</b>	<b>\$1,671.07</b>
<b>Total</b>	<b>\$3,128.55</b>

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## Appendix A. Filter Media Physical Properties

**Filtration Media:** Two filtration media were specified for pilot testing at the Taliaferro site: zeolite ZS 500H (GSA Resources, Cortona, AZ) and silica sand (National Suncoast Media). Photographs of the two media are shown in Figures A-55 and A-56. Physical characteristics of filtration media are summarized in Table A-13. The chosen filtration media have a particle size range equal to or greater than coarse sand. The media were chosen based the need to limit headloss of clean media in the Taliaferro filter pilot research project and the need to limit decline of hydraulic conductivity due to potential suspended solids capture in the filter. Another media selection goal was to have two media with approximately equal hydraulic conductivities. One goal of this testing was to measure the hydraulic conductivities of the actual filtration media, in order to verify that filters at the research site could be constructed according to the projected design.

**Physical Properties:** Preliminary testing was performed to characterize media physical properties. Media physical properties are listed in Table A-14. The test procedures employed were as follows:

1. Material was collected and washed with clean tap water. Washing was conducted by placing an approximately 3 liter volume of material in a 3 gallon bucket, filling the bucket to the 2 gallon level with tap water, vigorously stirring the slurry for 30 seconds, decanting the supernatant water, and repeating the next wash cycle. Sand was washed seven times, after which a noticeable decrease in turbidity and a fairly clear supernate resulted. Zeolite was washed eleven times, after which a noticeable decrease in supernatant turbidity resulted; substantial supernate turbidity remained after eleven washings.
2. The washed material was drained, placed in aluminum pans, and dried at 170F for 48 hours.
3. A clean measuring container was dried and a volume mark placed.
4. The measuring container was placed on a balance and tared.
5. Dried sand or zeolite was placed in the measuring container to the volume mark.
6. The mass of the sand or zeolite material was measured.
7. Water was added to the container volume mark, such that it just filled the pore spaces in the material.
8. The mass of the saturated sand or zeolite material was measured.
9. The saturated material was removed and the container was filled to the volume mark with water only.
10. The mass of the water was measured.
11. Volume at the container mark was calculated as the mass of water in the empty container (g) divided by the density of water (1 g/cc).
12. Bulk density was calculated as mass of dry material divided by the volume.
13. Porosity was calculated as the volume of water added to the dry media divided by the container volume.
14. Intrinsic density was calculated as the bulk density divided by the fraction of total volume occupied by the dry media (i.e. 1 - porosity).

The intrinsic density, porosity, and bulk density of the silica sand listed in Table A-13 are typical values for sand media. The physical properties of the zeolite media are significantly different than those of sand. The zeolite has a much higher porosity and lower bulk and intrinsic densities than sand. Zeolite may have appreciable internal pore structures that contribute to the high porosity and low densities.

**Hydraulic Conductivity:** Hydraulic conductivity tests were performed by using the constant head test apparatus shown in Figure A-57. The apparatus consisted of a vertical column with fine and coarse screens at the bottom to retain test media (Figure A-58). Water was introduced at the top of the column. Water passing through the column exited the bottom of the column into a water chamber, which maintained a constant head lower water level at the bottom. The overflow rate from the bottom chamber could be measured as the volume accumulated in an initially empty container divided by the elapsed time. Initial tests were performed without media. Without media, water exited the column as fast as it could be supplied (>200 ml/sec), without a buildup of water level within the column. Media was placed into the column, and water was introduced into the top of the column. The water flowrate was adjusted so that the water level in the column increased until water overflowed the side port near the top of the column. Under these conditions, the water level at the top of the column (overlying the media) remained constant, and a constant head difference resulted. Water flow was allowed to continue for five minutes before flowrates through the column were measured. After the first test, the column was drained, refilled and tested two more times. The hydraulic conductivities were calculated three separate times for each media, and are shown in Table A-14. For both media, calculated hydraulic conductivities were quite close. The averages of the three hydraulic conductivity values for zeolite and sand were 285 and 256 ft./day, respectively. The hydraulic conductivity value of zeolite is reasonably close to that of sand, which was one goal of the media selection. The Kozeny-Carmen equation predicts the hydraulic conductivity of porous media based on media physical properties:

$$K = \frac{pg}{u} \frac{n^3}{(1-n)^2} \frac{d^2}{180}$$

where K = hydraulic conductivity  
 p = density  
 g = gravitational constant  
 u = viscosity  
 n = porosity  
 d = particle diameter

The hydraulic conductivity of zeolite and sand media were calculated using the Kozeny-Carmen equation and the measured porosity and the particle size of each media. The sand media had a particle size range of 1180 to 3175  $\mu\text{m}$ . When a particle size of 2555  $\mu\text{m}$  was used, the Kozeny-Carmen equation predicted a hydraulic conductivity of 256 ft./day, which equaled the experimental result. For zeolite, with a particle size range of 850 to 2360  $\mu\text{m}$ , use of the smallest size (850  $\mu\text{m}$ ) resulted in a predicted hydraulic conductivity of 368 ft./day, which is 29 % higher than the experiment value. While the

high porosity of the zeolite material resulted in a high prediction of conductivity by the Kozeny-Carmen equation, the physical manifestation of porosity may have been reduced by the irregular nature of the zeolite particle surface.

**Headloss in Hillsborough Filter:** Headloss in the research filters was estimated using Darcy's Law for flow in saturated porous media:

$$Q = K A \Delta H / \Delta L$$

where Q = flowrate  
K = hydraulic conductivity  
 $\Delta H$  = headloss  
 $\Delta L$  = media depth.

For an applied flowrate over the filter surface area (Q/A) and media depth ( $\Delta L$ ), the headloss can be calculated from the hydraulic conductivity of the media. The headloss for the 24 inch deep research filters is shown in Table A-16. Filtration rates of 192 to 576 gal/ft<sup>2</sup>-day result in a headloss of 1.6 to 5 inch for zeolite and 1.8 to 5.4 inch for sand media. These headloss values can be accommodated within the existing physical configuration of the research filter installation. Therefore, there is no need to modify the design or operation of the research filters.



Figure A-55. Silica sand (1 large scale division = 1 cm).





**Figure A-56. Zeolite ZS500H (1 large scale division = 1 cm).**



**Figure A-57. Hydraulic conductivity test apparatus.**



**Figure A-58. Filtration media screening.**

**Table A-13. Filtration media physical properties.**

<b>Material</b>	<b>Zeolite 500H (Chabazite)</b>	<b>Silica sand</b>
Manufacturer Size Range	8x20	1/8 inch x #16
Size (μm)	850 - 2360	1180 - 3175
Bulk Density (g/cc)	0.615	1.532
Intrinsic Density (g/cc)	1.699	2.619
Porosity (-)	0.638	0.415
Saturated Bulk Density (g/cc)	1.253	1.947

**Table 14. Hydraulic conductivity tests of filtration media.**

<b>Hydraulic conductivity (ft/day)</b>	<b>Zeolite 500H (Chabazite)</b>	<b>Silica sand</b>
Media depth (inch)	24.0	24.0
Head difference (inch)	53.88	53.81
Area (in <sup>2</sup> )	7.21	7.21
Hydraulic conductivity Test 1 (ft/day)	281.1	259.0
Hydraulic conductivity Test 2 (ft/day)	285.4	253.7
Hydraulic conductivity Test 3 (ft/day)	288.5	255.6
Average hydraulic conductivity (ft/day)	285.0	256.1

**Table 15. Filtration Media Characteristics.**

<b>Hydraulic conductivity (ft/day)</b>	<b>Zeolite 500H (Chabazite)</b>	<b>Silica sand</b>
Average hydraulic conductivity (ft/day)	285.0	256.1
Porosity (-)	0.64	0.42
Representative particle size ( $\mu\text{m}$ )	850	2555
Kozeny-Carmen Equation (ft/day)	368	256

**Table 16. Projected headloss in Hillsborough Filter Research.**

<b>Filtration Rate</b>		<b>Headloss (inch)</b>	
<b>gal/ft<sup>2</sup>-day</b>	<b>ft./hour</b>	<b>Zeolite 500H (Chabazite)</b>	<b>Silica sand</b>
192	1.1	1.62	1.80
384	2.1	2.43	2.71
576	3.2	4.86	5.41

## Appendix B. Geotextile Filter Fabric

**Overview:** Research at the Taliaferro site employed zeolite ZS 500H (GSA Resources, Cortona, AZ) and silica sand (National Suncoast Media) as granular filtration media. Physical filtration, ion exchange, and aerobic and anaerobic biological reactions will affect nitrogen transformations within the filter media. A relevant aspect of the use of permeable media in stormwater filtration is the accumulation within the filter media of stormwater suspended solids, which can improve stormwater quality by removing suspended solids and associated pollutants. High solids loading, however, can lead to a decline in hydraulic conductivity and clogging. In this case, bypassing will render a filter ineffective. The filtration component of the Taliaferro research project was intended to target soluble forms of stormwater nitrogen. Geosynthetic fabrics were placed over the granular media for particle retention, both to remove suspended solids and to protect the hydraulic conductivity of granular filter media.

**Geosynthetics:** The geosynthetics that were deployed in the project are listed in Table B-17. The geosynthetics were employed at two locations within the filters:

1. Above the zeolite or sand filter media. Geosynthetic located above the zeolite or sand media assist in preventing stormwater suspended solids from accumulating in the filter media. In addition, the overlying geosynthetic will act as a removal process in itself for suspended solids.
2. Between the zeolite or sand filter media and the underlying gravel. At this location, geosynthetic will prevent the finer particle size zeolite or sand from entering the underlying gravel underdrain.

**Selection Criteria:** The selection criteria were:

1. Apparent size opening. Zeolite and sand have particle size ranges of 850 to 2360  $\mu\text{m}$  and 1180 to 3175  $\mu\text{m}$ , respectively (Table 1). As an approximate estimate, filtration media are effective at removing particles with a particle size of 20% or greater than the diameter of the filtration media. The 20% approximation results in estimates of 170 and 236  $\mu\text{m}$  as the minimum particle sizes that will be removed by the zeolite and sand media, respectively. The apparent openings of FW 700 and 170N are 212 and 149  $\mu\text{m}$ , respectively. These geosynthetics will be employed over the zeolite and sand media and should remove particles that would accumulate within the filter media. An option is to employ FW 300 or FW402 above the FW 700 or 170N, to protect the smaller pore size geosynthetic. The apparent openings of FW 300 and FW 402 are 600 and 425  $\mu\text{m}$ , respectively (Table B-17). These geosynthetics will be employed beneath the zeolite and sand media and will prevent migration into underlying sand.
2. Flowrate The experimental filters will typically operate at filtration rates of 0.1 to 2  $\text{gal/ft}^2\text{-min}$ . The flowrates of the clean geosynthetics are 18 to 145  $\text{gal/ft}^2\text{-min}$ , or 5 to over 1000 times the filtration rates that will be applied in the filters. In theory, all of the geosynthetics can be applied at any location. However, the effective flowrate of geosynthetics can decline with time if materials accumulated and clog the pore openings.

**Frame System:** Geotextile fabrics were mounted in the frame system shown in Figures B-59, B-60, and B-61. The frame system allowed the geosynthetics to be readily removed, cleaned and replaced. The use of readily maintainable geosynthetic filters could be developed as a full scale deployment feature of stormwater filters. A view through a woven geotextile is shown in Figure B-62.



**Figure B-59. Geotextile mounted on frame.**





**Figure B-60. Geotextile mounted on frame (deployment orientation).**



**Figure B-61. Geotextile frame.**





Figure B-62. Woven geotextile.

Table B-17. Geotextile fabrics.

<b>Geeotextile</b>	<b>Material</b>	<b>Apparent opening size<sup>1</sup> (mm)</b>	<b>Flowrate<sup>2</sup> (gal/ft<sup>2</sup>-min)</b>
Filterweave FW300	Woven mono and multi-filament polypropylene yarn	600	115
Filterweave FW402	Woven mono and multi-filament polypropylene yarn	425	145
Filterweave FW700	Woven mono and multi-filament polypropylene yarn	212	18
170N	Nonwoven; Polypropylene Staple Fibers	149	105

<sup>1</sup>ASTM D4751 <sup>2</sup>ASTM D4491



## Appendix C. Multi-Level Sampling System

A Multi Level Sampling System (MLSS) was developed to enable sampling at different media depths in zeolite media. The MLSS was installed in the filter bed in conjunction with media placement.

**MLSS Components:** Components of the Multi Level Sampling System included:

1. Multi Level Sampling System Module. The MLSS module is shown in Figure C-63. The custom constructed module consisted of a support column, five sampling ports installed at specific levels, tubing, and attachments. The ports were screened to prevent ingress of suspended solids (Figure C-64). The module was placed within the zeolite media at the centerline of the filter plan area. The module was mounted to the side wall of the filter chamber and was immobile.
2. Connectable tubing to connect the port lines to the sampling pump line.
3. A pump.
4. Tubing to connect pump to appropriate analytical chamber.

The prototype Multi Level Sampling System module provided five sampling ports located at 3, 7, 12, 17, and 22 inch depth below the surface of the 24 inch zeolite bed. The five ports were radially offset at approximately 72°. Radial offset, along with proper flowrate selection, was intended to minimize disturbances to the flow field within the zeolite media as sample is withdrawn. Sample moved from the zeolite media through the screened sample port, tubing, pump, to the tubing following the pump; sample will then be directed to an analytical chamber appropriate for the analysis that is to be performed. Analytical chambers included an open flow-through cell and sample collection bottles.



Figure C-63. Multi-level sampling system module.



Figure C-64. Multi-level sampling system port.

## Appendix D. Pondwater Characterization

Influent to the research process train consists of water pumped from a sump, which receives water from several surface ponds at the Taliaferro Stormwater Research Facility. Water quality measurements were conducted to assess influent pondwater quality. Samples were collected from a sampling port installed in the influent line just upstream of a tee that directs flow to either the stormwater storage tank (batch mode) or to the influent standpipe (direct mode). A representative result is listed in Table D-18 for Day 55 (11/08/2005). The results indicate that the pondwater is of circumneutral pH with a moderate alkalinity. Total suspended solids and turbidity are low, indicating the Taliaferro ponds serve as effective sedimentation basins. Chemical oxygen demand indicates a substantial presence of natural oxygen demanding materials, ostensibly dissolved organic carbon. The total nitrogen of 4.2 mg/L was dominated by organic nitrogen, with low concentrations of inorganic nitrogen species  $\text{NH}_3$ ,  $\text{NO}_2$  and  $\text{NO}_3$ . Prior to the sampling event, the Taliaferro pond water had received little influent for many weeks and the ponds exhibited extensive duckweed growth. Inorganic nitrogen forms may have been assimilated into plant biomass, accounting for their low solution concentrations.

The dissolved oxygen value of 0.26 mg/L is quite low and was unexpected, particularly since values of dissolved oxygen in the Taliaferro pond water columns were 4 mg/L and greater. The influent pondwater sample point was located just past the influent flowmeters, after the pond water had passed through two sumps in series on its way to the stormwater treatment train. The DO in the sumps was measured and was less than 0.5 mg/L in both the first and second sumps. A potential explanation for low DO is that sediment oxygen demand, either in the ponds or within the sumps, is consuming oxygen. The unexpectedly low DO in the influent pondwater may be somewhat artificial and caused by the use of sumps to collect and route pondwater to the stormwater treatment train. However, it is possible that low DO conditions could be created in many situations within urban stormwater management systems.

The low influent DO is significant for the research project because the oxidation of ammonia (nitrification) requires oxygen. Stoichiometrically, 4.1 grams or greater of oxygen per gram of ammonia nitrogen are required to support nitrification. The low influent DO suggests that ammonia removal by the filters would be oxygen limited for ammonia nitrogen levels greater than 0.6 mg/L.

Table D-18. Pondwater quality (11/08/2005).

Parameter	Value
Temperature, F	67.7
pH	7.1
Alkalinity, mg/L as CaCO <sub>3</sub>	94
Dissolved Oxygen, mg/L	4.1
Chemical oxygen demand, mg/L	29
UV 254 absorbance at 254 nm, cm <sup>-1</sup>	0.471
SUVA <sup>1</sup> , L/mg-cm	0.016
Total suspended solids, mg/L	0.8
Turbidity, NTU	1.7
Conductivity, uS/cm	275
Total Nitrogen, mg/L	4.2
NH <sub>3</sub> -N, mg/L	0.04
NO <sub>2</sub> -N, mg/L	< 0.002
NO <sub>3</sub> -N, mg/L	< 0.01

<sup>1</sup>Specific UV Absorbance; normalized to COD

## Appendix E. Nitrification Media Bench Evaluation

To guide the experimental design for the pilot research filters at the Taliaferro Stormwater Research Facility, two prototype bench scale filter columns were fabricated and assembled. These filter columns were used to evaluate the zeolite and sand media that will be used at the Taliaferro Pilot site.

**Column Apparatus:** The nitrification column apparatus is shown in Figure E-65. Components of the prototype columns include:

1. **Columns:** Two columns are mounted on a stand and operated in parallel on the same stormwater influent stream. Each column consists of a 64 mm i.d. acrylic tube of 33.5 cm height. Influent stormwater enters through a bottom port that connects to a conical bottom section. Effluent exits through a top port. An effluent sampling port is located on the effluent line. Multiple sampling ports are located in the sidewall to allow for profiling of chemical parameters.
2. **Influent reservoir:** Contains stormwater with amendments.
3. **Pump:** A multi-head peristaltic pump withdraws stormwater from the influent reservoir and pumps into the column inlet.
4. **Effluent Sampling Port:** An effluent sampling port is located on the effluent line, just after it exits the column.
5. **Effluent reservoir:** Collection reservoir for column effluent.

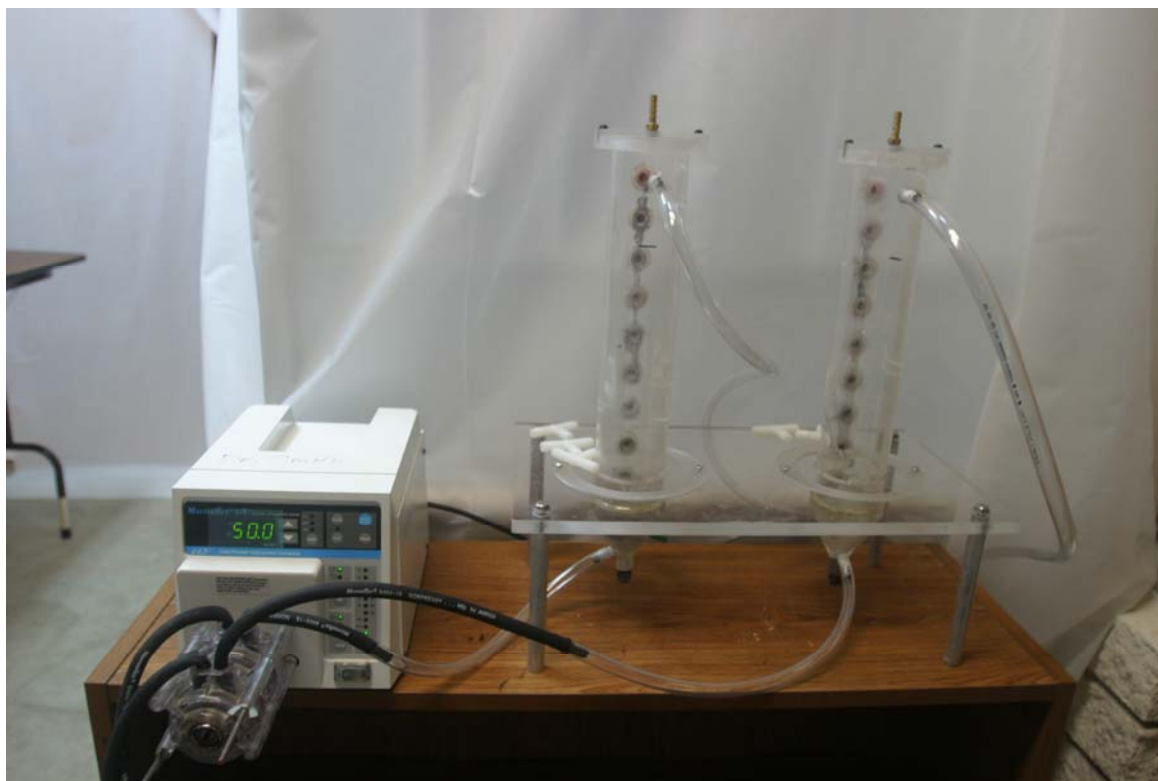
**Media:** Physical characteristics of ZS 500H and silica sand media are summarized in Table E-19. The chosen filtration media have a particle size range equal to or greater than coarse sand. The media were chosen based the need to limit headloss of clean media in the Taliaferro filter pilot research project and the need to limit decline of hydraulic conductivity due to potential suspended solids capture in the filter.

**Operation:** The peristaltic pump was calibrated and Taliaferro pond water transported to the laboratory and amended with ammonia to insure its presence and enable a side by side comparison of zeolite and sand media. Filters were inoculated with 200 ml of settled sludge collected from a separate stage nitrification process at the Howard Curran Wastewater Treatment Plant in Tampa, Florida. After inoculation, reactor and recycle lines were filled with un-amended Taliaferro pond water and allowed to circulate for 20 hours before commencing forward flow. The columns were operated without recycle. Operational characteristics of bench filter columns are shown in Table E-20, where loading rates were calculated based on average volumes of flow introduced into the filters.

**Results:** Operating results for zeolite and sand columns are shown in Figures E-66 and E-67, respectively. For the zeolite column, total inorganic nitrogen ( $\text{NH}_3\text{-N} + \text{NO}_2\text{-N} + \text{NO}_3\text{-N}$ ) was dominated by nitrate throughout the operational period, while both ammonia and nitrate were significant for sand effluent. Influent and effluent ammonia concentrations are compared in Figure E-68. The zeolite filter was highly effective in reducing  $\text{NH}_3\text{-N}$  for the entire period of operation, with ion exchange and biological reaction both occurring at different times. For the first 16 days, zeolite effluent levels of

ammonia and nitrate were both low, suggesting that ammonia was retained by ion exchange onto zeolite. After Day 16, zeolite effluent nitrate increased significantly, indicating that nitrification had become established. After Day 16, both ion exchange and biochemical reaction determined the fate of inorganic nitrogen in the zeolite filter. Significant concentrations of nitrate appeared in sand filter effluent after Day 16, suggesting that the establishment of nitrification occurred at the same time as the zeolite filter. The ammonia removal efficiency of the sand filter reached that of the zeolite filter after 30 days (Figure E-69).

A summary of bench filter performance during the start-up period is shown in Table E-21. Although significant nitrification appeared to be established at the same time, the zeolite filter removed ammonia immediately, resulting in low average effluent levels and high cumulative removal efficiency for ammonia. The ion exchange properties of zeolite enable ammonia to be effectively removed without the dependence on a previously well established nitrification process. The advantages of zeolite may be significant for non-steady operation and significant no-flow inter-event periods that characterize stormwater flows.



**Figure E-65. Nitrification column apparatus.**

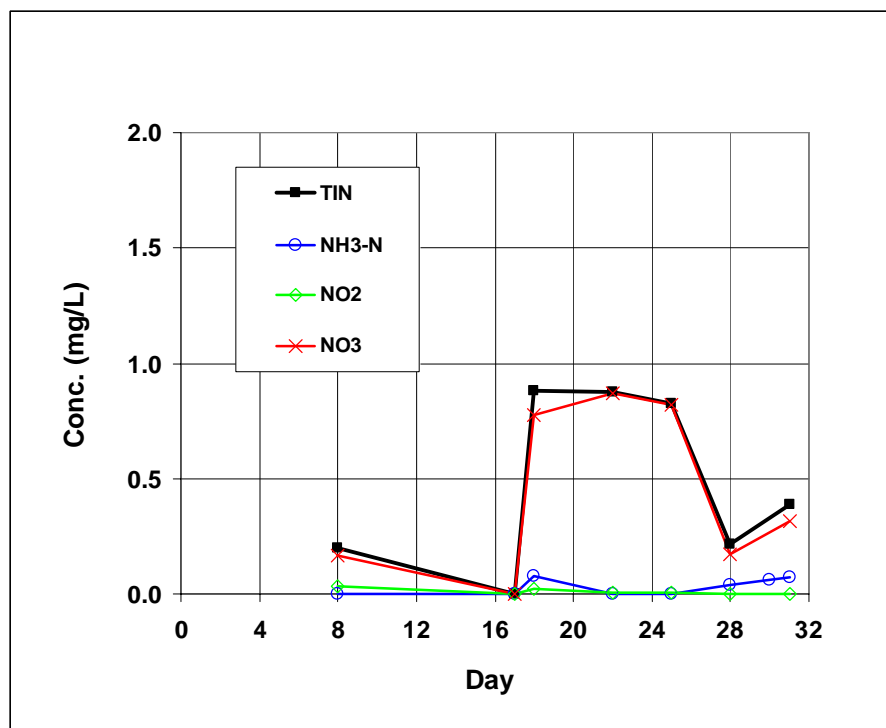


Figure E-66. Zeolite filter column effluent inorganic nitrogen.

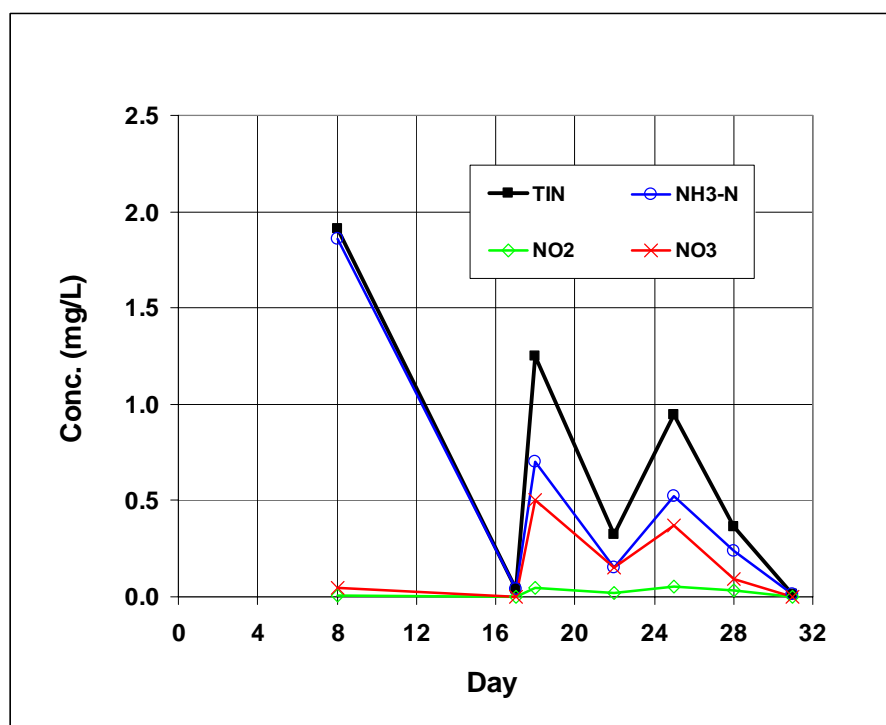


Figure E-67. Sand filter column effluent inorganic nitrogen.

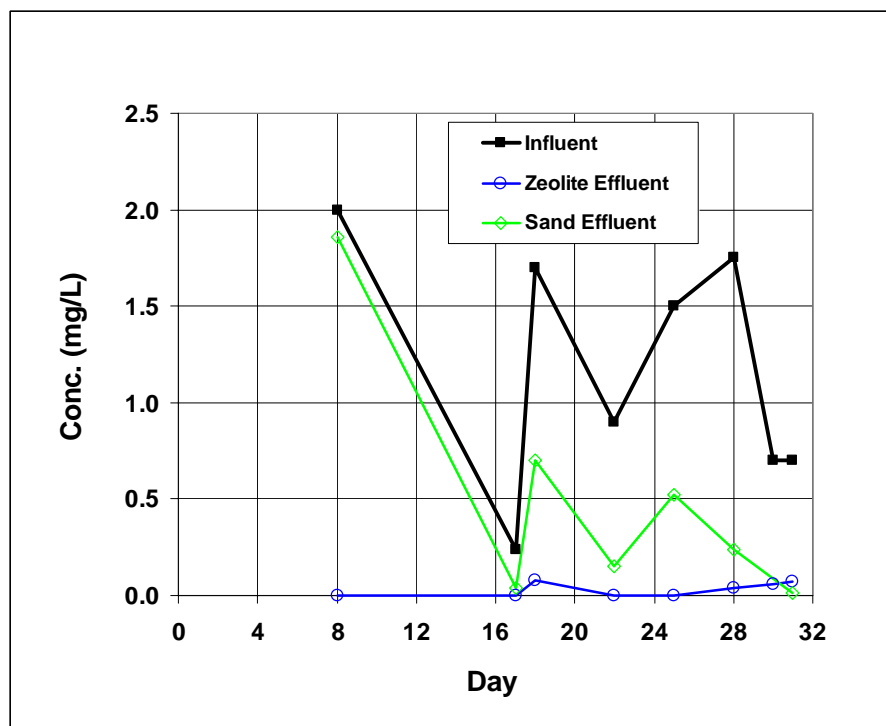


Figure E-68. Ammonia nitrogen concentrations.

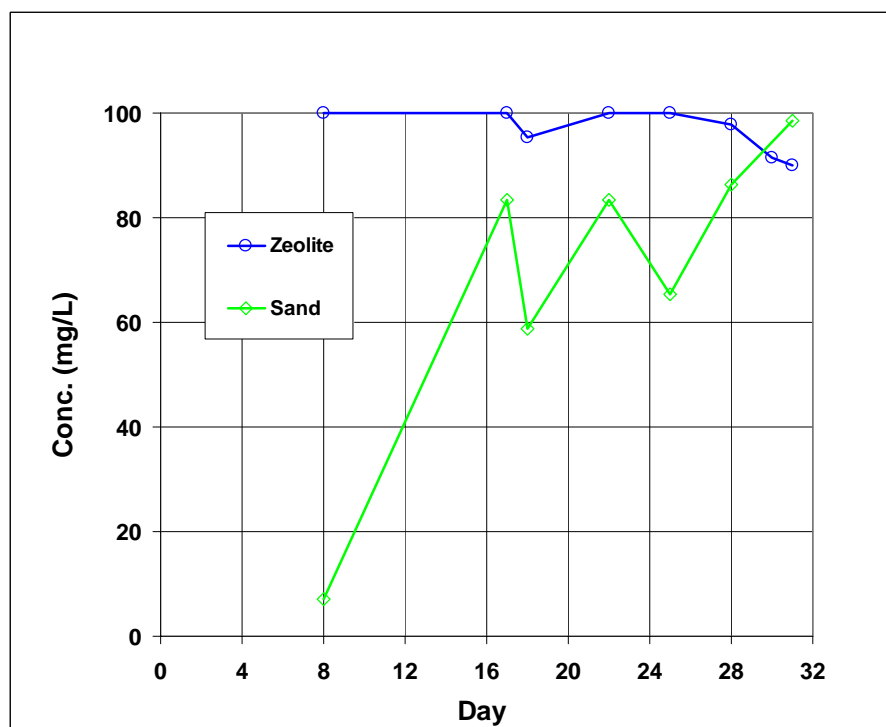


Figure E-69. Ammonia nitrogen removal efficiencies.



**Table E-19. Filtration media physical properties.**

<b>Material</b>	<b>Zeolite 500H (Chabazite)</b>	<b>Silica sand</b>
Size (µm)	850 - 2360	1180 - 3175
Bulk Density (g/cc)	0.615	1.532
Intrinsic Density (g/cc)	1.699	2.619
Porosity (-)	0.638	0.415
Hydraulic conductivity (ft/day)	285	256

**Table E-20. Operating characteristics of bench filter columns.**

<b>Empty Bed Volume, cm<sup>3</sup></b>	<b>980</b>
<b>Empty Bed Residence Time, min</b>	<b>163</b>
<b>Hydraulic Loading, gpm/ft<sup>2</sup></b>	<b>0.046</b>
<b>Average Influent NH<sub>3</sub>-N, mg/L</b>	<b>1.11</b>
<b>Average NH<sub>3</sub>-N Loading Rate, gram/m<sup>2</sup>-day</b>	<b>2.98</b>

**Table E-21. Bench filter start-up performance summary.**

	<b>Zeolite</b>	<b>Sand</b>
<b>Time to significant nitrification, days</b>	<b>17</b>	<b>17</b>
<b>Time to reach 95% ammonia removal, days</b>	<b>0</b>	<b>30</b>
<b>Average NH<sub>3</sub>-N effluent, mg/L</b>	<b>0.007</b>	<b>0.45</b>
<b>Cumulative NH<sub>3</sub>-N mass removal, %</b>	<b>99.4</b>	<b>59.7</b>

## Appendix F. Flow Perturbation to Bench Scale Nitrification Filters

Flowrate perturbation experiments were conducted on the zeolite and sand bench scale filters to assess their response to elevated flows and nitrogen loadings in a simulated event. The purpose was to provide guidance for flowrate perturbations to be conducted to the field pilot filters.

**Operating Conditions:** The filters were operated at 10.2 ml/min flowrate for 24 hours before perturbation. A ten fold increase in flowrate was applied to the each filter for 60 minutes, while influent  $\text{NH}_3\text{-N}$  concentration was held constant at 1.5 mg/L. A summary of the experimental conditions before, during and after the perturbation is shown in Table F-22. The applied hydraulic loading to the filters is shown in Figure F-70.

**Results:** Effluent inorganic nitrogen concentrations during and following flowrate perturbation are shown in Figures F-71 and F-72 for zeolite and sand filters, respectively.  $\text{NH}_3\text{-N}$  peaked at 0.1 mg/L in the zeolite filter effluent, while  $\text{NH}_3\text{-N}$  was much higher in sand filter effluent (0.85 to 0.95 mg/L) throughout the perturbation (Figure F-72). Effluent  $\text{NH}_3\text{-N}$  in zeolite and sand effluent are compared in Figure F-73. The areas under the  $\text{NH}_3\text{-N}$  curves in Figure F-73 were used to calculate cumulative  $\text{NH}_3\text{-N}$  mass leaving the filters from time zero to 190 hours, and compared to the additional mass of  $\text{NH}_3\text{-N}$  added to the filters during perturbation (8.24 mg/L, Figure F-70). Zeolite and sand filters released 0.4 and 30% the additional mass of  $\text{NH}_3\text{-N}$  added in perturbation. Zeolite substantially reduced both peak effluent  $\text{NH}_3\text{-N}$  and the mass of  $\text{NH}_3\text{-N}$  versus sand.

Comparison of Figures F-71 and F-72 indicates that effluent nitrate was substantially lower in the zeolite filter than in sand, both before and during the perturbation. This suggests that denitrification was more strongly established in the zeolite filter. Whereas nitrate levels increased slightly during perturbation in zeolite effluent, sand effluent nitrate decreased substantially during perturbation. Nitrate concentration decline can be explained by the limited capacity of nitrifying microorganisms to increase their metabolic rate in response to the increased  $\text{NH}_3\text{-N}$  loading during the flowrate perturbation. Zeolite effluent nitrate increases at 190 hours, possibly indicating nitrification of previously sorbed  $\text{NH}_3\text{-N}$ .

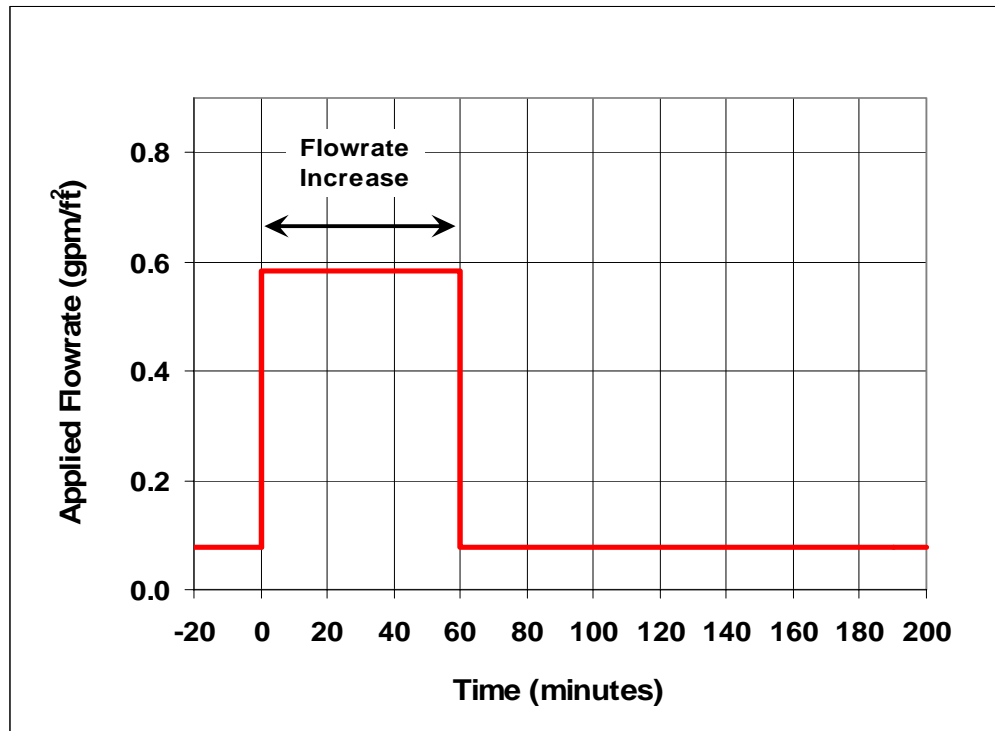


Figure F-70. Flowrate perturbation.

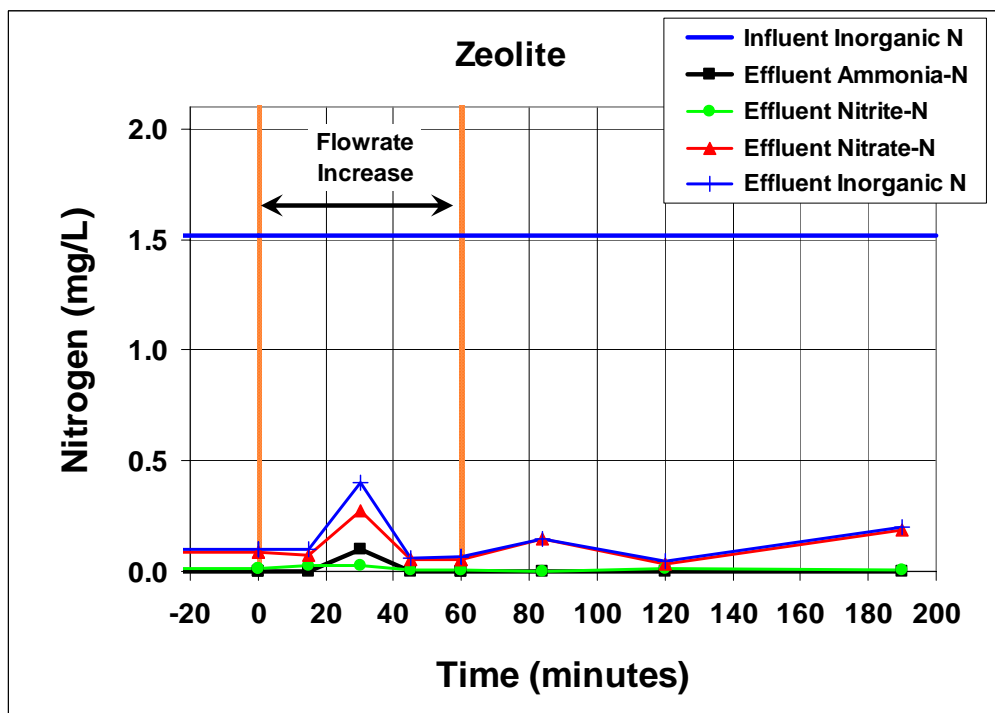


Figure F-71. Performance of zeolite filter column.

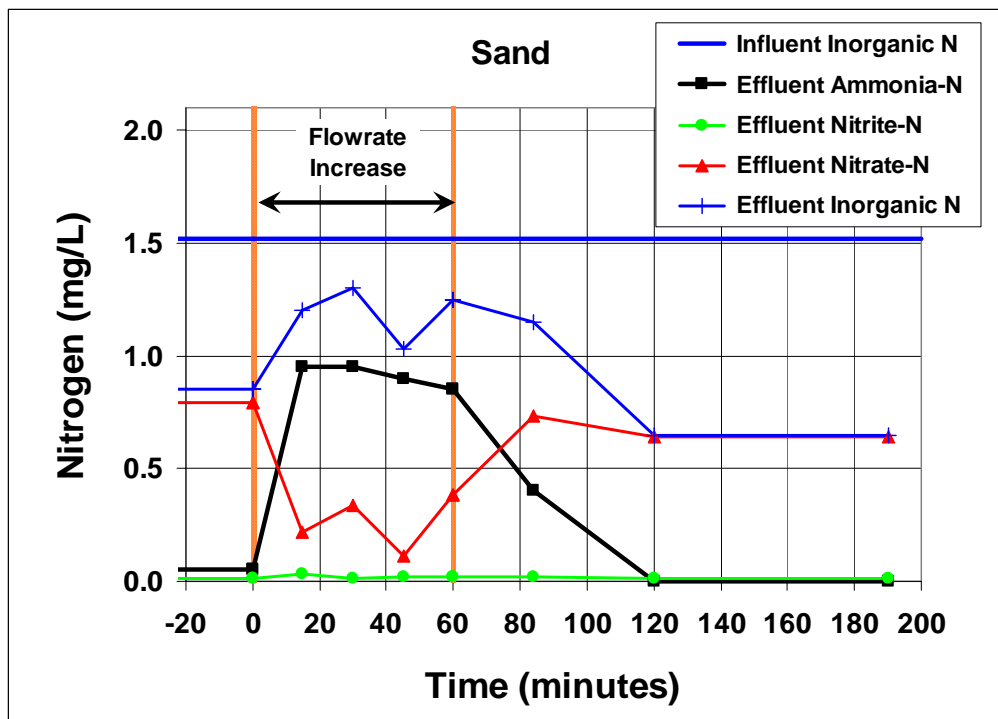


Figure F-72. Performance of sand filter column.

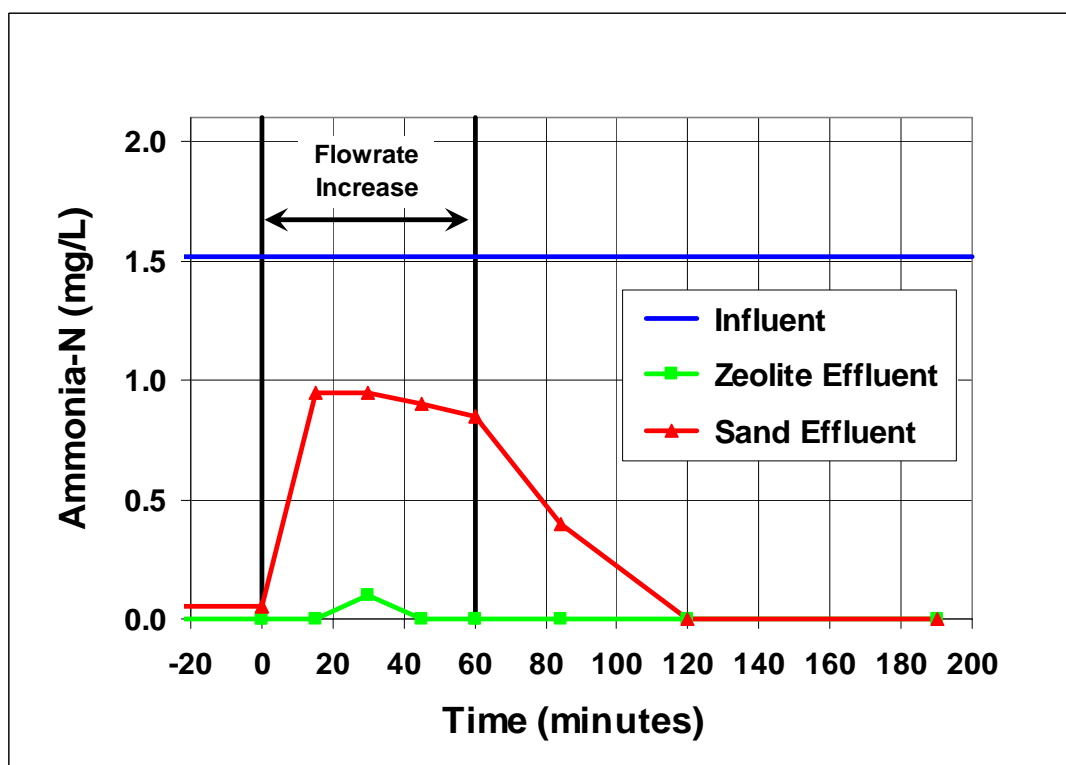


Figure F-73. Comparison of ammonia-n breakthrough in zeolite and sand filters.

**Table F-22. Operating characteristics of bench filter columns.**

	<b>Steady</b>	<b>Perturbation</b>
<b>Influent Flowrate, ml/min</b>	<b>10.2</b>	<b>102</b>
<b>Empty Bed Residence Time, min</b>	<b>96.4</b>	<b>9.6</b>
<b>Filtration Rate, gal/ft<sup>2</sup>-min</b>	<b>0.078</b>	<b>0.78</b>
<b>N loading rate, gram/ft<sup>2</sup>-day</b>	<b>0.63</b>	<b>6.3</b>

## Appendix G. Batch Leaching Experiments

Batch leaching experiments were conducted to assess the release of chemical oxygen demand from soybean hulls and barley straw, with pond water as control. The purpose was to assess the potential of these media for denitrification of oxidized nitrogen (nitrate and nitrite) from zeolite filters. To affect denitrification, the media would be hydrolyzed and release labile organic carbon that support denitrification.

**Operating Conditions:** Three batch reactors were established by placing a known dry mass of test material into 1125 cm<sup>3</sup> batch reactors and adding Taliaferro Pond water to bring the total volume of 1050 ml (Table G-23). The tested media were soybean hulls and barley straw and are shown in Figures G-74 and G-75. A third batch reactor served as a control, and contained Taliaferro Pond water only with no added carbon source. No inoculum was added. The batch reactors contained an air headspace of approximately 75 cm<sup>3</sup>. Reactors were covered with aluminum foil and incubated in the dark 18 to 22°C for over five weeks, without mixing.

**Results:** Leaching test results are shown in Figures G-76 through G-78. Chemical oxygen demand increased quickly and substantially in both soybean hull and barley straw batch reactors, while in COD in the pond water control changed little (Figure G-76). Both soybean hull and barley straw appear to be capable of providing carbon and electrons for denitrification. The rapid rates of COD release suggest that continuous submergence of these media might result in solubilization rates in excess denitrification requirements, and lead to rapid media exhaustion. Dissolved oxygen was rapidly depleted in soybean and barley reactors (Figure G-77). The pH rose in the pond water control; in both organic amended reactors pH declined significantly to Day 16 and then rebounded (Figure G-78). The results are consistent with depletion of oxygen, anaerobic hydrolysis, and release of organic fermentation products. In both reactors, some material floated on the surface while much was in a bottom slurry. On Day 21, a portion of the reactor liquid was removed and replaced with an equal volume of distilled water. Replacing a portion of the extract diluted the FCOD at Day 21, and COD declined thereafter. DO rose of Day 21 but fell to zero afterwards (Figure G-77). The pH declined with distilled water dilution of Day 21, but by Day 34 pH returned to its levels before distilled water addition (Figure G-78).



**Figure G-74. Unmodified soybean hulls (1 large scale division = 1 cm).**



**Figure G-75. Barley straw (1 large scale division = 1 cm).**

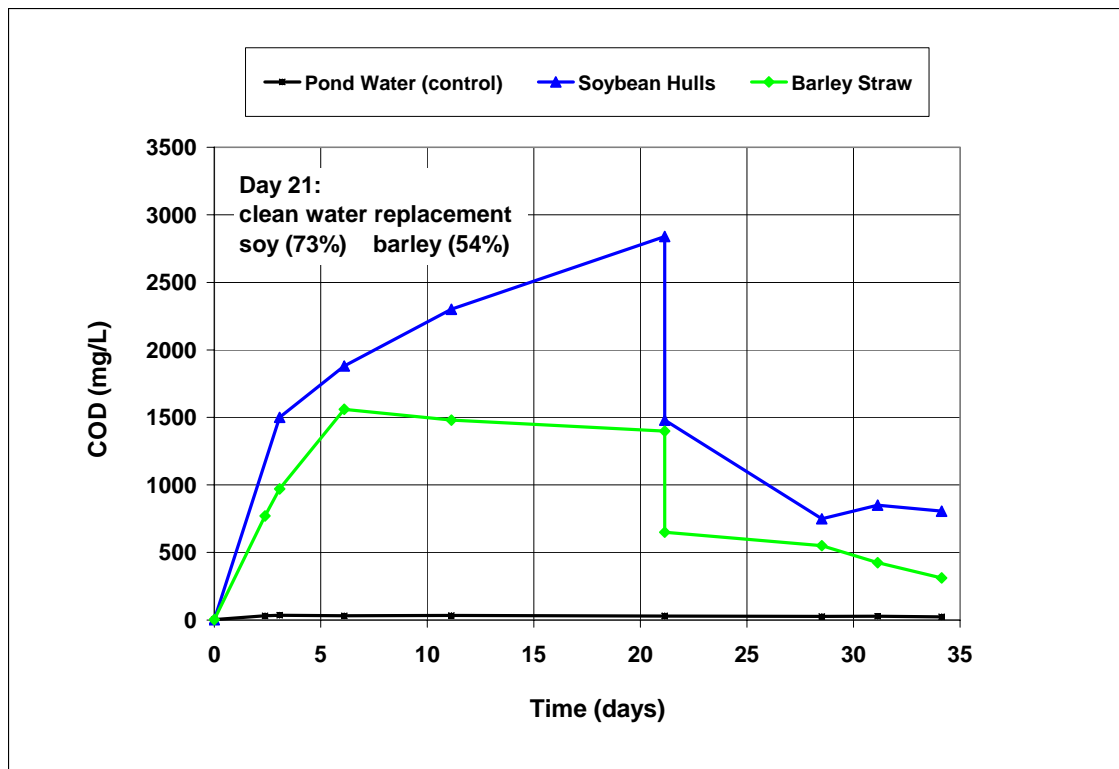


Figure G-76. Timecourse of chemical oxygen demand (COD) in leaching study.

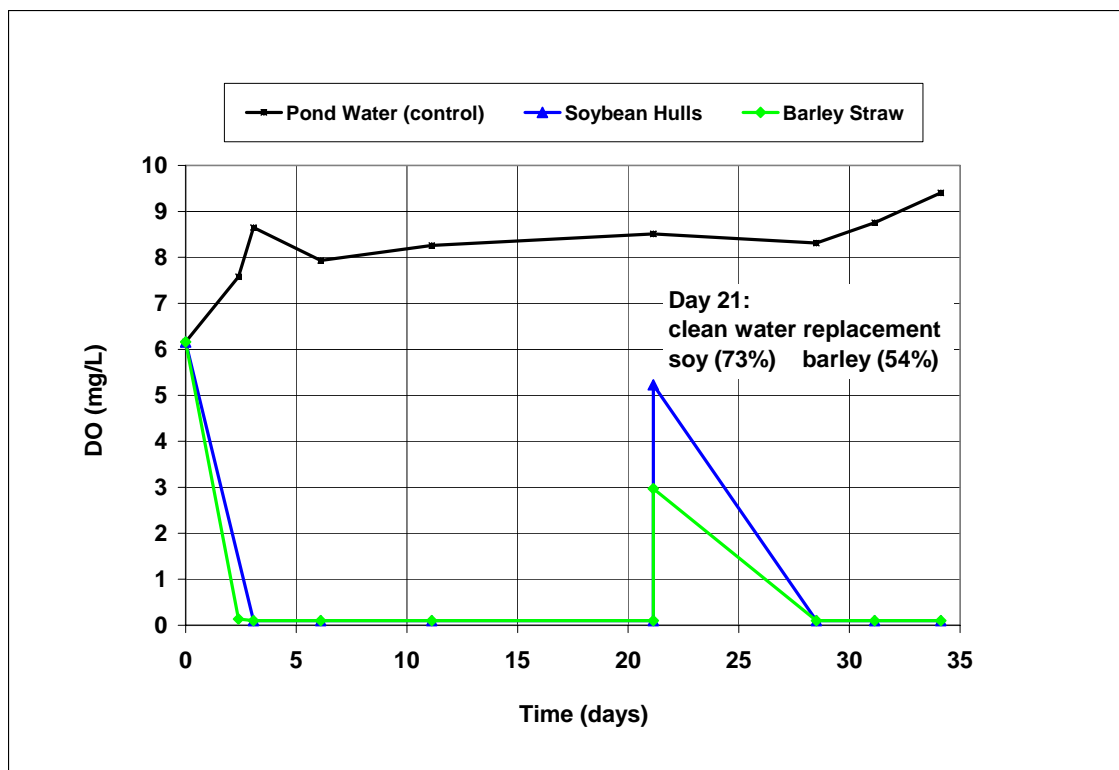


Figure G-77. Timecourse of dissolved oxygen (DO) in leaching study.



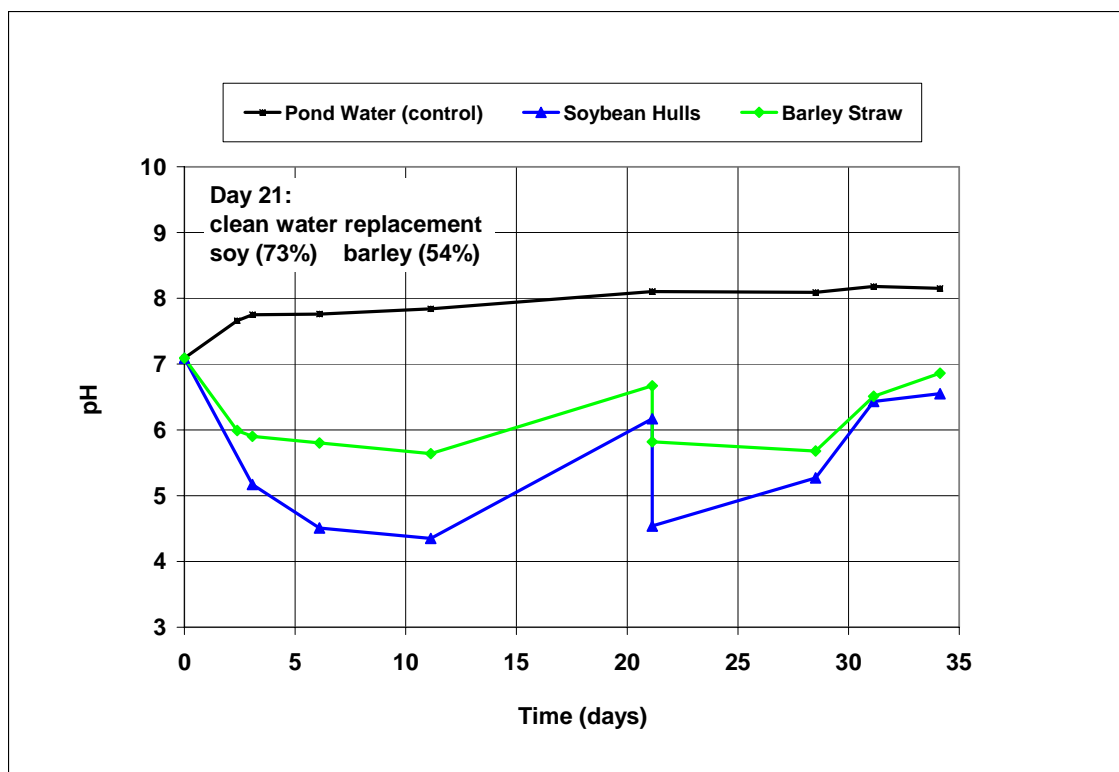


Figure G-78. Timecourse of pH in leaching study.

Table G-23. Batch leaching reactor characteristics.

	Soybean Hulls	Barley Straw
Mass material, g	17.6	15.1
Final volume, ml	1050	1050
Mass / Final Volume (mg/L)	16.8	14.4

## Appendix H. Denitrification Bench Evaluation

The research at the Taliaferro site employed zeolite ZS 500H to promote ammonia sorption and nitrification. Another research avenue that was explored is the use of media to enhance biological denitrification. Bench scale filter columns were used to evaluate denitrification media that could potentially be employed following zeolite filtration. In a stormwater treatment train, denitrification media could be incorporated in several configurations: as an additive in a modified filter design, to a second in-ground type filter following the zeolite filter, or to a separate denitrification column.

**Column Apparatus:** The denitrification column apparatus is shown in Figure H-80. Components of the prototype columns include:

1. **Columns:** Four columns are mounted on a stand and operated in parallel on the same stormwater influent stream. Each column consists of a 27 mm i.d. acrylic tube of 67.5 cm height. Influent stormwater enters through a bottom side port and effluent exits through a top side port. An effluent sampling port is located on the effluent line. A top port vents gases such as  $N_2$  that can be produced by biological denitrification within the column.
2. **Influent reservoir:** Contains stormwater with amendments.
3. **Pump:** A multi-head peristaltic pump withdraws stormwater from the influent reservoir and pumps into the column inlet.
4. **Effluent Sampling Port:** An effluent sampling port is located on the effluent line, just after it exits the column.
5. **Effluent reservoir:** Collection reservoir for column effluent.

**Media:** Denitrification media are summarized in Table H-24. The elemental sulfur and limestone media that were combined in one column are shown in Figures H-81 and H-82, and the pebble media in Figure H-83. (Soybean hull and barley straw media were illustrated in the previous appendix). The media were chosen for their ability to enhance denitrification, which they will affect by (1) providing electrons for biological denitrification, and (2) providing a surficial attachment area for denitrifying microorganisms. Soybean hulls and barley straw are organic materials and elemental sulfur is an inorganic electron donor. Limestone is added to the elemental sulfur to release alkalinity. As elemental sulfur undergoes dissolution and oxidation, acid is released. Limestone dissolution releases alkalinity, which counters the acid generation from elemental sulfur. The pebble media will release few electrons and serve as a control: pebbles can be used to assess denitrification from stormwater organic carbon where no external electron source is provided.

**Operation:** The peristaltic pump was calibrated for desired flowrates. Taliaferro pond water was transported to the laboratory and amended with nitrate to insure the presence of oxidized nitrogen. The four columns were seeded with 100 ml each of settled filter backwash from a tertiary denitrifying filter at the Howard Curran Wastewater Plant of the City of Tampa, filled with unamended Taliaferro Pond water, and water was circulated within the reactor for 22 hours with no forward flow; operation on amended Taliaferro Pond water was then commenced. Operating characteristics are summarized

in Table H-25, where loadings are expressed in terms of the average daily amount of influent applied. After 6 days, flow through the soybean column was greatly reduced due to swelling of the media. Efforts to restore flow were unsuccessful and operation of the soybean column was discontinued.

**Results:** Effluent nitrate and nitrite are shown in Figure H-84 through H-86. The barley straw column (Figure H-84) and sulfur/limestone column (Figure H-85) both reduced nitrate substantially, while higher nitrite accumulated in the sulfur/limestone column (Figure H-85). The pebble column also reduced nitrate and nitrite, although there was no removal on the last sample date (Figure H-86). Total oxidized nitrogen ( $\text{NO}_2 + \text{NO}_3$ )-N data for the three columns are shown in Figure H-87, and removal efficiency is shown in Figure H-88. From these figures, barley appears to have operated somewhat better than sulfur/limestone. However, the number of sample points was small and the period of operation was brief, and it is not possible to draw significant comparisons between the two media. The decline in removal efficiency in the pebble column at the last monitoring day stands out. The pebble media would not in itself supply carbon or electrons for denitrification, but electron donor could have originated from the organic carbon in the pond influent or from the original inoculation material. Lower organic carbon in pond water or depletion of inoculation carbon could have produced the deterioration in performance in the pebble column.



Figure H-79. Denitrification column apparatus.



**Figure H-80. Elemental sulfur pastilles (1 large scale division = 1 cm).**



**Figure H-81. Denitrification column limestone (1 large scale division = 1 cm).**



Figure H-82. Denitrification column pebbles (1 large scale division = 1 cm).

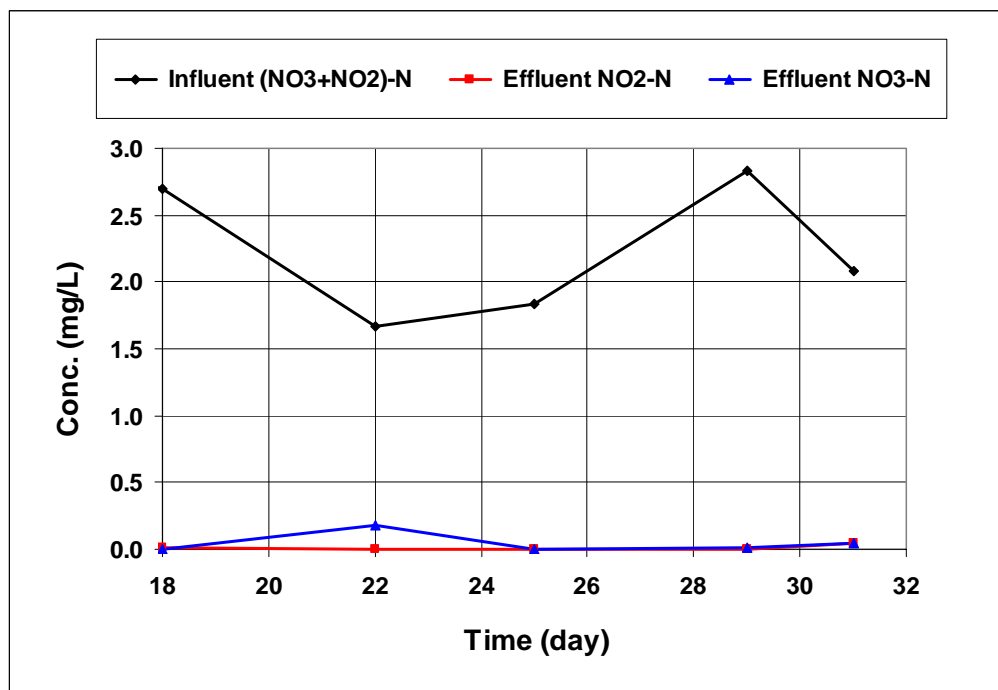


Figure H-83. Oxidized nitrogen in barley straw filter column.

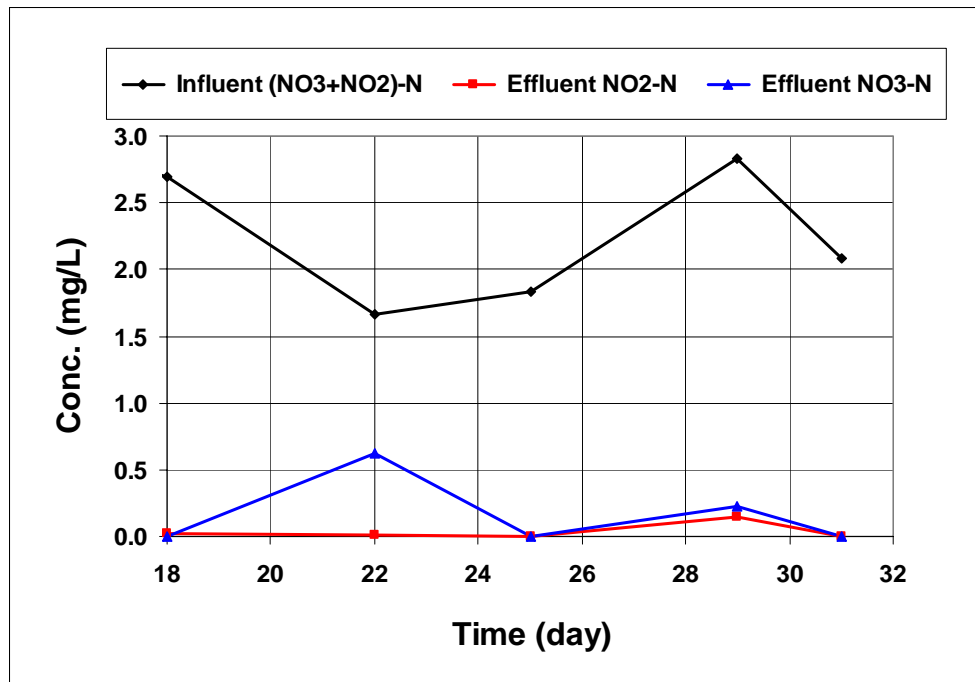


Figure H-84. Oxidized nitrogen in sulfur/limestone filter column.

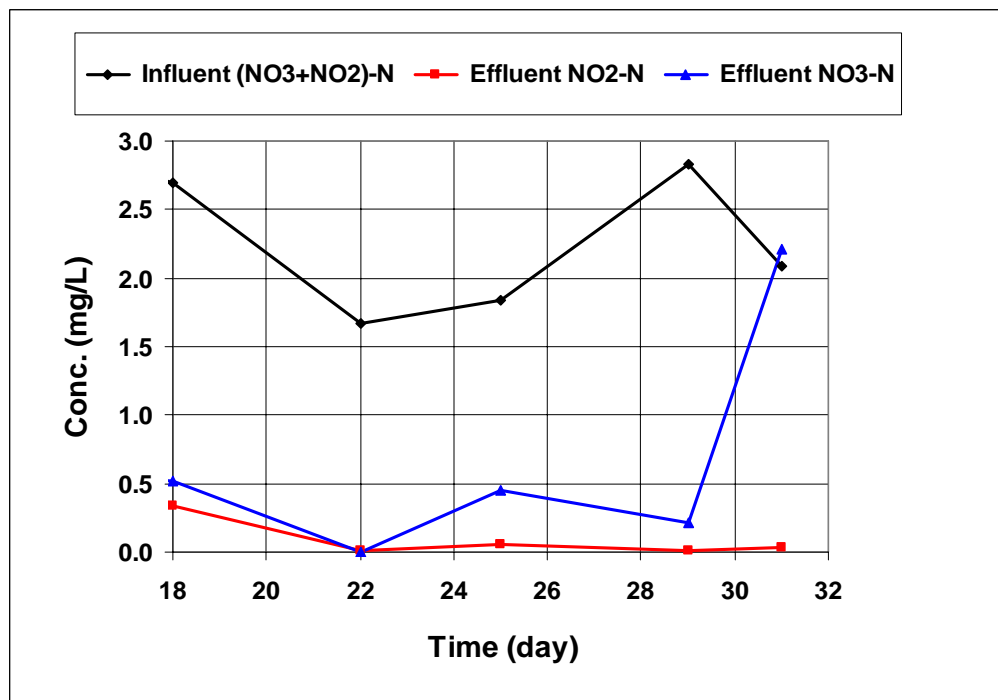


Figure H-85. Oxidized nitrogen in pebble filter column.

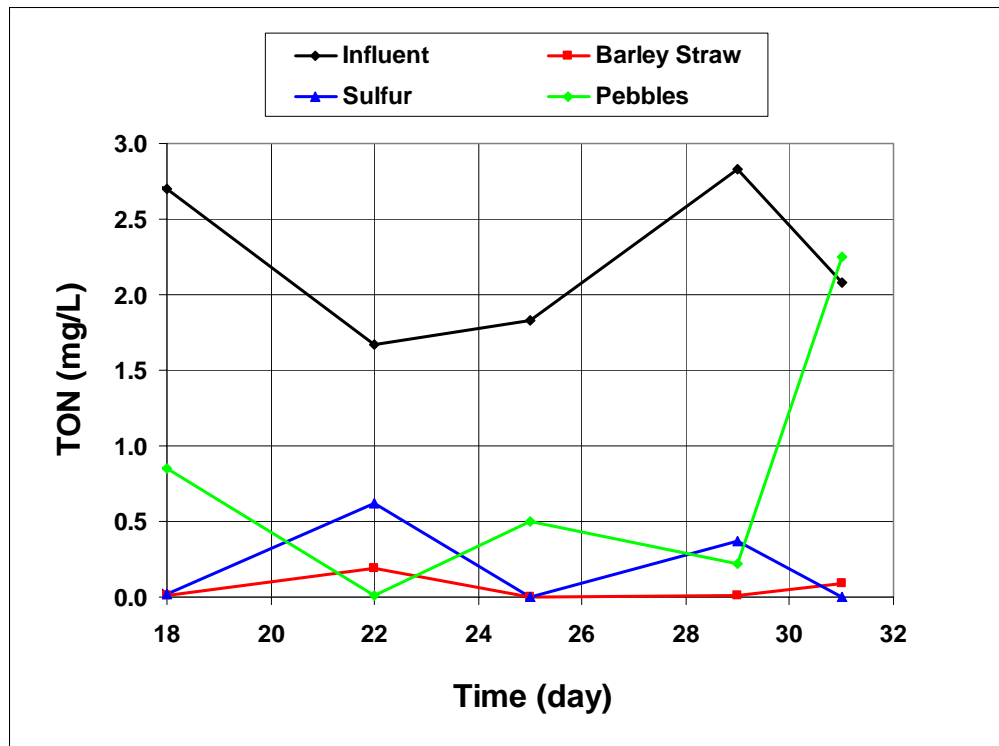


Figure H-86. Total oxidized nitrogen in column influent and effluents.

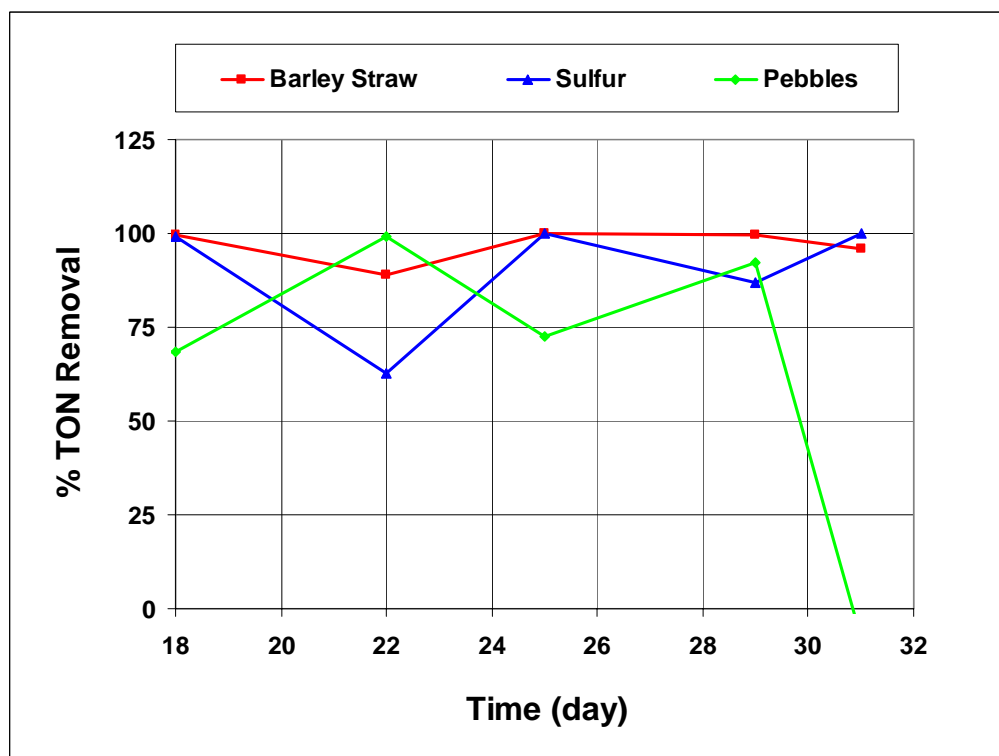


Figure H-87. Total oxidized nitrogen removal efficiency.

**Table H-24. Denitrification media.**

<b>Column</b>	<b>Media</b>	<b>Particle size (mm)</b>	<b>Source</b>
1	100% Unmodified soybean hulls	1.5 – 4 mm	U.S.D.A., New Orleans, La.
2	100% Barley straw	3 - 12 mm strands	Southeast U.S.
3	75% Elemental Sulphur (granular pastille) 25% Granular limestone	1 - 4 mm sulfur 4 – 7 mm limestone	Elemental sulfur: Georgia Pacific, Inc. Freeport, Texas
4	Pebbles (control)	3 - 5mm	Local Distributor, Tampa, FL.

**Table H-25. Operating characteristics of denitrification columns.**

<b>Empty Bed Volume, cm<sup>3</sup></b>	<b>298</b>
<b>Empty Bed Residence Time, min</b>	<b>300</b>
<b>Hydraulic Loading, gpm/ft<sup>2</sup></b>	<b>0.043</b>
<b>Average Influent NO<sub>3</sub>-N, mg/L</b>	<b>2.18</b>
<b>Average NO<sub>3</sub>-N Loading Rate, gram/m<sup>2</sup>-day</b>	<b>5.5</b>



## Appendix I. Tracer Testing

The stormwater treatment train was subject to tracer testing prior to and after filter operation on influent pondwater had commenced. Tracer tests were conducted by injecting a concentrated salt solution at constant flowrate into the process flow when operated at constant flowrate and monitoring of tracer in the effluent of the process components under evaluation. The tracer test evaluated the response to a step change of influent concentration, from background level to the new effective level (with tracer). For the tracer test to the zeolite filter, once the new effective level had been attained in filter effluent, the salt injection was discontinued and the return of filter effluent to its previous background level was monitored. A salt solution was used as tracer, and tracer was measured using a conductivity probe.

Tracer tests on the baffle box, sand filter and zeolite filter were conducted during the initial period of filter operation. For the filter tracer tests, salt was injected into the baffle box effluent pipe and effluent samples were collected in the filter effluent standpipe within the clearwell chambers. For the two-chambered baffle box tracer test, salt was injected into the pre-baffle box standpipe and effluent samples were collected just above the effluent weir of Chamber 1 and at the entrance of the effluent pipe of Chamber 2. Tracer test flowrates were 9.80, 9.25, and 12.36 gpm for sand filter, zeolite filter, and baffle box, respectively. The tracer tests were conducted under a six inch submergence regime of the zeolite and sand media.

Results of tracer tests are shown in Figures I-89 through I-92. Residence times for each operation were based on measurements of actual measured tank dimensions, operating water levels, and the displacement of water by filter media and gravel support.

The sand filter had a theoretical residence time of 11 minutes, but increases in effluent conductivity were measured within 3 minutes (Figure I-89). As expected, the breakthrough curve is centered around the theoretical residence time, with forward and trailing elements indicating preferential fluid movement through the media and hydrodynamic dispersion. The theoretical residence time in the zeolite filter was 15 minutes (Figure I-90), but increases in effluent conductivity were measured within several minutes. Similar to the sand filter, potential for rapid fluid movement through the media is indicated. Approximately six water residence times were required for effluent conductivity to approach the influent value, suggesting possible tracer interactions with the media. The tracer washout curve in Figure 2 shows that approximately six residence times are needed for return to background.

The baffle box tracer tests results (Figures I-91 and I-92) indicate the Chamber 2 (downstream) effluent response lagged the Chamber 1 (upstream) tracer response, as expected. The tracer response of Chamber 1 effluent follows closely a tracer wash-in model, when Chamber 1 is considered as a completely mixed reactor.

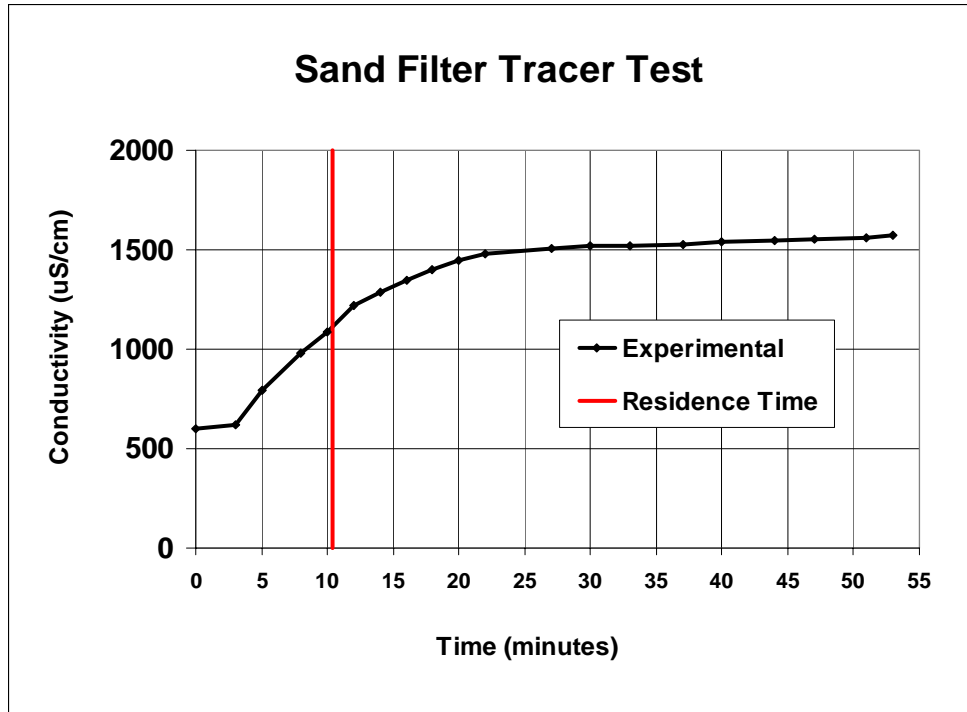


Figure I-88. Sand filter tracer test.

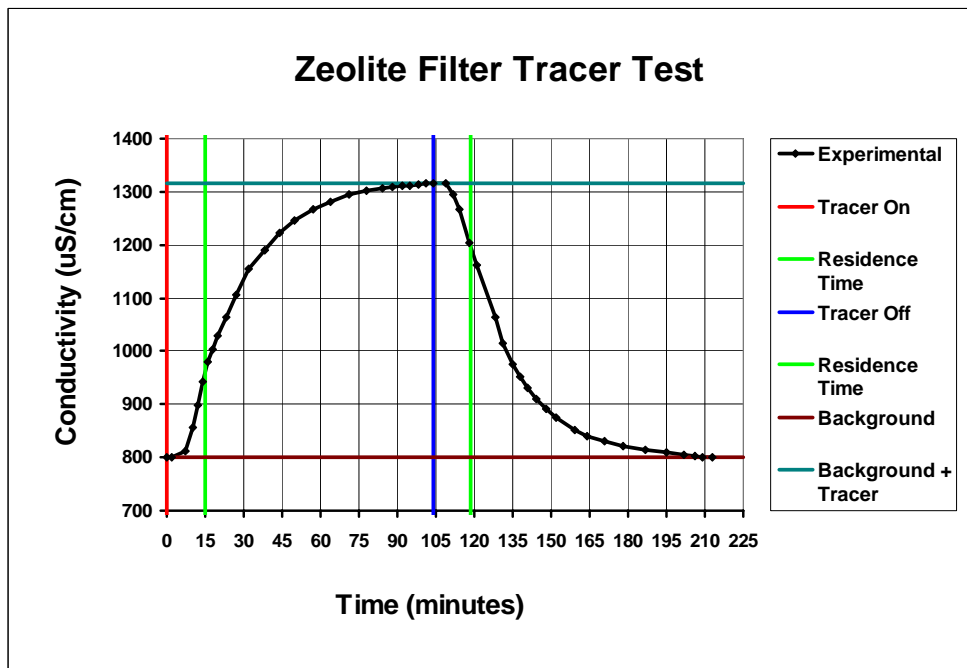


Figure I-89. Zeolite filter tracer test.

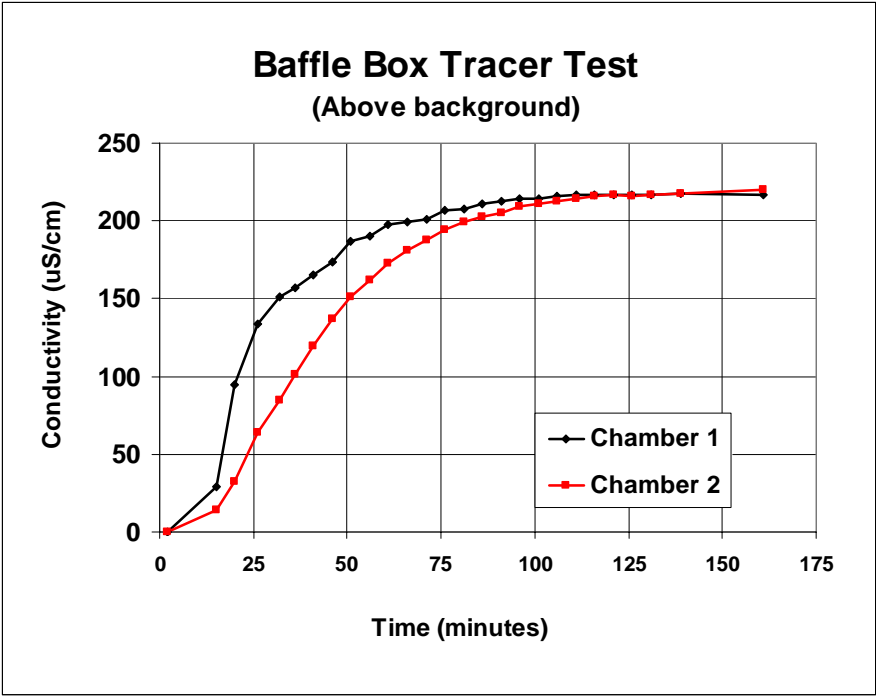


Figure I-90. Baffle box tracer test.

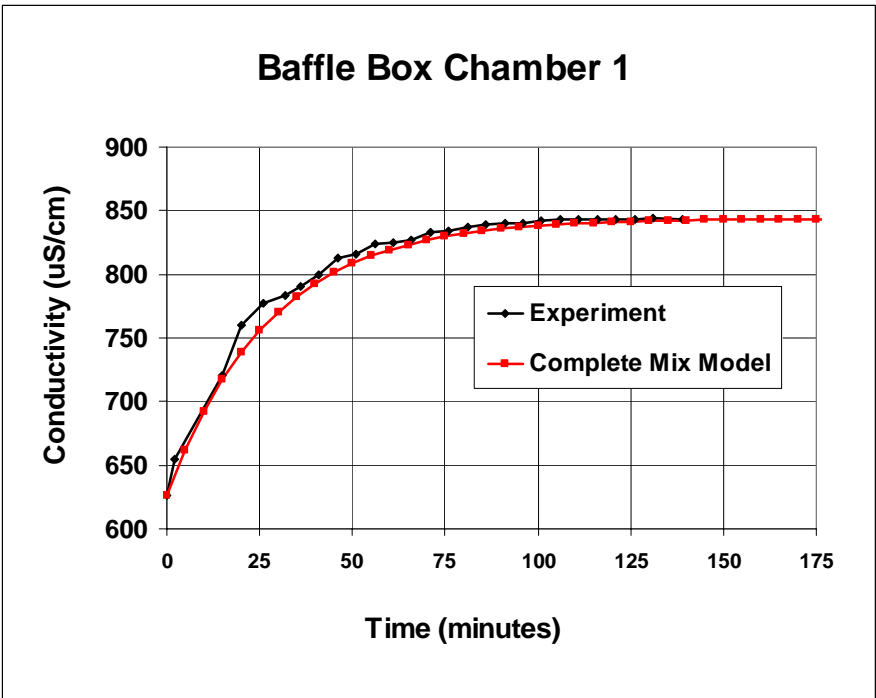


Figure I-91. Baffle box chamber 1 tracer versus model.

## Appendix J. Construction and Operations

Filter construction was provisionally completed on September 13 and operation was commenced on the following day. Since the start of operation, a continued series of modifications have been made as deficiencies were revealed in system components. This section contains selected photographs of filter construction and operations, as well as accompanying descriptive dialog.

Zeolite media placement is shown in Figure J-93, while filter chambers just after media placement are shown in Figure J-94. The media were smoothed before the placement of frame mounted geotextile fabrics (Figure J-95). A multi level sampling system was constructed and installed within the zeolite filter bed to enable the analysis of water quality parameters with depth in the filter (Figure J-96).

An influent flowmeter was installed to replace the original LCD paddle flowmeter which had malfunctioned (Figure J-97). The zeolite filter at startup is shown in Figure J-98, where filter effluent entering the clearwell can be seen to be exiting through the third port from the bottom. The port positioning provided for an initial filter operation at a six inch depth of media submergence.

The operating treatment train is shown in Figure J-99. In Figure J-100 are shown dosing pumps, while the start of treatment (sump) and end of treatment (effluent pipe) are shown in Figures J-101 and J-102, respectively. In Figure J-103 is shown a student assisting in sample collection, providing environmental education.

In Figure J-104 is shown a view on the media surface after several weeks of operation when the geotextile has been removed. The media surface under most of the geotextile had an appearance that was similar to that before startup, but the edge of the media near the walls was quite dark in appearance. This discoloration was due to influent seeping around the geotextile fabric frame into the filter media, without passing through the geotextile.

The geotextile fabric has been cleaned at approximately 10 day intervals through backwashing with a garden hose. Hydraulic conductivity following cleaning is significantly restored. In Figure J-105 is shown a partially backwashed fabric, where the boundary between backwashed and non-backwashed fabric areas is clearly visible. Close-up photographs of the material removed by the geotextile are shown in Figures J-106 and J-107. The increase in visible light transmission through the geotextile due to backwashing is shown in Figure J-108, and corroborates the substantial recovery of hydraulic conductivity resulting from backwashing. Although longer term operation is needed, it appears thus far that the geotextile fabrics have not been irreversibly clogged. With proper maintenance, geotextiles may have utility as pretreatments overlying stormwater filtration media.



**Figure I-92. Zeolite placement into filter bed.**



**Figure I-93. Filter chambers containing zeolite (right) and sand (left).**



**Figure I-94. Geotextile fabrics mounted in frame.**





**Figure I-95. Multi level sampling device placement in filter chamber.**



**Figure I-96. Influent flowmeter.**



Figure I-97. Startup of zeolite filter.



Figure I-98. Upstream view of the research process train.





**Figure I-99. Dosing pumps for nitrogen (top) and coagulant (bottom).**



**Figure I-100. Influent sump.**



**Figure I-101. Treated water entering filter clearwell.**



**Figure I-102. Student education through effluent sample collection.**





**Figure I-103. Removal of upper geotextile showing seepage at wall.**



**Figure I-104. Cleaning of geotextile; upper left section has been backwashed.**



**Figure I-105. Material collected on geotextile.**



**Figure I-106. Edge of geotextile backwash boundary.**





**Figure I-107. Light transmission through backwashed (left) and non-backwashed (right) geotextile fabrics.**