WOOD FILTERS AS AN INNOVATIVE TREATMENT METHOD FOR ROADWAY RUNOFF POLLUTANTS

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16. Abstract

A significant amount of contamination enters water bodies via stormwater runoff. To control this non-point source pollution problem, retention ponds are installed at many locations. In previous studies it has been shown that these ponds do not effectively remove *dissolved* constituents, such as heavy metals and PAHs. Results from previous laboratory tests suggest that wood fibers enhance the removal of dissolved contaminants from simulated runoff. Described in this report are the results of a pilot-scale wood filter test that was conducted at a retention pond in Providence, RI. One objective was to determine if wood fibers could effectively remove contaminants from the water under field conditions. A total of four filters were installed to determine sorption of nitrate, phosphate, copper, iron, zinc, and PAHs as a function of differences in wood mass, different residence times, and changes in temperature and pH.

The wood filters effectively removed between 25% and 36% of the dissolved PAH contaminants. However, simple design changes promise to enhance the filter efficiency to about 50%. The heavier molecular weight PAH compounds, i.e. the PAHs with higher organic carbon partitioning coefficients (e.g. benzo(a)pyrene), sorbed more readily than the lighter molecular weight compounds. The PAH sorption effectiveness of aspen wood was not affected by temperature or pH; however, the greater the mass of wood, the greater the sorption and effectiveness. The wood fibers appeared to promote nitrification, increasing the nitrate levels in the water, especially in the winter. The filters were 24% effective in removing phosphate from the water, but the wood leached phosphate after installation for a few days. Both copper (29%) and iron (40%) were effectively removed, especially under slightly acidic conditions. Zinc results were inconclusive because of zinc leaching from the galvanized wire mesh used to contain the wood fibers. Intense precipitation caused the filter to be less effective, and even flushed PAHs off the filter.

The laboratory tests demonstrated that Cedar wood is a very promising alternative to Aspen wood. Even after more than 50 days of continuous flushing with contaminated water, the PAH removal remained between 66% and 92%, depending on the compound studied.

17. Key Words

Wood Filter, Runoff Treatment, PAH Contaminants

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INTRODUCTION

Accidental or diffuse release of pollutants, for example from urban and industrial areas, including those resulting from widespread application of agrochemicals, clearly impinges on the quality of surface and ground water (Barbash and Resek, 1996; Bemknopf et al., 1997; Faure et al., 2000). For instance, stormwater runoff may contain elevated concentrations of heavy metals, such as zinc and copper, that originate from ordinary wear of brakes, tires, and other vehicle parts (e.g. Sansalone and Buchberger, 1997; Hares and Ward, 1999; Davis et al., 2001). Runoff may also contain elevated levels of organic compounds, including gasoline and oil- and grease-based hydrocarbons (e.g. Hoffman et al., 1984, Boving, 2002). Additional sources of stormwater contamination include accidental releases of toxic substances, excess application of fertilizer and pesticides, and – as an unintended consequence of prescribed burning and wildfires – deposition of airborne soot (e.g. Maruya et al., 1996). With precipitation, these contaminants wash off impermeable surfaces or erode from agricultural land, collect in drainage structures, and eventually discharge into surface- or groundwater bodies, potentially allowing the contaminants to enter drinking water resources.

Stormwater runoff from roadways in particular has been identified as one of the most important contributors of toxic compounds to the environment. Notably, Hoffman et al. (1984 and 1985) studied the chemical composition of stormwater runoff from Interstate 95 in Rhode Island. Their findings indicate that stormwater runoff from highways is an important source of organic and inorganic contaminants to adjacent water bodies. For example, in their study area over 50% of the total pollutant input, such as lead, zinc, and polycyclic aromatic hydrocarbons (PAH), into the Pawtuxet River originated from highway runoff. Almost 20 years later, Boving (2002) investigated roadway runoff and the performance of a newly constructed retention pond system along I-195 in Providence, Rhode Island. Preliminary data indicate that the contaminant load (PAH, zinc, and copper) in I-195 runoff is comparable to levels observed by Hoffman et al., 1984. These findings demonstrate that pollution reduction measures have been successful, given that since the Hoffman study was completed, the number of registered motor vehicles and associated emissions has increased by over 12% (USDOT, 1994). On the other hand, Boving's study also indicates that the retention pond system has been ineffectual in removing *dissolved* contaminants. Thus, a considerable fraction of PAHs (up to 20%) passes through the pond system and enters a nearby river and, subsequently, Narragansett Bay.

Upon entering the water, organic and inorganic contaminants are recalcitrant and remain in the environment for long periods, posing a threat to human health and marine environments (Tuhackova et al., 2001). Most polycyclic aromatic hydrocarbons (PAHs) are both a geotoxin and carcinogen (Harvey, 1997). Their presence in the marine environment causes a reduction in diversity of marine species (Grynkiewicz et al., 2002). Human and marine species are also susceptible to heavy metals. For instance, heavy metals can accumulate in algae, become part of many marine food chains, and may eventually impact higher marine life forms. Habitat loss is one of the one major consequences of the marine pollution problem (EPA, 2001).

The abatement of stormwater runoff pollutants is typically dealt with by structural best management practices (BMP). Detention ponds are an example of a stormwater BMP (EPA, 1999). Primary removal mechanisms are sedimentation of suspended solids and attenuation of contaminants in created wetlands (e.g. Mallin et al., 2002; Krishnappan and Marsalek, 2002). However, conventional BMPs often yield poor results or are severely limited by season (e.g. Boving, 2002). One reason is that sorbed contaminants may re-enter the runoff stream by desorption from contaminated sediment (Krein and Schorer, 2000). For instance, Ghosh et al. (2001) performed laboratory desorption studies with silt/clay sediment and found that at room temperature over 90% of the PAHs associated with the sediment desorbed, entering the dissolved state. Because of the failure of conventional BMPs to effectively remove dissolved pollutants, there is a need for innovative runoff attenuation technologies.

Precipitation, ion exchange, carbon exchange, and membrane filtration are current methods for removing heavy metals from water (Patterson et al., 1994; Sar et al., 2001; and Yu et al., 1999). These metal removal processes, however, are costly – especially when dealing with large volumes of stormwater (Palma et al., 2003). Less expensive organic materials, such as peat, sawdust, peanut and hazelnut shells, have been suggested for treating metal contaminated wastewater (Bryant et al., 1992; Brown et al., 2000; Ciminio et al., 2000; Schneegurt et al., 2001). Besides heavy metals, the contaminant removal ability of wood has been applied to pesticides, chemical dyes, and phosphate (Bras et al., 1999; Morais et al., 1999; Karthikeyan et al., 2004). Boving and Zhang (2004) conducted column studies with Aspen wood (*Populus tremula*), and four PAH compounds (naphthalene, anthracene, fluorene, pyrene). It was shown that filters made from Aspen wood are an effective, environmentally friendly technology for removing dissolved compounds from contaminated water. Similar results were reported by Mackay and Gschwend (2000) who examined the sorption of monoaromatic petroleum hydrocarbons (benzene, toluene, and *o*-xylene) onto Ponderosa pine and Douglas fir.

Table 1: Types of wood and lignin composition
(after Fengel and Wegner, 1989)

Types of wood	% Lignin
Aspen	21.0%
Poplar	20.9%
Oak	22.2%
Red cedar	32.5%
Red maple	22.8%
White birch	22.0%
American elm	21.7%
Jake pine	28.6%
European spruce	27.3%
Balsam fir	27.7%

The capability of wood to remove PAHs from the water is linked to its lignin content (Garbarini and Loin, 1986). For instance (Table 1), the composition of aspen wood, which was used in this study, is typically 51% cellulose, 26% hemicellulose, 21% lignin, 1% ash, and less than 1% inorganic (Fengel and Wegner, 1989). Table 1 also provides an overview of other wood species and their lignin content. The sorption of PAH to the wood is most likely facilitated by the formation of weak Van-der-Walls bonds. Like the PAHs, lignin is a hydrophobic compound. Because of that, it provides a thermodynamically attractive environment for other hydrophobic compounds to partition to. Hence, by association with the wood lignin, hydrophobic contaminants are removed from the aqueous solution. Hydrophobicity can be expressed in terms of partition coefficients. Partitioning coefficients in general identify the ability of a compound to transfer between atmospheric, aquatic, and sediment phases. The octanol water partition coefficient, K_{ow}, in particular determines the affinity of a compound to an organic phase. For example, PAHs have octanol water partition coefficients ranging from 10^3 to 10^7 (mol/L octanol)/(mol/L water). The amount of dissolved PAHs that can be removed from the water is generally controlled by the amount of natural organic matter present: more PAH is removed from solution when the fraction of organic carbon is high (Schwarzenbach et al., 1993). Therefore, increasing the amount of organic matter is expected to enhance the sorption of PAHs. Wood is organic matter, and because the wood lignin is also very hydrophobic, placing wood in stormwater runoff enhances the removal of PAHs and other hydrophobic compounds. This is the basis for the wood filter technology.

Table 2: PAH characteristics (after Schwarzenbach et al. (1993) and Montgomery (1996))

PAHs	Molecular Weight g/mol	log K_{ow} Octanol-water partitioning coefficient at 25°C
Naphthalene	128.16	3.36
Acenaphthylene	152.21	4.07
Acenaphthene	154.21	3.92
Fluorene	166.23	4.18
Phenanthrene	178.24	4.57
Anthracene	178.24	4.54
Fluoranthene	202.26	5.22
Pyrene	202.26	5.13
Chrysene	228.3	5.91*
Benzo(a)pyrene	252.32	6.50

Further, because PAHs with a high molecular weight (HMW) have a higher organic carbon partitioning coefficient (Cornelissen et al. 1999; Cho et al. 2002), HMW PAHs are expected to sorb more effectively to the wood than their less hydrophobic, low molecular weight (LMW) homologues. [LMW: naphthalene, acenaphthylene, acenaphthene, and fluorene] [HMW: phenanthrene, anthracene, fluoranthene, pyrene, chrysene, and benzo(a)pyrene].

HWM PAHs are typically more toxic and of greater concern when present in solution. Table 2 lists molecular weights and K_{ow} for all 10 PAH compounds analyzed.

While the removal of hydrophobic compounds is comparably well understood, the heavy metal removal mechanisms are still debated. Said et al. (1993) proposed that once a hydrated-metal complex is adsorbed to cellulose through hydrolysis, a positively charged metal ion interacts with the cellulose's hydroxyl groups. Other potential sorption sites on the cellulose surfaces may include carboxyl and carbonyl groups. Crist et al. (2003) investigated the sorption of Pb(II), Zn(II) and Cu(II) onto kraft lignin, a waste product from paper production. Their data indicates that the metal-wood partition coefficient, K, depends on pH. Crist et al. (2003) also suggest that metal sorption onto lignin is in direct relation to the aqueous metal concentration and the solid surface of the lignin. Srivastava et al. (1994) found that increasing the temperature increased the sorption of Pb(II) and Zn(II) onto black liquor, another product of the paper industry.

The principal objective of this study was to install a pilot-scale aspen wood filter in a well characterized detention pond and evaluate its effectiveness for removing *dissolved pollutants*, i.e. PAHs, nitrate, phosphate, iron, zinc, and copper. In addition, the lifetime (= capacity) of the wood filter, the operating/maintenance requirements, and proper disposal avenues for spent wood filter materials were studied. Also, contaminant removal as a function of filter mass and seasonality were investigated. Spatial changes in contaminant uptake within a filter were monitored and mass balance calculations were conducted to estimate how much wood is required for treatment. Concomitant laboratory experiments investigated if other woods (Cedar) provide an alternative to Aspen wood. Also, it was investigated if other dissolved contaminants, such as zinc and copper – can be treated by wood filters. Finally, the lessons learned from this pilot test culminated in a design study that will facilitate a future implementation of the wood filter technology.

MATERIALS AND METHODS

Site Description

The field site was a state-of-the-art roadway detention pond system off Interstate 195, exit 3 (Gano Street), in Providence, RI. The pond system was built in 1999 to decrease the flux of pollutants entering the Seekonk River from the surrounding urbanized areas and parts of I-195. The catchment area is approximately 5.26 hectare (Boving 2002). The traffic count for the area averages 150,000 vehicles per day, making it one of the most highly traveled sections of the Rhode Island road network (RIDOT, 1999).

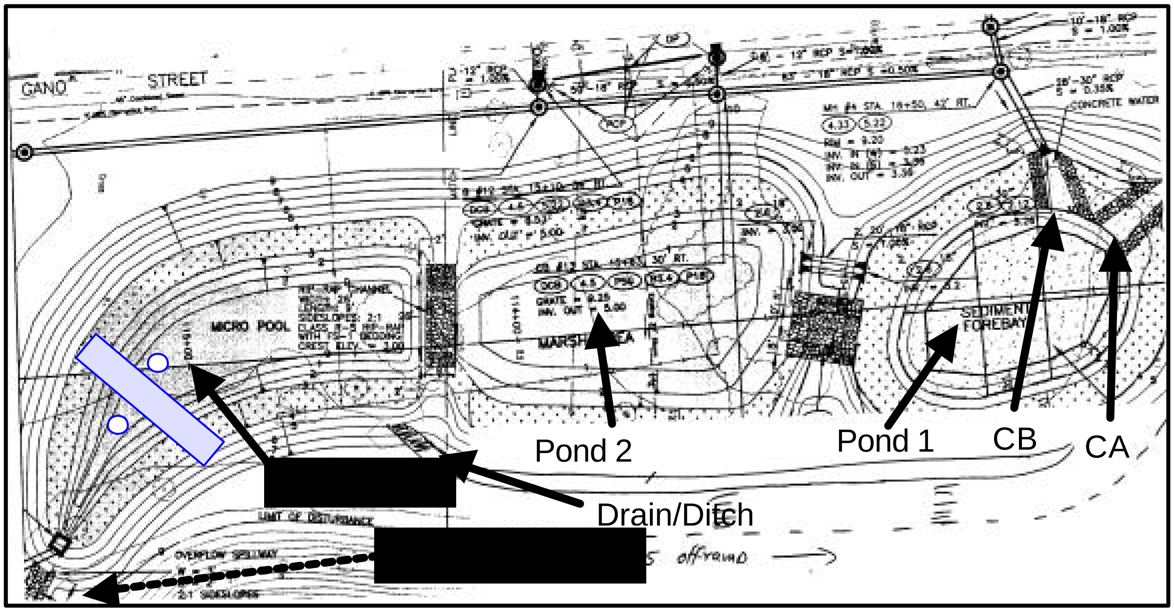

Figure 1: Plan view of the Gano Street pond system and wood filter location. This BMP consists of three ponds, a sedimentation pond, a created wetland, and a micro pond (from right to left). Roadway runoff enters the system through two culverts and a drain (bottom center). It leaves the system through a spillway at the termination of pond 3 (lower left corner). The water is being discharged into the Seekonk River, about half a mile before it flows into Narragansett Bay. The discharge pipe is outside the plan area, about 50 yards southwest from the overflow. (Plans by Maguire Group, provided by RIDOT). Also shown is the location of the wood filter (blue shaded box) and the up- and down gradient sample points (white circles) in Pond 3.

The detention system consists of three ponds (from inflow to outflow): settling pond, artificial wetland, and micro-pool (see Figure 1). The first pond is designed as a settling pool, allowing particles to flocculate and settle to the bottom, thereby removing contaminants from the water (Krishnappan and Marsalek, 2002). The second pond is an artificial wetland designed to decrease the dissolved contaminant load of the runoff. Also, suspended sediment during high flow periods becomes trapped in the created wetland as the water passes through the reed grass (Mallin, 2002). The third pond, a micro-pool, causes any remaining fine sediment to settle out. The capacity of each pond is listed in Table 3. The third pond was considered the best suited for the wood filters because it is the deepest of the three ponds, relatively narrow, and closest to the stormwater discharge point. Another site selection criterion was that prior to the installation of the wood filters, the contaminant flux through the Gano Street detention pond system was systematically investigated by Boving (2002).

Table 3: Pool dimension calculated from digitized blue prints of the Gano Street Pond system (Plans by McGuire Group, provided by RIDOT).

Pool Name	Capacity (cu. ft.)	Capacity (m^3)
Pool 1	11,041	312.5
Pool 2	11,256	318.6
Pool 3	12,156	344.0

Prior to the field campaign, all personnel involved in the project (field and lab personnel) visited the field site. During the site visitation, the sampling locations were identified, the appropriate sampling procedures were discussed, the correct use of field equipment was ensured, and sample handling and documentation procedures were manifested.

Wood Filter Design

The design and construction of the wood filter relied on commercially available aspen wood shavings. The wood shavings, string fibers 1 to 2 mm thick and at least 15 cm long were donated by *American Excelsior Company*. The wood was delivered in compressed 36 kg bales. The wood shavings were loosened and then used as received to construct the filters. To ensure stability and structure of the filter, a galvanized metal wire mesh frame was built to contain the aspen wood. The filter system consisted of several modules, each about 1 to 2 meters wide, 1 meter high, and 12 - 15 cm thick (see Figure 2). This modular design permitted easy installation and removal of the filter by one person and allowed overlapping of the filter modules to provide complete coverage across the pond. The entire filter system was approximately 5 - 8 meters long. The filter modules, suspended from a 2.5 cm galvanized steel pipe, spanned the micro-pool. The mass of wood varied from 36 - 115 kg dry weight, increasing in weight with each successive test. Four wood filters were constructed to determine the most advantageous filter size, amount of wood needed, duration of the wood filter's effectiveness, including the degree of contaminant sorption.

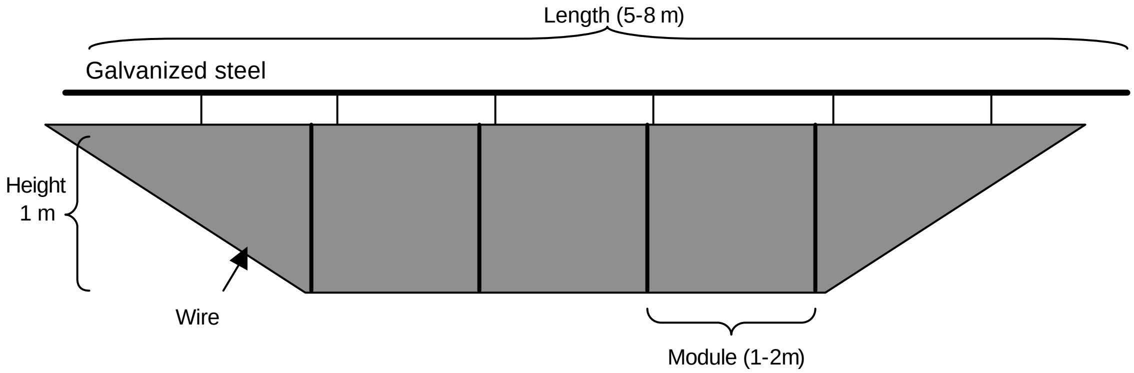

Figure 2: Cross section of the wood filter frame. The approximate shape of the filter was dictated by the cross section of the detention pond.

Sampling Methods and Preparation

Immediately following installation, samples were collected up gradient and down gradient from the wood filter (see Figure 2). Samples were collected in clean 4 L Boston round style amber glass bottles with Teflon® lined caps. Duplicate samples were taken periodically (about 10% of all samples). The parameters pH, electrical conductivity (ec), dissolved oxygen (DO), and temperature were measured in the field using an Orion 250A with H+ 9107 electrode, Orion 130A with a conductivity cell 013610 electrode, and an YSI Incorporated 55 DO meter, respectively. To ensure quality assessment/control (QA/QC), each instrument was calibrated before use according to the manufacturer's specifications. Because of vandalism, a rain gauge could not be installed at the site. Instead, precipitation and temperature data were obtained from the National Weather Service (NWS) - National Oceanic and Atmospheric Administration (NOAA) web site for the nearby T. F. Green Airport weather station (www.erh.noaa.gov/box/dailystns.shtml). Accurate flow measurements could not be obtained for several reasons: (1) water depths in Culvert A and B (see Fig. 1; inflow) were too shallow for installing flow meters, (2) runoff from the I-195 off ramp (see Fig. 1) drained directly into pond 3, and (3) an unknown amount of precipitation falling on the catchment area drained into sewage water lines and not into the detention pond system.

Aqueous samples for dissolved contaminant analysis (see Table 4) up gradient and down gradient from the wood filter were obtained daily during the first 2 to 3 weeks after filter installation. The samples were analyzed for the contaminants listed in Table 4. Later, the water was sampled once or twice a week. Seasonal influences, such as droughts or freezing of the ponds, prevented sampling in some instances. In addition, wood fibers were collected periodically to measure the PAH mass sorbed by the wood. Wood was sampled from various locations, i.e. wood from the top, bottom, center, and periphery of the filter system to determine spatial changes of PAH sorption. A long-term sorption test was performed to determine temporal changes in sorption.

Table 4: Contaminants analyzed

PAHs		**Heavy Metals**
Naphthalene		Total Iron (Fe^{2+}, Fe^{3+})
Acenaphthylene		Copper (Cu^{2+})
Acenaphthene		Zinc (Zn^{2+})
Fluorene		
Phenanthrene		
Anthracene		**Other Contaminants**
Fluoranthene		Nitrate (NO_3^-)
Pyrene		Phosphate (PO_4^{3-})
Chrysene		
Benzo(a)pyrene		

Filters were tested during one calendar year, beginning in spring 2003 and ending in winter 2004. The duration of each experiment was primarily controlled by the mass of wood used in the filter construction (i.e. filters with more wood mass remained in the pond longer) and by seasonal influence. The ultimate duration of each test was not determined by changes in the filter removal efficiency, i.e. filters were exchanged even before significant decreases in efficiency become evident. Table 5 summarizes the test conditions for all four wood filter tests (WFT) conducted.

Table 5: Wood filter test durations for all four tests (WFT1, WFT2, WFT3, and WFT4)

Filter Name	*Mass (kg)*	*Date Installed*	*Date Removed*	*Length (days)*	*Days Sampled*
WFT1	36	03/28/03	04/02/03	6	5
WFT2	55	05/05/03	05/28/03	24	9
WFT3	90	07/22/03	09/23/03	64	16
WFT4	115	11/18/03	01/06/04	49	18

Analytical Procedures

Sample preparation and analysis was conducted immediately after returning from the field site. Along with dissolved PAH concentrations, analysis was performed for nitrate (NO_3^-), phosphate (PO_4^{3-}), total dissolved iron (Fe^{2+}, Fe^{3+}), zinc (Zn^{2+}), and copper (Cu^{2+}). Note that nitrogen is reported as nitrate, not as nitrogen. Nitrate concentrations can be converted to nitrogen concentrations by multiplying with 0.226. Similar conversion from phosphate to phosphorous concentrations can be achieved by multiplying with 0.341. For non-PAH contaminant analysis, water samples were filtered through a Whatman 90 mm 0.45-micron GF/C glass microfiber filter and separated into three 125 mL HDPE bottles. Samples were preserved by adding 0.100 mL of 1 M analytical grade sulfuric acid to the phosphate sample to prevent biologic decomposition and 0.100 mL of 1 mole analytical grade nitric acid to the metal samples to prevent metal precipitation. All chemicals or lab supplies were purchased from *Fisher Scientific Inc.* or *Aldrich Inc.* if not indicated otherwise. After preservation, Hanna Ion Selective meters were used to analyze the dissolved concentrations of nitrate, phosphate, iron, zinc, and copper. All electrode interferences were accounted for to ensure accurate measurements. The lowest detection limit (according to manufacturer's specifications) was 0.001 mg/L for iron, 0.1mg/L for nitrate, and 0.01 mg/L for copper, zinc, and phosphate. The accuracy of the Hanna Ion Selective meters was ±0.01 mg/L iron, ±0.03 mg/L zinc, ±0.04 mg/L copper and phosphate, and ±0.5mg/L nitrate (according to manufacturer's specifications). Similar accuracies were determined when comparing the ion selective electrode results from standard samples with duplicate standard samples analyzed by an accredited environmental laboratory.

The dissolved PAHs were extracted using a liquid-liquid extraction method modified from MacKay and Gschwend (2001). One liter of runoff sample was filtered through a Whatman 90 mm 0.45-micron GF/C glass microfiber filter. An internal standard (100 µg/L 2-fluorobiphenyl 96%) and 100 mL methylene chloride (HPLC grade) were added to the sample, mixed together, and refrigerated at 4^0 C for 24 hours. During this time, the PAHs dissolved into the methylene chloride, which was then separated from the aqueous phase using a 1000 mL Pyrex brand Squibb Separator funnel. This extraction step was repeated twice, but without adding the internal standard. At the end of the extraction, a total of 300 mL of PAH-methylene chloride solution was obtained. The 300 mL PAH solution was concentrated to 10 mL by distillation, using an Aldrich Ace Claisen adapter with an Aldrich distilling adapter. The 10 mL concentrate was filtered through 2 grams of activated silica gel (Selecto Scientific) in an Alltech Silica Extra Clean column (60 Å porosity). Next, 5 mL of 8:1 hexane/methylene chloride and 15 mL of 3.4:1 hexane/methylene chloride were flushed through the silica gel to isolate the PAHs. The hexane/methylene chloride mixture was distilled to less than 10 mL for analysis. A Shimadzu GC-17A FID (Gas Chromatography–Flame Ionized Detector) with a J&W Scientific DB-5MS glass capillary column (30 m, 0.32 mm id, 0.25 µm film thickness) was used to analyze the 10 PAHs. The column temperature program was modified after EPA method 610 (40 CFR Part 136, Appendix A). An external PAH standard was used to calibrate the GC-FID (EPA method 610 PAH mixture; obtained from Ultra Scientific Inc.). The detection limit of the GC-FID ranged from 0.1 – 5 µg/L and increased with breakthrough time and PAH molecular weight. To ensure quality assurance, control blanks, sample duplicates, and standard repeats were analyzed frequently. If not stated otherwise, total PAH concentrations are always calculated by summing up the concentrations of all 10 individual PAH compounds.

The PAHs in the collected wood fibers were extracted using EPA method 3540 (Soxhlet extraction) (EPA SW846). In short, after removing any visible debris from the wood shaving samples, the wet wood shavings were cut into millimeter size fractions. About 15 to 20 grams wet wood (equaling 3 to 4 grams dry) were placed into a 30 x 80 mm Whatman Extraction Thimble. The PAHs were extracted with 300 mL of methylene chloride in a 500 mL Pyrex Brand Soxhlet Apparatus with Allihn Condenser for 24 hours. The sample was concentrated to less than 5 mL and analyzed using the same method as described above.

Quality control was performed on the instrumentation and preparation steps. The GC-FID and Hanna Ion Selective Meters were checked for accuracy using multiple standard concentration mixtures. Each preparation step was analyzed for the incorporated error. The error bars within the graphs indicate the error from the instrumentation and preparation steps (see Appendix).

Laboratory Tests

Testing wood other than Aspen: Red Cedar wood (*Thuja Plicata*) was selected for the laboratory study. Cedar's known decay resistance makes it a favorite choice for outdoor construction, including playground structures and roof shingles. Together with is comparably high lignin content (32.5%; see Table 1), its decay resistance makes Cedar an interesting alternative to Aspen wood. A commercial lathe was used to generate Cedar wood strands from a block of Cedar wood purchased at a local lumber yard. The wood strands were sieved through a 2 cm screen to remove any chunks of solid wood. The wood that passed through the sieve was washed with deionized water to remove wood dust. The clean wood was then soaked in deionized water for at least four weeks. The initial water content of the dry wood before soaking was approximately 8%. During the soaking procedure, the water was replaced on a periodic basis. At the end of the soaking, the water was analyzed by GC-FID for interfering compounds. Also, soaking wood fiber samples were collected periodically and inspected for visual changes (e.g. decay). No interfering compounds and no signs of decay were detected. After padding the wood dry with paper towels, its weight was determined and then oven dried at 105 ^0C. The difference between dry and wet weight was used to calculate the degree of water saturation per gram of dry wood.

Column experiments with Cedar wood were carried out to study the uptake (sorption) and release (desorption) of PAH under dynamic, i.e. flow-through conditions. About 3.5 *g* of water saturated wood was packed into a stainless steel column (HPLC preparatory column, ID: 2.2 *cm*, length: 7 *cm*; Alltech INC). An aqueous solution containing a mix 9 PAHs (see Table 4), each present at 10 *µg/L,* plus one PAH surrogate, 2-fluorobiphenyl, was pumped through the column using a precision piston pump (Acuflow Series I HPLC pump). Sodium azide at 50 *µg/L* was added to the contaminant solution as a biocide. No other background electrolyte solution was added. The flow velocity was held constant at 0.5 cm^3/min. Stainless steel tubing was used for all plumbing purposes. The PAH samples were collected by forcing the aqueous column effluent through 300 ml methylene chloride that was present at to bottom of the collection container. After about 1 liter of effluent passed through the methylene chloride, a new sample container was connected to the column and the PAH extraction process was repeated. The mix of methylene chloride, water, and PAH was stirred for 24 hours to transfer all PAH from the aqueous phase into the solvent. The solvent was then separated from the water and treated in the same way as the field samples (i.e. liquid-liquid extraction followed by distillation and purification). The chemical analysis was carried out following the same procedures as described above (GC-FID). Duplicates, blanks, and standards were analyzed frequently to assure quality control.

After flushing for 52 consecutive days, the contaminant solution was replaced by deionized water. The column experiment continued by using the deionized water to flush out the PAH adhering to the wood inside the column (desorption experiments). The column effluent concentration was determined as described above. The desorption experiment was terminated after 8 days because PAH effluent were below detection limit.

Removing contaminants other than PAH: The heavy metal (Zn, Cu) treatment effectiveness of Aspen wood was investigated. The aspen wood source was identical to the wood filter material used for the field pilot-test. Before use, the wood fibers were washed with deionized water to remove dust and other impurities. The water content of the aspen wood was determined by saturating wood fibers with deionized water for four weeks. Wood saturation was achieved when the water content of wood samples remained constant over three successive measurements. After saturation, the wood was oven-dried (24 *hr* at 105^oC) and weighed. The mass difference between saturated and dry wood translated into an average water saturation of 58%. Trace metal grade, concentrated HNO_3 , zinc sulfate, $ZnSO_4$ x 7 H_2O, and copper sulfate, $CuSO_4$ x 5 H_2O, were obtained from Aldrich Inc. (A.C.S. purity grade) and used as received. All solutions were prepared using E-pure water free of detectable traces of the target metals.

Sorption Isotherm Experiments: In preparation of the sorption isotherm experiments, the aspen wood fibers were soaked in deionized water for two days. Then, 200 *mL* of a copper sulfate or zinc sulfate solution ranging from 0 *mg/L* to 5 *mg/L* (as Me(II) concentrations) were added to 1.445 *g* (dry weight) aspen wood. No significant sorption differences between wet and dry aspen wood were found during preliminary experiments. Samples of 2 *ml* to 5 *mL* of each batch were collected over a period of one week to 12 days. Each sample was acidified with 20 *μL* concentrated HNO_3 using an autopipette with a high-density plastic tip. The metal concentration of each sample was analyzed on an Optima 300 XL ICP-OES in the Geology Department at Bates College. The mass of metal in solution for a given sample was subtracted from the mass in the starting solution to obtain the metal mass sorbed per gram of wood wool. The Freundlich isotherm was used to model the metal sorption onto the wood wool:

$$C^* = K\,C^j$$

Equation 1

where C^* is the mass of solute sorbed per dry mass of the solid sorbent [mg g^{-1}], K is the partition coefficient, C is the concentration of the solute in equilibrium with the solid sorbent [mg l^{-1}], and j is dimensionless, the Freundlich exponent (Fetter, 1993). To calculate K values, equilibrium solute concentrations were plotted against the mass of metal sorbed per gram of wood and a best-fit curve was determined. The equilibrium value K was obtained once sorbtive uptake of a compound to aspen wood stabilized, i.e., no more changes in the aqueous metal concentration were measurable over three consecutive measurements.

Column Experiments: The purpose of the column experiments was to investigate the sorption and desorption of Cu(II) and Zn(II) to and from aspen wood fibers. A 5% nitric acid-washed Kontes brand Glass Chromatography column (5 *cm* long and 2.5 *cm* I.D,) was packed with 1.445 *g* (dry weight) aspen wood. Prior to experimentation, a Fisher Variable Flow Peristaltic Pump (Pump II Model 3385) was used to flush E-pure water through the packed column until all trapped air was removed. During the sorption experiment, the column was flushed with a metal solution (concentrations ranging from 0.8 *mg/L* and 10 *mg/L* Cu(II) and 5.5 and 11 *mg/L* Zn(II)) at average flow rates that ranged from 0.5 *mL/min* to 0.7 *mL/min*. Periodic column effluent samples were collected in 15 *mL* polypropylene conical test tubes and acidified with 20 *mL* concentrated HNO_3. The sorption experiment concluded when the relative concentration (C/C_0, the ratio of effluent to influent concentration) reached a value close to 1 (influent concentration = effluent concentration). For the desorption experiments, the column was then flushed with E-pure water (pH = 5.6) in an attempt to flush out sorbed metals. Again, periodic samples were collected and acidified as described above. All samples were analyzed for metal concentration using an ICP-OES. The column experiments lasted for 3-10 days each.

RESULTS

The following section summarized the results obtained in the field and in the laboratory. Not all experimental data is displayed and the reader is referred to the appendix for additional figures, tables, and supporting information.

pH, ec, DO, Temperature, and Precipitation

Four wood filter tests were conducted during the year long experiment (see Table 5). The tests covered all four seasons and varying weather conditions (e.g. moderate droughts, frost, snow, and thunderstorms). The first wood filter (WFT1) was installed in the detention pond system for 6 days in late March/early April 2003. This first experiment served as a proof of concept test, determining if the wood fibers sorb contaminants under field conditions. WFT1 was the shortest of all tests and only a comparably small wood filter (36 kg) was installed (see Table 5). The second filter, WFT2, contained 55 kg of wood and remained in the detention pond system for 24 days during May 2003. During test WFT3, 90 kg of wood was used. The WFT3 duration was 64 days, from the end of July through September 2003. The final filter test, WFT4, was the largest in terms of wood mass (115 kg). This filter was installed for 49 days from the middle of November 2003 to the beginning of January 2004. The length of WFT4 was determined by the formation of ice on the pond, which prevented sampling of the water and wood after January 6, 2004.

Table 6: Average, minimum, and maximum values for pH, ec, DO, temperature, and precipitation observed during study period.
(na = not analyzed)

	WFT1	*WFT2*	*WFT3*	*WFT4*	*Yearly Avg.*
Average pH	8.0	7.9	6.3	7.0	7.3
Max. pH	8.5	8.7	6.7	7.6	
Min. pH	7.4	7.4	6.1	6.4	
Average ec (µS)	na	54.8	69.7	164.0	96.2
Max. ec	na	61.5	72.2	42.8	
Min. ec	na	51.1	67.7	711.0	
Average DO (mg/L)	7.5	5.7	3.7	5.3	5.6
Max. DO	8.4	7.5	4.7	6.4	
Min. DO	6.4	3.3	2.4	4.7	
Average temp (^{o}C)	10.5	16.8	24.2	6.1	14.4
Max. temp	13.9	22.8	25.3	10.0	
Min. temp	7.5	12.7	23.7	3.2	
Precip. total (mm)	54.6	67.8	248.7	173.2	1100
Largest rain event (mm)	40.4	35.6	64.5	30.2	

Table 6 summarizes the mean pH, ec, DO, and temperature values measured during each of the four test. Also included is the total amount of precipitation that was recorded during each test period. The annual pH average for stormwater entering the detention pond system was 7.3. In comparison, the National Stormwater Quality Database with 1668 observations around the United States measured an average pH of 7.5 (with a pH of 7.3 in residential areas) (NSQD, 2003). However, the pH fluctuated over the seasons. During the height of summer the pH was more acidic (6.3); while during the rest of the year the pH was close to or slightly higher than neutral (7.0 to 8.0). Similar seasonable changes were observed in electric conductivity. For instance, ec was the highest during winter (164.0 µS) because of presence of de-icing salt. The highest temperatures and the lowest dissolved oxygen (DO) values were measured during summer test WFT3.

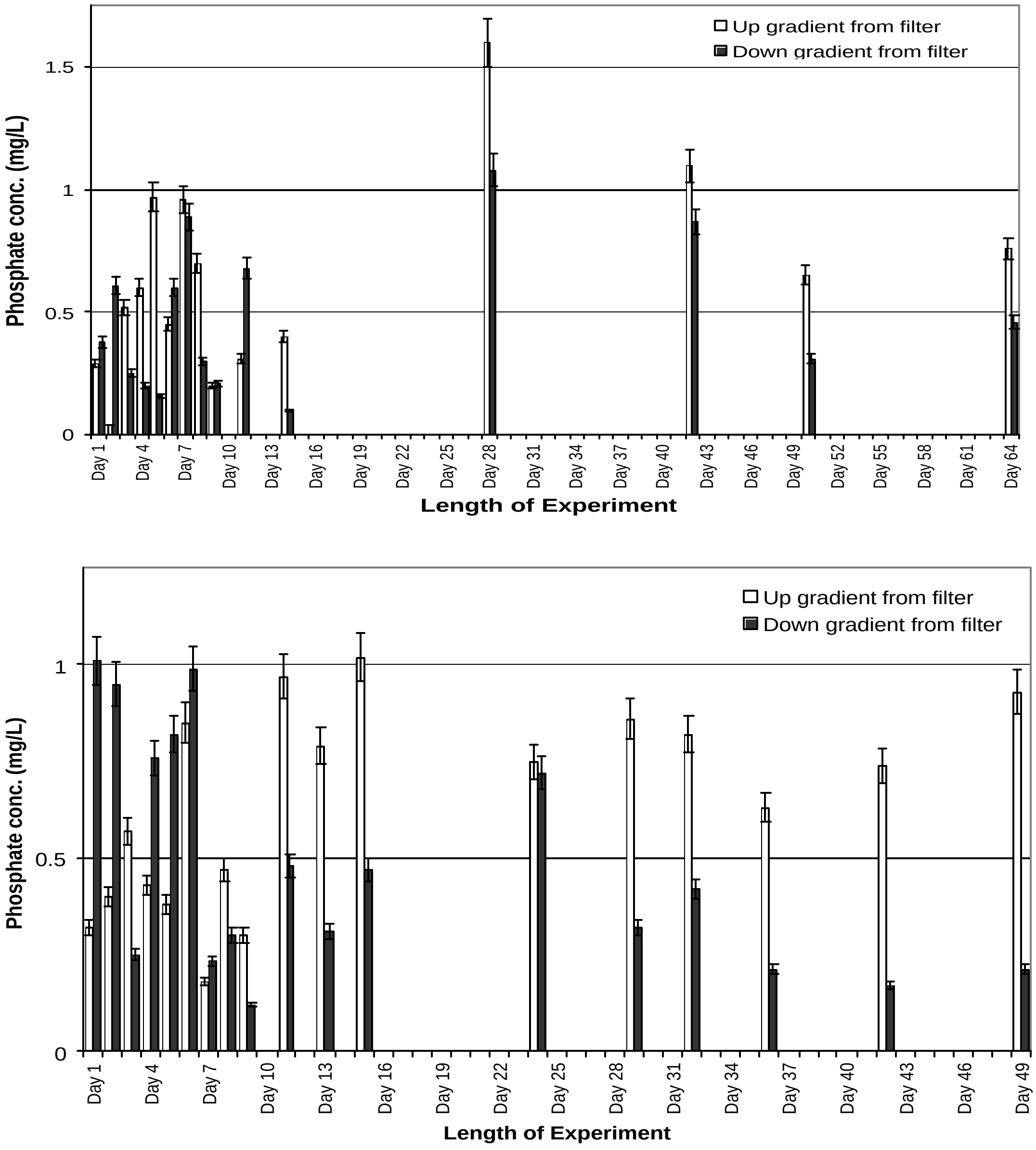

Figure 3a and 3b: Phosphate (PO_4^{3-}) concentrations (mg/L) up gradient and down gradient from the filter during WFT3 (3a) and WFT4 (3b). Graphs indicate initial phosphate leaching and later sorption.

Phosphate (PO_4^{3-}) and Nitrate (NO_3^-)

Phosphate and nitrate concentrations were measured only during WFT3 and WFT4. Figure 3 shows the phosphate concentrations up gradient and down gradient from the wood filter. Overall, the phosphate removal effectiveness of the wood filter increased over time. Removal effectiveness defined herein is the difference in concentration between the up gradient and down gradient samples (i.e. 50% removal efficiency equals 50% lower contaminant concentrations down gradient than up gradient. A negative sign indicates contaminant release from the filter and will be referred to as "negative efficiency"). Consistently higher downgradient concentrations during the first 6 days of WFT3 indicate that phosphate leached into the water from the wood filter. This increase may have been caused by the disturbance of the pond system during filter installation (i.e. re-suspension of settled sediment) or by leaching of phosphate from the wood itself. Laboratory leaching tests indicated that at least some phosphate leached from the wood (see Figure 4). The same tests also indicated that the leaching ceased after 8 days.

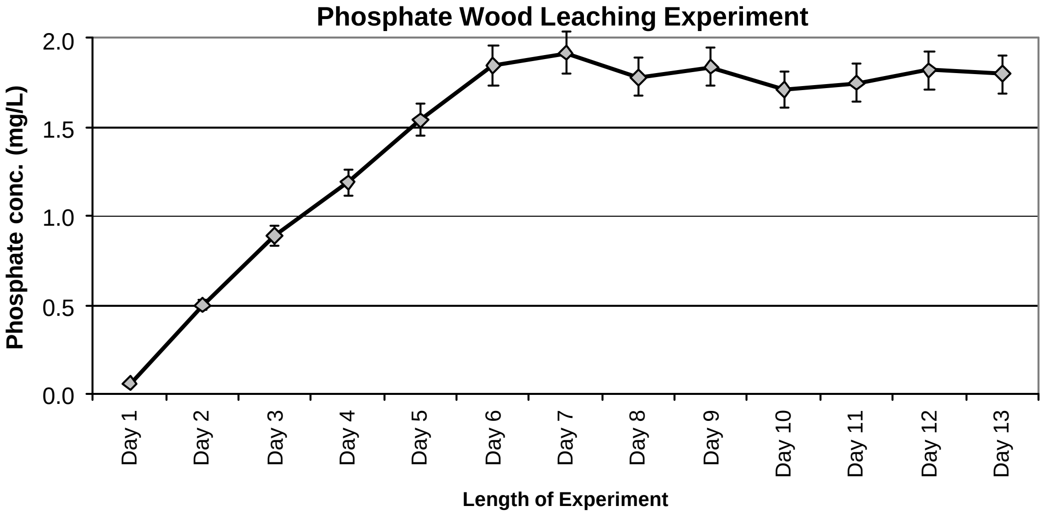

Figure 4: Phosphate wood leaching experiment. Graph indicates that some of the phosphate measured down gradient from the wood filters may have leached from the wood fibers. Once phosphate was leached for 8 days, no additional phosphate was added to the solution.

After the initial increase in phosphate concentration, lower down gradient concentrations were measured throughout the remaining 58 days of WFT3. During this portion of the test, the average phosphate concentrations were 39% lower after passage through the filter (0.63 mg/L up gradient and 0.38 mg/L down gradient). The cause for this increase in efficiency during the later stages of the experiment is unclear and needs to be investigated further. Based on the difference in average concentration between up- and down gradient samples[1], the total phosphate removal effectiveness over the entire WFT3 (64 days) was 24%.

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[1] Total removal effectiveness percentages are always calculated as the differences in average concentration between all up- and downgradient sample pairs.

Phosphate leaching also occurred during the first seven days of WFT4 when the average concentration up gradient was 0.46 mg/L, while down gradient the average concentration was 0.72 mg/L (-36% effective). During the last 42 days of the experiment, and similar to WFT3, phosphate was removed effectively. The average up gradient phosphate concentration was 0.75 mg/L compared to the down gradient concentration of 0.34 mg/L (55% effective). Figure 5 summarizes the phosphate removal effectiveness during WFT3 and WFT4.

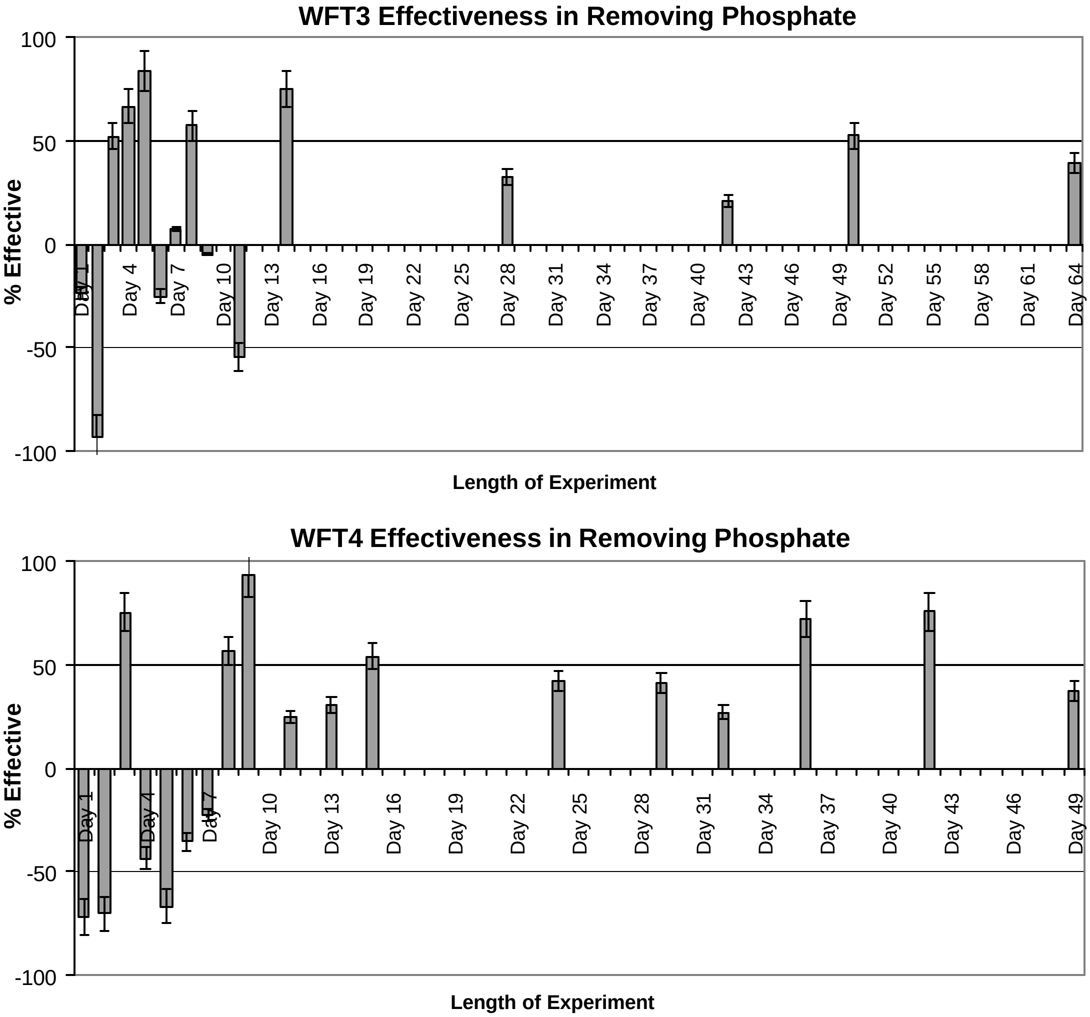

Figure 5a and 5b: WFT3 (*5a*) and WFT4 (*5b*) effectiveness in removing phosphate (PO_4^{3-}) from the runoff. Effectiveness is defined as the change in concentration from up gradient to down gradient of the filter. Hence, a positive value indicates phosphate removal, while a negative value signals addition of phosphate.

Figure 6 summarizes the nitrate removal effectiveness during WFT3 and WFT4 (see Appendix for other tests). The nitrate removal efficiency appears to vary significantly and unpredictably. The average nitrate concentration was 0.71 mg/L up gradient and 0.61 mg/L down gradient and 0.37 mg/L up gradient and 0.41 mg/L down gradient for WFT3 and

WFT4, respectively. This difference in concentration is less than the measurement accuracy. Hence, the results of WFT3 and WFT4 indicate that nitrate removal was insignificant.

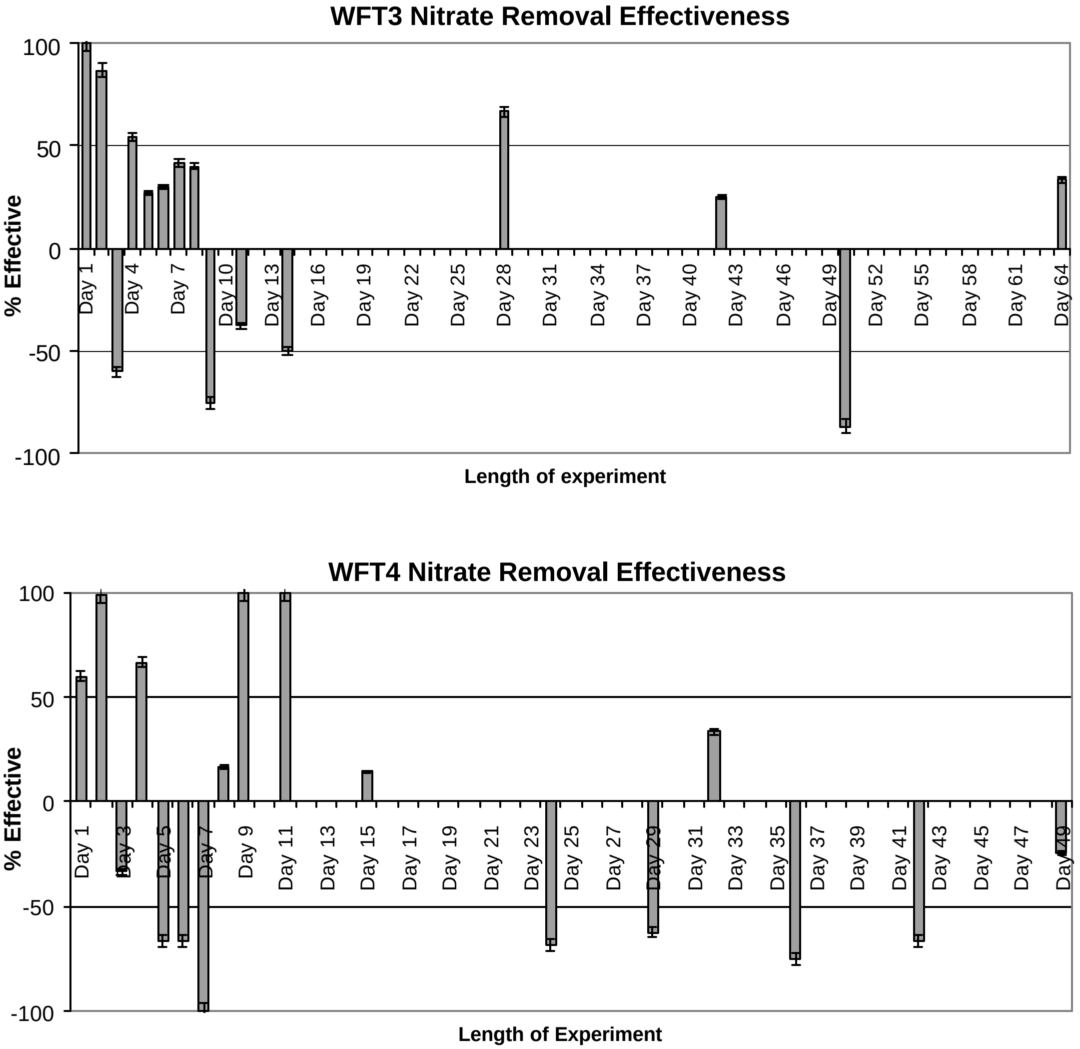

Figure 6a and 6b: WFT3 (*6a*) and WFT4 (*6b*) effectiveness in removing nitrate (NO_3^-).

Metals

Along with nitrate and phosphate, copper, iron, and zinc were measured during WFT3 and WFT4. Figure 7 shows the daily dissolved copper concentrations up and down gradient from the filter for WFT3 and WFT4. During both tests, copper concentrations were generally lower down gradient. For WFT3, the average up gradient and down gradient concentrations were 0.96 mg/L and 0.66 mg/L, respectively. In the case of WFT4, 0.23 mg /L of copper was removed (on average) from the influent.

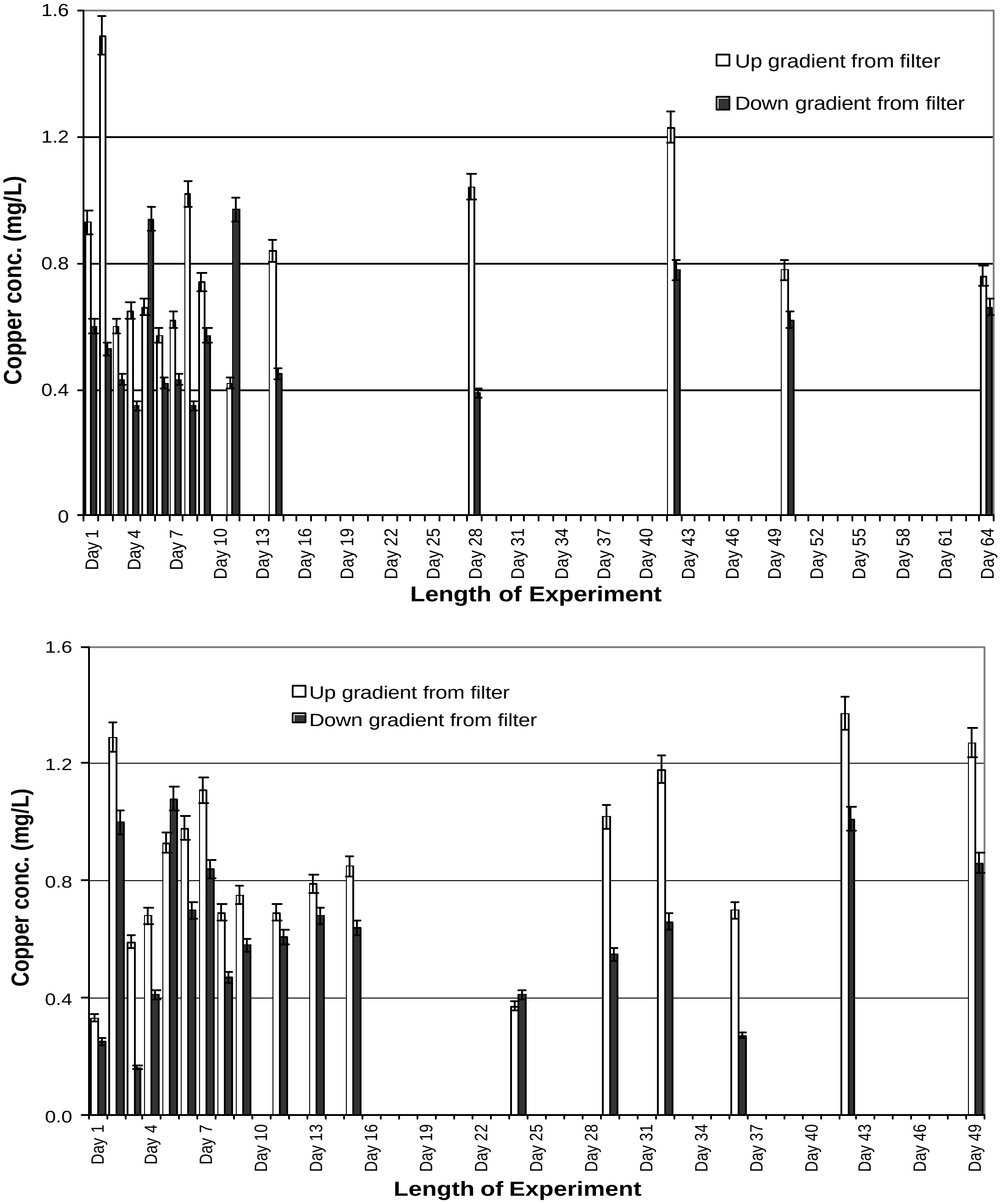

Figure 7: Copper (Cu^{2+}) concentrations (mg/L) up gradient and down gradient from the filter during WFT3 and WFT4.

From Figure 8, the dissolved copper removal efficiency varied from -57% to 66% during WFT3, with an overall effectiveness of 31%. During WTF4, it varied between -13% and 72% with an overall effectiveness of 27%. Negative efficiencies were observed during both experiments. However, these occurrences were limited to two sample events each and do not appear to reflect any trend. It appears that toward the end of WFT3 the copper removal effectiveness of the wood filter decreased. A similar decline in effectiveness was not evident during WFT4; probably due to the shorter test duration in combination with more wood mass used during WFT4.

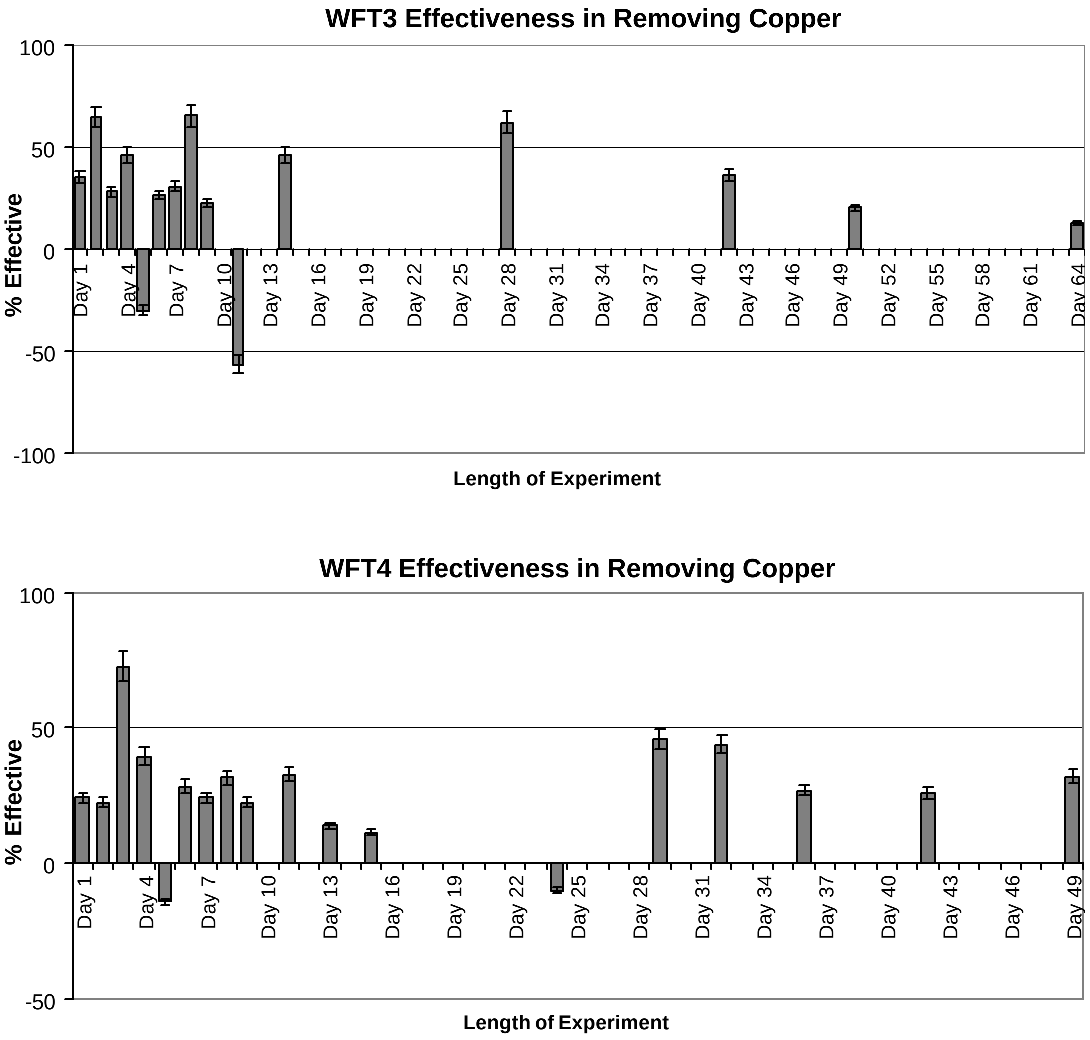

Figure 8: WFT3 and WFT4 effectiveness of removing copper from the runoff.

Iron results were similar to copper. Iron was effectively removed during both tests. During WFT3 the average up gradient iron concentration was 0.55 mg/L, while the average down gradient concentration was 0.25 mg/L. This translated into an average iron removal efficiency of 54%. An iron removal efficiency of 31% was measured during WFT4 (average iron concentrations up gradient and down gradient were 0.69 mg/L and 0.48 mg/L, respectively).

The average zinc concentrations up gradient and down gradient for WFT3 were 0.07 mg/L and 0.34 mg/L, respectively; while WFT4 up gradient and down gradient concentrations were 0.12 mg/L and 0.38 mg/L, respectively. The apparent increase in zinc concentration is caused by the material used in the filter construction. Lab leaching experiments confirmed that (1) the wood itself was not the source of the zinc and (2) the increase in zinc concentration was caused by corrosion of the galvanized chicken wire used in the construction of the wood filter modules. For this reason, zinc concentrations could not be utilized to determine zinc sorption to the wood filters.

Table 7 summarizes the average up and down gradient concentrations and contaminant removal effectiveness during WFT3 and WFT4 for NO_3^- PO_4^{3-} total Fe, Cu^{2+} and Zn^{2+}.

Table 7: Summary of average concentrations and removal effectiveness of Nitrate, Phosphate, and Heavy Metals from WFT3 and WFT4**.** <D: not detected

	WFT 3	*WFT 4*
Nitrate (NO_3^-) mg/L		
Effectiveness	**13.21%**	**-9.73%**
Avg. Conc. Up grad.	0.71	0.37
Avg. Conc. Down grad.	0.61	0.41
Max. Conc.	1.50 U	1.60 D
Min. Conc.	< D	< D
Phosphate (PO_4^{3-}) mg/L		
Effectiveness	**23.90%**	**24.04%**
Avg. Conc. Up grad.	0.55	0.64
Avg. Conc. Down grad.	0.42	0.49
Max. Conc.	0.97 U	1.02 U
Min. Conc.	0.10 D	0.12 D
Iron (Fe^{2+}, Fe^{3+}) mg/L		
Effectiveness	**54.09%**	**31.65%**
Avg. Conc. Up grad.	0.55	0.69
Avg. Conc. Down grad.	0.25	0.48
Max. Conc.	1.70 U	1.26 U
Min. Conc.	0.06 D	0.06 D
Copper (Cu^{2+}) mg/L		
Effectiveness	**31.23%**	**26.75%**
Avg. Conc. Up grad.	0.96	0.866
Avg. Conc. Down grad.	0.66	0.634
Max. Conc.	2.04 U	1.37 U
Min. Conc.	0.35 D	0.25 D
Zinc (Zn^{2+}) mg/L		
Effectiveness	**-78.30%**	**-68.54%**
Avg. Conc. Up grad.	0.07	0.12
Avg. Conc. Down grad.	0.34	0.40
Max. Conc.	1.06 D	1.08 D
Min. Conc.	0.02 U	0.03 U

U = up gradient D = down gradient

Note: Zinc was included, although its concentration was affected by leaching from galvanized metal parts used in the construction of the wood filter.

Dissolved PAHs

The assessment of the wood filter removal efficiency for dissolved PAH concentrations was a major research objectives of this pilot-scale wood filter tests. The dissolved PAH concentrations were measured during all four tests (WFT1 through WFT4). During the shortest test, WFT1, the average daily concentration of total PAHs in the filter effluent was 17.6 µg/L; whereas, 21.4 µg/L of PAHs (on average) were measured up gradient. The overall dissolved PAH removal effectiveness during WFT1 was 17.8 % (see Figure 9).

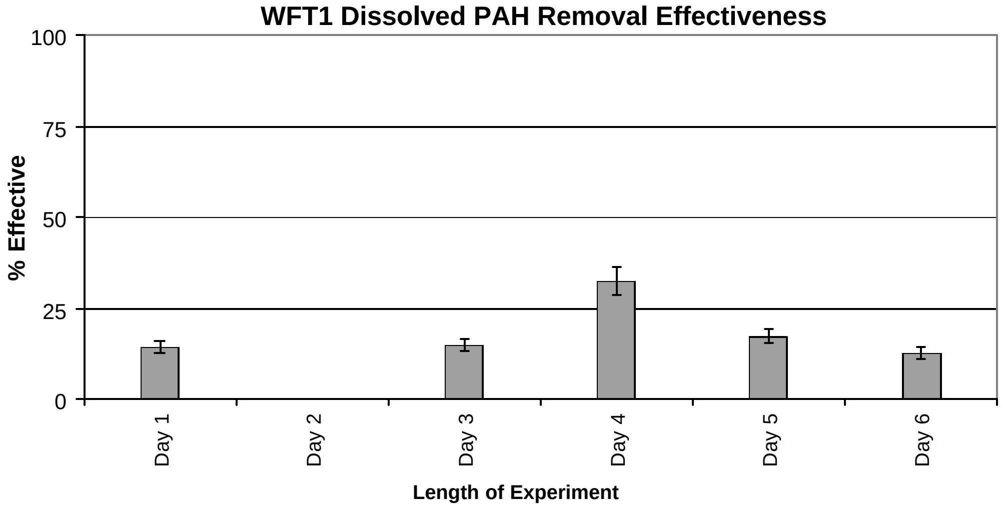

Figure 9: Effectiveness of WFT1 in removing dissolved PAHs from solution. No sample was taken on day 2.

Figure 10 displays the daily concentrations of naphthalene, the lightest molecular weight PAH analyzed; and fluoranthene, one of the heavier molecular weight PAHs analyzed during WFT1. The average naphthalene concentration were higher down gradient) than up gradient from the filter (2.61 µg/L versus 1.79 µg/L). Contrary, the average daily fluoranthene concentration were 2.44 µg/L and 1.46 µg/L up gradient and down gradient, respectively. In terms of removal effectiveness, the wood was not efficient in removing naphthalene, but removed 40% of the fluoranthene. As expected, these results indicated that the wood filter removed HMW PAHs more effectively from solution than LMW PAHs. Figure 11 indicates this relationship of heavy molecular weight PAHs having higher wood sorption concentrations.

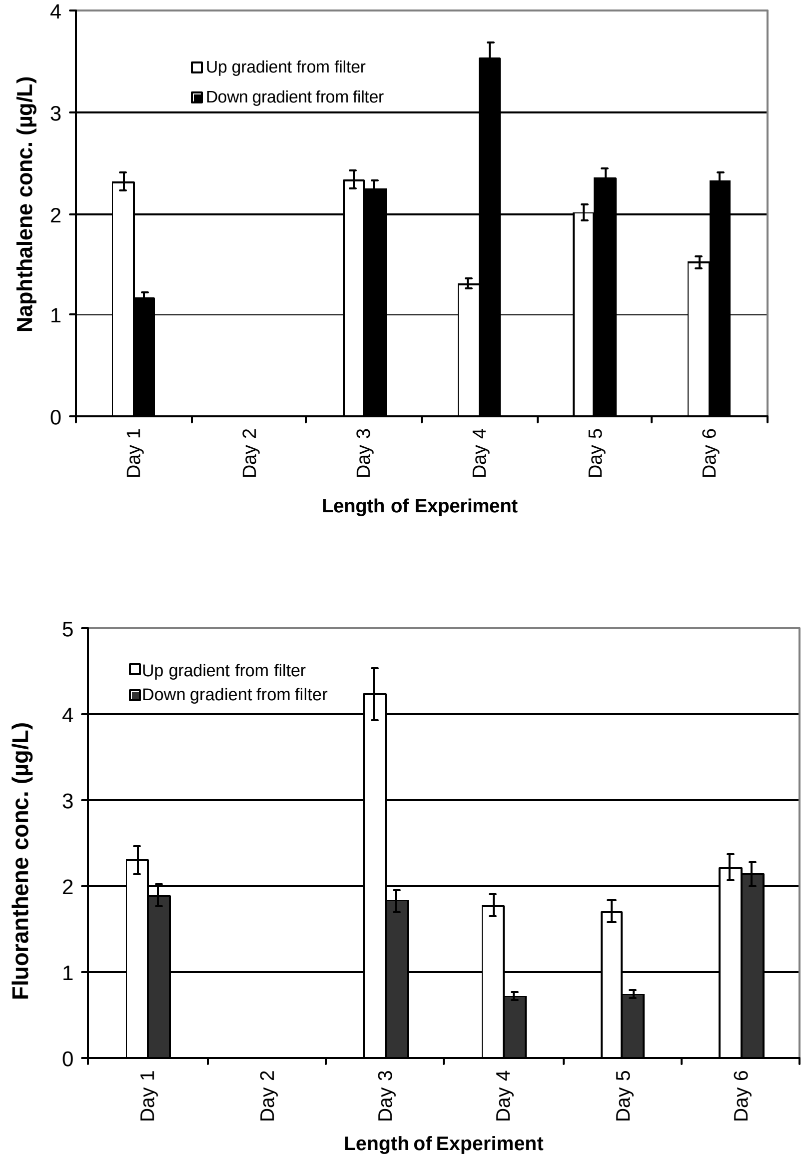

Figure 10: Removal of a dissolved light molecular weight PAH (naphthalene) and a high molecular weight PAH (fluoranthrene) by the wood filter during WFT1.

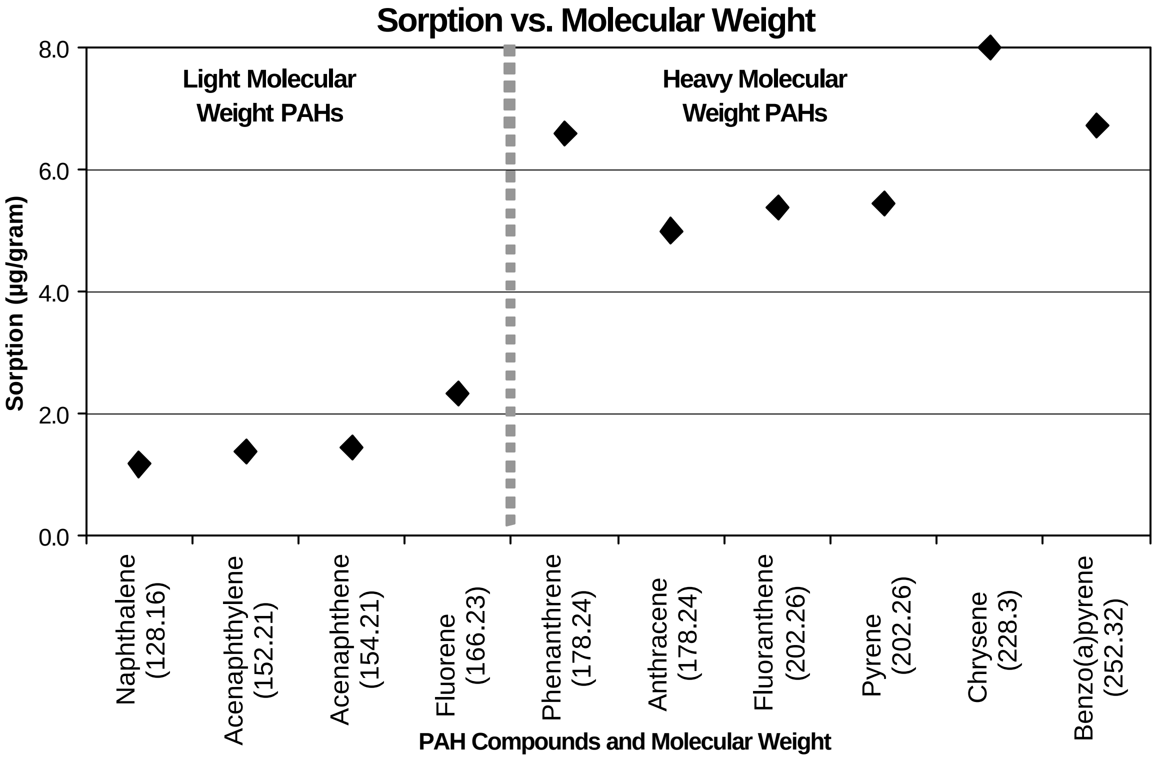

Figure 11: Average sorption during WFT2, WFT3, and WFT4 versus molecular weight. Samples from filter center bottom.

During WFT2, the average daily PAH concentrations up gradient and down gradient were 22.6 µg/L and 16.6 µg/L, respectively (see Table 9). Removal efficiencies as low as -35% and as high as 56% were observed (see Figure 12). On average, 25% of the dissolved PAHs were removed by the wood filter.

WFT3 differed from the previous tests because the dissolved PAH concentrations were lower during the test period. The average up gradient PAH concentration was 11.7 µg/L versus more than 20 µg/L during the proceeding tests. This decrease in PAH concentration was most likely caused by algae blooms and lush vegetation that began growing in the detention pond system during the test period. These plants increased the organic material in the pond. With more organic material for PAHs to sorb to, less PAHs remained in solution. As indicated in Figure 13, the PAH removal efficiency during WFT3 ranged from 4% to over 50% with an overall effectiveness of 30.8%.

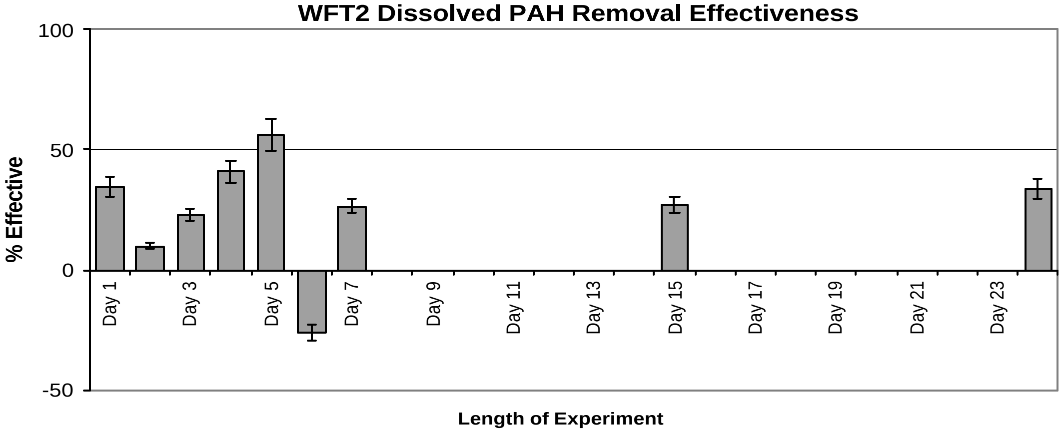

Figure 12: Dissolved PAH removal effectiveness during WFT2. The overall effectiveness was 25%.

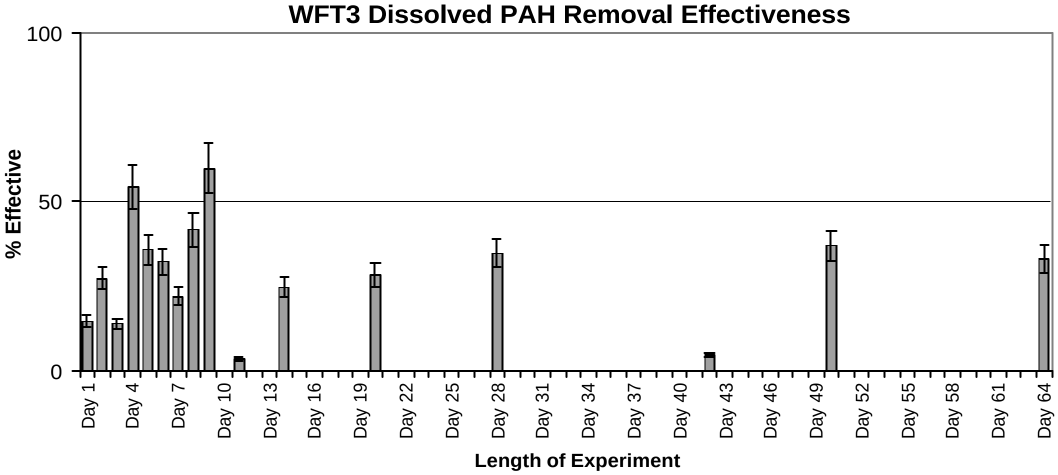

Figure 13: Dissolved PAH removal effectiveness during WFT3. The overall effectiveness was 31%.

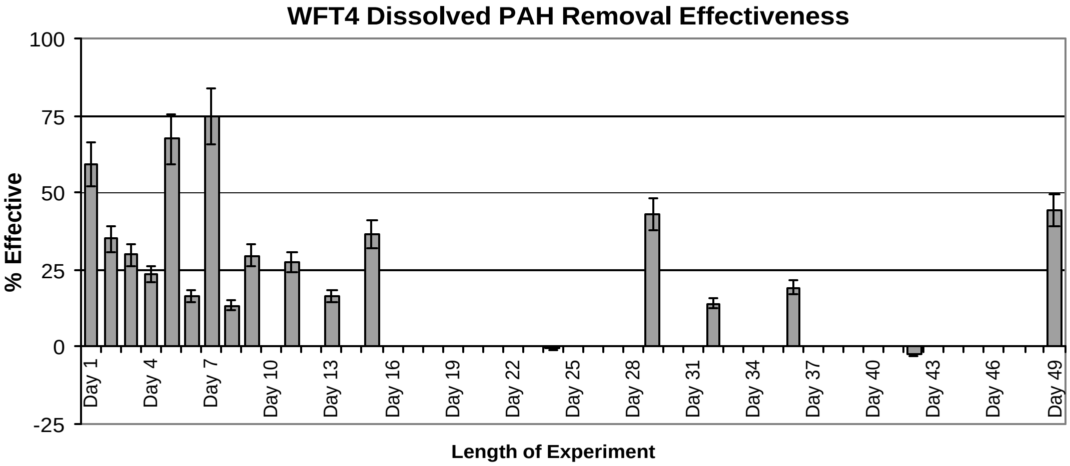

Figure 14: Dissolved PAH removal effectiveness during WFT4. The overall effectiveness was 36%.

The final test, WFT4, was the largest in terms of wood mass (115 kg). It was also the most effective at removing dissolved PAH constituents. The filter removed 35.6 % of the dissolved PAHs entering the wood filter (Range: -0.88% to 74%; see Figure 14 and Table 9).

Figure 15 shows that increasing the wood mass resulted in higher removal efficiencies. The overall total PAH removal effectiveness ranged from 17.8% for the smallest filter (WFT1) to 35.6% for the largest filter (WFT4).

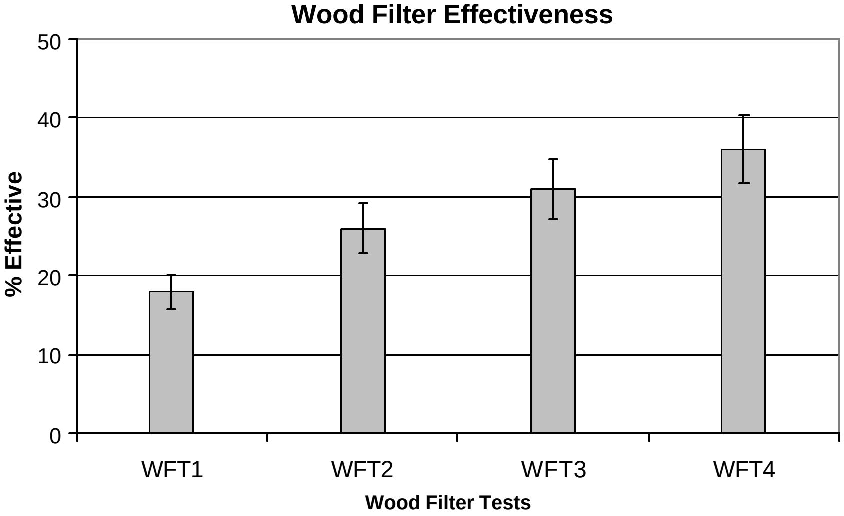

Figure 15: Overall effectiveness of WFT1, WFT2, WFT3, and WFT4 in removing dissolved PAHs from solution.

Table 8 summarizes the total amounts of PAHs removed by the wood during WFT2, WFT3, and WFT4 (no PAH mass removal per gram of wood was calculated for the first test, WFT1). The average PAH uptake per unit mass of wood remained essentially the same during all three test. The total mass of removed PAH increased from 1.4 g to 3.0 g and reflects the increasing amount of wood used for filter construction (see Table 5).

Table 8: Summary of the PAH removals observed during tests WFT2 through WFT4.

Wood Filter Test	Avg. PAH uptake per kg wood (mg/kg)	Total PAH removed (grams)
WFT2	25.2	1.4
WFT3	24.3	2.2
WFT4	26.2	3.0

Table 9: Total and individual dissolved PAH compound removal effectiveness.

	WFT1	*WFT2*	*WFT3*	*WFT4*	*Avg. effect.*
Total PAH (µg/L)					.
Effectiveness	**17.8%**	**26.3%**	**30.8%**	**35.6%**	**30.9%**
Avg. Conc. Up grad.	21.4	22.6	11.8	21.8	
Avg. Conc. Down grad.	17.6	16.6	8.1	13.8	
Naphthalene (µg/L)					
Effectiveness	**-22.5%**	nd	**9.7%**	**16.0%**	**12.9%**
Avg. Conc. Up grad.	1.90	nd	0.48	2.01	
Avg. Conc. Down grad.	2.30	nd	0.43	1.69	
Acenaphthylene (µg/L)					
Effectiveness	**-17.9%**	**42.3%**	**19.1%**	**35.7%**	**32.4%**
Avg. Conc. Up grad.	1.34	0.98	0.45	0.86	
Avg. Conc. Down grad.	1.58	0.56	0.37	0.55	
Acenaphthene (µg/L)					
Effectiveness	**21.7%**	**39.6%**	**14.9%**	**21.4%**	**25.3%**
Avg. Conc. Up grad.	1.08	1.45	0.39	1.34	
Avg. Conc. Down grad.	0.85	0.88	0.33	1.05	
Fluorene (µg/L)					
Effectiveness	**27.0%**	**-7.4%**	**34.4%**	**46.1%**	**24.4%**
Avg. Conc. Up grad.	3.65	2.90	1.95	2.22	
Avg. Conc. Down grad.	2.67	3.11	1.28	1.06	
Phenanthrene (µg/L)					
Effectiveness	**25.4%**	**44.7%**	**28.2%**	**38.9%**	**37.3%**
Avg. Conc. Up grad.	0.98	4.51	1.55	4.25	
Avg. Conc. Down grad.	0.73	2.49	1.11	2.60	
Anthracene (µg/L)					
Effectiveness	**19.4%**	**47.8%**	**37.1%**	**17.1%**	**34.0%**
Avg. Conc. Up grad.	2.88	4.88	1.88	3.40	
Avg. Conc. Down grad.	2.33	2.55	1.18	2.82	
Fluoranthene (µg/L)					
Effectiveness	**40.4%**	**3.9%**	**20.4%**	**47.4%**	**23.9%**
Avg. Conc. Up grad.	2.44	1.36	0.74	1.69	
Avg. Conc. Down grad.	1.46	1.30	0.59	0.89	
Pyrene (µg/L)					
Effectiveness	**34.1%**	**10.9%**	**45.1%**	**36.9%**	**31.0%**
Avg. Conc. Up grad.	4.34	1.78	1.23	1.87	
Avg. Conc. Down grad.	2.86	1.58	0.67	1.18	
Chrysene (µg/L)					
Effectiveness	**1.1%**	**25.8%**	**40.6%**	**66.5%**	**44.3%**
Avg. Conc. Up grad.	1.28	1.94	1.44	2.93	
Avg. Conc. Down grad.	1.27	1.44	0.85	0.98	
Benzo(a)pyrene (µg/L)					
Effectiveness	**0.3%**	**2.4%**	**20.6%**	**19.8%**	**14.2%**
Avg. Conc. Up grad.	1.72	2.78	1.66	1.41	
Avg. Conc. Down grad.	1.71	2.71	1.32	1.13	

Table 9 summarizes all test results, including individual PAH compounds. The average effectiveness was calculated based on test WFT2 through WFT4. Test WFT1 was excluded because of its short duration and preliminary character. Overall, naphthalene, which is the lightest molecular weight PAH, had the lowest average removal effectiveness of 12.9% (Range: 9.7% to 16%); while chrysene (the second heaviest molecular weight and highest K_{ow} PAH analyzed) had the highest average sorption effectiveness of 44.3% (Range: 25.8% to 66.5%). Note that only a limited amount of data exist for the "heaviest" PAH analyzed, benzo(a)pyrene, because of analytical problems. All tests combined resulted in a total PAH removal of 30.9%.

Amount of PAHs Sorbed to Wood Matrix

Calculating the amount of PAHs that sorbed to unit weight of the wood filter matrix was an important factor in determining the effectiveness of this water treatment technology. During two tests (WFT2 and WFT3) a spatial distribution analysis was conducted to establish if sorption was a function of location within the filter, i.e. did certain parts of the wood filter preferentially sorb contaminants. In addition, possible temporal variations in contaminant-wood interaction were studied during WFT4.

For the spatial analysis, wood samples were collected from the center top, center bottom, and from sections closest to the pool's edge. Sampling for spatial analysis occurred at the end of the tests. As shown in Table 10, the highest PAH concentrations were measured at the center bottom of the wood filter. The lowest concentrations were found in those parts of the filter that were only under water during storm events: the filter periphery and its top section. These results indicate that the always submersed bottom part of the filter was most effective. The results also reflect one shortcoming of the filter design used in this pilot test: a significant amount of wood mass was only effective during high flow conditions. Hence, about 2.3 to 2.8 times greater filter efficiencies could have been achieved by placing all wood mass in the water at all times.

Table 10: Spatial analysis of the wood removal effectiveness. Reported values indicate the amount of PAH mass taken up per unit weight of wood.

Location of Sampling	*WFT2 (µg/g)*	*WFT3 (µg/g)*
Center bottom	48.7	41.7
Center top	16.2	15.7
Periphery	16.3 to 20.2	17.9 to 21.7
Ratio of center bottom concentration to rest of filter	2.8	2.3

The center bottom samples were also investigated for preferential uptake of individual PAH. From Figure 16 it is evident that the PAHs with highest molecular weight were also the PAHs most efficiently removed from the filter's effluent. For example, the HMW PAHs phenanthrene (7.8 µg/g), anthracene (6.9 µg/g), and chrysene (5.9 µg/g) were removed more efficiently than the LMW PAHs (e.g. naphthalene).

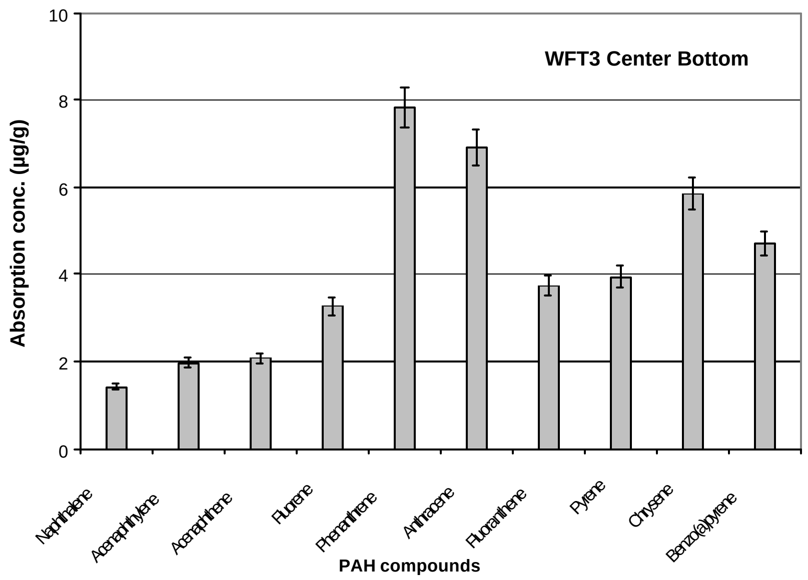

Figure 16: Uptake of individual PAHs per gram of wood during test WFT3. Wood samples were obtained from the submerged center bottom part of the wood filter.

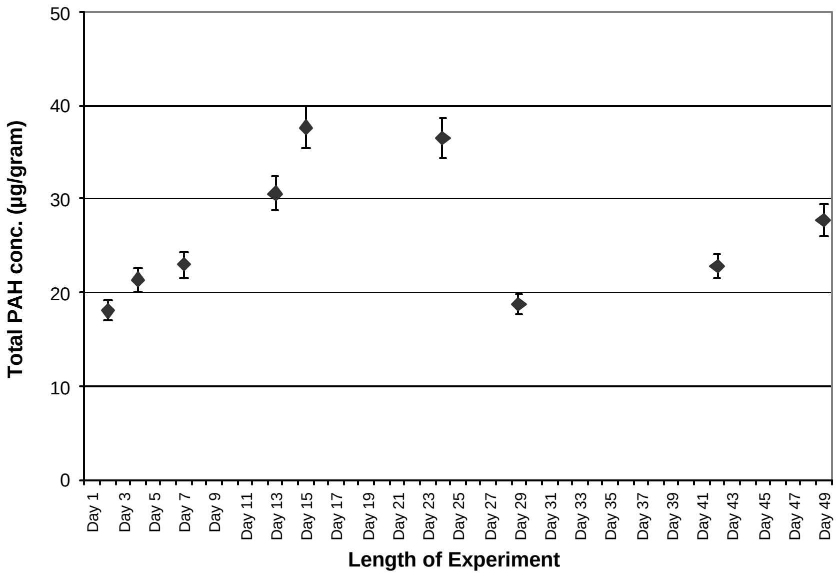

Figure 17: WFT4 long-term monitoring of the total PAH loading to the wood filter.

During WFT4, wood samples were collected throughout the duration of the test to determine how the PAH sorption changed over time. All samples were collected from the center bottom. Due to sampling protocol, the initial week was sampled more frequently than the subsequent weeks. This skewed the data toward the initial week of installation. Despite this sampling protocol, a decrease in efficiency was seen during the latter portions of each wood filter test. As depicted in Figure 17, the amount of PAH mass sorbed by the wood increased sharply from 1.8 µg/g background to 18 µg/g by day two. Afterwards, the PAHs sorbed steadily to the wood until day 15 of the experiment when the filter reached its highest PAH loading of 37.6 µg/g. Between days 16 and 24, the PAH loading onto wood remained essentially unchanged. From day 24 to 29, PAHs appeared to have desorbed from the wood, followed by once again by a steady increase for the remainder of the test period.

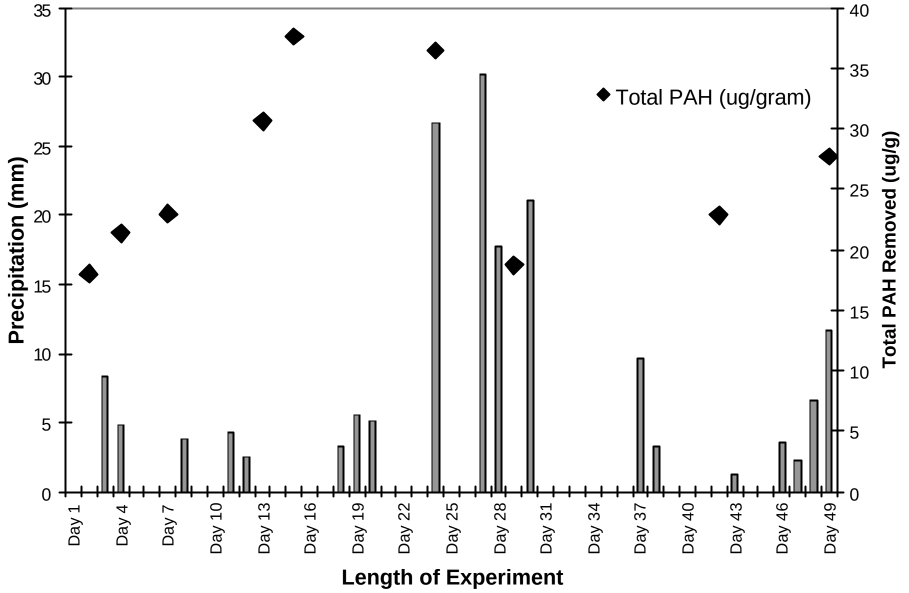

Figure 18: Correlation of total PAH loading with precipitation during length of experiment (WFT4). Graph indicates that some PAHs were flushed off the filter during multiple large rain events between days 24 to 28 (December 11 – 15, 2004).

Effect of Precipitation

The temporal changes in PAH uptake by the wood filter are related to the meteorological conditions during the test period. For instance, the decrease in PAH loading between day 24 and 29 in Figure 17 coincided with an exceptionally heavy rainstorm that lasted from December 11 to 15, 2003 (74.6 mm of precipitation). Over this period, PAH loading on the filter decreased by 50% from 37.6 µg/g to 18.7 µg/g. Figure 18 shows this rain event in relation to the wood PAH concentrations. This observed response of the wood filter to this particularly strong storm indicated that at least some of the PAHs associated only weakly to the filter, leading to remobilization when flow through the filter was very high for an extended length of time. This remobilized fraction may represent PAHs associated with colloidial matter deposited on the wood filter or biofilms that grew on the wood fibers. This indicates that the PAH removal can not entirely be attributed to the wood, but that other processes (biofilm formation, deposition of fines) contribute to the filter performance. The particles and PAH washed off the filter during the storm did not cause a spike in the dissolved PAH concentration downgradient water samples. In fact, up and downgradient PAH concentrations are almost identical or even indicate some residual removal effectiveness. Hence, it appears that the initially small particles formed larger aggregates while adhering to the wood filter. When these aggregates and the contaminants associated with them washed off the filter, they were large enough to be retained by the 0.45-micron filter used in sample preparation. Because "dissolved" is operationally defined as the aqueous fraction that passes through a 0.45-micron filter, the contaminants associated with these larger aggregates are effectively removed from solution and expected to settle out eventually. An alternate explanation for the PAH desorption from the wood filter is dissolution and dilution into less contaminated runoff water entering the pond during later stages of a storm. Typically, contaminant concentrations are highest at the onset of a storm ("first flush"). With increasing storm duration, concentrations in the runoff decrease (Barrett et al., 1998). These lower concentrations may promote the dissolution/desorption of PAHs from the wood filter. Also, heavy rain events caused the flow velocity in the detention pond to increase, which led to decreasing contact time of the filter with the contaminants. This, in turn, lowered the removal effectiveness of the filter.

Similar results were obtained during another strong rain storm that was sampled during WFT3 on August 1, 2003, when 26.4 mm of rain fell in 24 hours. Table 11 summarizes the observed changes in filter effectiveness during both storms. Table 11 also shows that besides PAH, all other compounds (phosphate, nitrate, and copper) except for iron appeared to have washed off the filter at least partially. For example, in the case of dissolved copper the filter removal effectiveness during the August storm was -57% compared to an overall effectiveness of 31% for the entire WFT3 test period. Contrary to copper, phosphate, and nitrate, even during heavy storms, iron was still removed – albeit at a lower efficiency level.

Table 11: Sorption fluctuations of (NO_3^-), (PO_4^{3-}), (Total Fe), (Cu^{2+}), and total PAHs during August 1 and December 11, 2003 rain events compared to overall effectiveness

Effectiveness	WFT3 8/1/2003	WFT3 overall	WFT4 12/11/2003	WFT4 Overall
Nitrate	-37.5%	13%	-69%	-10%
Phosphate	-54.4%	26%	2.29%	26%
Iron	15.6%	54%	10.0%	31%
Copper	-56.7%	31%	-9.7%	27%
Total PAHs	4.7%	31%	-0.9%	36.3%

Effect of Seasons

The wood filters were tested during all seasons. Even though the PAH concentrations were about 50% higher during winter than in summer, the filters exhibited no significant changes in PAH sorption during the seasons (i.e. PAH removal was not affected by temperature, DO, or pH fluctuations). The measured summer PAH removal effectiveness was 30.8% versus 35.6% in winter. The 4.8% increase in effectiveness can be attributed to the increase in the mass of the filter. Copper and iron were more effectively removed during the summer (WFT3) than the winter (WFT4). Heavy metals sorb more readily to organic material when the pH is between 4 and 6.5. During the summer months the average pH of the stormwater was 6.3; while during the winter the average pH was 7.0. With lower pH the amount of contaminants removed by the filter during the summer was higher. Changes in temperature or the amount of wood mass in the system did not greatly influence the metal removal. The compounds nitrate and phosphate did not demonstrate any seasonality effects.

Wood Filter Disposal:

An evaluation of appropriate contaminated wood filter disposal avenues indicated that proper disposal has to be addressed locally. For example, in Rhode Island, contaminated wood filter are accepted in sanitary landfills. In Switzerland, the *Ordinance on Air Pollution Control* (Graf, 2002) provides that contaminated wood can be used, for example, as fuel in incinerators. Local rules and regulations may prohibit the use of these disposal avenues elsewhere. To address this problem, leaching studies on contaminated wood filters should be carried out to evaluate the contaminant remobilization potential. Depending on the outcome of these studies, sanitary landfill disposal may be the most appropriate disposal avenue for loaded wood filters.

Laboratory Testing of Cedar Wood

The results of the laboratory column tests with Cedar wood illustrate that Cedar wood very effectively removes dissolved PAHs. Figure 19 shows the column effluent concentration of the LMW PAH whereas Figure 20 summarizes the HMW PAH concentrations. Low and high molecular weight PAH concentrations remained near the detection limits for the duration of the experiment. Fluoranthene and chrysene, which were the highest molecular weight compounds studied, were detected in only 3 and 1 samples, respectively, during late stages of the experiment. The analytical resolution of the HMW PAH is somewhat scattered because the effluent concentrations remained near the lower detection limit for most of the experiment. The final concentration of the LMW PAHs were 66% to 92% less than the inflow concentrations, indicating that the Cedar filter remained very effective even after more than 50 days of flushing.

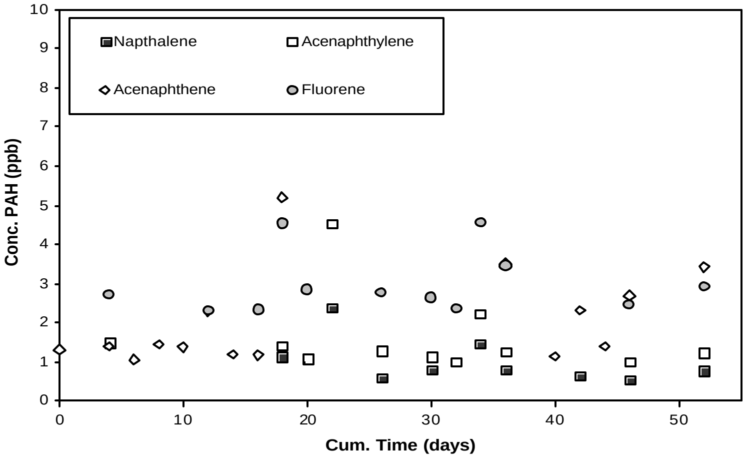

Figure 19: Results of the column sorption experiment with Cedar wood and a mix of 9 PAH compounds. Shown are the effluent concentration of the four low molecular weight PAHs naphthalene, acenaphthylene, acenaphthene, and fluorene. The influent concentration for each PAH compound was 10 µg/L.

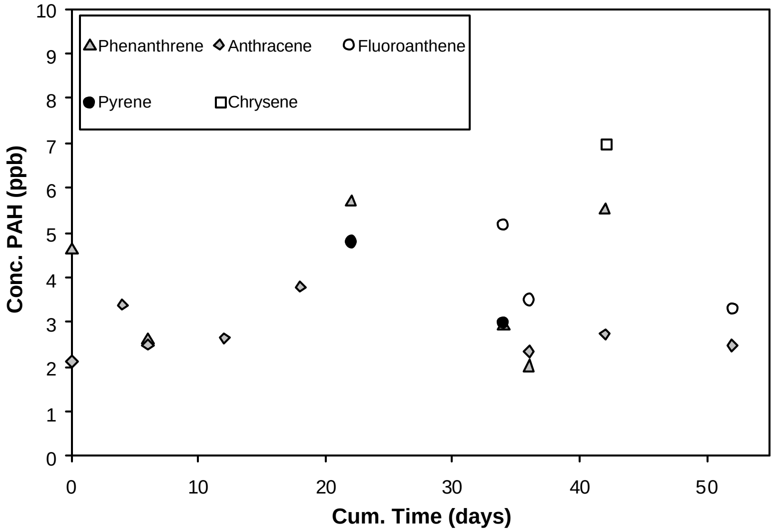

Figure 20: Results of the column sorption experiment with Cedar wood and a mix of 9 PAH compounds. Shown are the effluent concentration of the five high molecular weight PAHs phenanthrene, anthracene, fluoroanthene, pyrene, and chrysene. The influent concentration for each PAH compound was 10 µg/L.

Sorption Isotherm Experiments: Figure 21 shows the results of the Zn(II) and Cu(II) sorption isotherm experiments. In both cases, sorption equilibrium was reached within 168 hours. The sorptive metal uptake was nonlinear over the range of concentrations analyzed (0 mg/L to 5 mg/L; initial concentration). Applying the Freundlich isotherm, an equilibrium *K* value of 0.51 and 0.77 was calculated for Zn(II) and Cu(II), respectively. The Freundlich exponents, *j*, for both metals were similar, i.e., 0.29 for Zn(II) and 0.31 for Cu(II). Equations 1 and 2 describe the sorption isotherms:

$$C_{Zn} = 0.51\,C_0^{\,0.29}$$

Equation 1

$$C_{Cu} = 0.77\,C_0^{\,0.31}$$

Equation 2

The higher *K* value for Cu(II) indicates that Cu(II) tends to sorb more effectively to aspen wood relative to Zn(II).

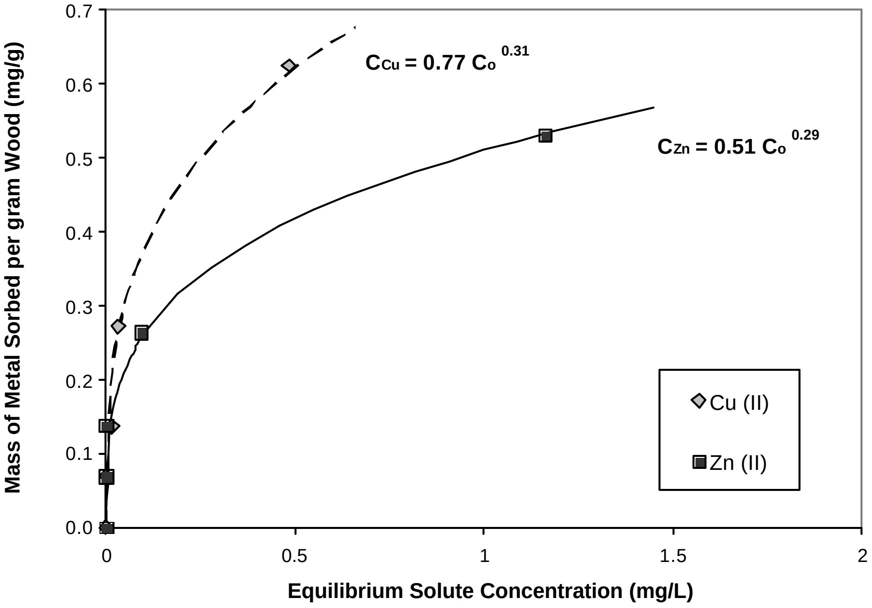

Figure 21: Equilibrium solute data for Cu(II) and Zn(II) plotted alongside best-fit Freundlich isotherms. A *K* value of 0.77 l g^{-1} was calculated for Cu(II) and a value of 0.51 l g^{-1} was calculated for Zn(II). The Freundlich exponents for Cu(II) and Zn(II) were similar (0.31 and 0.29, respectively). The equilibration time was 168 hours.

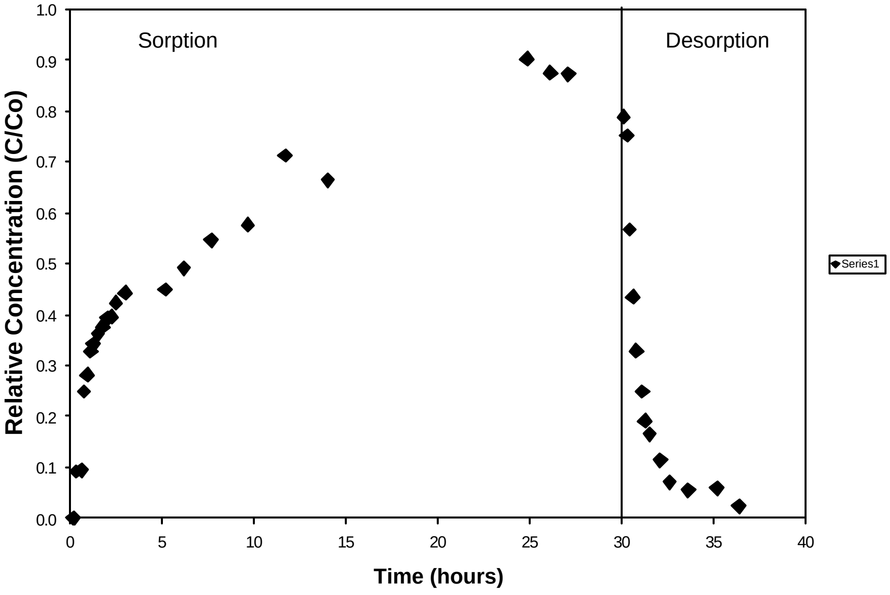

Figure 22: Relative concentration (C/Co) of an aqueous Cu(II) solution in column effluent. The column was packed with 1.445 g (dry) aspen wood. The influent concentration during the sorption experiment was 10 mg/L Cu(II). During the following desorption experiments, deionized water was flushed through the column.

Table 12: Summary of column sorption and desorption experiments with Cu(II) and Zn(II) solutions. All mass values are per unit weight of wood (*mg/g*).

Metal	Concentration *mg/L*	Total Input *mg/g*	Total Output mg/g	Mass Sorbed *mg/g*	Percentage Sorbed	Mass Desorbed *mg/g*	Percentage Desorbed
Cu (II)	0.85	0.32	0.05	0.27	84 %	0.006	2 %
	10	6.74	4.44	2.31	34 %	0.099	4 %
Zn (II)	5.5	2.77	1.67	1.10	40 %	0.077	7 %
	11	3.94	2.70	1.24	31 %	0.028	2 %

***Column Experiments**:* Figure 22 summarizes the results of a column experiment using a 10 *mg/L* Cu(II) solution flushed through 1.445 *g* (dry) aspen wood fibers. After 30 hours of flushing with Cu(II) solution, the sorption experiment was followed by flushing the wood with deionized water to investigate Cu(II) desorption. Additional experiments were carried out using a 0.85 *mg/L* Cu(II) solution and Zn(II) solutions at 5.5 *mg/L* and 11 *mg/L*. The results of these experiments are summarized in Table 12. Over the first hour of the sorption experiment, the relative Cu(II) effluent concentration increased sharply, i.e., from zero to approximately 0.3 C/Co. Afterwards, the effluent concentration continued increasing, but at a much slower rate. The effluent concentration approached the influent concentration (C/C_0=1.0) after about 30 hours of flushing. At this time, 974 ml of Cu(II) solution, containing 9.74 mg Cu(II), had been flushed through the column. During the following desorption experiment, the Cu(II) concentration dropped below 0.2 mg/L within 6 hours (87 ml total flushing volume). Over the course of the sorption experiment, 2.3 *mg* Cu(II) per gram of aspen wood were removed from solution. Compared to the Cu(II) mass input, this is equivalent to a removal efficiency of about 34%. During the desorption experiment, only 0.1 *mg* Cu(II) was released back into the flushing solution (deionized water) over a 6 hour period (4% of amount sorbed).

The sorption experiment indicates that the removal of dissolved Cu(II) by aspen wood was most effective during the first 12 hours of the experiment, when the rate of Cu(II) uptake was the greatest. The high degree of initial removal effectiveness can be explained by rapid surface complexation of the metal ion onto the wood surface. Once the easily accessible surface complexation sites were filled up, further metal uptake was slow, but steady. This observation can be explained by diffusive transport of metal ions into the wood matrix. Figure 3 shows the changing removal effectiveness in terms of metal Cu(II) mass entering and leaving the column. The difference between input and output was equal to the amount of Cu(II) sorbed to the wood (per gram). From Figure 23 it is evident that the metal removal effectiveness decreased with time. For example, after about 25 hours of flushing, the mass of sorbed Cu(II) remained essentially constant (2.3 *mg* Cu(II) per gram of aspen wood). This implies that around this time the wood filter had reached its maximum removal effectiveness. The desorptive release appeared to be steady and linear (see Figure 23). Extrapolating the linear part of the desorption curve, it would take (theoretically) about 470 hours (ca. 19.6 days) to remove all the sorbed Cu(II). Thus, the desorptive release of Cu(II) is much slower compared to the sorptive uptake.

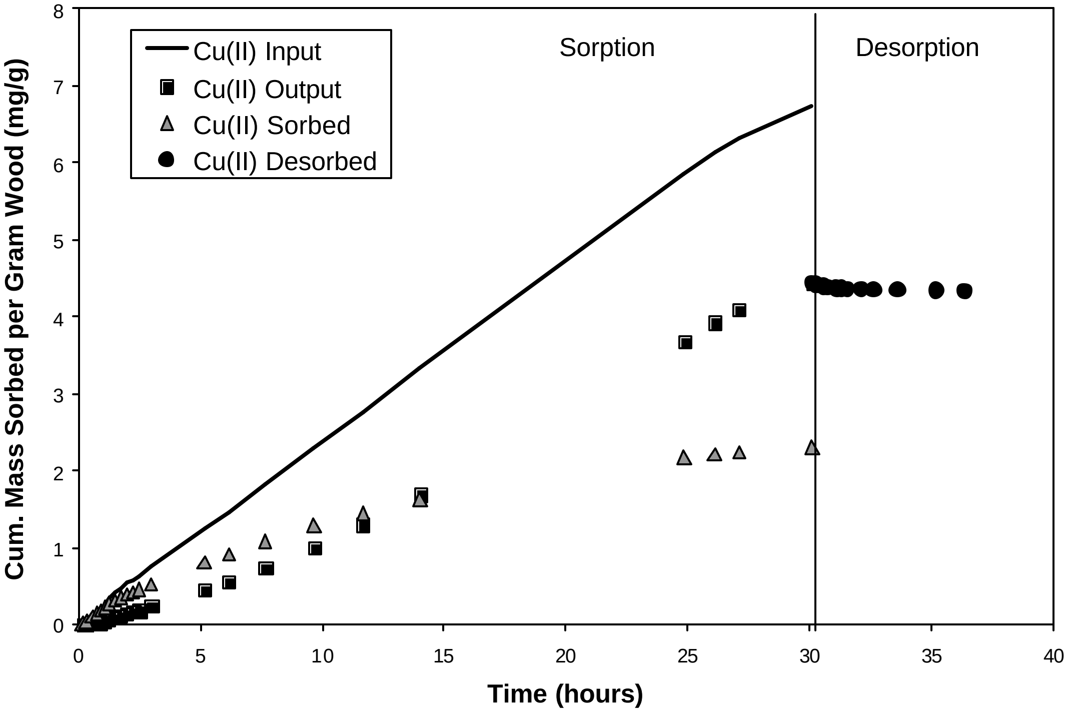

Figure 23: Mass balance for the sorption and desorption experiment using 10 *mg/L* Cu(II) solution.

Compared to the Cu(II) experiments, the experiments conducted with Zn(II) solution exhibited similar results (see Table 12). The main differences between the Zn(II) and Cu(II) column experiments were that (a) the effluent Zn(II) concentration reached C/Co=1 sooner and (b) the desorptive release of the Zn(II) from the wood was slower, i.e., Zn(II) effluent concentration dropped below 0.1 *mg/L* soon after flushing with deionized water began. The total measurable amount of Zn(II) desorbed accounted for about 2 % to 7 % of the sorbed mass.

Figure 24 shows the time dependency of the measured removal effectiveness for Cu(II) and Zn(II) solutions ranging in concentrations from 0.8 *mg/L* Cu(II) to 11 *mg/L* Zn(II). For both metals, the removal effectiveness increased with decreasing metal concentration. For example, the removal effectiveness was still high (near 80%) after flushing 0.8 mg/L Cu(II) solution for 24 hours. During the same time, the removal effectiveness dropped to below 20% when a higher concentrated Cu(II) solution was flushed through the column (10 *mg/L*). These results reconfirm the sorption isotherm experiments, which showed that the metal-wood interaction is non-linear with a Freundlich exponent <1.

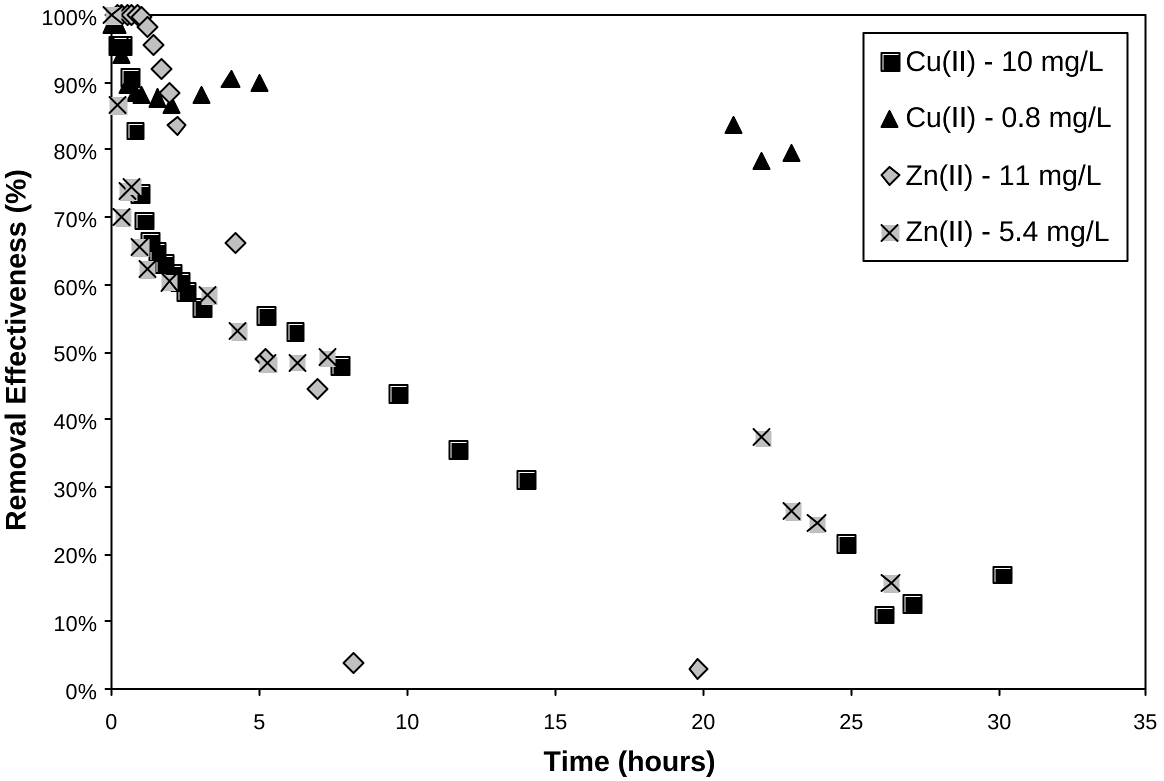

Figure 24: Time dependent removal effectiveness of Cu(II) and Zn(II) solutions ranging in concentrations from 0.8 mg/L Cu(II) to 11 mg/L Zn(II).

SUMMARY AND CONCLUSION

This study examined the effectiveness of a pilot-scale wood filter system to remove dissolved contaminants from a detention pond system. The operational definition of dissolved contaminant is the pollutant fraction that passes through a Whatman 0.45 µm GF/C glass microfiber filter. The fraction of contaminants associated with colloids <0.45 µm was not investigated. It was demonstrated that aspen wood filters effectively removed 10 PAH compounds, phosphate, copper, and iron from stormwater runoff. The effectiveness of the filters varied due to flow rate changes, PAH molecular weight, seasonal fluctuations in pH, and filter size. The wood filter tests varied in length between one to nine weeks.

The PAH removal observed during the pilot-scale filter tests was lower than the laboratory results reported by Boving and Zhang (2004). During previous laboratory experiments the removal effectiveness of individual PAH compounds by Aspen wood was initially as high as 90% and later decreased to 70% after approximately 30 days (Boving and Zhang, 2004). The highest field efficiency was 35.6% for the largest filter (WFT4). Several differences between these two studies have to be pointed out. First, the laboratory experiments were conducted with a single PAH compound solution. The individual PAH compounds were dissolved in deionized water and temperature and pH were held constant. Under these conditions, pyrene, anthracene, and fluorene mass uptake by aspen wood was 74 µg/g, 67 µg/g, and 25.5 µg/g, respectively. During the field experiments the average uptake of the three previously mentioned compounds was 2.2 µg/g pyrene, 4.2 µg/g for anthracene, and 1.7 µg/g for fluorene. The difference between the field and laboratory may be caused by competitive sorption of the various organic and inorganic contaminants present in stormwater runoff. Also, the lab experiments were conducted at PAH concentrations well above (50 ug/L), which were about an order of magnitude or more higher than the PAH concentrations measured in the field. The difference in concentration can potentially influence the sorption behavior, as expected for compounds that sorb in a non linear fashion. Also, high electrical conductivities – especially during winter - point to the presence of high salt concentrations, i.e. high ionic strength of the Stormwater runoff. Competitive sorption together with high ionic strength appear the most likely factors decreasing the filter efficiency under field conditions.

Another important variable was the mass of wood used in the filter construction. For example, tripling the wood mass doubled the PAH removal efficiency (WFT1 versus WFT4). But, increasing the wood mass changed the wood filter geometry, i.e. comparably more wood mass was residing above the water when larger filters were installed. The field tests demonstrated, however, that the highest removal efficiencies were achieved in those parts of the filter that remained submerged at all times. This part of the filter removed 37.6 µg/g to 48.7 µg/g of all 10 PAHs studied (WFT2, WFT3, and WFT4). This removal effectiveness is much closer to the laboratory values (25.5 µg/g to 75 µg/g for individual compounds) reported by Boving and Zhang (2004). Hence, the spatial variability in the filter effectiveness suggests that current filter design does not exploit the full removal capacity of the wood. This finding has important implications for future application of the wood filter technology. For instance, to increase the efficiency of the filter, the wood should (1) always be submerged and (2) the filter should be thicker in the center of the flow channel. By adjusting the filter design this way, it is expected that the filter can remove 50 % or more PAHs from solution.

Compared to the laboratory experiments by Boving and Zhang (2004), which were conducted at room temperature (22 ^{0}C), the average water temperature during the field test was lower 14.4^{0}C. Even though PAH sorption is temperature dependent, i.e. it decreases with increasing temperature (Sleep and McClure, 2001), the field test result indicate that temperature did not influence the filter performance. Also, PAH removal appears to be pH independent and does not vary with variable PAH inflow concentrations.

In contrast to the PAH, changes in pH significantly alter the sorption rate of heavy metals onto wood. This confirms findings reported elsewhere (e.g. Brown et al., 2000; Cimino et al., 2000; Palma et al., 2003). The pH dependency of heavy metal removal was reflected in the wood filter test results: when pH was low (summer filter) more iron and copper sorbed to the wood (WFT3 averaged 54.0% iron and 31.2% copper removal), while during the higher pH winter test (WFT4), only 31.6% iron and 26.7% copper were removed from solution.

Table 13: Overall sorption capacity per gram for each of the 10 PAHs analyzed for during tests WFT2, WFT3, and WFT4

Center bottom wood sample		WFT2 µg/gram	WFT3 µg/gram	WFT4 µg/gram	average µg/gram
Naphthalene	LMW	1.0	1.4	1.1	1.2
Acenaphthylene		1.0	2.0	1.2	1.4
Acenaphthene		1.5	2.1	0.7	1.4
Fluorene		2.1	3.3	1.6	2.3
Phenanthrene	HMW	3.0	7.8	8.9	6.6
Anthracene		4.9	6.9	3.2	5.0
Fluoranthene		6.3	3.7	6.1	5.4
Pyrene		5.7	3.9	6.6	5.4
Chrysene		13.0	5.9	5.1	8.0
Benzo(a)pyrene		10.3	4.7	5.1	6.7
LMW PAH Total		5.6	8.7	4.7	6.3
HMW PAH Total		43.2	33.0	35.0	37.1
Total PAH		*48.8*	*41.7*	*39.7*	*43.4*

In total, 6.6 grams of PAHs were removed by 260 kg of wood during tests WFT2, WFT3, WFT4. Almost half the mass (3.0 grams) was removed by the largest filter (WFT4). Boving (2002) calculated that 118.8 grams of dissolved PAHs flow through the Providence detention pond system each year. This researcher also estimated that, based on his laboratory experiment, about 1000 kg wood would be necessary to remove the annual PAH load from the stormwater passing through this detention pond system. The field test showed that with the current filter construction, 4660 kg of wood would be needed to effectively remove the dissolved PAH load, (4.6 times the estimated amount and 16 times the amount of wood used during this pilot-scale test). The wood filter field tests also demonstrated that the wood filter design can be improved, e.g. by keeping the wood submerged at all times and by increasing the filter thickness in the center of the flow channel. It is likely that an optimized wood filter system should require only 2440 kg of wood (2.4 times the mass estimated from previous lab experiments by Boving, 2002) to remove the entire dissolved PAH load from the Providence retention pond system.

During the field tests individual PAH compounds sorbed to the wood in varying amounts, as indicated in Table 13. Naphthalene, having the lowest organic carbon partitioning coefficient, was the least sorbed compound with an average efficiency of only 1.1% and sorption rate of 1.2 µg/g during the four filter tests. Chrysene, having a high organic carbon partitioning coefficient, was removed from solution at 33.5% and had an average sorption rate of 8.0 µg/g. In terms of molecular weight, the LMW PAHs exhibited an average removal effectiveness of 17.9% for all four filters, while the HMW PAHs had an average removal effectiveness of 27.9%. Likewise, the PAH mass uptake by the wood of the LMW compounds was only 6.3 µg/g versus 37.1 µg/g for HMW PAH. As expected, the wood filter removed the heavier molecular weight compounds more effectively.

PAH sorption onto the wood fibers also was found to be a function of time. During all four wood filter tests the highest PAH removal rates were measured during the first weeks after installation. For instance, during the first 9 days of WFT4, the removal effectiveness was exceeded 70% (38.1% on average). During the remaining 40 days of WFT5, the filter was only 22.1 % effective. The high initial PAHs removal during the first few days after installation was also observed during the three WFT2 and WFT3. The duration of WFT1 was too short to determine a removal trend. It is possible that the decrease in filter performance is caused by sedimentation of fines onto the filter or by biofilm growth. There are indications that a fraction of PAHs and other contaminants are associated with depositions on the filter surface. Because these depositions appear to be washed off the filter during heavy storms (= high flow velocities), the contaminant removal was found to be partially reversible. Because this problem appears only associated with exceptionally heavy rain events and can be circumvented by changing the wood filter design. For instance, decreasing the flow velocity during high rain events by increasing filter volume would slow the erosion of filter. Also, once the flow velocity increased beyond some threshold, a portion of the water could be diverted around the filter through an emergency overflow. Also, the wood fibers, originally tan in color, turned black at the end of the filter test and became brittle when dry. These changes indicate that wood decomposition may have impacted the filter performance. But, further studies are needed to determine how deposition of sediments, wood decay, or formation of biofilms on the filter may influence the filter performance.

Nitrate and phosphate showed different wood sorption characteristics during the field tests. While nitrate was not effectively removed by the wood filter, phosphate was – at least during the latter stages of the filter experiments. The initially observed phosphate leaching confirms the results presented by Park and Cho (2003), who performed laboratory leaching experiments with wood and leaf material. They determined that fast non-microbial leaching resulted in initial increase of phosphate concentration. The phosphate leaching ceased, however, during subsequent microbial decay of the wood.

Dissolved copper and iron were more effectively removed during summer (WFT3) than winter (WFT4). This seasonable change coincides with changes in pH. During the summer months the average pH of the stormwater was 6.3; while during the winter the average pH was 7.0. With lower pH the amount of contaminants removed by the filter during the summer was higher. These results are in conformance with results reported elsewhere. Metal sorption was more significantly affected by variations in pH than a function of temperature or the amount of wood mass in the system.

The wood filter system was designed to remove dissolved PAHs and heavy metals from the Providence detention pond system. The installation of the wood filters was successful in removing a portion of the contaminants entering the system. The effectiveness of the filters varied due to seasonal fluctuations in pH and temperature. The average filter removal of phosphate, iron, and copper was 26%, 42%, and 29%, respectively. PAH concentrations on average were 28% lower down gradient from the filter. The effectiveness of the wood fibers to sorb PAHs was not a function of PAH concentrations in the water. Heavier molecular weight PAHs sorbed more readily to the filter than the lighter molecular weight PAHs. It was determined that increasing the filter size improved the removal effectiveness.

The lifetime (i.e. maximum capacity before filter becomes inefficient) was found to be longer than the maximum test duration (WFT3; 64 days). To calculate the lifetime of the wood filter, 6 or more months are needed to determine how long the filter remains effective. Ineffective wood filter need to be disposed off. The most appropriate disposal route in Rhode Island was found to be landfilling. However, in regions where waste incineration is practiced, wood filters are best incinerated.

Data gathered during this pilot wood filter test indicate this technology may be most useful in protecting pristine environments where the contaminant influx is low. If the input of PAHs into the system is low, the apparent maximum sorption capacity of the filter (30 - 40 µg/g) would require less frequent exchange of the filter. Hence, lesser amounts of wood would be necessary to achieve comparable PAH removal. If the PAH input is relatively high – as was the case for the Providence field site - the amount of wood necessary to treat the PAH contamination and the operating/maintenance cycle becomes impracticable.

Many variables are associated with the field pilot test that could not be controlled. Based on the data gathered during the field test, certain observations can be determined and are displayed in Table 14. These variables need to be isolated in the laboratory for a more detailed analysis. For example, increased flow rates appear to decrease filter effectiveness. Performing column experiments with varying flow velocities would help determine what flow rate would be most advantageous for sorption. This would improve future filter design. This research did not differentiate between dissolved PAHs and PAHs associated with colloids, which are clusters of molecules neither in solution nor able to be filtered with the suspended load. The interaction between the filter and the dissolved PAHs or colloid PAHs was not studied.

Significant design changes are necessary for the continued improvement of this wood filter contaminant removal technology. The design of the field pilot filter was to allow all the water in the detention system to pass through the filter. Unfortunately, this exposed a significant amount of the filter mass to the atmosphere, preventing a greater removal of contaminants. Increasing the mass of the filter did increase efficiency, but not in proportion to the wood mass added.

Future research is needed to establish the wood filter technology as a practical stormwater treatment system. Cadmium, nickel, and lead are other heavy metals previously determined to sorb in the laboratory that could be examined in the field. A future test should use a redesigned system that centers the mass of wood and allows permanent immersion, leading to a further increase in pollution removal effectiveness. Also, longer residence times can be achieved by using an elongated (i.e. wider) filter design. Additionally, during large rain events, 25 mm or greater, a system overflow/bypass may be necessary to minimize remobilization of contaminants.

Table 14: Changes in variables during field test
+ = Removal was affected by this variable
- = Removal was not affected by this variable
ud = Undeterminable from the data gathered

Contaminants	Mass	pH	DO	EC	Temp	Contaminant Concentration	Flow Rates
PAHs	+	-	-	ud	-	Low concentrations equally removed	+
Iron	-	+	ud	ud	+ affected pH	Concentrations equal during tests	+
Copper	-	+	ud	ud	+ affected pH	Concentrations equal during tests	+
Nitrate	ud	ud	+	ud	+ caused lower or higher DO	Higher nitrate in summer	+
Phosphate	-	+	ud	ud	+ affected pH	Concentrations equal during tests	+

The biodegradation of PAH is a possible contaminant attenuation process that may further enhance the wood filter treatment efficiency. In all lab studies, experimental work was conducted under abiotic conditions (using sodium azide as a biocide). Hence, lab experiments did not provide additional information about the possible contribution of bacteria to the PAH removal. Under field conditions, the filter's overall removal effectiveness was treated as a "black box" process, i.e. no experiments were devised to study contributions of bacterial degradation to the overall PAH removal. This interesting aspect of wood filter technology needs more in depth study and may justify a follow up field study.

Measuring the flow rate of the detention pond would have allowed calculation of the volume of water that passed through the filter. Unfortunately, water flow rates could not be measured during this pilot-scale test. The water flow rates would have permitted calculations of the mass flux rates through the system, which would have helped to determine the wood filter effectiveness more accurately. Being able to determine the volume of water passing the filter with the concentration change up and down gradient would allow for a calculation of mass of contaminants removed by the filter. Nonetheless, the pilot-scale wood filter test yielded important insights into the workings of this technology under field conditions. Future research will benefit from these findings and may open the door for this new water treatment technology.

Disposal of loaded wood filters in sanitary landfills and incineration were identified as potential disposal avenues. However, an evaluation of appropriate contaminated wood filter disposal avenues indicated that proper disposal has to be addressed locally. Local rules and regulations may prohibit the sanitary landfill disposal or incineration elsewhere. To address this problem, detailed leaching studies on contaminated wood filters should be carried out to evaluate the contaminant remobilization potential. Depending on the outcome of these studies, sanitary landfill disposal may be the most appropriate disposal avenue for loaded wood filters.

The laboratory tests demonstrated that Cedar wood is a very promising alternative for Aspen wood. Even after more than 50 days of continuous flushing with contaminated water of low, uniform ionic strength, the dissolved PAH removal remained between 66% and 92%, depending on the compound studied. Also, Aspen wood has been found to have metal (Cu, Zn) removal capabilities that can be quantified using a Freundlich isotherm model. Although metal removal was observed, its effectiveness is less than that of hydrophobic organic contaminants. More studies are needed to investigate the effect of pH on wood-metal interaction and changes in the ionic strength of the flushing solution on the contaminant removal effectiveness (as, for instance, caused by seasonable presence of road salt in the storm water runoff).

ACKNOWLEDGEMENTS

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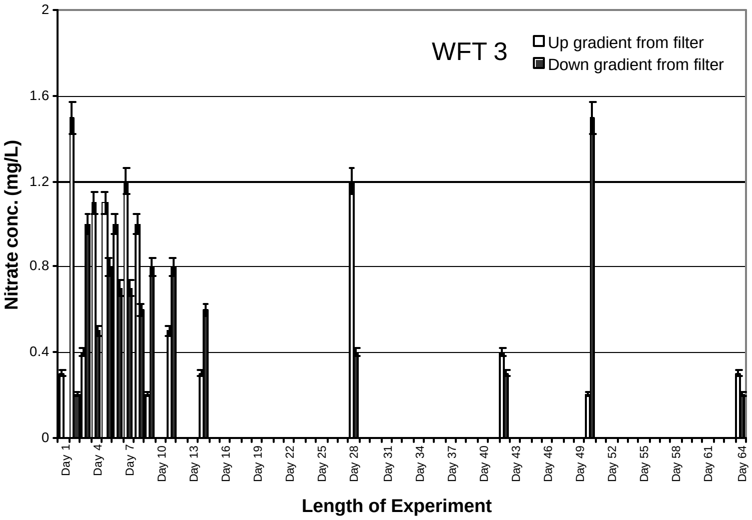
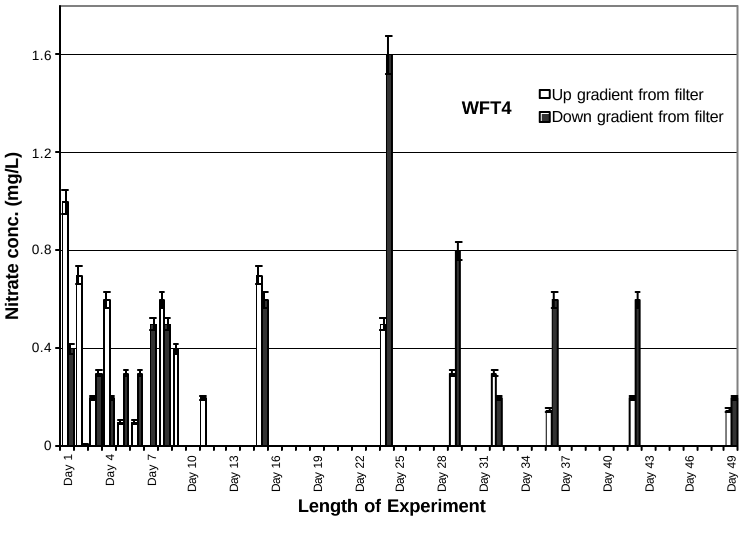
APPENDICES

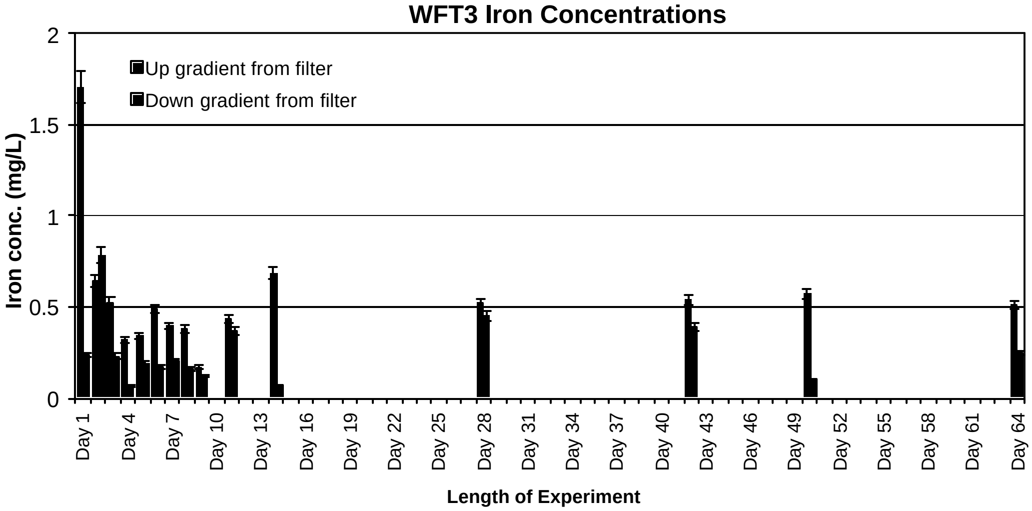
Appendix A: Up and Down Gradient Graphs

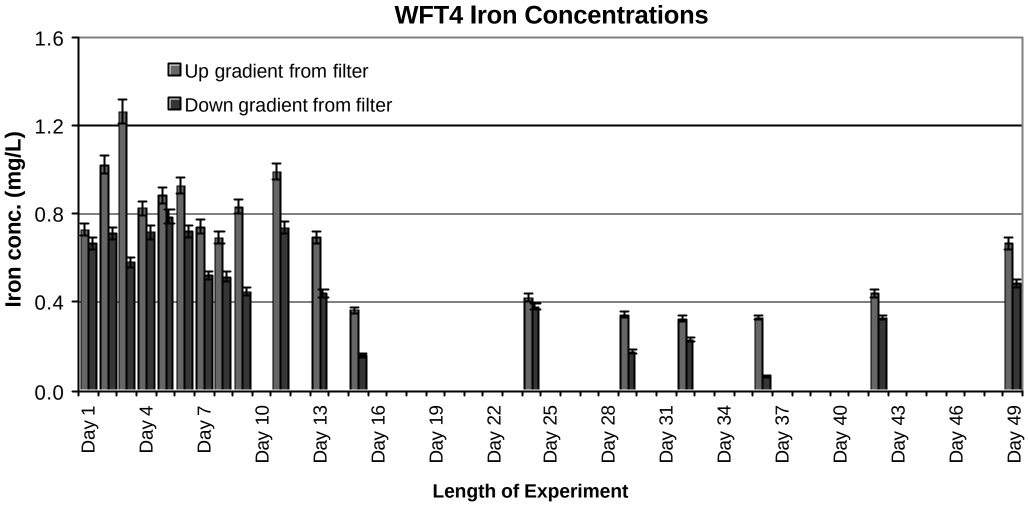
Nitrate:



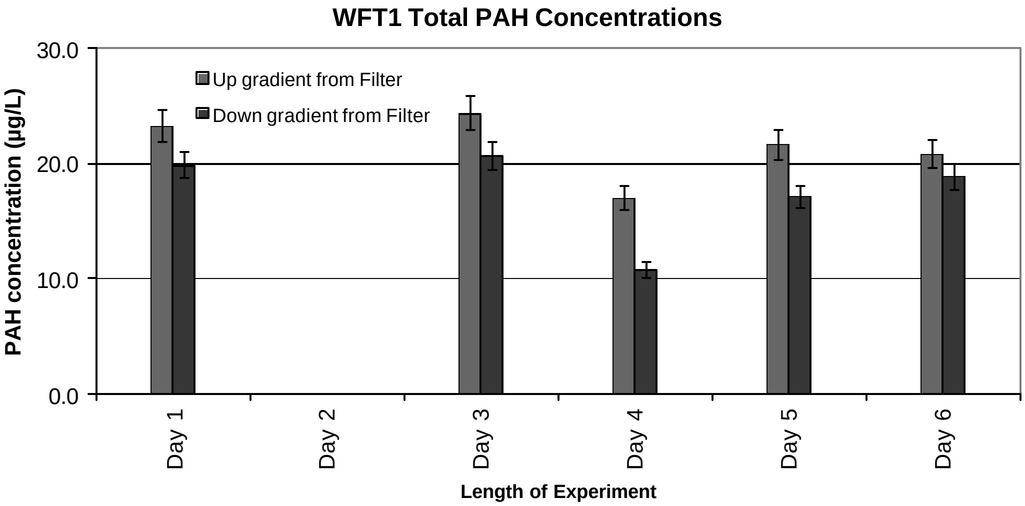


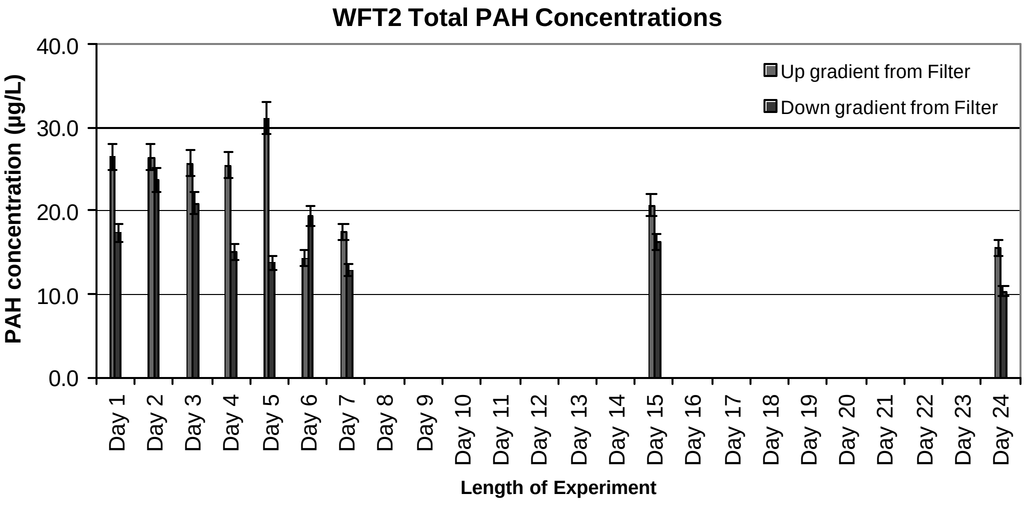
Iron:


WFT3 Iron Concentrations
Up gradient from filter
Down gradient from filter
Iron conc. (mg/L)
2
1.5
1
0.5
0
Day 1
Day 4
Day 7
Day 10
Day 13
Day 16
Day 19
Day 22
Day 25
Day 28
Day 31
Day 34
Day 37
Day 40
Day 43
Day 46
Day 49
Day 52
Day 55
Day 58
Day 61
Day 64
Length of Experiment

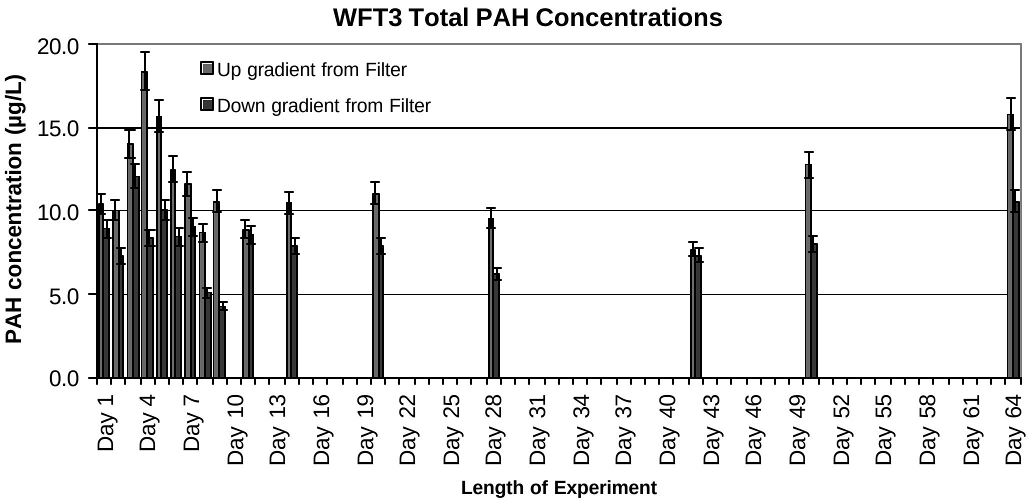

WFT4 Iron Concentrations
Up gradient from filter
Down gradient from filter
Iron conc. (mg/L)
1.6
1.2
0.8
0.4
0.0
Day 1
Day 4
Day 7
Day 10
Day 13
Day 16
Day 19
Day 22
Day 25
Day 28
Day 31
Day 34
Day 37
Day 40
Day 43
Day 46
Day 49
Length of Experiment

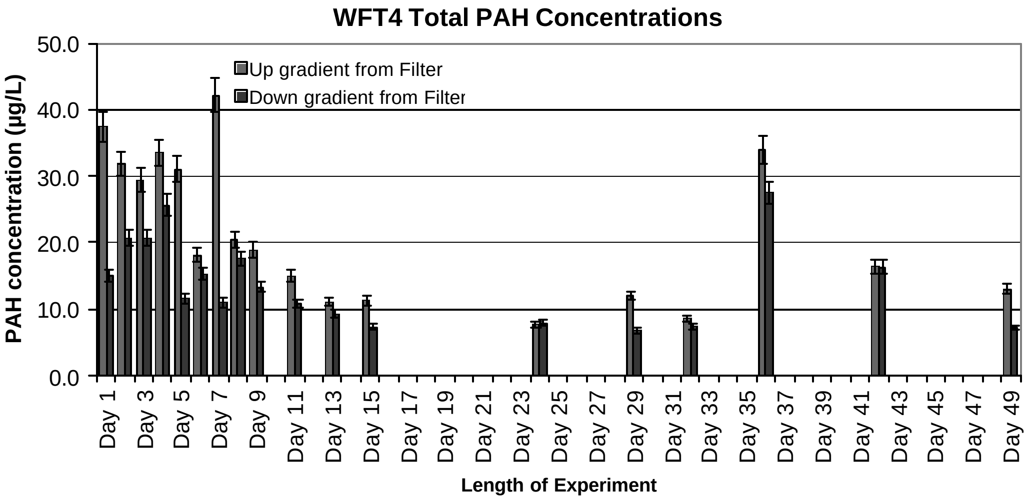
PAH


WFT1 Total PAH Concentrations
PAH concentration (µg/L)
30.0
20.0
10.0
0.0
Up gradient from Filter
Down gradient from Filter
Day 1
Day 2
Day 3
Day 4
Day 5
Day 6
Length of Experiment


WFT2 Total PAH Concentrations
PAH concentration (µg/L)
40.0
30.0
20.0
10.0
0.0
Up gradient from Filter
Down gradient from Filter
Day 1
Day 2
Day 3
Day 4
Day 5
Day 6
Day 7
Day 8
Day 9
Day 10
Day 11
Day 12
Day 13
Day 14
Day 15
Day 16
Day 17
Day 18
Day 19
Day 20
Day 21
Day 22
Day 23
Day 24
Length of Experiment

PAH


WFT3 Total PAH Concentrations
PAH concentration (µg/L)
20.0
15.0
10.0
5.0
0.0
▨ Up gradient from Filter
■ Down gradient from Filter
Day 1
Day 4
Day 7
Day 10
Day 13
Day 16
Day 19
Day 22
Day 25
Day 28
Day 31
Day 34
Day 37
Day 40
Day 43
Day 46
Day 49
Day 52
Day 55
Day 58
Day 61
Day 64
Length of Experiment


WFT4 Total PAH Concentrations
PAH concentration (µg/L)
50.0
40.0
30.0
20.0
10.0
0.0
▨ Up gradient from Filter
■ Down gradient from Filter
Day 1
Day 3
Day 5
Day 7
Day 9
Day 11
Day 13
Day 15
Day 17
Day 19
Day 21
Day 23
Day 25
Day 27
Day 29
Day 31
Day 33
Day 35
Day 37
Day 39
Day 41
Day 43
Day 45
Day 47
Day 49
Length of Experiment

Appendix B: Background Data

WFT1 - Background Data

Date	Time	pH	ec (µs)	DO (mg/L)	Temp (^oC)	Precip. (mm)
03/28/03	10:20	8.51	na	7.78	12.1	0
03/29/03	12:00	7.44	na	8.05	13.9	12.4
03/30/03	10:15	8.06	na	8.40	12.1	40.4
03/31/03	10:30	7.58	na	6.79	7.5	0.7
04/01/03	17:00	8.40	na	7.55	8.1	0.0
04/02/03	10:00	8.12	na	6.44	9.4	1.0

na = not analyzed

WFT2 - Background Data

Date	Time	pH	ec (µs)	DO (mg/L)	Temp (^oC)	Precip. (mm)
05/05/03	12:00	8.65	54.9	na	15.9	0.0
05/06/03	17:00	7.89	51.1	na	15.9	2.0
05/07/03	17:30	7.82	61.0	na	22.8	0.0
05/08/03	10:00	7.89	51.2	3.34	15.0	3.3
05/09/03	11:30	7.93	51.5	5.84	14.8	0.3
05/10/03	11:30	7.37	56.8	7.51	18.6	0.0
05/11/03	13:00	7.49	61.5	6.78	22.1	6.4
05/27/03	11:00	8.10	55.6	4.06	13.8	0.0
05/28/03	11:30	7.95	54.3	7.98	14.4	0.3

na = not analyzed

WFT3 - Background Data

Date	Time	pH	ec (µs)	DO (mg/L)	Temp (^oC)	Precip. (mm)
07/22/03	13:00	6.29	67.7	3.81	23.7	25.9
07/23/03	14:00	6.23	71.6	3.52	23.9	0.5
07/24/03	11:30	6.31	68.5	2.36	23.9	15.0
07/25/03	11:30	6.17	70.8	4.14	24.6	0.0
07/26/03	10:30	6.58	70.0	3.08	23.8	0.0
07/27/03	10:00	6.68	71.1	3.53	24.2	0.0
07/28/03	12:00	6.49	72.2	4.70	25.3	0.0
07/29/02	11:30	6.19	68.8	3.41	24.7	4.3
07/30/03	10:00	6.41	69.5	3.24	24.3	0.0
08/01/03	12:00	6.14	67.3	4.32	23.5	26.4
08/04/03	11:00	6.24	72.1	4.12	23.9	1.0
08/10/03	13:00	6.35	69.5	3.87	24.1	0.0
08/18/03	12:00	6.10	68.5	3.67	24.1	0.0
09/02/03	11:00	6.05	67.8	3.78	24.2	41.1
09/09/03	13:00	6.37	69.5	4.05	24.0	0.0
09/23/03	12:00	6.58	72.3	4.22	24.2	1.7

WFT4 - Background Data						
Date	Time	pH	ec (µs)	DO (mg/L)	Temp (^{o}C)	Precip. (mm)
11/17/03	15:00	6.56	42.9	7.30	5.5	1.3
11/18/03	8:00	6.44	42.8	4.94	4.7	0.0
11/19/03	8:00	6.53	52.3	6.37	6.0	0.0
11/20/03	12:00	7.63	76.2	5.60	10.0	8.4
11/21/03	9:00	6.96	68.5	6.06	8.4	4.8
11/22/03	12:00	6.72	76.2	5.62	9.5	0.0
11/23/03	10:00	6.83	71.8	5.50	8.4	0.0
11/24/03	10:00	7.60	63.3	4.88	6.4	0.0
11/25/03	12:00	6.59	70.5	4.65	7.0	4.8
11/26/03	15:00	7.22	72.8	4.98	6.8	0.0
11/28/93	11:00	7.33	na	na	6.9	4.3
11/30/03	15:00	7.41	na	na	6.4	0.0
12/02/03	13:00	6.87	na	na	6.1	0.0
12/11/03	12:00	7.34	711.0	5.42	5.2	26.7
12/16/03	11:00	6.93	278.0	4.71	4.3	0.0
12/19/03	10:00	6.68	231.0	5.91	4.2	0.0
12/23/03	13:00	7.18	185.0	5.32	3.9	0.0
12/29/03	12:00	7.10	215.0	4.58	3.7	0.0
01/06/04	10:00	6.95	368.0	4.78	3.2	0.0

na = not analyzed

Appendix C: Nitrate, Phosphate, and Heavy Metals

WFT3 - Nitrate, Phosphate, and Heavy Metal Data

Sample	Date	Nitrate (mg/L)	Phosphate (mg/L)	Copper (mg/L)	Zinc (mg/L)	Iron (mg/L)
WFT3-1 Up	07/22/03	0.3	0.29	0.93	0.09	1.700
WFT3-1 Down	07/22/03	0.0	0.38	0.60	0.25	0.236
WFT3-2 Up	07/23/03	1.5	0.19	1.52	0.05	0.644
WFT3-2 Down	07/23/03	0.2	0.61	0.53	0.13	0.782
WFT3-2 Up Dup	07/23/03	1.4	0.18	1.50	0.06	0.629
WFT3-2 Down Dup	07/23/03	0.2	0.62	0.53	0.15	0.777
WFT3-3 Up	07/24/03	0.4	0.25	0.60	0.02	0.522
WFT3-3 Down	07/24/03	1.0	0.52	0.43	0.08	0.228
WFT3-4 Up	07/25/03	1.1	0.60	0.65	0.07	0.320
WFT3-4 Down	07/25/03	0.5	0.30	0.35	0.17	0.064
WFT3-5 Up	07/26/03	1.1	0.77	0.66	0.06	0.342
WFT3-5 Down	07/26/03	0.8	0.26	0.94	0.25	0.188
WFT3-6 Up	07/27/03	1.0	0.45	0.57	0.04	0.488
WFT3-6 Down	07/27/03	0.7	0.72	0.42	0.26	0.170
WFT3-7 Up	07/28/03	1.2	0.96	0.62	0.05	0.396
WFT3-7 Down	07/28/03	0.7	0.59	0.43	0.25	0.204
WFT3-7 Up Dup	07/28/03	1.0	0.91	0.70	0.07	0.390
WFT3-7 Down Dup	07/28/03	0.6	0.50	0.42	0.21	0.201
WFT3-8 Up	07/29/02	1.0	0.70	1.02	0.05	0.380
WFT3-8 Down	07/29/02	0.6	0.30	0.35	0.26	0.160
WFT3-9 Up	07/30/03	0.2	0.40	0.74	0.05	0.168
WFT3-9 Down	07/30/03	0.8	0.21	0.57	0.34	0.122
WFT3-10 Up	08/01/03	0.5	0.31	0.42	0.06	0.436
WFT3-10 Down	08/01/03	0.8	0.68	0.97	0.39	0.368

Up = up gradient
Down = down gradient
Dup = duplicate sample

WFT3 - Nitrate, Phosphate, and Heavy Metal Data Continued						
Sample	Date	Nitrate (mg/L)	Phosphate (mg/L)	Copper (mg/L)	Zinc (mg/L)	Iron (mg/L)
WFT3-11 Up	08/04/03	0.3	0.40	0.84	0.11	0.684
WFT3-11 Down	08/04/03	0.6	0.10	0.45	0.66	0.066
WFT3-11 Up Dup	08/04/03	0.2	0.48	0.82	0.08	0.679
WFT3-11 Down Dup	08/04/03	0.7	0.16	0.38	0.60	0.078
WFT3-12 Up	08/18/03	1.2	0.75	1.04	0.08	0.520
WFT3-12 Down	08/18/03	0.4	0.32	0.39	0.25	0.450
WFT3-13 Up	09/02/03	0.3	0.72	1.23	0.10	0.537
WFT3-13 Down	09/02/03	0.4	0.49	0.78	0.31	0.389
WFT3-14 Up	09/09/03	0.2	0.65	0.78	0.16	0.572
WFT3-14 Down	09/09/03	1.5	0.31	0.62	1.06	0.100
WFT3-15 Up	09/23/03	0.3	0.76	0.76	0.12	0.510
WFT3-15 Down	09/23/03	0.2	0.46	0.66	0.45	0.246
WFT3-15 Up Dup	09/23/03	0.3	0.69	0.82	0.07	0.504
WFT3-15 Down Dup	09/23/03	0.3	0.48	0.60	0.40	0.255

Up = up gradient
Down = down gradient
Dup = duplicate sample

WFT4 - Nitrate, Phosphate, and Heavy Metal Data

Sample	Date	Nitrate (mg/L)	Phosphate (mg/L)	Copper (mg/L)	Zinc (mg/L)	Iron (mg/L)
WFT4 - Back	11/17/03	0.3	0.31	0.53	0.08	0.584
WFT4-1 Up	11/18/03	1.0	0.32	0.33	0.09	0.731
WFT4-1 Down	11/18/03	0.4	1.01	0.25	0.42	0.673
WFT4-2 Up	11/19/0 3	0.7	0.40	1.29	0.10	1.02
WFT4-2 Down	11/19/03	0.0	0.95	1.00	0.29	0.711
WFT4-2 Up Dup	11/19/0 3	0.9	0.35	1.22	0.10	1.00
WFT4-2 Down Dup	11/19/03	0.2	0.91	0.96	0.33	0.698
WFT4-3 Up	11/20/03	0.2	0.57	0.59	0.05	1.26
WFT4-3 Down	11/20/03	0.3	0.25	0.16	0.71	0.584
WFT4-4 Up	11/21/03	0.6	0.43	0.68	0.13	0.833
WFT4-4 Down	11/21/03	0.2	0.76	0.41	0.13	0.721
WFT4-5 Up	11/22/03	0.2	0.48	0.93	0.03	0.895
WFT4-5 Down	11/22/03	0.3	0.82	1.08	0.15	0.797
WFT4-6 Up	11/23/03	0.2	0.85	0.98	0.10	0.931
WFT4-6 Down	11/23/03	0.3	0.99	0.70	0.21	0.722
WFT4-7 Up	11/24/03	0.0	0.18	1.11	0.14	0.743
WFT4-7 Down	11/24/03	0.5	0.23	0.84	0.31	0.526
WFT4-7 Up Dup	11/24/03	0.1	0.11	1.04	0.11	0.731
WFT4-7 Down Dup	11/24/03	0.4	0.25	0.84	0.35	0.521
WFT4-8 Up	11/25/03	0.8	0.47	0.69	0.08	0.691
WFT4-8 Down	11/25/03	0.5	0.30	0.47	0.68	0.524
WFT4-9 Up	11/26/03	0.4	0.30	0.75	0.12	0.837
WFT4-9 Down	11/26/03	0.0	0.12	0.58	0.38	0.455
WFT4-10 Up	11/28/03	0.2	0.97	0.85	0.10	0.992
WFT4-10 Down	11/28/03	0.2	0.48	0.64	0.56	0.744

Up = up gradient
Down = down gradient
Dup = duplicate sample

WFT4 - Nitrate, Phosphate, and Heavy Metal Data Continued

Sample	Date	Nitrate (mg/L)	Phosphate (mg/L)	Copper (mg/L)	Zinc (mg/L)	Iron (mg/L)
WFT4-11 Up	11/30/03	0.0	0.79	0.79	0.16	0.709
WFT4-11 Down	11/30/03	0.0	0.31	0.68	0.19	0.442
WFT4-11 Up Dup	11/30/03	0.0	0.72	0.79	0.11	0.703
WFT4-11 Down Dup	11/30/03	0.0	0.35	0.63	0.21	0.432
WFT4-12 Up	12/02/03	0.7	1.02	0.69	0.15	0.37
WFT4-12 Down	12/02/03	0.6	0.47	0.61	0.21	0.16
WFT4-13 Up	12/11/03	0.5	0.75	0.37	0.13	0.42
WFT4-13 Down	12/11/03	1.6	0.72	0.41	0.23	0.38
WFT4-14 Up	12/16/03	0.3	0.86	1.02	0.21	0.34
WFT4-14 Down	12/16/03	0.8	0.32	0.55	0.43	0.18
WFT4-15 Up	12/19/03	0.3	0.82	1.18	0.15	0.323
WFT4-15 Down	12/19/03	0.2	0.42	0.66	0.22	0.232
WFT4-15 Up Dup	12/19/03	0.4	0.73	1.11	0.15	0.333
WFT4-15 Down Dup	12/19/03	0.2	0.41	0.62	0.26	0.224
WFT4-16 Up	12/23/03	0.2	0.63	0.70	0.17	0.33
WFT4-16 Down	12/23/03	0.6	0.21	0.51	1.08	0.06
WFT4-17 Up	12/29/03	0.2	0.74	1.37	0.15	0.44
WFT4-17 Down	12/29/03	0.6	0.17	1.01	0.70	0.33
WFT4-18 Up	01/06/04	0.2	0.93	1.27	0.16	0.67
WFT4-18 Down	01/06/04	0.2	0.21	0.86	0.33	0.49

Up = up gradient
Down = down gradient
Dup = duplicate sample

Appendix D: Dissolved PAH Data

WFT1 - Dissolved PAH Concentrations

Sample	Date	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT1-1 Up	3/28/03	2.31	1.74	1.95	4.17	1.37	3.19	2.30	5.36	nd	0.78	23.18
WFT1-1 Down	3/28/03	1.17	3.29	0.00	1.19	1.62	3.23	1.88	7.44	nd	0.00	19.82
WFT1-2 Up	3/30/03	2.33	0.99	1.18	2.09	2.60	3.18	4.23	5.66	0.65	1.43	24.36
WFT1-2 Down	3/30/03	2.24	1.36	0.61	2.28	nd	1.77	1.82	4.82	3.17	2.61	20.69
WFT1-2 Up Dup	3/30/03	2.41	0.86	1.16	2.22	nd	3.05	4.11	5.93	0.77	nd	20.51
WFT1-2 Down Dup	3/30/03	2.10	1.28	0.52	2.28	nd	1.76	1.65	4.91	3.13	nd	17.63
WFT1-3 Up	3/31/03	1.31	1.12	1.14	3.91	0.92	2.24	1.77	1.54	2.19	0.85	16.98
WFT1-3 Down	3/31/03	3.54	1.25	2.19	3.27	nd	nd	0.71	0.00	nd	0.50	11.45
WFT1-4 Up	4/1/03	2.01	1.53	0.06	5.49	nd	4.01	1.70	6.80	nd	nd	21.61
WFT1-4 Down	4/1/03	2.35	2.00	0.59	4.87	2.03	5.24	0.73	nd	nd	nd	17.82
WFT1-5 Up	4/2/03	1.52	1.33	nd	2.61	nd	1.80	2.21	2.34	3.56	5.52	20.88
WFT1-5 Down	4/2/03	2.32	nd	nd	1.73	nd	1.38	2.13	2.04	3.16	5.45	18.22

WFT2 - Dissolved PAH Concentrations

Sample	Date	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT2-1 Up	5/5/03	nd	1.61	0.82	2.00	7.72	7.69	1.75	2.86	2.06	0.00	26.50
WFT2-1 Down	5/5/03	nd	1.05	0.33	7.04	2.37	2.45	0.99	1.86	1.25	0.00	17.35
WFT2-2 Up	5/6/03	nd	1.72	0.87	2.09	4.89	4.79	3.05	2.65	1.86	4.44	26.35
WFT2-2 Down	5/6/03	nd	0.60	0.16	4.30	6.07	3.98	3.13	1.72	0.71	3.09	23.78
WFT2-3 Up	5/7/03	nd	0.68	3.44	2.06	6.90	5.78	0.88	1.58	2.18	2.18	25.69
WFT2-3 Down	5/7/03	nd	0.55	1.94	3.77	2.56	2.28	1.29	1.84	2.44	4.55	21.23
WFT2-3 Up Dup	5/7/03	nd	0.75	3.19	2.00	6.54	5.68	0.98	1.41	2.04	2.65	25.24
WFT2-3 Down Dup	5/7/03	nd	0.50	1.90	3.55	2.38	2.35	1.25	1.99	2.40	4.10	20.42
WFT2-4 Up	5/8/03	nd	0.00	0.09	9.40	3.74	0.74	0.98	3.16	0.88	6.08	25.07
WFT2-4 Down	5/8/03	nd	0.00	0.02	5.04	2.31	1.93	0.85	1.44	1.30	2.34	15.23
WFT2-5 Up	5/9/03	nd	0.91	2.30	6.31	3.21	5.86	1.78	2.86	2.07	5.66	30.95
WFT2-5 Down	5/9/03	nd	0.81	1.20	0.49	1.70	1.32	0.76	1.41	1.31	4.75	13.74
WFT2-6 Up	5/10/03	nd	0.00	0.22	0.81	3.14	3.10	1.00	1.14	1.53	3.08	14.02
WFT2-6 Down	5/10/03	nd	0.00	0.63	2.26	5.49	4.19	0.00	1.99	1.03	3.82	19.42
WFT2-7 Up	5/11/03	nd	1.20	1.83	0.52	4.89	5.28	0.59	0.12	2.11	0.93	17.48
WFT2-7 Down	5/11/03	nd	0.35	0.81	3.11	1.93	1.22	0.78	1.16	1.57	1.90	12.84
WFT2-7 Up Dup	5/11/03	nd	1.29	1.99	0.53	4.96	5.59	0.68	0.32	2.18	0.78	18.32
WFT2-7 Down Dup	5/11/03	nd	0.45	0.75	3.33	1.85	1.48	0.77	0.98	1.47	1.64	12.72
WFT2-9 Up	5/19/03	nd	1.35	1.98	0.81	4.61	6.85	2.17	0.74	2.17	0.00	20.69
WFT2-9 Down	5/19/03	nd	0.74	2.07	1.25	0.00	2.97	3.92	2.02	1.48	1.82	16.27
WFT2-10 Up	5/28/03	nd	1.31	1.52	2.09	1.52	3.85	0.00	0.91	1.68	2.62	15.48
WFT2-10 Down	5/28/03	nd	0.97	0.73	0.76	0.00	2.59	0.00	0.82	2.67	2.11	10.65

WFT3 - Dissolved PAH Concentration

Sample	Date	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT3-1 Up	7/22/03	0.77	0.69	0.60	0.71	0.46	2.54	1.53	0.82	0.77	1.54	10.43
WFT3-1 Down	7/22/03	0.75	0.75	0.87	0.71	0.75	1.11	1.09	0.70	0.76	1.44	8.91
WFT3-2 Up	7/23/03	0.75	0.75	1.30	0.46	0.55	1.71	0.62	1.00	1.30	1.55	10.00
WFT3-2 Down	7/23/03	0.99	1.07	0.44	0.90	3.09	0.80	nd	0.00	0.00	0.00	7.28
WFT3-3 Up	7/24/03	nd	nd	0.75	5.17	0.88	2.55	nd	0.93	1.39	2.32	14.00
WFT3-3 Down	7/24/03	nd	0.80	0.37	3.90	0.60	0.92	0.93	1.98	0.64	1.93	12.06
WFT3-4 Up	7/25/03	0.75	nd	nd	0.50	3.47	1.04	nd	5.07	6.27	1.26	18.36
WFT3-4 Down	7/25/03	0.61	nd	nd	0.76	1.19	0.80	0.60	0.63	1.76	2.03	8.38
WFT3-4 Up Dup	7/25/03	0.75	nd	0.69	0.77	3.31	1.24	0.85	4.58	6.01	1.0	19.2
WFT3-4 Down Dup	7/25/03	0.55	nd	0.54	0.88	1.10	0.85	0.51	0.85	1.89	1.58	8.75
WFT3-5 Up	7/26/03	0.63	0.81	0.12	1.12	5.51	1.59	1.26	1.12	1.71	1.79	15.66
WFT3-5 Down	7/26/03	0.61	0.88	0.03	0.79	1.99	1.11	0.69	1.05	0.69	2.21	10.06
WFT3-6 Up	7/27/03	nd	0.87	0.39	3.80	0.94	2.01	nd	1.24	1.47	1.73	12.47
WFT3-6 Down	7/27/03	nd	nd	0.25	3.31	0.52	1.10	nd	0.82	1.01	1.42	8.43
WFT3-7 Up	7/28/03	1.32	0.89	nd	0.64	0.72	1.74	2.12	0.84	1.35	1.98	11.60
WFT3-7 Down	7/28/03	0.71	0.60	nd	1.23	0.60	1.67	0.83	0.95	0.90	1.55	9.04
WFT3-8 Up	7/29/03	nd	nd	nd	4.27	1.09	1.58	nd	nd	0.85	0.90	8.70
WFT3-8 Down	7/29/03	nd	nd	nd	1.00	0.80	1.28	nd	nd	1.08	0.93	5.08
WFT3-9 Up	7/30/03	nd	nd	nd	4.23	0.47	1.94	0.84	nd	1.23	1.85	10.56
WFT3-9 Down	7/30/03	nd	nd	nd	0.50	nd	1.08	nd	nd	1.19	1.48	4.24

WFT3 - Dissolved PAH Concentration Continued

Sample	Date	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT3-10 Up	8/1/03	0.10	nd	nd	2.46	0.36	1.22	1.06	1.42	0.86	1.39	8.88
WFT3-10 Down	8/1/03	0.99	0.63	0.18	0.85	1.78	0.28	1.99	0.74	0.60	0.52	8.57
WFT3-10 Up Dup	8/1/03	0.41	0.54	1.02	2.10	1.12	1.65	1.02	1.89	0.75	1.87	12.37
WFT3-10 Down Dup	8/1/03	1.58	0.52	0.25	0.32	1.75	0.58	1.35	0.98	0.65	0.81	8.79
WFT3-11 Up	8/4/03	nd	nd	nd	2.46	0.85	1.68	1.29	0.66	1.77	1.78	10.49
WFT3-11 Down	8/4/03	nd	nd	nd	3.09	nd	1.24	0.75	nd	1.24	1.58	7.91
WFT3-12 Up	8/10/03	1.11	0.77	1.00	2.14	1.54	1.44	0.96	1.20	0.86	nd	11.01
WFT3-12 Down	8/10/03	0.79	0.42	1.13	1.02	1.24	1.89	0.57	0.70	0.12	nd	7.89
WFT3-13 Up	8/18/03	0.84	1.59	1.35	0.38	1.03	1.00	0.52	1.41	0.70	0.72	9.55
WFT3-13 Down	8/18/03	0.70	0.44	1.35	0.50	0.64	nd	0.21	0.81	0.95	0.64	6.24
WFT3-14 Up	9/2/03	0.50	0.49	0.52	1.14	0.65	0.68	0.86	1.43	0.80	0.63	7.68
WFT3-14 Down	9/2/03	0.41	0.25	0.62	0.87	0.76	0.39	1.29	0.98	1.06	0.68	7.32
WFT3-15 Up	9/9/03	0.36	nd	nd	0.83	3.35	2.62	0.76	0.70	0.82	3.32	12.77
WFT3-15 Down	9/9/03	0.36	nd	nd	0.43	1.30	1.39	0.47	0.42	1.02	2.64	8.04
WFT3-15 Up Dup	9/9/03	0.49	nd	nd	1.12	3.14	2.64	0.89	0.98	1.22	3.58	14.06
WFT3-15 Down Dup	9/9/03	0.39	nd	nd	0.58	1.22	1.59	0.45	0.36	1.08	2.91	8.59
WFT3-16 Up	9/23/03	0.52	0.36	0.15	0.80	2.93	4.66	nd	1.76	0.84	3.77	15.78
WFT3-16 Down	9/23/03	nd	nd	nd	0.54	2.54	3.83	nd	0.99	0.62	2.03	10.56

WFT4 - Dissolved PAH Concentrations

Sample	Date	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
Background	11/17/03	1.33	0.48	0.01	0.58	7.51	5.78	3.84	2.65	1.72	3.69	27.59
WFT4-1Up	11/18/03	1.77	0.50	2.9	1.67	nd	6.08	4.88	15.71	0.76	3.15	37.42
WFT4-1Down	11/18/03	2.54	0.67	1.11	0.79	nd	4.49	0.81	2.77	0.97	1.00	15.15
WFT4-2 Up	11/19/03	2.42	0.44	1.2	2.54	14.15	6.21	0.80	1.55	0.90	1.64	31.85
WFT4-2 Down	11/19/03	2.75	0.85	0.76	1.84	4	6.70	1.08	1.13	0.53	1.06	20.70
WFT4-3 Up	11/20/03	4.73	0.75	0.24	3.02	9.37	4.53	0.95	0.83	2.86	2.15	29.43
WFT4-3 Down	11/20/03	2.43	0.63	0.76	1.51	4.65	4.71	1.22	0.59	2.64	1.51	20.65
WFT4-3 Up Dup	11/20/03	4.21	1.10	0.55	3.69	8.46	4.59	0.91	1.06	2.49	2.87	29.93
WFT4-3 Down Dup	11/20/03	2.29	0.86	0.76	1.79	4.15	4.25	1.11	0.65	2.38	1.67	19.91
WFT4-4 Up	11/21/03	3.96	0.12	1.02	1.85	15.05	0.67	2.00	1.97	6.01	0.90	33.55
WFT4-4 Down	11/21/03	2.95	0.70	0.29	0.95	12.57	0.99	0.99	3.96	1.24	1.05	25.69
WFT4-5 Up	11/22/03	0.80	0.53	3.72	8.51	4.18	6.31	0.72	1.78	4.54	nd	31.09
WFT4-5 Down	11/22/03	1.74	0.71	1.51	1.57	0.12	0.83	1.30	1.79	1.54	0.51	11.62
WFT4-6 Up	11/23/03	2.96	0.50	0.17	0.3	7.97	2.46	0.60	0.52	1.19	1.49	18.16
WFT4-6 Down	11/23/03	2.08	0.37	0.13	0.77	5.79	1.27	0.50	0.50	0.86	2.96	15.23
WFT4-7 Up	11/24/03	4.53	0.82	0.36	1.6	4.47	0.89	3.16	1.11	22.44	2.80	42.18
WFT4-7 Down	11/24/03	3.68	0.01	0.33	0.64	2.01	0.32	0.75	0.93	1.28	1.07	11.02
WFT4-8 Up	11/25/03	2.76	0.50	1.12	1.31	3.05	3.84	0.77	0.80	1.56	4.70	20.41
WFT4-8 Down	11/25/03	2.13	0.28	0.58	0.67	1.76	6.51	0.46	0.79	0.95	3.56	17.69
WFT4-8 Up Dup	11/25/03	2.25	0.50	1.42	1.29	2.87	4.10	1.08	0.80	1.48	4.25	20.04
WFT4-8 Down Dup	11/25/03	1.87	0.36	0.69	0.87	1.42	5.87	0.54	0.69	0.75	3.21	16.27

WFT4 - Dissolved PAH Concentrations Continued												
Sample	Date	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT4-9 Up	11/26/03	1.02	0.57	0.07	1.55	1.22	6.62	1.22	2.01	2.36	2.24	18.88
WFT4-9 Down	11/26/03	1.84	0.37	0.24	0.47	1.12	1.58	0.93	1.70	3.09	1.99	13.33
WFT4-10 Up	11/28/93	0.77	0.46	0.56	1.26	0.99	5.36	0.99	1.63	1.08	1.82	14.92
WFT4-10 Down	11/28/93	0.68	0.65	0.38	1.78	1.79	3.00	0.57	0.84	1.15	nd	10.84
WFT4-11 Up	11/30/03	1.37	0.90	0.01	0.71	1.29	1.59	1.23	1.63	1.09	1.25	11.07
WFT4-11 Down	11/30/03	1.36	0.57	0.01	0.49	0.84	3.75	1.02	1.24	nd	nd	9.28
WFT4-12 Up	12/2/03	0.95	0.51	1.3	0.65	0.99	2.13	1.53	1.24	1.04	0.94	11.28
WFT4-12 Down	12/2/03	0.80	0.41	1.02	0.36	0.71	0.95	1.23	1.08	nd	0.68	7.24
WFT4-13 Up	12/11/03	1.36	nd	0.25	0.3	1.29	1.37	0.91	0.82	1.47	nd	7.77
WFT4-13 Down	12/11/03	1.87	1.14	1.37	0.62	0.84	1.26	0.17	0.23	0.34	nd	7.84
WFT4-14 Up	12/16/03	0.98	6.61	2.17	0.29	0.46	1.49	nd	nd	nd	nd	12.00
WFT4-14 Down	12/16/03	0.91	0.67	1.96	0.33	0.83	2.14	nd	nd	nd	nd	6.84
WFT4-14 Up Dup	12/16/03	1.48	5.42	2.07	0.58	0.98	1.54	1.45	nd	2.54	nd	16.06
WFT4-14 Down Dup	12/16/03	0.99	0.98	1.52	0.45	0.83	1.24	0.98	nd	1.87	nd	8.86
WFT4-15 Up	12/19/03	1.03	0.80	2.18	0.74	1.46	2.37	nd	nd	nd	nd	8.58
WFT4-15 Down	12/19/03	0.70	1.10	2.27	0.39	1.21	1.69	nd	nd	nd	nd	7.36
WFT4-16 Up	12/23/03	nd	nd	0.76	7.14	3.57	5.03	7.80	1.97	5.44	2.34	34.05
WFT4-16 Down	12/23/03	nd	nd	0.36	5.01	2.36	5.05	3.10	3.61	3.09	5.00	27.58
WFT4-17 Up	12/29/03	1.33	0.29	5.79	0.44	1.14	3.45	2.78	nd	nd	nd	15.22
WFT4-17 Down	12/29/03	0.76	0.35	5.48	0.48	2.59	4.17	1.82	nd	nd	nd	15.65
WFT4-18 Up	1/6/04	3.39	1.10	0.26	1.5	5.83	0.88	nd	nd	nd	nd	12.96
WFT4-18 Down	1/6/04	1.13	0.44	0.33	0.39	3.54	1.38	nd	nd	nd	nd	7.21

Appendix E: Sorbed PAH Data

WFT2 - Sorbed PAHs Spatial Distribution

Sample	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT2- Center Bottom	1.03	0.95	1.48	2.10	3.03	4.88	6.27	5.71	13.03	10.27	48.75
WFT2- Center Top	5.27	0.43	0.08	0.84	5.57	3.80	0.67	0.94	1.38	0.85	19.83
WFT2- Right	1.86	0.52	3.07	1.65	4.06	4.37	2.72	0.42	0.72	0.80	20.20
WFT2- Left	0.44	0.66	0.60	0.61	4.49	4.61	0.90	1.27	1.74	0.95	16.27

WFT3 - Sorbed PAHs Spatial Distribution

Sample	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT2 - Center Bottom	1.42	1.96	2.08	3.27	7.83	6.92	3.73	3.94	5.86	4.72	41.73
WFT2 - Center Top	1.43	0.55	0.10	2.10	3.04	0.51	0.57	4.92	0.91	1.60	15.73
WFT2 - Mid Right	1.52	2.32	0.59	2.12	3.85	1.45	2.70	5.00	0.96	1.18	21.70
WFT2 - Mid Left	3.15	1.97	0.08	0.83	2.61	0.77	2.12	1.70	1.58	3.19	17.99

Appendix F: Long-term Sorption

WFT4 - Long-term PAH Sorption

Sample	Date	Naphthalene (ug/l)	Acenaphthylene (ug/l)	Acenaphthene (ug/l)	Fluorene (ug/l)	Phenanthrene (ug/l)	Anthracene (ug/l)	Fluoranthene (ug/l)	Pyrene (ug/l)	Chrysene (ug/l)	Benzo(a) pyrene (ug/l)	Total PAHs (ug/l)
WFT4-Day 2	11/19/03	0.42	1.17	0.99	5.93	3.90	1.61	1.24	1.21	0.36	0.72	17.55
WFT4- Day 4	11/21/03	0.48	0.66	0.56	1.14	8.15	3.02	1.92	1.02	2.26	1.29	20.51
WFT4-Day 7	11/24/03	0.66	0.69	1.07	2.38	9.39	2.87	1.19	1.30	1.30	1.04	21.89
WFT4-Day 13	11/30/03	0.69	0.69	0.51	0.99	1.37	1.98	1.68	3.33	1.97	15.37	28.57
WFT4-Day 15	12/02/03	1.05	1.24	0.74	1.62	8.86	3.19	6.11	6.63	5.09	5.13	39.67
WFT4-Day 24	12/11/03	0.73	1.12	0.79	1.43	20.10	2.35	1.79	0.83	2.23	2.33	33.69
WFT4-Day 29	12/16/03	0.39	0.51	3.19	0.80	8.47	1.90	0.68	2.29	0.55	0.64	19.41
WFT4-Day 42	12/23/03	0.95	1.03	1.39	1.28	8.86	1.98	1.88	1.16	2.16	1.07	21.77
WFT4-Day 49	12/29/03	0.00	0.81	0.77	0.91	13.43	2.85	1.38	0.95	2.44	1.06	24.61

Appendix G: Leaching Experiment

Laboratory leaching tests were performed to determine if any of the analyzed contaminants originated from the wood fibers themselves. Two tests were conducted with 10 grams of wood placed into 1 liter of water. The first investigated the microbial decay of the wood material and how it is linked to nitrification. The wood for the nitrate leaching tests was placed in stormwater collected from the Providence detention pond. Deionized (DI) water was not used during the nitrate leaching test because of the lack of microbial activity in DI water. Nitrate background levels were measured before the wood was placed into the stormwater. Nitrification occurred during the later portion of this experiment.

Table G1: Wood Leaching data

Date	Nitrate (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Iron (mg/L)	Copper (mg/L)	Zinc (mg/L)
	stormwater	DI water	DI water	DI water	DI water	DI water
Background	0.0	0.0	0.0	0.0	0.0	0.0
3/11/2004	0.3	0.1	0.06	0.001	0.04	0.01
3/12/2004	0.0	0.0	0.50	0.026	0.07	0.02
3/13/2004	0.0	0.0	0.89	nd	0.06	nd
3/14/2004	0.1	0.0	1.19	0.004	0.02	0.01
3/15/2004	0.0	0.0	1.54	0.004	0.01	nd
3/16/2004	0.0	0.1	1.85	0.003	nd	nd
3/17/2004	0.0	0.1	1.92	nd	nd	0.02
3/18/2004	0.1	0.0	1.78	0.002	0.02	nd
3/19/2004	0.3	0.0	1.84	nd	0.05	nd
3/20/2004	0.3	0.0	1.71	nd	0.01	nd
3/21/2004	0.2	0.1	1.75	nd	nd	nd
3/22/2004	0.3	0.0	1.82	nd	nd	nd
3/23/2004	0.6	0.2	1.8	0.003	0.03	nd
3/24/2004	0.5	0.0	na	nd	nd	nd
3/25/2004	0.5	0.0	na	nd	nd	0.02
3/26/2004	0.8	0.0	na	nd	nd	nd
3/27/2004	0.9	0.0	na	nd	nd	nd
3/28/2004	0.8	0.1	na	nd	nd	nd
3/29/2004	1.0	0.0	na	nd	nd	nd
3/30/2004	0.8	0.0	na	nd	nd	nd

na = not analyzed
nd = not detected

The second leaching test determined if the wood leached nitrate, phosphate, iron, copper, and zinc. During this test all wood samples were placed in DI water to ensure a zero baseline. Sodium azide was added to the DI water to prevent microbial activity. There was no leaching of nitrate, iron, copper, or zinc from the wood during this 20 day experiment (Table G1). Phosphate was leached and reached equilibrium around day 8 and sampling continued with no change in concentration for five more days.

In addition to the two wood leaching experiments, a metal leaching experiment was conducted on the metal frame to determine if iron, copper, or zinc leached from the filter frame. The results of this experiment concluded that neither iron nor copper were leached from the filter frame. However, zinc concentrations increased significantly during the first few days of this experiment (Table G2). These high concentrations indicated a significant amount of zinc coating was present on the metal filter frame. This zinc coating prevented analysis of the wood filter's effectiveness in removing zinc from the roadway runoff.

Table G2: Metal Leaching Data

Date	Iron (mg/L)	Copper (mg/L)	Zinc (mg/L)
	DI water	DI water	DI water
Background	0.0	0.0	0.0
4/19/2004	nd	0.02	0.01
4/20/2004	0.008	nd	0.66
4/21/2004	nd	0.01	0.63
4/22/2004	0.026	0.08	0.72
4/23/2004	0.019	0.13	1.08
4/24/2004	0.011	0.08	0.92
4/25/2004	0.013	0.05	1.11
4/26/2004	0.007	0.08	1.33
4/27/2004	0.029	nd	1.42
4/28/2004	0.010	0.02	1.48
4/29/2004	0.014	nd	1.41
4/30/2004	0.008	nd	1.32
5/1/2004	nd	0.01	1.12
5/2/2004	nd	nd	1.32
5/3/2004	0.006	nd	0.98
5/4/2004	nd	0.03	1.12
5/5/2004	nd	nd	1.20

Appendix H: Analytical Techniques

Constituent or Property	**Method**
pH (Field)	Orion 250A with H+ 9107 electrode
Electric Conductivity (Field)	Orion 130A with a conductivity cell 013610 electrode
Dissolved Oxygen and Temperature (Field)	YSI Incorporated 55 DO meter
(NO_3^-), (PO_4^{3-}), (Fe), (Zn^{2+}), (Cu^{2+})	Hanna Ion Selective meters
10 Dissolved PAH compounds	EPA method 610, A Shimadzu GC-17A FID (Gas Chromatography–Flame Ionized Detector) with a J&W Scientific DB-D glass capillary column (30 m, 0.32 mm id, 0.25 µm film thickness)
10 Sorbed PAH compounds	EPA method 3540, A Shimadzu GC-17A FID (Gas Chromatography–Flame Ionized Detector) with a J&W Scientific DB-D glass capillary column (30 m, 0.32 mm id, 0.25 µm film thickness)

Appendix I: Quality Assessment/Control (QA/QC)

Quality assessment and control (QA/QC) was performed to determine the accuracy of the sample preparation and analytical instruments. The preparation of the water samples for PAH analysis has inherent error during the distillation process and silica gel filtering. Also, slight error occurred during operation and measurement using the GC-FID. The error from the sample preparation and instruments was determined by making known PAH concentrations from an Ultra Scientific PAH standard. Quality control analysis of these known PAH standards was performed multiple times (>3) to calculate the average error associated with sample preparation and instrument analysis. Table I1 indicates the average error from the GC-FID for all 10 PAH compounds analyzed. The detection limit of the GC-FID ranged from 0.1 µg/L to 5 µg/L, increasing with breakthrough time and PAH molecular weight. The GC-FID measurement had an average error of ±1.87%. The heavier weight molecular PAHs, especially benzo(a)pyrene, had higher error. The heavier weight PAHs are more difficult for the GC-FID to detect because of higher temperature and pressure during the latter stages of analysis.

Table I1: Percent error of GC-FID data

PAH compounds	Expected Standard Conc. (mg/L)	Actual Standard Conc. (mg/L)	Avg. % error ±
Naphthalene	1.002	0.987	1.50
Acenaphthylene	1.002	1.012	1.00
Acenaphthene	1.002	0.983	1.90
Fluorene	1.002	1.007	0.50
Phenanthrene	1.002	1.011	0.90
Anthracene	1.002	0.993	0.90
Fluoranthene	0.100	0.102	2.00
Pyrene	0.100	0.098	2.00
Chrysene	0.100	0.097	3.00
Benzo(a) pyrene	0.100	0.105	5.00
		Total avg. % error	**1.87**

QA/QC was performed on the silica gel and sample distillation preparation steps to determine the range of error in these techniques. PAH standards were made, passed through the silica gel, and then run on the GC-FID. Adding the silica gel preparation step increased the percent error. The average percent error during the filtering process was ±3.79%, approximately double the error from only the GC-FID (Table I2). The heavy molecular weight PAHs have a consistently higher percent error than the light molecular weight PAHs.

Table I2: Percent error of silica gel preparation step data

PAH compounds	Expected Standard Conc. after silica gel (mg/L)	Actual Conc. after silica gel (mg/L)	Avg. % error ±
Naphthalene	1.002	0.969	3.29
Acenaphthylene	1.002	1.031	2.89
Acenaphthene	1.002	0.979	2.30
Fluorene	1.002	1.023	2.10
Phenanthrene	1.002	0.984	1.80
Anthracene	1.002	0.977	2.50
Fluoranthene	0.100	0.104	4.00
Pyrene	0.100	0.095	5.00
Chrysene	0.100	0.106	6.00
Benzo(a) pyrene	0.100	0.108	8.00
		Total avg. % error	**3.79**

The distillation process is designed to allow the PAHs in the environment to be concentrated and measured within the detection limit of the GC-FID. This distillation error has the largest percent error because it incorporates the GC-FID, silica gel, and distillation errors. PAH standard concentrations for this quality control assessment were adjusted to fall within the GC-FID detection limit after the distillation step. The average error for all 10 PAH compounds for this step is ±6.28% (Table I3). All of the PAH samples underwent the distillation and silica gel processes. The combined error could be as high as ±12.56%. This error margin, however, only slightly affected the concentrations calculated in the detention pond and wood fibers during the pilot-scale test. For example, WFT4 had an average up gradient and down gradient PAH concentration of 21.8 µg/L and 13.9 µg/L, respectively. Incorporating the ±6.28% error into up gradient and down gradient concentrations, the range would be between 23.2 µg/L to 20.4 µg/L for the up gradient and 14.9 µg/L to 13.1 µg/L for the down gradient. Recalculating the wood filter effectiveness with the percent error PAH concentrations, the filter effectiveness ranged from 27.7% to 43.8%. Incorporating the percent error from the preparation and analysis shifts the PAH removal effectiveness by roughly 8% from the actual calculated effectiveness of 35.6%. This shift in effectiveness still indicates that the filters removed PAHs from the detention pond system.

The Hanna Ion Selective meters were used to analyze nitrate, phosphate, and heavy metals. External standard solutions from Fisher Scientific Inc. were used for Zn, Cu, and Fe, while sodium nitrate and sodium phosphate laboratory standards were used for the nitrate and phosphate quality control assessment. According to the manufacturer, Hanna Ion Selective meters have resolution limits of 0.1mg/L for nitrate, 0.01 mg/L for copper, zinc, and phosphate, and 1.0 µg/L for iron. The average percent error for all the compounds measured with the Hanna Ion Selective meters are listed in Table I4. The external and laboratory standards were analyzed 5 times to generate this average error.

Table I3: Percent error of distillation and silica gel preparation steps data				
PAH compounds	standard (µg/l)	Expected Distilled Conc. (mg/L) 300 mL to 3.39 mL	Actual Distillation Conc. (mg/L)	Avg. % error ±
Naphthalene	10.0	0.885	0.923	4.12
Acenaphthylene	10.0	0.885	0.838	5.61
Acenaphthene	10.0	0.885	0.919	3.70
Fluorene	10.0	0.885	0.948	6.65
Phenanthrene	10.0	0.885	0.849	4.24
Anthracene	10.0	0.885	0.841	5.23
Fluoranthene	1.00	0.089	0.095	6.84
Pyrene	1.00	0.089	0.082	7.93
Chrysene	1.00	0.089	0.097	8.76
Benzo(a) pyrene	1.00	0.089	0.098	9.69
			Total avg. % error	**6.28**

Table I4: Percent error of Hanna Ion Selective meter data			
	Expected Standard Conc. (mg/L)	Actual Measured Conc. (mg/L)	Avg. % error ±
Nitrate (NO_3^-)	3.00	3.14	4.67
Phosphate (PO_4^{3-})	1.00	0.94	6.00
Copper (Cu^{2+})	1.00	0.96	4.00
Iron (Fe)	0.10	0.11	8.00
Zinc (Zn^{2+})	1.00	0.93	7.00

Appendix J: 2-Fluorobiphenyl

2-Fluorobiphenyl was added to the water samples to act as an external standard. This chemical was used was to indicate the quantity of PAHs that were lost through the PAH preservation and distillation processes. Though not found in nature in significant concentrations 2-Fluorobiphenyl, has similar properties as the PAHs analyzed. Also, 2-fluorobiphenyl breakthrough time (25.333 minutes) on the GC-FID is between naphthalene and acenaphthylene. Other possible tracers, such as 1-fluoronaphthalene, conflicted with the PAH analysis because the tracer had a similar breakthrough time as one of the PAHs being analyzed. During the research 2-fluorobiphenyl was not performing as anticipated. The concentrations were consistently lower than expected. 100 µg/L (33.3 µg) were added to 300 mL of methylene chloride and distilled down to approximately 3 mL, a concentration increase of 100 times. With this concentration factor, the expected 2-fluorobiphenyl value should have been 3.3 mg/L; however, less than 1 mg/L was measured.

To investigate the apparent mass loss, three 2-fluorobiphenyl solutions were mixed at concentrations of 100 µg/L, 1 mg/L, and 2 mg/L and passed through the silica gel. The GC-FID analysis of the 100 µg/L solution indicated no 2-fluorobiphenyl was present after passing through the silica gel. Likewise, the 1 mg/L and 2 mg/L 2-fluorobiphenyl solutions lost 80% and 68%, respectively, during the silica gel stage. Most, if not all, of the 2-fluorobiphenyl was removed during the silica gel step. Therefore, 2-fluorobiphenyl could not be used as an external standard.