

WSDOT BMPs FOR STORMWATER RUNOFF IN CONFINED SPACES

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"Confined Spaces BMP's"

WSDOT BMP's for Stormwater Runoff in Confined Spaces

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1.0 INTRODUCTION

1.1 Problem Statement

To improve traffic flow and increase vehicular safety, precipitation must be drained from impervious roadways, bridges, ferry docks and parking surfaces as quickly as possible. In the past, this water was allowed to flow directly into the nearest receiving body of water, such as a river, lake or estuary. Today, however, the environmental consequences of the pollutants contained in stormwater runoff generally prohibit disposing of it in this manner. To be in compliance with water quality regulations, National Pollutant Discharge Elimination System (NPDES) permits, and local jurisdiction requirements, the Washington State Department of Transportation (WSDOT) has developed and adopted numerous design options which are currently being integrated into both new and existing highway projects as part of their overall Best Management Practices (BMPs).

Unfortunately, stormwater runoff from transportation facilities such as bridges, ferry docks and highways in metropolitan areas and from highways with limited shoulders or right-of-way land pose a special problem for designers because of the lack of space for treatment alternatives. This lack of space (due to physical limitations or financial constraints) prevents standard BMP solutions from being implemented. Furthermore, the concept of confined space BMPs can be expanded to include urban highways where little right-of-way is available outside of the median and roadway. For example, a properly designed wet pond may require over an acre of land to obtain the requisite hydraulic detention time. In downtown Seattle and other highly urbanized areas, the land costs would be prohibitive.

1.2 Project Objectives

Currently, there is insufficient documentation to determine which BMPs are most effective in confined areas, or what are each BMP's associated construction and maintenance costs. Furthermore, no specific data is available from the State of Washington. The overall objectives of this project are to provide data concerning performance, operation and maintenance requirements for confined area BMPs and to evaluate the effectiveness of various filter media for use in filtration vaults. Such data will help WSDOT personnel specify stormwater quality improvement projects that satisfy water quality goals with the least cost, the highest likelihood of success, and the greatest environmental benefit.

This project puts existing information together in a coherent document according to specific criteria, thereby helping WSDOT personnel to quickly and accurately determine the optimum water quality management strategy to incorporate into retrofit and new projects. The project also allows local information to be utilized in choosing final solutions as additional material becomes available. The results of this study will enable WSDOT projects to meet water quality objectives with lower cost or higher net benefit.

1.3 Approach

To achieve those objectives, a diverse field of filter media were tested in laboratory column experiments to establish hydraulic and pollutant treatment capabilities. A synthetic stormwater runoff was developed in order to maintain control on the pollutants applied to the media. Effluent samples were analyzed over time to determine removal efficiencies, and, thereby, potential field application maintenance requirements. The top performing media was used for vault design recommendations.

This report is divided into five chapters including the bibliography. Chapter 1 summarizes the objectives and procedures. Chapter 2 presents the background information regarding pollutants in highway runoff. Chapter 3 details the column experiments set-up and results. Conclusions and recommendations are given in Chapter 4 while the bibliography is in Chapter 5.

2.0 HIGHWAY RUNOFF WATER QUALITY

2.1 Background

The Federal Highway Administration (FHWA) (Driscoll *et al.*, 1990) and a number of other state and local governments have conducted studies on the water quality of highway runoff. These studies indicate that highway runoff may carry varying amounts of heavy metals (cadmium, copper, lead, zinc) and various other pollutants (e.g., TSS, oil, gasoline). At high concentrations, metals are toxic to aquatic life. While high concentrations are not typical of highway runoff, metals do not readily degrade in the environment and thus have the potential to bioaccumulate in some fish and aquatic organisms. Other pollutants effect the environment in a variety of ways. Excessive TSS loadings for example may damage aquatic habitat. Oil and gasoline can create a sheen on the water which deters the absorption of oxygen needed by aquatic species, and may also be detrimental to water fowl and other organisms. As a result, alternatives to directly dumping untreated water into a nearby receiving stream are becoming mandatory in many progressive states. These alternatives are becoming part of an overall BMP for each area.

Many alternatives are currently being used in the State of Washington and in the rest of the country. The Washington State Department of Ecology (Ecology) (1992) has developed a guidance document, the *Stormwater Management Manual for the Puget Sound Basin*, indicating many of the known processes. WSDOT has also developed and implemented a similar design document, the *Highway Runoff Manual* (WSDOT, 1995). These documents identify such methodologies as grass filter strips or swales, detention basins, and constructed wetlands. Each of these methods has provided water quality improvements at various locations around the country.

These treatment technologies, however, all require additional acreage. In places such as ferry dock terminals, bridge decks, narrow highways, or metropolitan streets, it is difficult to find sufficient land for construction of stormwater treatment facilities. Moreover, the land costs in metropolitan areas are prohibitive to technologies involving large surface areas such as constructed wetlands.

The development of confined spaces design criteria requires a broad understanding of the current knowledge base pertaining to highway quality and quantity processes. In many instances, entire books have been written concerning the processes discussed in this chapter and additional information is being published every day. Time and space limitations make it impossible to explain all of the complex relationships in lengthy detail. Instead, this chapter synthesizes the background information necessary to understand the chemical, biological and physical processes occurring in stormwater treatment systems.

2.2 Constituents of Concern in Highway Runoff

Numerous references have defined constituents in highway runoff that could result in negative environmental impacts (Shaheen, 1975; Barrett *et al.*, 1993; Driscoll *et al.*, 1990; Field, 1993; Portele *et al.*, 1982). Stormwater runoff constituents that are frequently cited as being "of concern" include heavy metals, deicing agents, hydrocarbons, pesticides, and fertilizers (Kobriger and Geinopolos, 1984). A list of typical

highway stormwater constituents and their concentrations is presented in Table 2.1. It should be pointed out that the range of total suspended solids concentrations is quite variable. The annual loading for total suspended solids is 314-11,862 kg/ha/yr depending on specific site locations. The results of this study do not attempt to consider this variability. This is potentially significant because the usability of the filter methods decreases substantially if excessive maintenance is required.

As further indicated in the table, highway runoff exhibits a wide range of both constituent types and their concentrations for other pollutants as well as TSS. Reported concentrations for some constituents such as copper vary by more than two orders of magnitude. While this sort of variation is the exception rather than the rule, the range of concentrations and loads reported can easily vary by a factor of 10 or more. Similar variability has been reported in nearly every study devoted to quantifying stormwater pollutant concentrations in highway runoff (Driscoll *et al.*, 1990; Harrison and Wilson, 1985; Stotz, 1987; Ball *et al.*, 1991). This is a result of the broad range of system specific conditions that affect runoff quality, and of the inability of researchers to control and quantify all of the external factors affecting pollutant concentrations. Several of the factors which have proven to be the most significant are presented below (Yu, 1993; Racine *et al.*, 1982; Chui *et al.*, 1982):

1. Traffic characteristics, including speed, volume, and braking.
2. Climate conditions, including intensity and form of precipitation, wind, and temperature.
3. Maintenance policies, including sweeping, mowing, repair, and deicing.
4. Surrounding land use, including residential, commercial, industrial, and rural.
5. Percent of pervious and impervious areas.
6. Age and condition of vehicles.
7. Anti-litter laws and regulations covering vehicle emissions.
8. Use of special additives in vehicular operation.
9. Vegetation types on the highway right-of-way.
10. Accidental spills.

Efforts to correlate pollutant concentrations to one or more of the items listed above have been attempted. Table 2.2 lists pollutant concentrations found in highway runoff from both urban and rural highways as a function of average daily traffic (ADT) (Driscoll *et al.*, 1990). However, attempts to broadly characterize the quality of highway runoff have produced less than satisfying results. Moreover, studies such as that conducted by Dorman *et al.*, found pollutant concentrations in highway runoff to be site specific, meaning that correlation between sites or studies would be impossible (Dorman *et al.*, 1988). The discrepancies between studies may also be linked, at least in part, to a lack of consistent measurement of system parameters or improper reporting. The difficulty and expense in obtaining the information required in the above list should be obvious. Yet, if critical factors are left out, comparisons between sites are nearly impossible.

Critical pollutant levels for selected highway related substances and their impacts were first published in an FHWA study in 1984 (Dupuis *et al.*, 1984). These findings are summarized below in Table 2.3. Care must be exercised when developing and using a table such as this due to the highly system specific conditions that control the impact of pollutants on the environment. Furthermore, the concept of impact should be better defined. For example, domestic water supply impact may imply an aesthetic impact such as taste and odor or it may imply an impact to human health.

Table 2.4 illustrates a more comprehensive list of the primary sources of metals in roadway runoff. Sansalone and Buchberger also demonstrated a dramatic decline in lead (Pb) concentrations in highway runoff since the virtual elimination of leaded fuel (1997).

Although runoff constituent characterization is relatively comprehensive in terms of the range of conditions and number of samples collected, insufficient data exists that define the "state" or form of the constituent required for accurate assessment of metals speciation and solid/aqueous phase partitioning. There is currently a considerable amount of discussion regarding the form of pollutant discharged into receiving waters. It is commonly envisioned that dissolved pollutants are available for biological consumption while sediment or particulate bound pollutants may be less detrimental to the environment.

Table 2.1 Average Values of Constituents in Highway Runoff.
(after Driscoll *et al.*, 1990)

Constituent	Concentration (mg/L unless noted)	Load (kg/ha/year)	Load (kg/ha/event)
SOLIDS			
Total	437-1147		58.2
Dissolved	356	148	
Suspended	45-798	314-11,862	84-107.6
Volatile, dissolved	131		
Volatile, suspended	4.3-79	45-961	0.89-28.4
Volatile, total	57-242	179-2518	10.5
METALS (total)			
Zn	0.056-0.929	0.22-10.40	0.004-0.025
Cd	ND-0.04	0.0072-0.037	0.002
As	0.058		
Ni	0.053	0.07	
Cu	0.022-7.033	0.030-4.67	0.0063
Fe	2.429-10.3	4.37-28.81	0.56
Pb	0.073-1.78	0.08-21.2	0.008-0.22
Cr	ND-0.04	0.012-0.010	0.0031
Mg	1.062		
Hg (x 10 ⁻³)	3.22	0.007	0.0007
NUTRIENTS			
Ammonia, as N	0.07-0.22	1.03-4.60	
Nitrite, as N	0.013-0.25		
Nitrate, as N	0.306-1.4		
Nitrite + Nitrate	0.150-1.636	0.8-8.00	0.078
Organic, as N	0.965-2.3		
TKN	0.335-55.0	1.66-31.95	0.17
Nitrogen, as N	4.10	9.80	0.02-0.32
Phosphorous, as P	0.113-0.998	0.6-8.23	
MISCELLANEOUS			
Total coliforms number/100 mL	570-6200		
Fecal coliforms number/100 mL	50-590		
Sodium		1.95	
Chloride		4.63-1344	
PH	7.1-7.2		
Total Organic Carbon	24-77	31.3-342.1	0.88-2.35
COD	14.7-272	128-3868	2.90-66.90
BOD ₅	12.7-37	30.60-164	0.98
Polynuclear Aromatic Hydrocarbons (PAH)		0.005-0.018	
Oil and Grease	2.7-27	4.85-767	0.09-0.16
Specific Conductance (µmohs/cm @ 25°C)	337-500		
Turbidity (JTU)	84-127		

Table 2.2 Pollutant Concentrations in Highway Runoff Site Median Concentrations
 (after Driscoll *et al.*, 1990)

Pollutant	Urban Highways ADT > 30,000 (mg/L)	Rural Highways ADT < 30,000 (mg/L)
TSS	142	41
VSS	39	12
TOC	25	8
COD	114	49
Nitrate + nitrite	0.76	0.46
TKN	1.83	0.87
PO ₄	0.4	0.16
Cu	0.054	0.022
Pb	0.4	0.08
Zn	0.329	0.08

**Table 2.3 Critical Pollutant Levels and Their Impacts on Receiving Waters
From Highway Related Sources**
(after Dupuis *et al.*, 1984)

Constituent	Critical Level	Impact	Source(s)
Cd	59 µg/L	Saltwater aquatic life	Tire wear
Chloride	250 mg/L	Domestic water supply	Deicing
Cr	50 µg/L	Human health	Brake
Cu	< 1 mg/L	Taste and odor	Brake, Engine and Tire wear
Fe	50 µg/L	Domestic water supply	Body rust
Pb	50 µg/L	Human health	Tire wear, exhaust
Ni	100 µg/L	Human health	Diesel
Nitrate	10 mg/L	Domestic water supply	Fertilizers
Oil and Grease	No floating oils	Freshwater aquatic life	Oils and greases
Phosphate	0.10 µg/L	Marine/estuarine waters	Fertilizers
TSS	Compensation point for photosynthetic activity should not be reduced by more than 10%	Freshwater fish and other aquatic life	Pavement wear, sanding
Zn	5 mg/L	Taste and odor	Oil and grease

Table 2.4 Sources of Anthropogenic Constituents in Urban Pavement Runoff

(after Sansalone and Buchberger, 1997)

Pollutant	Brakes	Tires	Frame and Body	Fuels and Oils	Pavement Type		Deicing Salts	Litter
					Concrete	Asphalt		
Cd	Secondary	Primary						
Cr		Primary						
Cu	Primary	Primary						
Fe		Primary	Primary					Primary
Pb	Secondary	Secondary		Secondary			Secondary	
Ni		Primary						
V				Primary				
Zn	Primary	Primary	Primary					
Chlorides							Primary	
Organic Solids						Primary		Primary
Inorganic Solids			Secondary		Secondary	Primary		Primary
PAH				Secondary		Primary		
Phenols						Primary		

Legend: Primary Source  Secondary Source 

The percentages of dissolved (f_d) and particulate (f_p) pollutant forms can be calculated using the following two equations:

$$f_d = \frac{\text{Dissolved}}{\text{Dissolved} + \text{Particulate Bound}} = \frac{1}{1 + K_d m}$$

$$f_p = \frac{\text{Particulate Bound}}{\text{Dissolved} + \text{Particulate Bound}}$$

The expression K_d in the denominator of the first equation is called the *partitioning coefficient* and can be expressed as (Weber *et al.*, 1991):

$$K_d = \frac{C_s}{C} = K_{oc} f_{oc}$$

where C is the dissolved pollutant concentration (mg/L), C_s is the particulate-bound mass typically expressed in terms of mg/kg of dry solids, K_{oc} is the organic carbon partition coefficient, f_{oc} is the fraction of organic carbon, and m is the solids concentration expressed as total suspended solids (kg/L). The right-hand side of the last equation is strictly valid only in cases where the fraction of organic carbon in the soils is greater than approximately 1 percent (Karickhoff *et al.*, 1979). Based on ongoing, unpublished research by the authors, 50-75% of soils found in detention ponds receiving highway runoff have an organic carbon fraction greater than 1 percent.

It is difficult to obtain definite values for either the dissolved fraction or the partitioning coefficient because many environmental factors play important roles. Table 2.5 illustrates the role that suspended solids play in determining K_d (Mills, 1982). Figure 2.1 illustrates the variability of the dissolved fractions and partitioning coefficients for Cu, Cd, Zn, Pb and Al in stormwater collected from an urban highway setting (Sansalone and Buchberger, 1997). While certain general trends can be seen, specific quantitative results are difficult to identify. For example, the dissolved fraction of Cd increases between the April 8th event and the July 15th event as does the fractions of dissolved Cu and Zn. However, the dissolved fraction of Pb decreases between the April 30th rainfall event while the dissolved fraction of Al dramatically increases. Furthermore, relatively small decreases in the dissolved Cu and Zn percentages can be seen in the September 8th event while a 50 percent reduction in Cd occurs. Similar scatter is evident in the partitioning data. The seasonality of the dissolved metals concentrations may be attributed to highway maintenance practices such as deicing agents and road salt, but that has not yet been confirmed.

Table 2.5 Speciation of Metals as a Function of Suspended Solids Concentration
(after Mills, 1982)

Metal	SS (mg/L)	K_d (L/kg)	Percent Dissolved	Percent Adsorbed
As	1	5×10^2	70	30
	10	9×10^4	50	50
	100	2×10^4	30	70
	1000	3×10^3	24	76
Cd	1	4×10^0	20	80
	10	3×10^5	25	75
	100	2×10^4	30	70
	1000	2×10^3	40	60
Cr	1	3×10^0	25	75
	10	4×10^5	20	80
	100	5×10^4	17	83
	1000	5×10^3	15	85
Cu	1	1×10^0	50	50
	10	2×10^5	30	70
	100	3×10^4	25	75
	1000	6×10^3	14	86
Pb	1	3×10^2	75	25
	10	2×10^5	30	70
	100	1×10^5	10	90
	1000	9×10^4	1	99
Hg	1	3×10^0	25	75
	10	2×10^5	30	70
	100	2×10^4	30	70
	1000	1×10^3	45	55
Ni	1	5×10^2	70	30
	10	1×10^5	50	50
	100	4×10^4	20	80
	1000	9×10^3	10	90
Zn	1	1×10^0	40	60
	10	2×10^5	30	70
	100	4×10^4	17	83
	1000	1×10^4	10	90

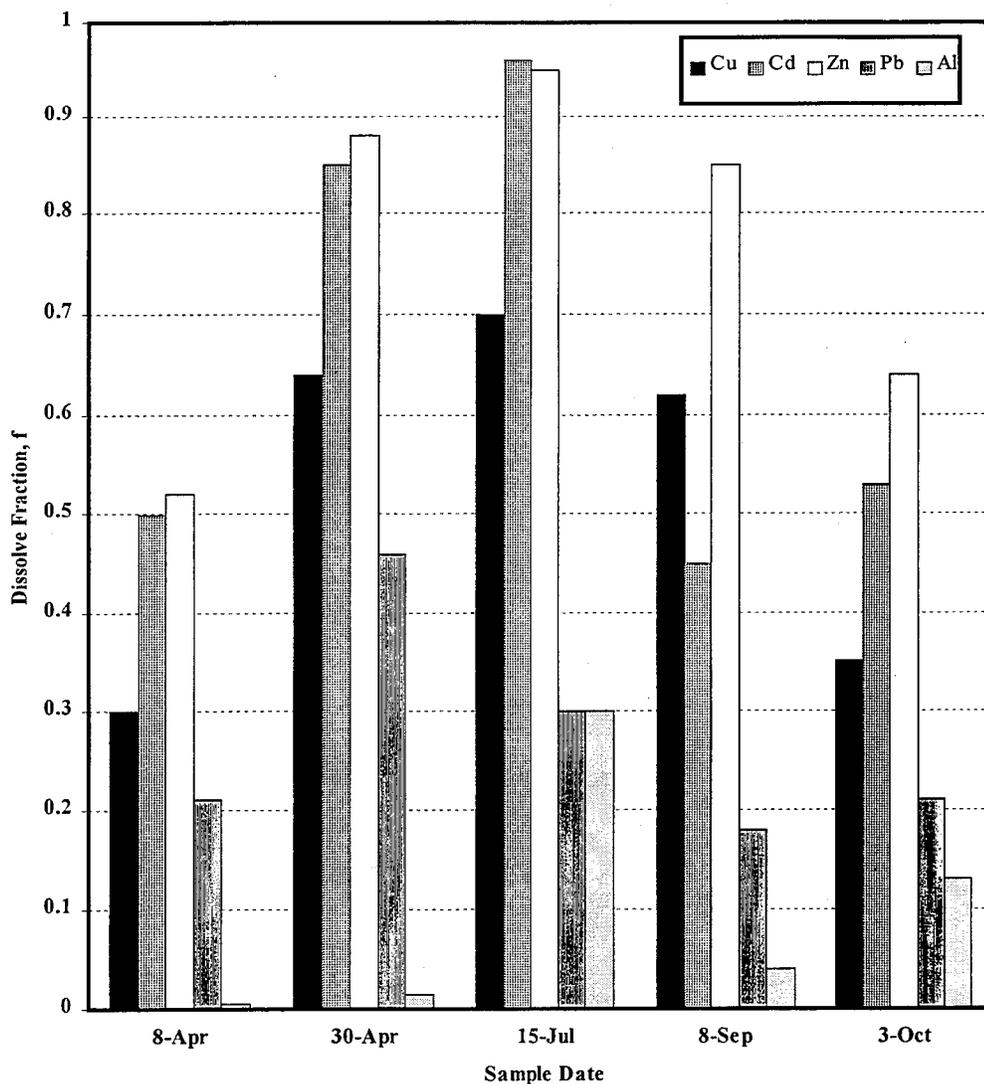


Figure 2.1 Dissolved Fraction and Partitioning of Metals from Urban Highway

(after Sansalone and Buchberger, 1997)

One of the important parameters indirectly listed in Table 2.5 which is not generally identified in most analyses is mineralogy. The suspended solids data suggest that the only relevant parameter is concentration, which is certainly not the case. The role of mineralogy in the availability of sediment-bound pollutants may be extremely important. Figure 2.2 illustrates the ability of the three predominant clay types to adsorb Zn under a variety of pH conditions (Funk *et al.*, 1975). At a neutral pH of 7.0 there is three times as much cation exchange capacity for illite as there is for kaolinite.

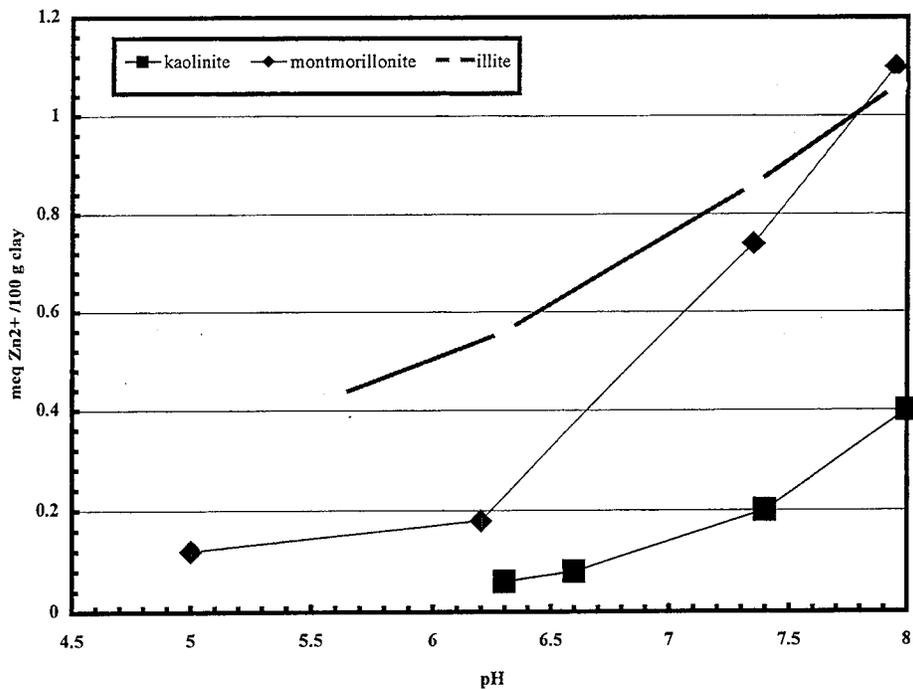


Figure 2.2 Adsorption of Zn as a Function of pH and Mineralogy
(after Funk *et al.*, 1975)

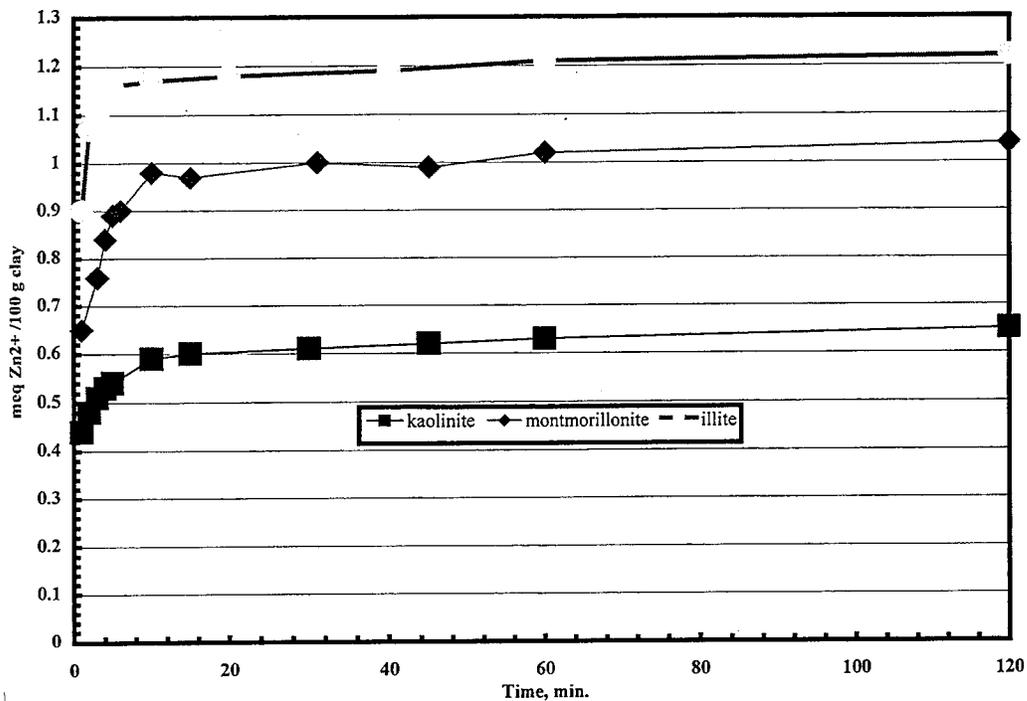


Figure 2.3 Zinc Adsorption Versus Time to Reach Equilibrium
(after Funk *et al.*, 1975)

As shown in Figure 2.3, the sorption kinetics for illite is slightly greater than that for kaolinite or montmorillonite. After 10 minutes the rate of adsorption begins to approach steady state. It takes approximately 20 minutes to observe the same phenomenon in the other two minerals. However, equilibrium for all three clays is reached at approximately the same time as illustrated by the similar slopes of the three lines at times greater than 80 minutes.

An understanding of the interaction of constituents with the particulate phase is vitally important when evaluating BMP removal effectiveness and potential environmental impacts. Since some fraction of most constituents of concern partition onto particulates (e.g., sediment), and since sediment is often effectively removed in stormwater BMPs, an understanding of this relationship is required for effective BMP design. Conversely, since constituents are generally considered more toxic when in the dissolved versus particulate bound state (Lee and Jones-Lee, 1996), merely reporting a reduction of constituents as a function of the total concentration presents an incomplete picture of BMP effectiveness.

A further complication occurs because not all adsorption mechanisms result in irreversible reactions. Normal fluctuations in temperature and basic water chemistry parameters (e.g. pH and oxidation reduction potential (ORP)) can affect the equilibrium concentrations of the sorbed contaminants and the surrounding water. This could potentially result in the release of a constituent from the trapped sediment into the water column, thereby reintroducing them to the environment.

The majority of the current stormwater quality data presents metal and hydrocarbon concentrations as total concentrations, with no distinction made between the soluble and particulate bound fractions. Metals, organics, and nutrients common to highway runoff can have high partition coefficients, existing primarily on the solid phase (sediment). Morrison, for example, reported that the soluble portions of the total Cu, Pb, and Zn in stormwater runoff was 10%, 1%, and 30%; while Driscoll, based on the EPA's NURP study, reports soluble portions of Cu, Pb, and Zn of 40%, 10%, and 40%, respectively, as reasonable estimates for preliminary analysis (Driscoll *et al.*, 1990, USEPA, 1983). Based on the same NURP study, Cole concluded that a 40% soluble metals fraction is a reasonable estimate (Cole *et al.*, 1984). Paulson's analysis of the NURP data agreed well, indicating Cu, Pb, and Zn soluble fractions of 30%, 20%, and 50%, for four study sites in Fresno, CA (Paulson *et al.*, 1992). It is important to note that the NURP study data is predominately based on urban runoff and it is possible that highway runoff in non-urban areas would have different partition coefficients.

Sediment size is also known to affect partitioning. In general, smaller particles adsorb more contaminant per unit mass than larger particles (Shaheen, 1975; Amy *et al.*, 1974; Hopke *et al.*, 1980; Cole and Yonge, 1993; and Svensson, 1987). Yonge and Price, for example, found that 4 μm sediment particles exhibited a six-fold increase in sorption capacity (mass/mass) over 17 μm particles while Zn exhibited a 4.6-fold increase (1995, 1996). Although smaller particles will afford enhanced partitioning and lower soluble phase concentrations, they exhibit lower removal efficiencies in detention pond BMPs due to their lower settling velocities. An understanding of the key controlling factors is required to better define the

relationship between dissolved and “bound” metal species. These controlling factors can include particle size and concentration, alkalinity, and ammonia concentration (Paulson *et al.*, 1992; Price and Yonge, 1996).

Studies have also found that the environmental impacts from metals are dependent on the speciation or form in which the metals exist in the dissolved state. The factors most influencing metal speciation are pH, complexation, and redox conditions (Palmer and Wittbrodt, 1991; Hathhorn and Yonge, 1996). Unlike many organic compounds, metals do not degrade because the pollutants are themselves elements (Dorman *et al.*, 1988). It is possible, however, for the valence state of the metal to change via redox processes (e.g., Cr⁺⁶ to Cr⁺³). This may affect the toxicological importance of the dissolved metal. For example, a more toxic Cr⁺⁶ can be reduced to a less toxic and less mobile Cr⁺³ (Palmer and Wittbrodt, 1991). Dorman *et al.* also found that toxic organo-metal complexes may be susceptible to degradation, resulting in the formation of less toxic metal oxides (1988).

As was shown in Table 2.1, water quality analysis of highway runoff has indicated the presence of petroleum hydrocarbons in various phases and concentrations. This is of concern because many hydrocarbon components have been found to exhibit carcinogenic effects (Gavens *et al.*, 1982). The concentrations fluctuate according to site characteristics and measurement techniques. One problem with comparing different studies is the inconsistency of hydrocarbon reporting. Some studies report “oil and grease” values but this lumps polar organic compounds together with hydrocarbons and does not distinguish between anthropogenic and biogenic hydrocarbons (Fam *et al.*, 1987). Other studies often measure Total Petroleum Hydrocarbon (TPH) or Polynuclear Aromatic Hydrocarbon (PAH) as well as oil and grease (Hoffman *et al.*, 1984; Madonato and Uchirin, 1994). PAHs are the benzene elutable fractions of hydrocarbons formed in combustion processes (Bomboi and Hernandez, 1991). The eight PAH compounds that have been reported in highway runoff are: phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(a)pyrene, and benzo(g,h,i)perylene (Hewitt and Rashed, 1992).

Like most metals, petroleum hydrocarbons are generally hydrophobic and thus they readily adsorb to sediments. However, unlike metals, PAHs are degradable through both chemical and biological reactions. Under typical environmental conditions the half lives of some PAHs have been found to be only a few hours (Neff, 1979). Other studies claim that this is the reason that PAH concentrations are not correlated with antecedent dry periods (Eganhouse and Kaplan, 1981). Huter *et al.*, found that 85% of the TPHs found in urban runoff were “particulate-associated” (1979). Barrick also showed a correlation of high molecular weight PAHs to “street-dust accumulation” (1982). Consequently, filtration devices are an effective means of mitigation.

2.3 Traditional BMPs

2.3.1 Infiltration Basins

One BMP for both water quality and quantity listed in the WSDOT *Highway Runoff Manual* (1995) is the infiltration pond or basin. Infiltration basins use the same basic principles in stormwater treatment as infiltration trenches. However, they can be used as a detention pond as well. Infiltration basins provide very good hydraulic treatment. Infiltration, storage, and detention act to reduce the peak and volume of the runoff hydrograph (Urbonas and Stahre, 1993). The problem is that the size required for infiltration basins is often greater than the space available in highway rights-of-way. This creates a tradeoff between basin size and treatment efficiency (Schueler, 1987). Hydraulically, larger basins allow greater infiltration and storage, thereby providing better treatment quantitatively by reducing overflows and qualitatively by increasing the residence time for sedimentation. Environmentally, Table 2.6 shows the relationship between detention basins sized for different storms and pollutant removal efficiencies.

Table 2.6 Removal Efficiencies for Different Size Infiltration Basins

(after FHWA, 1996)

Pollutant	Design Storm Magnitude		
	1.27 cm (0.5 in)	2.54 cm (1.0 in)	5.08 cm (2.0 in)
Sediment	75%	90%	99%
Total Phosphorus	50-55%	60-70%	65-75%
Total Nitrogen	45-55%	55-60%	60-70%
Trace Metals	75-80%	85-90%	95-99%
BOD	70%	80%	90%
Bacteria	75%	90%	98%

Again, infiltration basins suffer from clogging. The advantage of infiltration basins over infiltration trenches is ease in maintenance (FHWA, 1996). For example, operation success is determined by simple observation, and repairs can be made by draining the pond.

The infiltration basin has been popular as a BMP in Washington State (WSDOT, 1995) because it can be effective in the control of large stormwater flows and in the sedimentation of suspended solids. However, recent findings have shown the potential for groundwater contamination may be present in areas

of shallow groundwater tables (Duchene, 1994; Hathhorn and Yonge, 1996). Washington State has a “groundwater anti-degradation policy” (WAC-173-200-030) which permits zero degradation of groundwater. A detailed study of metal migration through soil columns was performed by Igloria (1995) to determine potential impact of infiltration on groundwater. In this study, net removal of pollutants was good; however, pollutant mass was observed at the outlet of the soil columns. Therefore, given current Washington State law, infiltration basins may not be viable BMPs in susceptible locations.

2.3.2 Detention Facilities

Detention facilities used by WSDOT include dry ponds, wet ponds, and vaults (WSDOT, 1995). These BMPs use storage and retention as primary mechanisms for hydraulic treatment of stormwater (Barrett *et al.*, 1993). Storage of stormwater reduces the peak discharge which reduces potential flooding and erosion downstream (Barrett *et al.*, 1993).

The dry pond performs well with respect to hydraulic treatment and is the least expensive to build (Hartigan, 1989; Barrett *et al.*, 1993). However, the dry pond lacks in pollutant treatment capabilities (Schueler, 1989; Yu, 1993). Any contaminant treatment must occur through sedimentation which depends on the detention time of the pond (FHWA, 1996). A major problem with dry ponds is the operation and maintenance costs associated with cleaning litter and debris (Barrett *et al.*, 1993).

Wet ponds are the same as dry ponds except water remains in the pond at all times. Wet ponds are generally less effective hydraulically for a given size relative to dry ponds (Hartigan, 1989). Hydraulic treatment capabilities are compromised by smaller detention volumes (Hartigan, 1989). However, wet ponds offer improved pollutant treatment through longer residence times, better sedimentation, and biological activity (Schueler, 1989; Hvitved-Jacobsen, 1990; Barrett *et al.*, 1993).

2.3.3 Sand Filters

Sand filters are very similar to the well known rapid sand filter used for drinking water treatment, although it is not listed as a BMP in the WSDOT *Manual* (1995). Figure 2.2 illustrates a typical sand filter cross section for stormwater treatment.

The sand filter uses straining, sedimentation, adsorption, chemical transformation, and microbial decomposition. Filtration is the primary mechanism of removal. Particulate removal efficiencies are generally in the 80 % - 90 % range (FHWA, 1996). The pollutants associated with good removal efficiencies include total suspended solids, heavy metals, total organic carbon, and organic nitrogen (Barrett *et al.*, 1993).

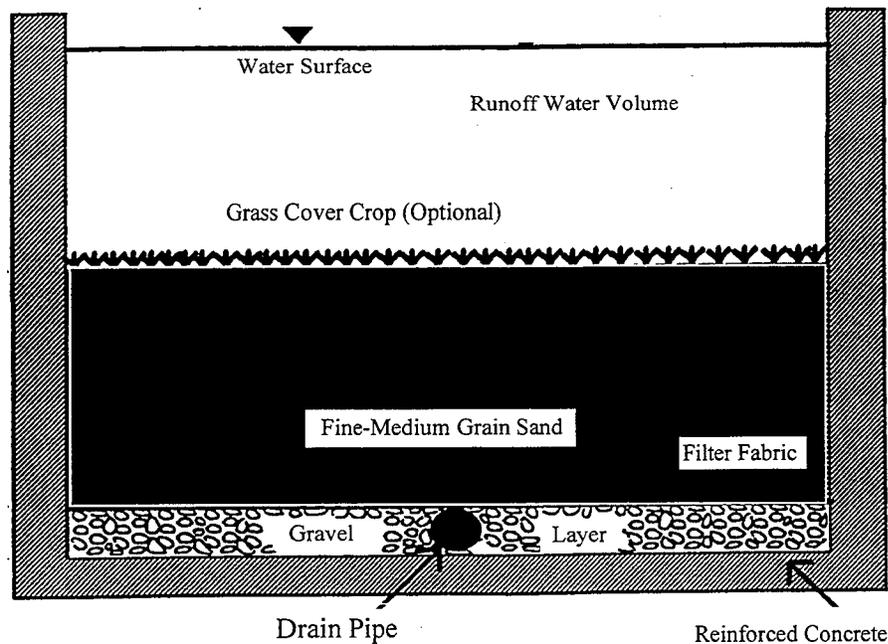


Figure 2.4 Typical Sand Filter

(after Barrett *et al.*, 1993)

Two major disadvantages of the sand filter are clogging and poor hydraulic treatment in terms of pollutant adsorption and removal. Like infiltration practices, the sand filter is especially sensitive to clogging (FHWA, 1996). Sand filters perform very little hydraulic treatment standing alone; therefore, it is recommended to use detention BMPs in conjunction with the filter (Urbonas and Stahre, 1993).

2.3.4 Grassed Swales and Filter Strips

WSDOT (1995) lists both biofiltration swales and vegetative filter strips as water quality BMPs. Grass-lined swales and filter strips are very similar. Grass-lined swales are gently sloped shallow vegetated channels and filter strips are vegetated slopes in which sheet flow dominates the runoff flow pattern. Like sand filters, these BMPs perform poor hydraulic treatment. In an ongoing project with the WSDOT, filter strips are currently being tested. Preliminary observations show very poor hydraulic treatment in strips containing low permeable soils.

Both of these BMPs use the same mechanisms for stormwater treatment. Filtration and infiltration are the primary mechanisms for contaminant removal. Literature presents conflicting results in pollutant

removal efficiencies. In a study at Washington State University, high removal rates of heavy metals were observed (Newberry and Yonge, 1996). On the other hand, FHWA suggest low to moderate removal efficiencies (1996). A study performed by Harper *et al.* in 1984 showed removal rates of heavy metals were highly dependent on pH and chemical speciation of the metal ions. Much work still is needed on the removal efficiencies of grass swales and filter strips. Nevertheless, grassed swales and filter strips are most beneficial when used in conjunction with other BMPs as a pre-treatment mechanism. For example, including this type of BMP in conjunction with an infiltration trench greatly increases the life of the primary BMP by removing large suspended solids (FHWA, 1996).

3.0 COLUMN EXPERIMENT

3.1 *Related BMPs: Stormwater Filter Systems*

The following discussion of commercially available stormwater filter systems is based solely on product literature. None of the claims have been tested to verify their hydraulic or treatment efficiencies. This section purely informational; it is not intended as an endorsement for any of these products.

CSF Treatment Systems, Inc. has developed a product called the Compost Stormwater Filter (CSF[®]). According to the general information document prepared by the company, this device allows for a high level of water quality treatment that meets or exceeds the levels provided by conventional BMPs, yet requires substantially less area for installation (CSF, 1995). The compost filter media used in a CSF is a recycled material composed primarily of composted leaves. The leaf compost undergoes a final processing to stabilize the material and increase its permeability characteristics. The final product is a very stable media with a high humic acid content. The compost filter provides multiple pollutant removal mechanisms. First, it acts as a mechanical filter to remove fine sediments. Second, it is an ion exchanger removing solubilized ionic pollutants such as metals. Third, it provides molecular adsorption sites to remove organics. Fourth, it provides biological substrate sites for organisms to aid in the degradation of organic compounds such as oil and grease.

The compost filters are designed to be most effective for treatment of first flush flows. Since the filters are maintained in the dry season, they function better early in a rain season where pollutant concentrations frequently are highest. In general, the compost filter efficiency is highest when pollutant concentrations are highest. Filter maintenance is critical to achieving high levels of performance. Maintenance cycles must be scheduled around anticipated rain seasons.

The actual function of the CSF is quite simple. Stormwater flows into the unit through a scum baffle and cascades onto an energy dissipator. The water flows onto the surface of the compost and infiltrates. Water infiltrating through the compost media collects into an underdrain and discharges through the outlet. In the event that the flow into the filter exceeds the design capacity or the infiltration rate of the compost has been reduced due to sediment loading, water will pond up. Once ponding water reaches the invert of the overflow weir, it then bypasses the filter bed and discharges to the outlet. Even in the event of an overflow, the scum baffles continue to provide for the removal of floatables, solids, and surface films. The single Drop-In unit can treat a range of water quality flows from 7.93 L/s to 18.1 L/s (0.28 cfs to 0.64 cfs). Figure 3.1 illustrates a CSF StormFilter[™] Schematic.

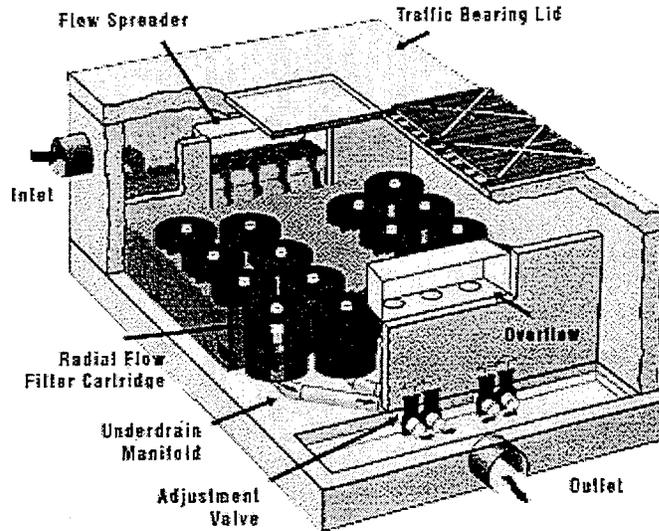


Figure 3.1 CSF StormFilter™ Schematic

(after CSF, 1995)

The CSF® has been shown to consistently remove in excess of 90% of the total suspended solids entering the filter (CSF, 1995). The solids are mechanically filtered out by the compost media, the majority of which are deposited on the surface of the filter. Given light loadings of oil and grease in ranges of 20 mg/L, the CSF® has typical removal efficiencies of 85%. The CSF® is not recommended to treat heavy loadings of oil and grease unless gross removal is done upstream with an oil/water separator. Metals such as lead, copper, and chromium present in stormwater are removed by the CSF® in ranges from 85%-95% depending on the metal. The CSF® is particularly efficient in removing soluble metals by mechanisms of cation exchange within the compost media itself, a property not available with most other BMPs.

Total phosphorus removal rates vary with the incident loadings. The CSF® performs best during the first flush flows when total phosphorus loading are their highest, yielding removal efficiencies as high as 77%. As loading rates decrease later in the storm event, the removal efficiencies decrease. The overall total phosphorus removal rate is approximately 45%. Similarly, total Kjeldahl nitrogen decreases by about 50%. Though total phosphorus and total nitrogen decrease, soluble phosphorus and nitrates typically show a slight increase of about 1.0 mg/L. The pH of compost itself is slightly basic and data indicate that it will raise the effluent pH by about 0.1 to 0.2.

The Stormceptor system is another confined space BMP for stormwater quality treatment. According to Stormceptor Corporation literature, the Stormceptor is a precast modular water quality structure that can be installed in existing and with new storm drain systems (1996). It is an innovative, economical and effective device that removes a high percentage of oil, sediment, and other urban runoff pollutants. It has a unique design that prevents the resuspension or scouring of previously collected

pollutants, even during periods of peak water flow. This means that the *Stormceptor* cannot become a pollution source unlike most other stormwater BMPs. *Stormceptor* can be used as a primary water quality device, as a pretreatment device, as a spill control device, or as a general stormwater device to remove bulk solids and floatables. The device includes a built in diversion (by-pass) structure that allows the first flush (80% to 90% of all rain hours) to enter the treatment chamber, but diverts the problem causing flushing storms (10% to 20% of all rain hours) around the treatment chamber. The diversion feature allows the unit to have a smaller volume as compared to flush through devices. A 1.27 cm (0.5 in) rainfall (which is greater than 60% to 70% of all storm events), six hour storm (average storm duration for all storm events) is fully treated, i.e. no by-passing, through the device. The *Stormceptor* design also includes a water locking feature that prevents trapped hydrocarbons (VOCs, floating oils and gasoline) from being resuspended or easily volatilizing into the atmosphere.

The unit is made as a precast concrete structure, which appears and installs like a precast concrete manhole. A fiberglass version is also available. The unit design flexibility allows it to be used in-place of a manhole or bend structure and in situations where drainage grade lines are restricted due to topography, high groundwater, or utility conflicts. The unit needs only 2.54 cm (1 in) of fall through structure. The unit comes in various sizes and is best suited for all types of land uses with drainage areas from 0.10 ha to 4.05 ha (0.25 ac to 10 ac). Treatment rates, prior to bypass flow occurring, are from 18.1 L/s to 70.8 L/s (0.64 cfs to 2.5 cfs). The expected life of this unit is 50 to 100 years. Figure 3.2 shows a schematic of the *Stormceptor*.

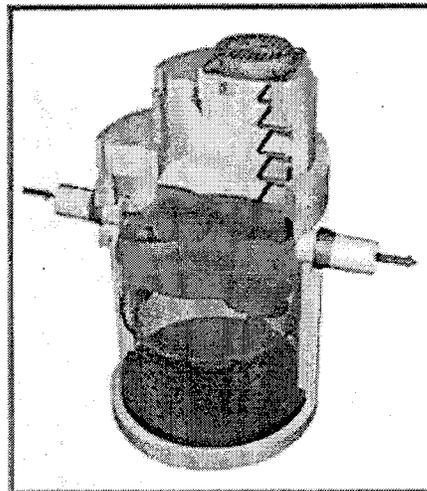


Figure 3.2 Stormceptor Schematic

(after Stormceptor, 1996)

According to Stormceptor Corporation literature (1996), the unit is effective at removing and retaining materials that are trapped; the retained material cannot be flushed out. It removes on average 60% to 80% and greater of total suspended sediment load, more effective than traditional ultra urban water quality devices. Long term phosphorus removal for Stormceptor is estimated to be 25% or greater. It removes on average 70% to 100% of floatable oil and grease, more effective than conventional water quality devices. The unique design prevents reemulsion of collected petroleum products. It also has minimal temperature impacts to treated runoff. It must be pointed out that manufacturer's data is generally derived from bench-scale tests using constant hydraulic and pollutant loads which may not accurately reflect actual field conditions.

The Stormceptor meets requirements to utilize best available technology and will meet and exceed most storm drainage water quality numerical permit limits, such as for NPDES permits. The unit works best when large debris (large jugs, lumber, bundles of paper, etc.) are screened out of the stormwater entering the unit. The Stormceptor like all water quality separators requires periodic maintenance. Typical water quality inlet maintenance is recommended to be done four or more times a year, but the Stormceptor requires less frequent maintenance due to its unique design. Maintenance of the Stormceptor is generally done one time per year.

Hydraulically, the Stormceptor treats a large percentage of all rain events (average 90 to 120 rain events per year) in a given year; 95.1% of all rain events are less than 4.21 cm (1.66 in). The unit fully treats 4.27 cm (1.68 in) of runoff from a 24 hour uniform storm. It fully treats 80% to 90% of annual flow volume; it fully treats 1.27 cm (0.5 in) of runoff from a 24 hour, Type II SCS storm.

A third commercially available stormwater treatment vault is the Stormtreat System. According to its Internet information, Stormtreat is a unique, multi-stage, stormwater treatment system that removes and reduces a broad range of pollutants including bacteria, petroleum hydrocarbons, metals, and nutrients. The Stormtreat System meets EPA's recommended 80% removal of Total Suspended Solids (TSS), and can be easily sized to meet more stringent state standards in critical water resource areas. By providing highly efficient treatment of the first flush, the Stormtreat System compares favorably with other stormwater BMPs on a per-acre treated basis.

The Stormtreat System significantly reduces the need for unsightly and land-intensive detention facilities. It treats all of the smaller (routine) storms and treats the first flush of the large (less common) storms. As a result of this treatment, flood control can be accomplished by using more aesthetically pleasing landscape buffers or smaller detention facilities. Maintenance is simplified by standardized procedures and is limited to annual inspections (and replacement of grit filter bag) and sediment pumping once every three to five years using standard septic system pumper.

The Stormtreat System incorporates effective pre-treatment by directing stormwater through Stormtreat's unique, multi-stage, total suspended solids removal system prior to infiltration. This includes a grit-filter bag to trap the larger floatables which may find their way past the catch basin preceding the unit, a series of sedimentation chambers fitted with "skimmers" (which significantly enhance the settling

efficiency of particulates by continually drawing from just below the surface of the water, and “decanting” it to the next chamber, and a gravel filter which serves as a substrate for a constructed wetland. Larger-diameter particulates are trapped inside the sedimentation chambers and smaller (silt and clay-sized) particles are filtered in the gravel wetland substrate. The smaller particles are predominantly organic in composition and therefore can be decomposed in the wetland soils by bacteria which reside within the wetland plant root zone. Treated stormwater is then infiltrated into the 1.91 cm (0.75 in) stone used for backfill in the excavation around and under the Stormtreat tanks. This stone is highly permeable and serves to transmit the treated water downward until it encounters the parent soils. During peak flow periods, the infiltration rate may exceed the permeability of the parent soils and the stone backfill area serves as a temporary storage reservoir. As this area fills with water, a substantially larger leaching surface is encountered by the treated stormwater.

The Stormtreat System is constructed of recycled polyethylene. Figure 3.3 illustrates a schematic of a Stormtreat unit. Figure 3.4 provides a pollutant removal summary of the Stormtreat System.

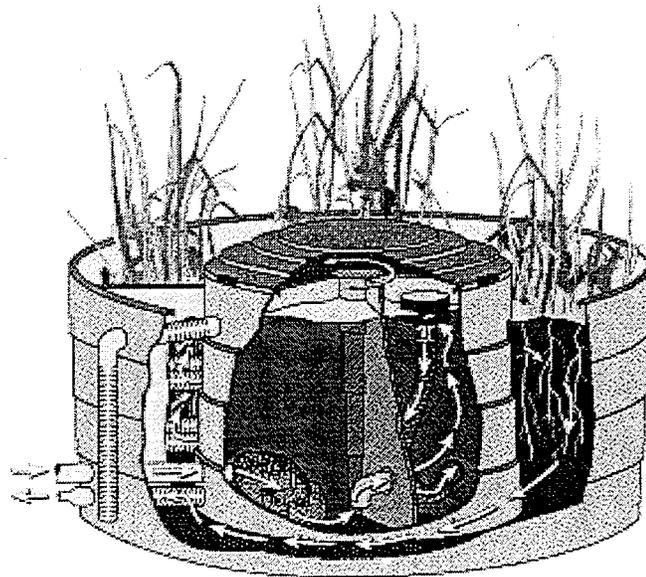


Figure 3.3 Stormtreat System Tank

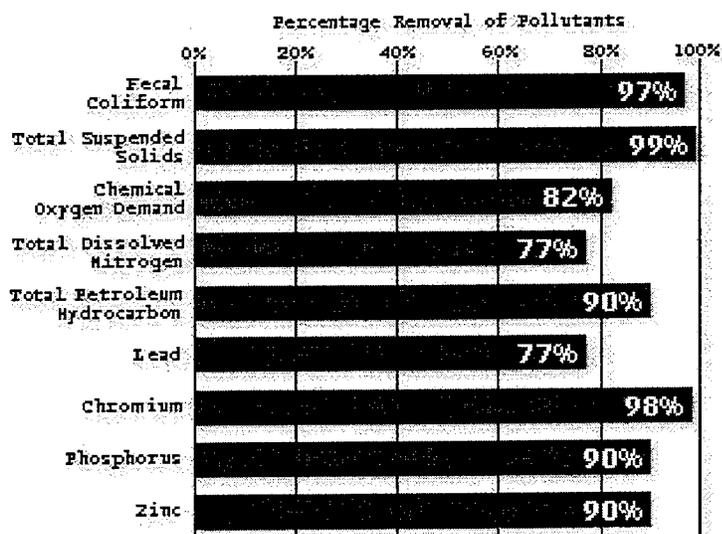


Figure 3.4 Pollutant Removal Summary for the Stormtreat™ System

(data taken from manufacturer's literature)

A fourth commercially available stormwater filter device is the Hydro-Kleen H-2000 from Bamcon Engineering (Pollution Engineering, 1998). It uses a treated paper pulp filter medium combined with a special texture-activated carbon filter medium to eliminate hydrocarbons, organically bound heavy metals, polychlorinated biphenyls, volatile organic compounds, and other contaminants from stormwater. Adsorbed materials are locked into the primary medium's fibers; the secondary medium polishes the stream.

The Vortechs Stormwater Treatment System is yet another commercially available unit. It is constructed of precast concrete and features a compact, below-grade profile. According to company literature (Vortechs, 1998), the system incorporates a combination of treatment structures that efficiently remove pollutants from runoff at rates up to 0.71 cms (25 cfs) without washing out. The company also claims that its "proven performance and low maintenance" helps speed up the permitting process and reduces site owners' post-construction clean-out costs. A major advancement in oil and grit separator (OGS) technology, the Vortechs Stormwater Treatment System efficiently removes grit, contaminated sediments, heavy metals, and oily floating pollutants from surface runoff. This innovative design combines two unique treatment structures to eliminate turbulence within the system, ensuring proper physical separation and capture of sediment and oils.

This system offers three chambers for treating stormwater: grit, oil, and flow control. Figure 3.5 presents an illustration of the Vortechs Stormwater Treatment System. The swirling motion created by the

Vortechs System's tangential inlet directs settleable solids toward the center of the grit chamber. During peak storms, this structure dissipates potentially disruptive flows. Sediment is caught in the swirling flow path and settles back onto the pile after the storm event is over. The center barrier of the unit traps floatables in the oil chamber, even during clean-out. Unlike conventional oil traps that lack flow controls and extra tank capacity, the Vortechs System is highly resistant to flow surges. For flow control, as a storm event builds in intensity, the low-flow control within the Vortechs System will cause the inlet pipe to become submerged. This process floats oily pollutants up above the inlet pipe, and out of the influent stream. Consequently, the Vortechs System keeps captured pollutants inside the trap by reducing forces which encourage resuspension and wash-out.

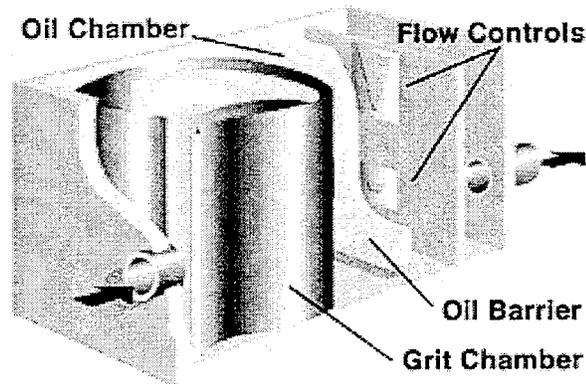


Figure 3.5 Schematic of the Vortechs Stormwater Treatment System

(after Vortechincs, 1998)

The Vortechs System has four operational phases. During the Initial Wet Weather Phase of operation, a two-month/24-hour storm event will cause the water level to rise above the top of the inlet pipe. This influent control feature effectively reduces inlet velocity and turbulence. Depending on the geographic region, approximately eighty-five to ninety percent of storm events will not exceed this two-month intensity, and sediment and floatables removal rates during this phase are very high. With the Transition Phase, as the inflow rate increases above the low flow control, the tank fills and oily contaminants accumulated from previous storms begin to float upwards. With the inlet submerged, the oily layer is well above the influent flow path, which prevents reentrainment of floating contaminants. Swirling action increases at this stage; this in turn increases sediment removal rates, and forces material which may have been deposited at the end of the inlet pipe during low flows into the center of the chamber. On- or

off-line detention basins can be designed to fill during this phase to further increase storage volume. The Full Capacity Phase operation begins when the high-level high-flow outlet begins to discharge. During this phase storm drains are operating at peak capacity and the Vortechs System can be designed to match predetermined peak storm level (a "10-year storm", for example). Treatment efficiencies for the Vortechs System remain constant during this phase, while conventional "plug flow" OGSs have been shown to fail and drop down to negative treatment efficiencies. During the Storm Subsidence Phase, treated runoff is decanted out of the Vortechs System at a controlled rate, restoring the water level to a low dry-weather volume. This reveals a conical pile of accumulated sediment in the center of the grit chamber. Besides facilitating inspection and cleaning, the low water level significantly reduces maintenance costs by reducing pump-out volume.

A fifth commercial stormwater treatment system is available from CDS Technologies. According to its literature (CDS, 1998), CDS has developed a compact screening system that maintains its function of capture at all times--a non-blocking, large-flow screening system that can be installed into existing stormwater drainage systems below ground level. Through its research, CDS Technologies has determined that by controlling the water, it is possible to control the solids travelling in it. The force of the water itself is what mobilizes the solids in it, and is what causes other trapping methods to block and lose their solids loads. The CDS system controls the water to enable a natural separation of solids from the water carrying them.

The compact design of the unit, compared to its very high separation and capture performance, is achieved by the application of the CDS technology. Figure 3.6 illustrates the CDS Screening System. This innovative technology not only keeps the separation screen from blocking and working at high separation efficiency, but also directs the solid pollutants to the lower catchment chamber, and the floatables to the surface of the upper chamber. CDS is an unequalled process of separating and retaining solids, such as industrial, commercial and domestic litter, organic debris including vegetation and grass clippings, as well as coarse sediments from liquids in new and existing stormwater drains. With the inclusion of an oil retention baffle, the technology can also offer effective capture of spilled oils. CDS's capture and retention of pollutants is more efficient and more cost-effective than other systems, due to the technological breakthrough of using the force of the water itself to control the pollutants in the water. Configured to maintain a circular flow within the unit, CDS keeps the pollutants moving in this circular pattern, either settling into a sump or floating on top of the water within the unit. Unlike conventional vortex systems, CDS's outflow moves radially through its screen, which acts as a barrier to keep captured solids from escaping. A storm by-pass weir allows excess flows to continue down the stormwater system, rather than going through the CDS unit. This prevents the unit from flooding or losing its captured materials. CDS technology has been proven to be over 95% effective in segregating pollutants from water.

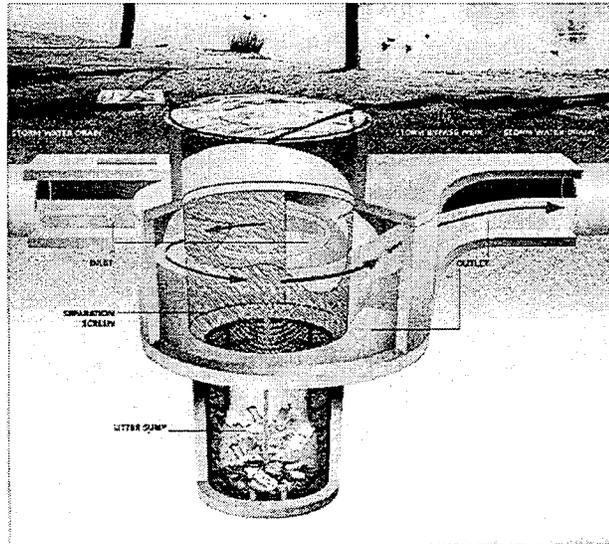


Figure 3.6 Illustration of the CDS Treatment System
(after CDS, 1998)

High volume storms typically have low pollutant concentrations, particularly during the wet season, when the roads are washed-off more often. The philosophy of the CDS system is to trap the majority of pollutants entering a stormwater system during the “first flush” of rainfall before the debris can be carried downstream. By trapping pollutants discarded by humans (such as plastic bags, cigarette butts, fast food packaging and oil washed from roadways) as well as items from the natural environment that are also responsible for waterway pollution (including leaves, branches, dead animals and gravel), CDS provides the world’s first non-mechanical, non-blocking screening technology. According to the product literature, this breakthrough technology renders all other trapping methods obsolete.

An evaluation of commercially available catch basin inserts, vaults without filter media, for the treatment of stormwater runoff from developed sites was conducted by the Interagency Catch Basin Insert Committee in Seattle, WA (1995). Their recommendations were: 1) to not use inserts if the objective was to remove fine particulate pollutants, 2) to use inserts in unpaved areas where the sediment concentration in the stormwater was expected to be high and include a substantial percentage of coarse material, 3) to not use inserts in new developments in lieu of oil/water separators, but considered the acceptable when used as an oil-control BMP at existing sites, 4) to not use inserts where the objective was to remove dissolved pollutants, 5) to use inserts where the removal of trash and debris was the objective, 6) to use inserts when an existing catch basin lacks a sump or has an undersized sump and where downstream treatment did not exist, and 7) to use inserts as a means of reducing maintenance costs of downstream BMPs.

3.2 Introduction to Filter Columns Experiments

The overall objectives of this project are to provide data concerning performance, operation and maintenance requirements for confined area BMPs and to evaluate the effectiveness of BMPs which use a combination of filter media in vaults or existing medians. Such data will allow water resource specialists to specify stormwater quality improvement projects that satisfy water quality goals with the least cost, the highest likelihood of success, and the greatest environmental benefit.

To achieve those objectives, filter media were tested in laboratory column experiments to establish hydraulic and pollutant treatment capabilities. The intent of this study was to investigate filter media options that are commonly (versus commercially) available, with an emphasis on recycled or alternative use materials. A total of fifteen materials were tested: aquarium rocks, cedar bedding, charcoal, corn cobs, garden bark, glass beads, kitty litter, iron oxide coated sand, peat moss, persolite, sand, sand/steel wool, WSU compost, CH zeolite, and XY zeolite. Iron oxide coated sand (Chang *et al.*, 1997), peat moss (Ho *et al.*, 1996) and sand (WSDOT, 1996) were chosen based on a literature review while the others were chosen based on the professional opinions of the researchers. Effluent samples were analyzed over time to determine removal efficiencies, and, thereby, potential field application maintenance requirements. The top performing media was used for confined space BMP design recommendations.

3.3 Filter Columns Experiments' Objectives

To judge the potential effectiveness of stormwater vaults in confined spaces, the quantitative treatment of stormwater must be examined. By determining the behavior of water transport through a column, some estimations of the effectiveness of water quality treatment can be made from a fundamental point of view.

The specific objectives of this part of the study were two-fold:

1. To determine the hydraulic and pollutant treatment performances of various filter media with respect to a synthetic stormwater runoff.
2. To make design recommendations for the application of stormwater water vaults at the Ship Canal Experimental BMP Research Facility field site.

3.4 Filter Columns Experiments' Approach

The approaches used to satisfy the filter column experiment objectives include three major categories. They were:

1. Create a synthetic stormwater runoff based on pollutant concentrations found in the literature.

2. Design column experiments to determine hydraulic and pollutant removal abilities of various filter media.
3. Determine the feasibility of using stormwater vaults in confined spaces and develop design recommendations based on data obtained from experimentation.

3.5 Experimental Methodology

3.5.1 Synthetic Stormwater Runoff

As stated previously, the filter media effluent were tested for cadmium, copper, lead, and zinc as total metals, nitrate, orthophosphate, pH, TSS, and TPH to determine their pollutant removal abilities. In order to have the greatest amount of control on pollutant constituents and concentrations applied to the media, a synthetic stormwater runoff was created. Instead of overloading the column with high concentrations of pollutants to find the breakthrough time, a synthetic runoff was created that accurately represented concentrations found in highway runoff in order to have a better understanding of maintenance schedules. In an effort to reproduce that runoff as accurately as possible, a literature review was conducted to ascertain average highway runoff concentrations of the desired pollutants tested for this project. Barrett *et al.* (1993) summarized ranges of commonly found highway runoff pollutant concentrations from around the country. To further refine those ranges to be particularly applicable in Seattle, several Washington State highway runoff characterizations were consulted, including WSDOT documents (1982, 1985a, 1985b, and 1990), Clark *et al.* (1981), Asplund *et al.* (1981), and Chui *et al.* (1982). Based on those reports, the synthetic highway runoff for this project was designed to have the following concentrations: cadmium 0.06 mg/L; copper 0.10 mg/L; lead 1.00 mg/L, zinc 0.50 mg/L; nitrate 0.85 mg/L; phosphate 0.30 mg/L, TPH 0.10 mg/L, and 145 mg/L suspended solids (see Table 3.1).

To create the desired pollutant concentrations, chemical standards were obtained in solid (dissolvable) or liquid form. Because so many types of chemical standards are available, an effort was made not to have any coupling of pollutants. This was avoided in all cases except for nitrate. The best available form of lead was as lead nitrate. To compensate for the coupling of lead and nitrate in the synthetic stormwater, lead nitrate was added to meet the desired lead concentration, the associated amount of nitrate was calculated, then a nitrate standard was added to meet the desired nitrate concentration. The following standards were used for the synthetic stormwater: cadmium sulfate, cupric sulfate, lead nitrate, zinc chloride, liquid nitrate, liquid phosphate, and TPH in water. The TPH in water consisted of 37.5% hexadecane, 37.5% iso-octane, and 25% chlorobenzene. An example of the calculations to determine the amounts of chemical standards required to produce specific pollutant concentrations in a synthetic stormwater “recipe” follows.

Synthetic Stormwater Recipe Calculations.

The desired formulation for the synthetic stormwater runoff is presented in Table 3.1. The mass of each chemical standard required to produce the pollutant concentrations typically found in highway stormwater runoff can be determined by utilizing the following procedure:

Table 3.1 Desired Runoff Pollutant Concentrations

Desired Pollutant	Chemical Standard	Standard Form	Desired Concentration (mg/L)
Cadmium	Cadmium sulfate	3CdSO ₄ •8H ₂ O	0.06
Copper	Cupric sulfate	CuSO ₄	0.10
Lead	Lead nitrate	Pb(NO ₃) ₂	1.00
Zinc	Zinc chloride	ZnCl ₂	0.50
Nitrate (as N)	Nitrate	NO ₃ -N	0.85
Phosphate (as P)	Phosphate	PO ₄ -P	0.30
TPH	TPH w/o fatty acids in water	TPH	0.10

Solution: Determine the amount of desired pollutant present in each standard, then determine how much of the standard is needed to produce the desired concentration. Assume 100 g (0.22 lb) for metal standards; other standards are as indicated.

Cadmium:

$$100 \text{ g } 3\text{CdSO}_4 \cdot 8\text{H}_2\text{O} \cdot \frac{1 \text{ mol } 3\text{CdSO}_4 \cdot 8\text{H}_2\text{O}}{769.39 \text{ g } 3\text{CdSO}_4 \cdot 8\text{H}_2\text{O}} \cdot \frac{3 \text{ mol Cd}}{1 \text{ mol } 3\text{CdSO}_4 \cdot 8\text{H}_2\text{O}} \cdot \frac{112.4 \text{ g Cd}}{1 \text{ mol Cd}} = 43.83 \text{ g Cd}$$

$$\frac{0.06 \text{ mg Cd}}{1 \text{ L water}} \cdot \frac{100000 \text{ mg } 3\text{CdSO}_4 \cdot 8\text{H}_2\text{O}}{43826 \text{ mg Cd}} = \frac{0.14 \text{ mg } 3\text{CdSO}_4 \cdot 8\text{H}_2\text{O}}{1 \text{ L water}}$$

Copper:

$$100 \text{ g } \text{CuSO}_4 \cdot \frac{1 \text{ mol } \text{CuSO}_4}{159.61 \text{ g } \text{CuSO}_4} \cdot \frac{1 \text{ mol Cu}}{1 \text{ mol } \text{CuSO}_4} \cdot \frac{63.546 \text{ g Cu}}{1 \text{ mol Cu}} = 39.81 \text{ g Cu}$$

$$\frac{0.10 \text{ mg Cu}}{1 \text{ L water}} \cdot \frac{100000 \text{ mg } \text{CuSO}_4}{39813 \text{ mg Cu}} = \frac{0.25 \text{ mg } \text{CuSO}_4}{1 \text{ L water}}$$

Lead:

$$100 \text{ g Pb(NO}_3)_2 \cdot \frac{1 \text{ mol Pb(NO}_3)_2}{331.20 \text{ g Pb(NO}_3)_2} \cdot \frac{1 \text{ mol Pb}}{1 \text{ mol Pb(NO}_3)_2} \cdot \frac{207.19 \text{ g Pb}}{1 \text{ mol Pb}} = 62.56 \text{ g Pb}$$

$$\frac{1.0 \text{ mg Pb}}{1 \text{ L water}} \cdot \frac{100000 \text{ mg Pb(NO}_3)_2}{62557 \text{ mg Pb}} = \frac{1.60 \text{ mg Pb(NO}_3)_2}{1 \text{ L water}}$$

Zinc:

$$100 \text{ g ZnCl}_2 \cdot \frac{1 \text{ mol ZnCl}_2}{136.28 \text{ g ZnCl}_2} \cdot \frac{1 \text{ mol Zn}}{1 \text{ mol ZnCl}_2} \cdot \frac{65.37 \text{ g Zn}}{1 \text{ mol Zn}} = 47.98 \text{ g Zn}$$

$$\frac{0.50 \text{ mg Zn}}{1 \text{ L water}} \cdot \frac{100000 \text{ mg ZnCl}_2}{47967 \text{ mg Zn}} = \frac{1.04 \text{ mg ZnCl}_2}{1 \text{ L water}}$$

Nitrate: Note, because lead is present as lead nitrate, the nitrate contribution associated with the lead amount already determined first must be calculated. The remaining required nitrate is added from the nitrate standard.

$$\frac{1.60 \text{ mg Pb(NO}_3)_2}{1 \text{ L water}} \cdot \frac{28 \text{ mg NO}_3 - \text{N}}{124 \text{ mg Pb(NO}_3)_2} = \frac{0.36 \text{ mg NO}_3 - \text{N}}{1 \text{ L water}}$$

$$\frac{0.85 \text{ mg NO}_3 - \text{N}}{1 \text{ L water}} - \frac{0.36 \text{ mg NO}_3 - \text{N}}{1 \text{ L water}} = \frac{0.49 \text{ mg NO}_3 - \text{N}}{1 \text{ L water}}$$

$$\frac{0.49 \text{ mg NO}_3 - \text{N}}{1 \text{ L water}} \cdot \frac{1 \text{ mL NO}_3}{1 \text{ mg NO}_3 - \text{N}} = \frac{0.49 \text{ mL NO}_3 - \text{N}}{1 \text{ L water}}$$

Phosphate:

$$\frac{0.30 \text{ mg PO}_4 - \text{P}}{1 \text{ L water}} \cdot \frac{1 \text{ mL PO}_4}{0.05 \text{ mg PO}_4 - \text{P}} = \frac{6.0 \text{ mL PO}_4 - \text{P}}{1 \text{ L water}}$$

TPH: Note, serial dilutions are required since the TPH concentration in water from the chemical standard is greater than the desired concentration.

$$\frac{62.2 \text{ mg TPH}}{250 \text{ mL water}} = \frac{248.8 \text{ mg TPH}}{1 \text{ L water}}$$

- 10 mL of standard in 90 mL of water yields 24.88 mg/L TPH;
- 10 mL of 24.88 mg/L TPH in 90 mL of water yields 2.488 mg/L TPH;
- 10 mL of 2.488 mg/L TPH in 90 mL of water yields 0.2488 mg/L TPH;
- 50 mL of 0.2488 mg/L TPH in 50 mL of water yields 0.1244 mg/L TPH.
- 80 mL of 0.1244 mg/L TPH in 10 mL of water yields 0.992 mg/L TPH.

Answer: Table 3.2 lists the amounts of chemical standards necessary to produce the desired pollutant concentration in 1 L of water.

Table 3.2 Results of Runoff Calculations

Pollutant	Concentration (mg/L)	Standard Amount
Cadmium	0.06	0.14 mg
Copper	0.10	0.25 mg
Lead	1.00	1.60 mg
Zinc	0.50	1.04 mg
Nitrate (as N)	0.85	0.49 mL
Phosphate (as P)	0.30	6.0 mL
TPH	0.10	see serial dilution description

The last constituent for the synthetic stormwater runoff was suspended solids. Clay-sized particles were chosen for the sediment since the solids needed to stay in suspension as much as possible in a mostly quiescent aquarium tank. In order to ensure that the suspended solids would be representative of those found on Seattle streets, the *King County Area Washington Soil Survey* was consulted to determine the types of clays found in the Seattle area (SCS, 1973). King County has three principle kinds of clays: glacial, alluvial, and shales interstratified with sandstone. Reproducing the shale/sandstone combination would be too difficult, so that was eliminated as a possible sediment for the synthetic runoff mixture. Seattle has only a few local deposits of alluvial clay, thereby contributing relatively little as a source of

sediment in runoff, so that type was also eliminated. Besides being the only remaining option, glacial clay was also chosen because the *Soil Survey* (1973) stated that “clays in the immediate vicinity of Seattle are all glacial clays.”

Further evidence that glacial clay should be used for this synthetic runoff recipe came from two vintage books on clays in Washington State. Ries (1927) stated that glacial lake clays were widely distributed throughout the western part of the state in the Puget Sound region. He described the clay as blue and stratified. Shedd (1910) described the glacial clay in the Seattle area as bluish, tough and plastic. The clay used in these experiments was blue glacial till (Catalogue Number 301) obtained from Seattle Pottery Supply. Both screened and unscreened till was available. Based on sieve analysis data from both types, the screened blue glacial till was chosen for the suspended sediment in the synthetic runoff mixture. Figure 3.7 shows the grain size distribution curves for the screened and unscreened tills, and Table 3.3 lists the chemical properties of the chosen screened blue glacial till. The concentrations of the trace metals are all low compared to the amount of pollutant being added so the clay material has little impact on the total amount of pollutant in the runoff. However, the clay did provide adsorption sites so the dissolved metals concentrations were somewhat lower than originally measured.

The synthetic stormwater runoff was made in 34 L (9 gal) batches in 37.9 L (10 gal) aquarium tanks. Using the above calculations, chemical standards were added to create the desired concentrations for 34 L (9 gal) of water. Deionized water was used instead of tap water to eliminate the presence of groundwater trace elements such as iron and calcium and the added chlorine and fluoride from the treatment plant. An electric hand mixer with a plastic housing was used for the initial mixing of chemicals and deionized water, and subsequently was used approximately every three minutes during each test run to maintain the clay sediment in suspension. Before each column experiment, a sample of the runoff water was taken from the tank for chemical analysis.

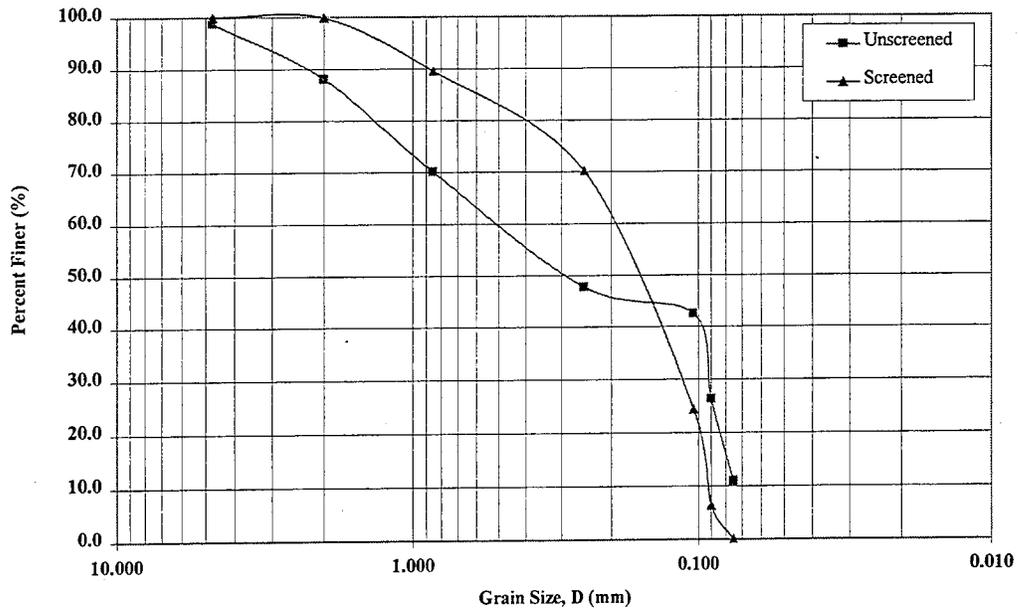


Figure 3.7 Blue Glacial Till Grain Size Distributions

Table 3.3 Blue Glacial Till Chemical Analysis

Standard Fertility Test

pH	P ug/g	K ug/g	O.M. %	NO ₃ -N ug/g	NH ₄ -N ug/g
8.0	2.7	303	1.17	3.5	3.6

EPA 3050 Total Recoverable Trace Element Screen

Ca ug/g	Mg ug/g	K ug/g	Na ug/g	Zn ug/g	Mn ug/g	Cu ug/g	Fe ug/g	P ug/g	S ug/g	Pb ug/g	Cr ug/g	Cd ug/g	Ba ug/g	Ni ug/g	Co ug/g	Be ug/g	Mo ug/g	As ug/g
12000	15000	3600	930	71	570	40	30000	620	770	43	65	3.5	160	76	26	0.53	16	130

3.5.2 Experimental Setup

The filter column configuration, depicted in Figures 3.8 and 3.9, consists of 50 mm x 1000 mm (1.97 in x 39.4 in) glass chromatograph column extensions supported vertically on a wood frame by two size 2 ¼ three-pronged clamps. The large column size was selected in an attempt to minimize short circuiting and wall effects on the flow of water through the media. A size 75 pinch clamp holds a size 50 chromatograph column cap on the bottom of each column extension. A Buna-N, N-229 O-ring seals the connection between column and cap, with a 51 mm (2.00 in) glass disc filter stone resting inside the cap. The synthetic stormwater is stored in a 37.8 L (10 gal) aquarium tank and is pumped into each column through 6.35 mm (¼ in) Tygon tubing with a 6-600 rpm peristaltic pump and electronic speed controller. The runoff water filters through the column into the bottom cap and is drained into a 4 L (1.06 gal) Erlenmeyer flask on the floor through 6.35 mm (¼ in) Tygon tubing. Samples bottles are filled with the Tygon tubing by by-passing the Erlenmeyer flask. Figure 3.10 illustrates a close-up view of the column, glass disc, cap, and tubing arrangement.

Because the glass stone filters much of the sediment flushed from the column, a different disc is required when collecting samples for TSS analysis. Using a standard perforated drain pipe as the model, a slotted, 51 mm (2.00 in) Plexiglas disc was created. The disc has three 19 mm (0.75 in) by 2 mm (0.08 in) slots spaced 19 mm (0.75 in) apart, allowing sediment to pass freely into sample bottles. Figure 3.11 shows the Plexiglas slotted disc.

Fifteen filter media were tested for performance characteristics in treating stormwater runoff: aquarium rocks, cedar bedding, charcoal, corn cobs, garden bark, glass beads, iron oxide coated sand, kitty litter, peat moss, persolite, sand, sand/steel wool, WSU compost, CH zeolite, and XY zeolite. To test each medium, a column is filled with 0.3 m (1 ft) of filter material. The pump speed is adjusted so that the column maintains a 15.24 cm (6 in) runoff water head above the filter medium. At intervals of 0, 5, 10, 20, 30, 45, 60, and 90 minutes after starting the pump, samples are taken for chemical analysis and flow rates are timed for hydraulic analysis. The 0 minute sample time is the initial water that filters through the medium. This does not occur instantaneously, but is labeled as the 0 minute sampling interval. All of the subsequent intervals occur at the indicated time after the onset of the test run.

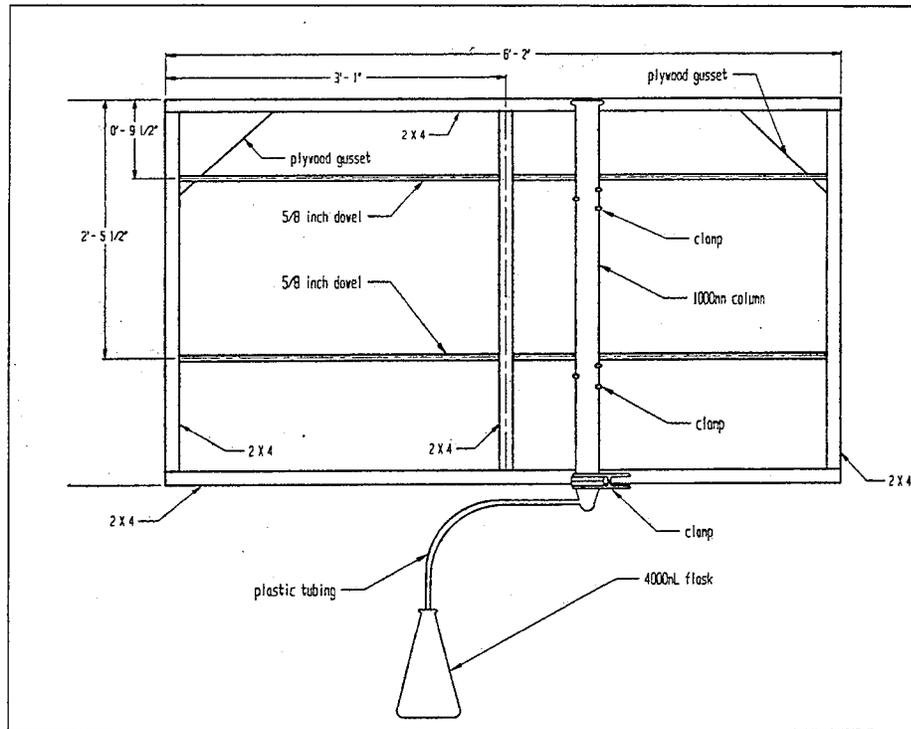


Figure 3.8 Experimental Schematic

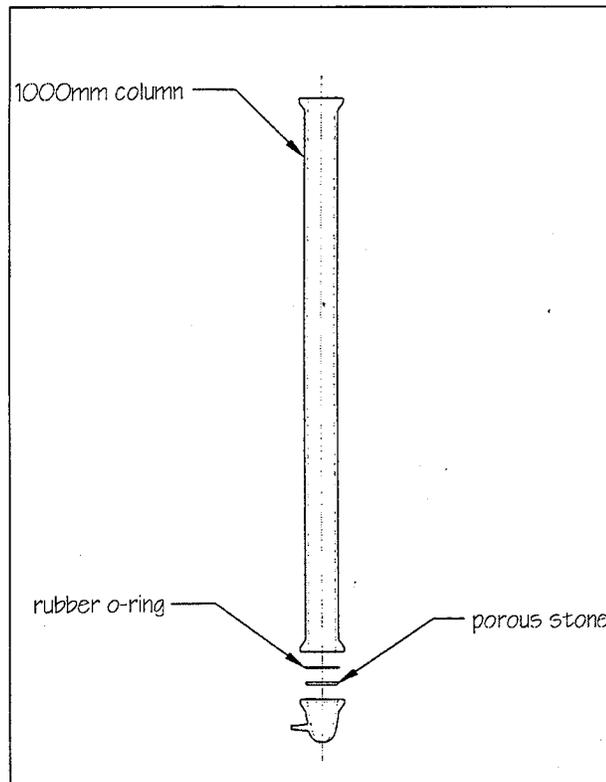


Figure 3.9 Column Detail

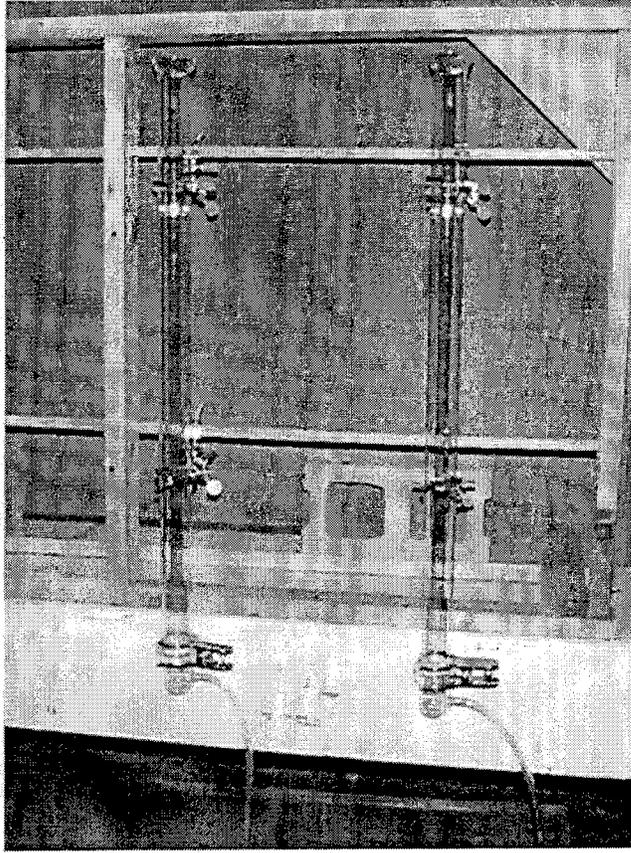


Figure 3.10 Close Up of Experimental Setup

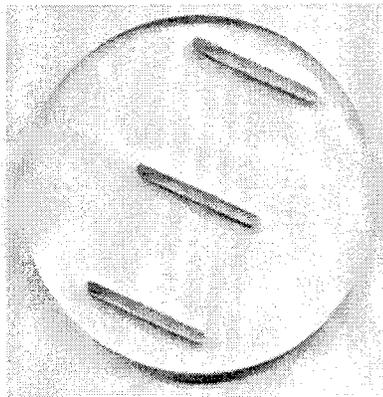


Figure 3.11 Slotted TSS Plexiglas Disc

3.6 Analysis

3.6.1 Physical and Chemical Analyses

Samples of each medium were submitted to the University of Idaho Analytical Sciences Laboratory for chemical and physical analyses. Those results are presented in Tables 3.4 and 3.5. The chemical tests were required in order to determine if the filters were leaching. If the effluent metal or nutrient concentrations were greater than the influent concentrations for a particular filter, that medium would not be acceptable for a stormwater treatment BMP. The physical analysis of bulk density was required to determine the porosity of the media in the columns.

Table 3.4 Filter Media Bulk Density

Filter Media	Bulk Density (g/cm ³)
Aquarium Rocks	1.58
Cedar Bedding	0.09
Charcoal	0.35
Corn Cobs	0.43
Garden Bark	0.20
Glass Beads	1.45
Kitty Litter	0.69
Peat Moss	0.61
Persolite	0.19
Sand	1.62
WSU Compost	0.47
CH Zeolite	0.51
XY Zeolite	0.87

Table 3.5 Filter Media Chemical Analysis

Standard Fertility Test

Filter Media	pH	P μg/g	K μg/g	O.M. %	NO ₃ -N μg/g	NH ₄ -N μg/g
Aquarium Rocks	NA*	NA	NA	NA	NA	NA
Cedar Bedding	4.7	56	400	52	1.2	15
Charcoal	8.9	140	1000	23	1700	2.9
Corn Cobs	5.0	120	7000	63.3	<0.4	3.9
Garden Bark	4.5	90	1200	48	1.2	9.5
Glass Beads	NA	NA	NA	NA	NA	NA
Kitty Litter	5.1	6.3	480	0.73	1.9	16
Peat Moss	5.7	42	350	38	24	6.5
Persolite	9.1	5.3	97	0.12	1.3	2.5
Sand	7.1	1.2	<2.7	0.12	<0.4	0.4
WSU Compost	8.6	1400	11000	30	330	4.4
CH Zeolite	6.7	0.8	1600	0.20	230	8.2
XY Zeolite	7.6	3.1	5400	0.11	4.2	4.6

Table 3.5 Continued

EPA 3050 Total Recoverable Trace Element Screen

Filter Media	Ca ug/g	Mg ug/g	K ug/g	Na ug/g	Zn ug/g	Mn ug/g	Cu ug/g	Fe ug/g	P ug/g	S ug/g	Pb ug/g	Cr ug/g	Cd ug/g	Ba ug/g	Ni ug/g	Co ug/g	Be ug/g	Mo ug/g
Aquarium Rocks	NA*	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cedar Bedding	4200	130	910	390	<3.0	14	8.7	90	94	430	<22	<4.4	1.5	2.6	9	<4.4	0.41	0.41
Charcoal	35000	2600	2100	11000	22	130	14	5400	550	2500	20	16	1.2	600	13	4.2	0.45	0.45
Corn Cobs	530	320	8900	200	16	6.2	6.9	82	440	420	11	3.1	0.33	2.3	4.0	<1.3	0.09	<4.6
Garden Bark	5000	1100	1800	2700	32	140	10	1800	430	760	<11	8	1	52	6.7	<2.2	0.11	0.11
Glass Beads	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Iron Oxide Coated Sand	8280	302	506	268	2900	164000	8230	300000	390	1200	680	<4	1400	<1	<7	518	<1	<5
Kitty Litter	6700	10000	5100	400	95	140	13	29000	530	1800	52	180	3.7	330	32	10	1.4	1.4
Peat Moss	12000	6800	1800	770	43	220	23	13000	500	2200	29	28	1.8	87	21	8.3	0.49	0.49
Persolite	720	190	1500	5700	9	470	3.3	530	31	180	<11	<2.2	<0.70	12	3.9	<2.2	0.24	0.24
Sand	160	20	<246	86	2.1	<0.28	<2.3	120	5.5	110	<9.5	<1.3	<0.30	0.59	<2.8	<1.3	<0.038	<4.6
Steel Wool	1460	298	<100	2820	866	1760	154	70400	<15	170	100	<4	9.4	10	<7	<5	<1	55.9
WSU Compost	25000	5900	13000	3100	88	190	36	13000	2600	3000	39	33	2.5	490	24	8.4	1.3	13
CH Zeolite	1600	14200	654000	145000	547	5344	<4	174000	9900	1200	265	33	7.4	17000	<7	<5	45.2	33.8
XY Zeolite	9090	384	239000	3230	86	52	184	136000	<15	4900	<30	1832	16	4953	1090	<5	4953	536

*Not Applicable, unable to analyze via this method

3.6.2 Hydraulic Analyses

The first hydraulic test performed on each medium was a time-interval discharge rate to document the progression of filter clogging. The filter media was initially unsaturated. At intervals of 0, 5, 10, 20, 30, 45, 60, and 90 minutes after the onset of the test run, the time required to fill a 50 ml (3.05 in³) graduated cylinder was recorded. If the test period did not last the entire 90 minute period, results were graphed only for the duration of that run. Those results are plotted in Figure 3.12; the actual data points are given in Table 3.6. It must be noted that these flow rates were for a filter surface area of 0.002 m². By dividing the numbers in Table 3.6 by this area, a discharge rate of m³/day/m² of media (gpd/ft²) could easily be computed. Aquarium rocks, charcoal, glass beads, and CH zeolite showed no effects of clogging. This was expected from the aquarium rocks, charcoal, and glass beads because of their relatively large “grain” sizes, but was not expected for the CH zeolite. The corn cobs exhibited a steady decline in flow rate, but this was not due to clogging from the synthetic runoff. As the corn cobs became increasingly saturated, they expanded or swelled in the column, sealing off pathways through which the water could travel. The organic media including garden bark, peat moss, and WSU compost showed sharp decreases in flow rates as the fine materials were flushed through the column and on to the TSS disc, clogging the disc. After the initial migration of fines to the bottom of the column, their flow rates leveled off for the remainder of the testing period. The three sand media, IOCS, sand, and sand/steel wool, and the persolite did exhibit clogging due to the runoff water. A layer of dark sediment, the clay used in the synthetic stormwater, was visible in the top 5.08 cm (2.0 in) of the light colored media. Presumably it was also present in the IOCS but it was not readily seen due to the dark color of that sand. Because of the small grain sizes of these media, the clay suspended in the runoff influent was sufficient to clog the top portions of these columns.

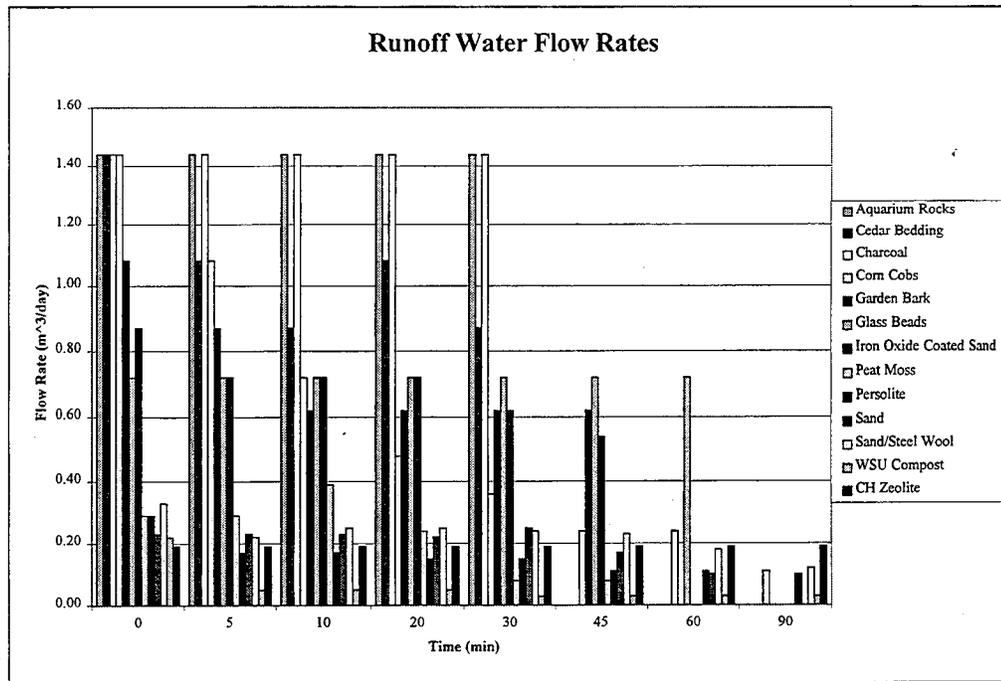


Figure 3.12 Runoff Water Flow Rates for all Media

Table 3.6 Filter Column Discharge Rates (m^3/day) Measured at Specified Time Intervals

Medium	0 min	5 min	10 min	20 min	30 min	45 min	60 min	90 min
Aquarium Rocks	1.44	1.44	1.44	1.44	1.44	NA	NA	NA
Cedar Bedding	1.44	1.08	0.87	1.08	0.87	NA	NA	NA
Charcoal	1.44	1.44	1.44	1.44	1.44	NA	NA	NA
Corn Cobs	1.44	1.08	0.72	0.48	0.36	0.24	0.24	0.11
Garden Bark	1.08	0.87	0.62	0.62	0.62	0.62	NA	NA
Glass Beads	0.72	0.72	0.72	0.72	0.72	0.72	0.72	NA
Iron Oxide Coated Sand	0.87	0.72	0.72	0.72	0.62	0.54	NA	NA
Peat Moss	0.29	0.29	0.39	0.24	0.08	0.08	NA	NA
Persolite	0.29	0.17	0.17	0.15	0.15	0.11	0.11	0.10
Sand	0.23	0.23	0.23	0.22	0.25	0.17	0.10	NA
Sand/Steel Wool	0.33	0.22	0.25	0.25	0.24	0.23	0.18	0.12
WSU Compost	0.22	0.05	0.05	0.05	0.03	0.03	0.03	0.03
CH Zeolite	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19

The second hydraulic test performed on each medium was to determine the runoff water infiltration rate for initially unsaturated material. Not only did this test provide an indication as to the time required to pass 30.3 L (8 gal) of water through the column filter, it also furnished more quantitative information about the clogging rates of the different media. Table 3.7 presents the results of this test. The infiltration rate was calculated from the last measured flow rate for each medium. For those media that did not exhibit any clogging, aquarium rocks, charcoal, glass beads, and CH zeolite, these infiltration rates can be used for design calculations. For all other media, these rates are not conservative since the effects of clogging were not measured after 90 min from the onset of the experiment. Safety factors based on the clogging trend (measured as a reduction in discharge) for each respective medium need to be included in design calculations.

Table 3.7 Filter Media Infiltration Rates

Filter Media	Infiltration Rate (cm/sec)
Aquarium Rocks	0.866
Cedar Bedding	0.095
Charcoal	0.786
Corn Cobs	0.246
Garden Bark	0.648
Glass Beads	0.411
Iron Oxide Coated Sand	0.519
Peat Moss	0.026
Persolite	0.063
Sand	0.123
Sand/Steel Wool	0.138
WSU Compost	0.048
CH Zeolite	0.032

3.6.3 Environmental Analyses

The second area of testing was for pollutant treatment efficiency. All tests were begun with unsaturated media. A simple qualitative test was that of effluent color. As shown in Figures 3.14 and 3.15, color was an issue for some of the filter media. Each flask contained a sample of filtered runoff water. Charcoal, sand, aquarium rocks, glass beads, persolite, and sand and steel wool showed no color change.

Cedar bedding and garden bark had slight yellow tints, while corn cobs, CH zeolite, and peat moss had significant yellow tints. It is important to note that the corn cob and the CH zeolite effluents were also turbid; the peat moss effluent was transparent. The most significant color change occurred with the WSU compost which had a heavy brown-red tint. The iron-oxide coated sand had a heavy brown-red tint when the column was first flushed with water. The color diminished to a light brown-red after subsequent flushings.

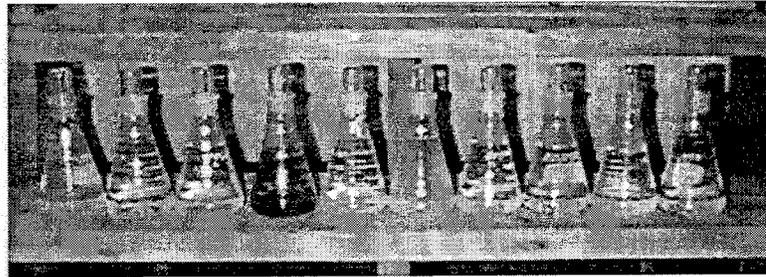


Figure 3.13 Color Comparisons of Filtered Runoff Water (charcoal, cedar bedding, sand, WSU compost, aquarium rocks, corn cobs, glass beads, peat moss, persolite, garden bark)

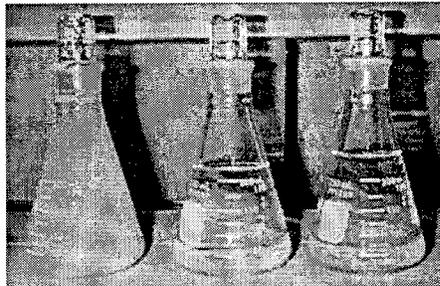


Figure 3.14 Color Comparisons of Filtered Runoff Water (CH zeolite, sand and steel wool, iron-oxide coated sand)

The remainder of the media pollutant treatment abilities are described by filter type. Chemical analysis for metals was conducted at the LBB2 Analytical Laboratory at Washington State University; analysis for nutrients was conducted at the Water Quality and Waste Analysis Laboratory at Washington State University an Ecology certified laboratory.

TPH analysis with gas chromatography (GC) was attempted at the Environmental Engineering Laboratory at Washington State University. The following is a description of the attempts to quantitatively analyze the effluent samples. Unfortunately, none of the approaches proved effective, and consequently, TPH results are not included in this report.

The column chosen for the GC analysis was a Supelco Carbowax amine fused silica capillary column (Catalog #2-5354) 60 m (197 ft) long, with an inside diameter of 0.53 mm (0.002 in) and film thickness of 1.00 μm (0.0004 in). This column was chosen because of its ability to analyze TPH's in water with direct aqueous injection into the oven. Figure 3.16 shows the column test with the three TPH's included in the synthetic runoff, chlorobenzene, iso-octane, and hexadecane, dissolved in the recommend test solvent Methyl tert butyl ether. Evident in the GC output are the distinctive and separate spikes for each TPH. Figure 3.17 present a typical GC output for the media effluent samples. Only one spike, that for water, is as distinctive and separate as those produced in the test case. The other smaller spikes are too numerous and closely spaced to accurately determine which are the result of the TPH's purposefully added to the synthetic runoff and which are other organics present in the filter media.

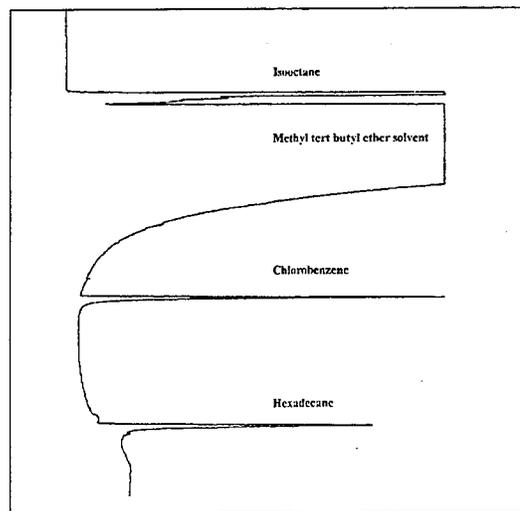


Figure 3.15 Gas Chromatography Column Test for Synthetic Runoff TPH's

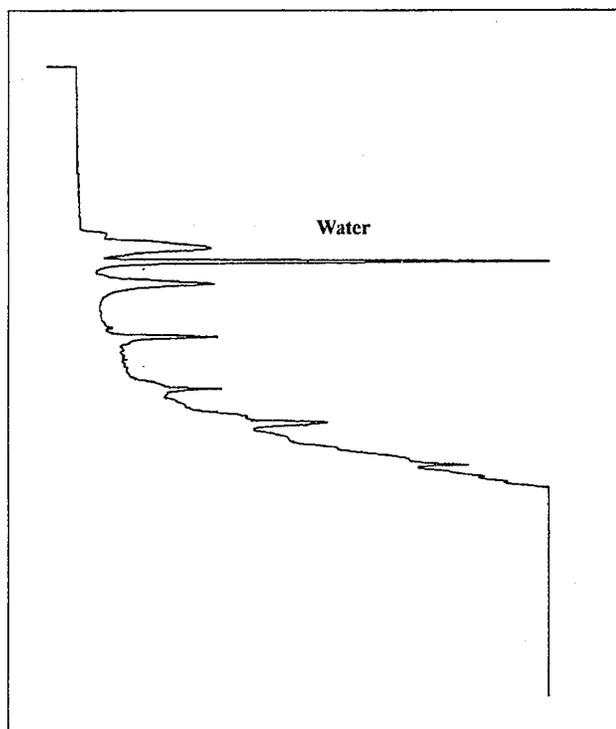


Figure 3.16 Typical GC Output for Filter Media Effluent

In addition to the quantitative analysis difficulties, obtaining a representative sample for injection into the GC proved problematic. This is directly related to the relatively low solubilities of the selected TPH's in water. Chlorobenzene has a solubility in water of 460 mg/L; iso-octane's solubility is 2.44 mg/L; and hexadecane's solubility is 0.00005 mg/L (Gustafson *et al.*, 1996). Because of their hydrophobic nature, very little TPH actually succeeded in passing through the column of filter media into the effluent sample bottles. The amount that did generally exhibited a tendency toward self-association or the formation of micelles. If the injection needle were randomly placed into a micelle, the GC output for that TPH was uncharacteristically high. Conversely, if the needle were placed away from a micelle, the GC output was uncharacteristically low for any TPH. Shaking the sample did little to improve this problem. In the end, it was determined that TPH concentrations could not accurately be determined for the effluent samples.

3.6.3.1 Aquarium Rocks

The aquarium rock filter was purchased from a local pet store. According to the packaging information, it is made of silicas, agates and water worm pebbles. It is nontoxic, prewashed, and environmentally safe. Figures 3.17-3.20 illustrate the changes in pollutant concentrations over the test period; Table 3.8 lists the results in tabular form. The metals removal data is plotted in Figure 3.17. Copper and cadmium were not treated by the aquarium rocks; their concentrations stayed essentially constant throughout the testing period. The 0 min interval showed an initial flush of zinc. Subsequent intervals showed no zinc removal, suggesting that the rocks may have had zinc present in the coating that was washed off by the initial water entering the column. Lead concentrations increased over time, suggesting that the rocks were leaching lead, again perhaps from the coatings. Nitrate removal is presented in Figure 3.18. Based on engineering judgement, the 0 minute data point was eliminated as an outlier. The aquarium rocks were not effective at removing nitrate; each time interval showed slight production of nitrate. Figure 3.19 presents the orthophosphate removal data. Essentially there is no removal at any time interval tested. Total suspended solids data is plotted in Figure 3.20. Approximately half of the solids were removed at each sampling interval. Finally, Table 3.8 shows that the pH dropped dramatically after its initial contact with the aquarium rocks. After the 0 minute interval, the pH readings began to stabilize around 5.5. The sudden drop in pH is also attributed to the coatings present on the rocks being washed off with the first flush of water through the column.

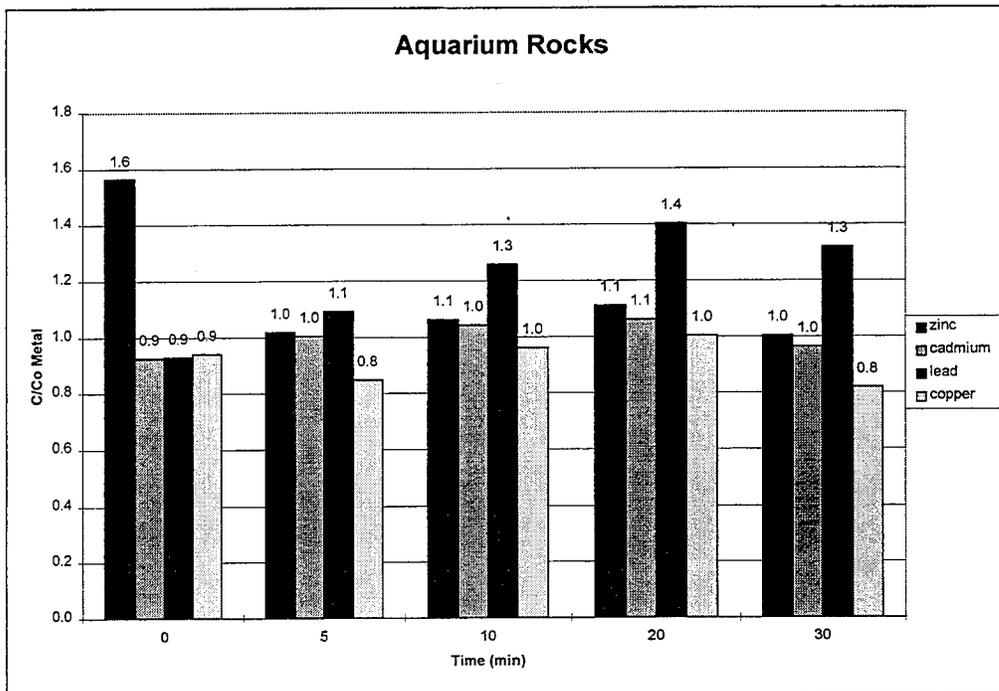


Figure 3.17 Metals Analysis of Aquarium Rock Effluent

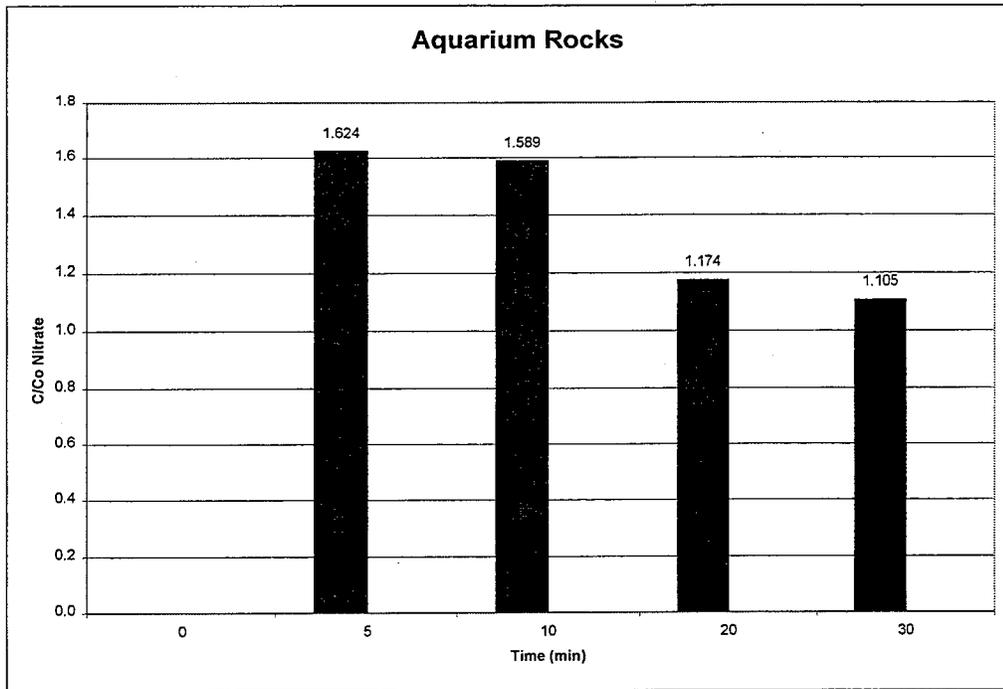


Figure 3.18 Nitrate Analysis of Aquarium Rock Effluent

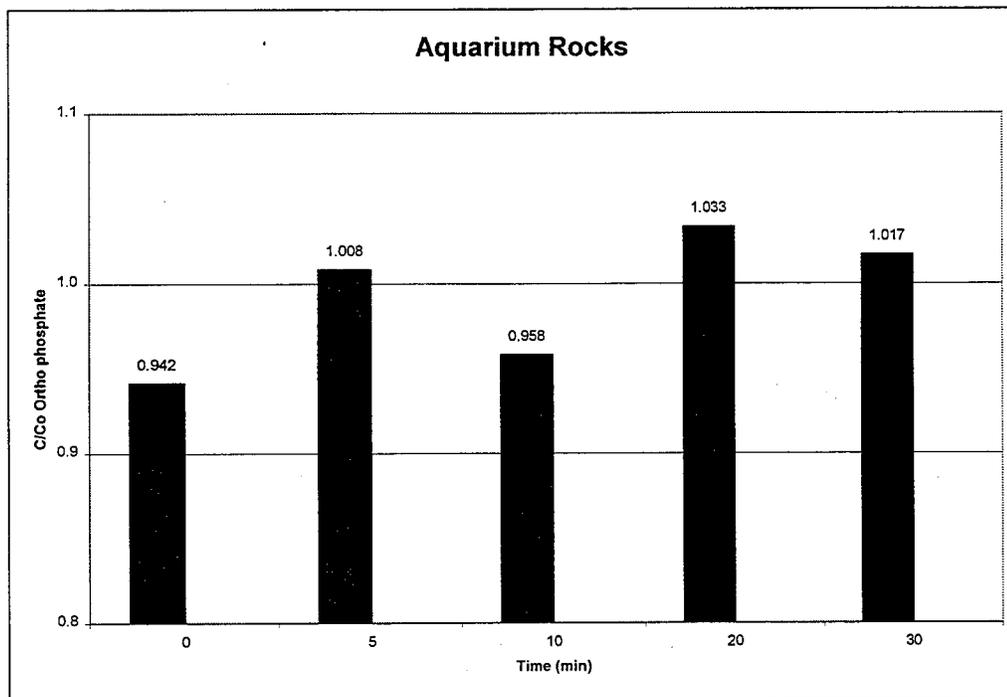


Figure 3.19 Phosphate Analysis of Aquarium Rock Effluent

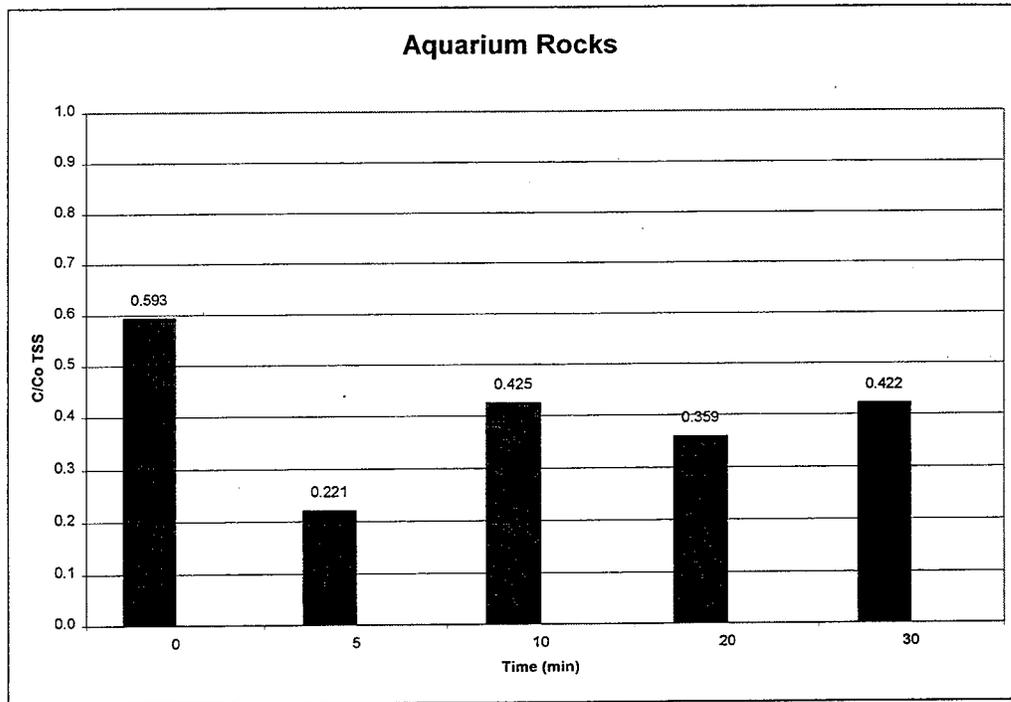


Figure 3.20 TSS Analysis of Aquarium Rock Effluent

Table 3.8 Environmental Testing Results for Aquarium Rock Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	64.9	95.3	465.8	464.6	0.598	0.120	145.0	8.56
0	60.1	433.6	89.7	726.7	*	0.113	86.0	3.32
5	65.2	80.8	508.3	473.2	0.971	0.121	32.0	5.05
10	67.7	91.7	586.1	493.2	0.950	0.115	61.6	5.22
20	69.0	95.8	653.9	516.6	0.702	0.124	52.0	5.36
30	62.6	78.1	614.7	466.6	0.661	0.122	61.2	5.54

3.6.3.2 Cedar Bedding

The cedar bedding filter material was purchased at a local pet store. According to its packaging information, it is aromatic cedarwood shavings containing natural oils. It is screened and dust free. Figure 3.21 illustrates the grain size distribution for this material. Figures 3.22-3.25 show the changes in pollutant concentrations over the test period. Metals removals are plotted in Figure 3.22. There is an overall trend of increasing removal for all metals tested. By the 90-minute interval, 70% to 90% of the metals had been removed. Figure 3.23 shows that very little nitrate, approximately 15%, was removed with the cedar bedding column. Phosphate removal was even less effective, as shown in Figure 3.24. Each time interval showed production of orthophosphate from the filter column. Figure 3.25 shows that TSS removal was high at each time interval. The increase in concentration at the last sampling time suggests that the column had reached the breakthrough for TSS by the 30-minute interval. Table 3.8 shows that the pH fluctuated around 5.5 throughout most of the test period, dropping only slightly after initial contact with the cedar bedding. It should be noted that some of the cedar bedding material floated to the top of the 6 inch head of water during the test period.

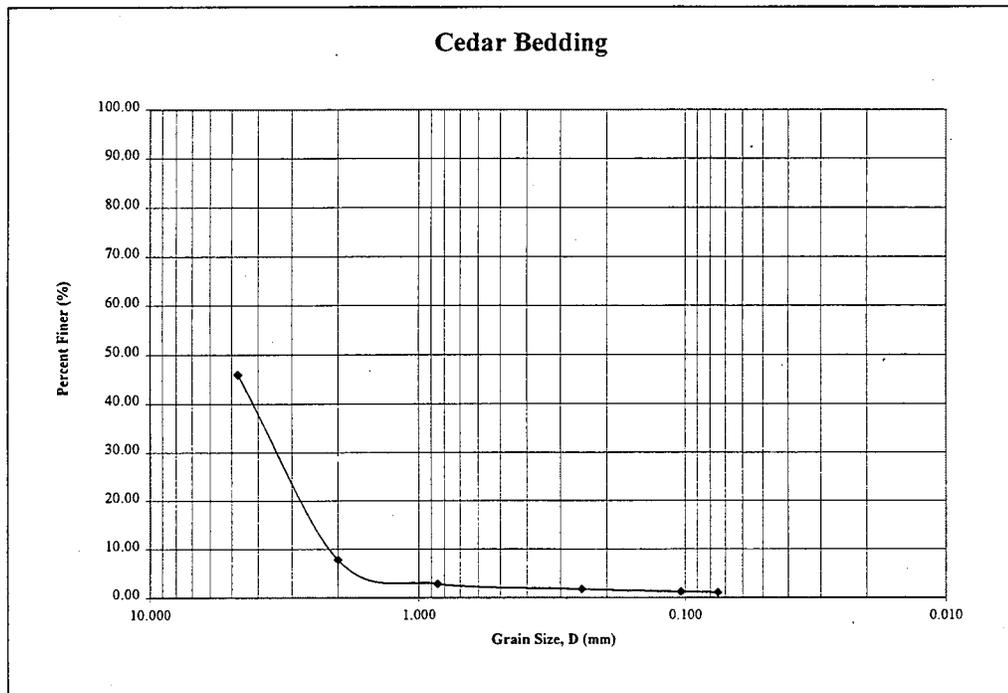


Figure 3.21 Sieve Analysis of Cedar Bedding Filter Medium

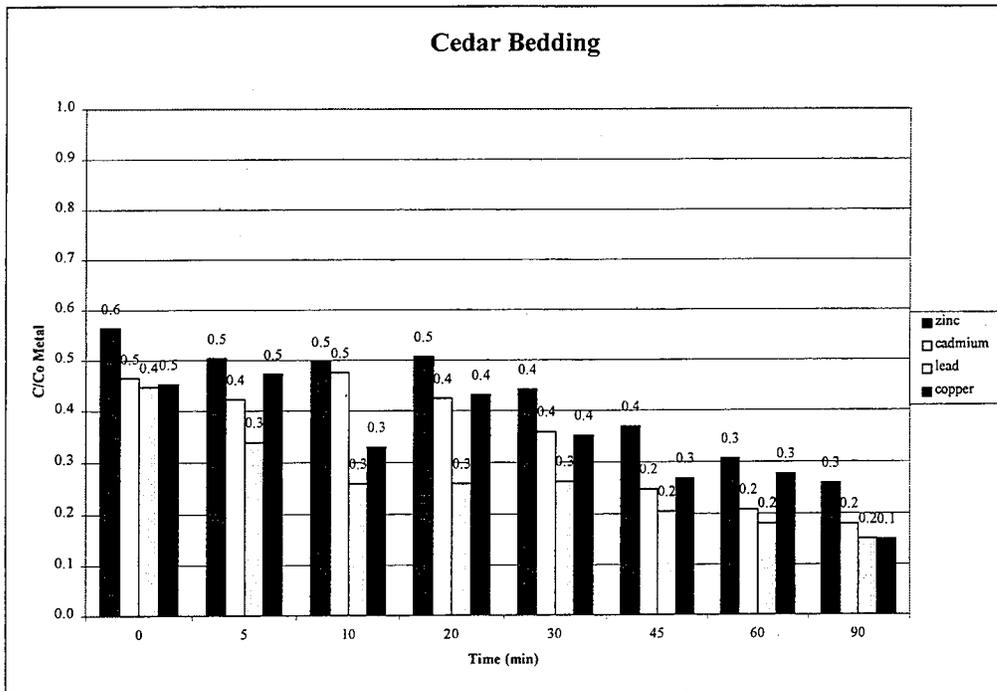


Figure 3.22 Metals Analysis of Cedar Bedding Effluent

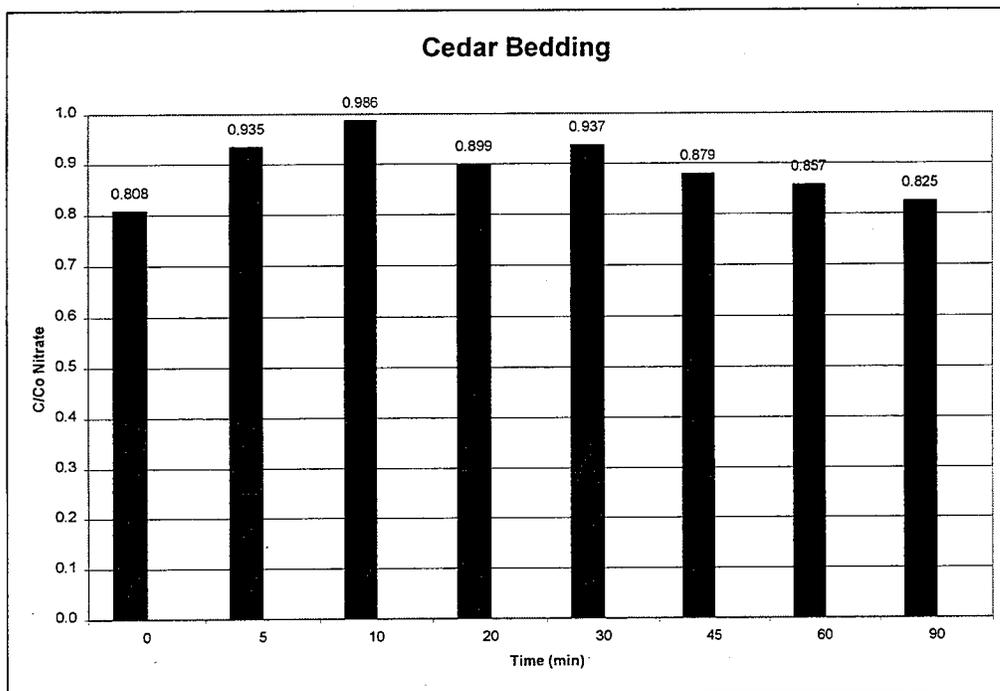


Figure 3.23 Nitrate Analysis of Cedar Bedding Effluent

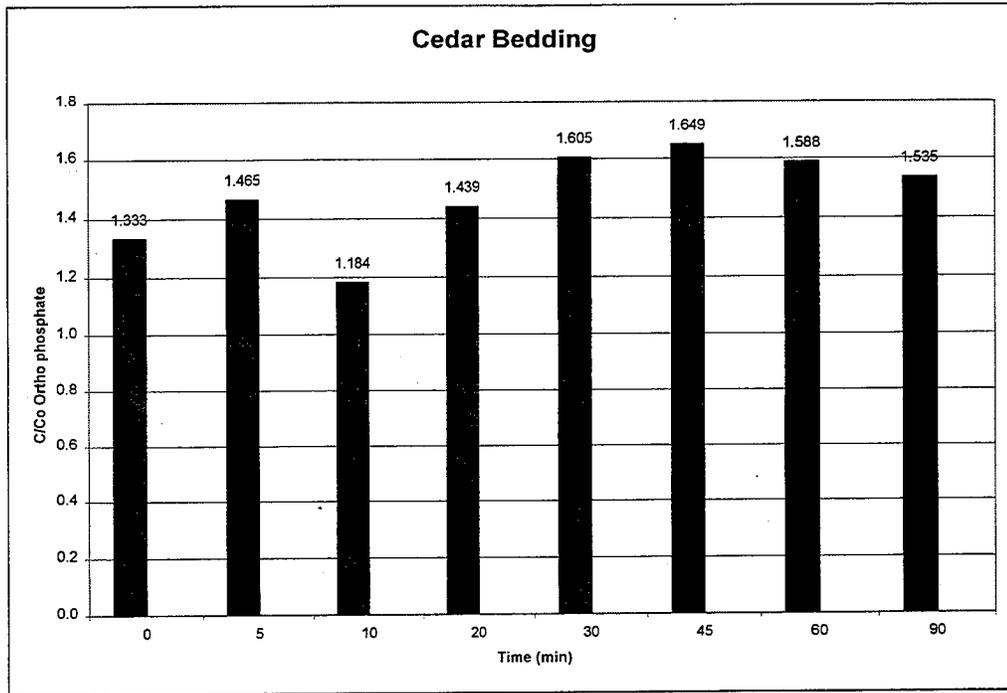


Figure 3.24 Phosphate Analysis of Cedar Bedding Effluent

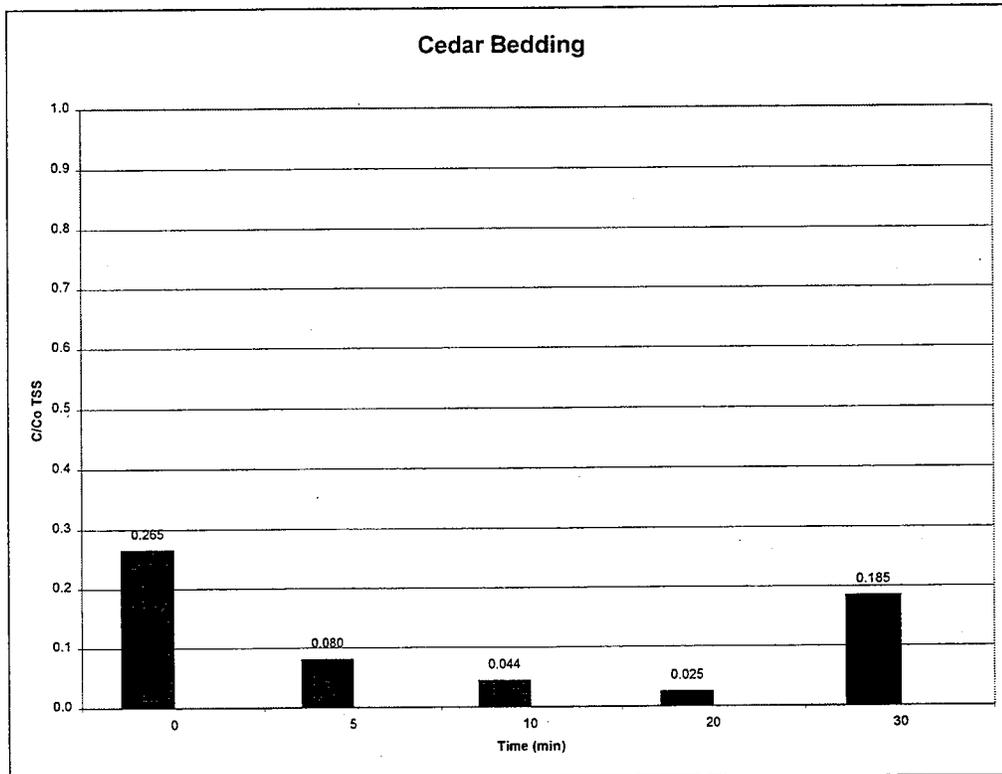


Figure 3.25 TSS Analysis of Cedar Bedding Effluent

Table 3.9 Environmental Testing Results for Cedar Bedding Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	42.9	78.1	854.3	410.7	0.811	0.114	145.0	6.19
0	19.9	35.3	381.3	232.0	0.655	0.152	38.4	6.13
5	18.1	36.9	289.7	207.0	0.758	0.167	11.6	5.44
10	20.4	25.7	220.9	204.4	0.800	0.135	6.4	5.49
20	18.2	33.7	221.0	208.4	0.729	0.164	3.6	5.36
30	15.4	27.5	224.3	181.3	0.760	0.183	26.8	5.33
45	10.6	20.9	154.5	151.6	0.713	0.188	--	5.31
60	8.9	21.6	154.5	125.8	0.695	0.181	--	6.72
90	7.7	11.7	129.0	106.2	0.669	0.175	--	5.38

3.6.3.3 Charcoal

The charcoal filter medium is horticultural charcoal purchased from Wal-Mart. Its packaging information states that this charcoal helps absorb normal odors from plant decay as well as salts and other impurities. Figure 3.26 shows its grain size distribution. Figures 3.27-3.30 present the change in pollutant concentration over the test period. As shown in the 0 min time interval in Figure 3.27, the charcoal filter has a large first flush of metals, approximately twice the initial stormwater concentration for all metals. Zinc, cadmium, and copper are subsequently reduced approximately 20% from the initial concentrations, but lead remains essentially untreated throughout the testing period. Nitrate and orthophosphate analyses also revealed a first flush of pollutants for the 0 min interval. As shown in Figure 3.28, nitrate concentrations initially almost tripled the runoff concentration. The concentrations then decreased by more than half, but remained higher than the nitrate concentration in the synthetic stormwater. Orthophosphate treatment was very similar to nitrate removal. Figure 3.29 shows a higher first flush concentration, four times greater than the initial concentration, at the 0 min time interval. Subsequent sampling intervals yielded concentrations reduced by as much as 66%, but each remained greater than the initial stormwater concentration. Total suspended solids analysis again revealed a first flush approximately four times greater than the runoff water. This was mainly the result of charcoal fines being washed from the column. Once the fines were eliminated, the charcoal filter removed nearly 45% of the TSS. The last two sampling intervals, however, saw a slight increase in the TSS concentration, suggesting that the column was beginning to experience some breakthrough of solids. Table 3.10 shows little change in pH throughout the duration of the test. It should be noted that some of the charcoal material floated to the top of the 6 in head of water during the test period.

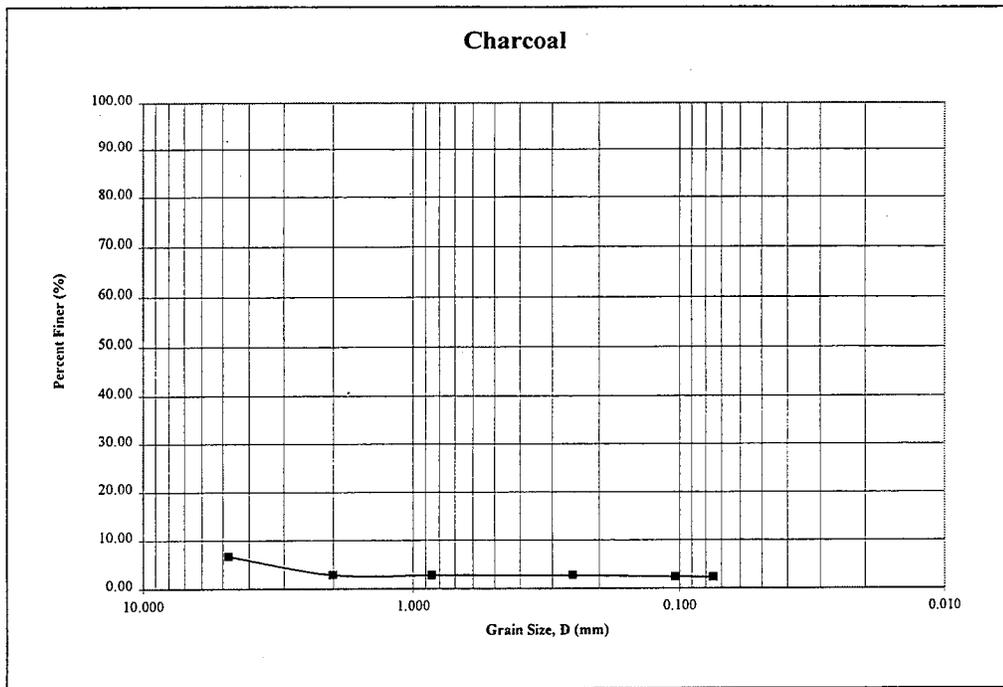
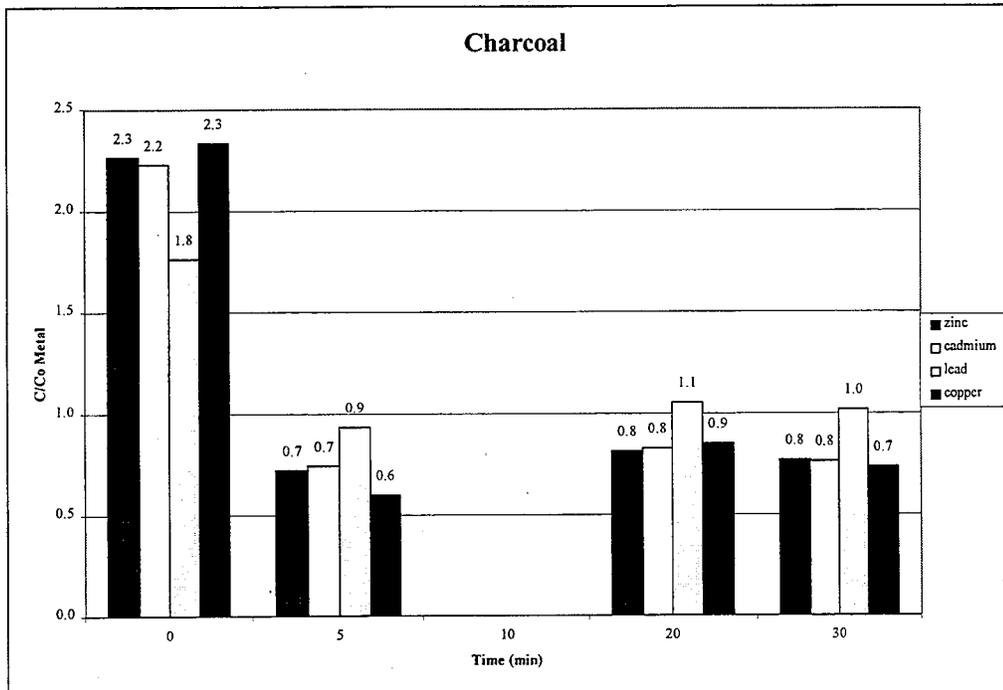


Figure 3.26 Sieve Analysis of Charcoal Filter Medium



Note: 10 min. sample lost due to instrument error

Figure 3.27 Metals Analysis of Charcoal Effluent

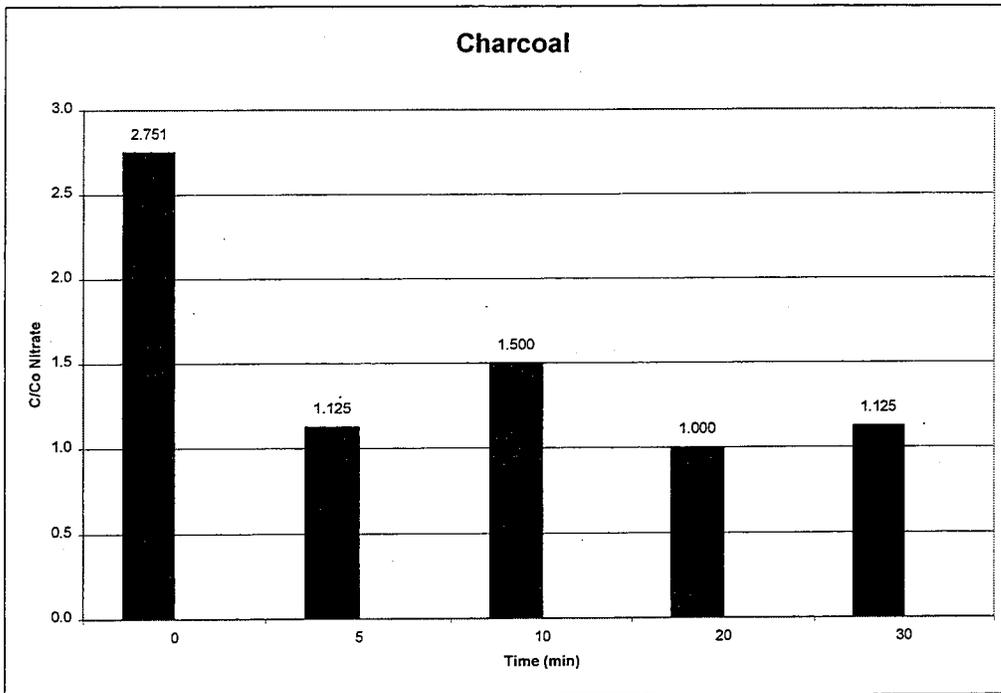


Figure 3.28 Nitrate Analysis of Charcoal Effluent

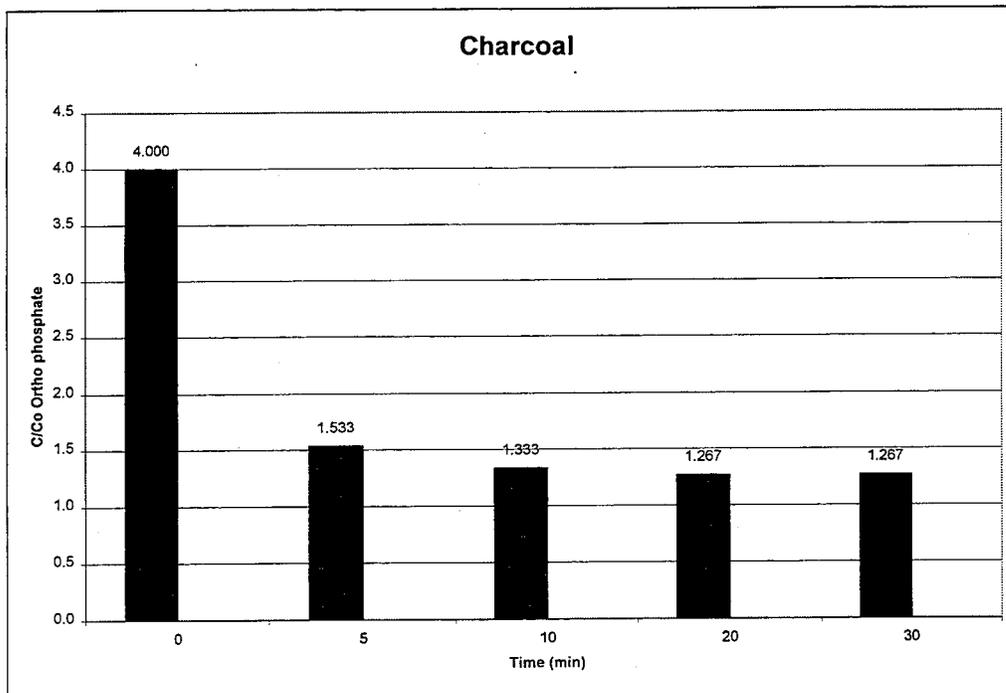


Figure 3.29 Phosphate Analysis of Charcoal Effluent

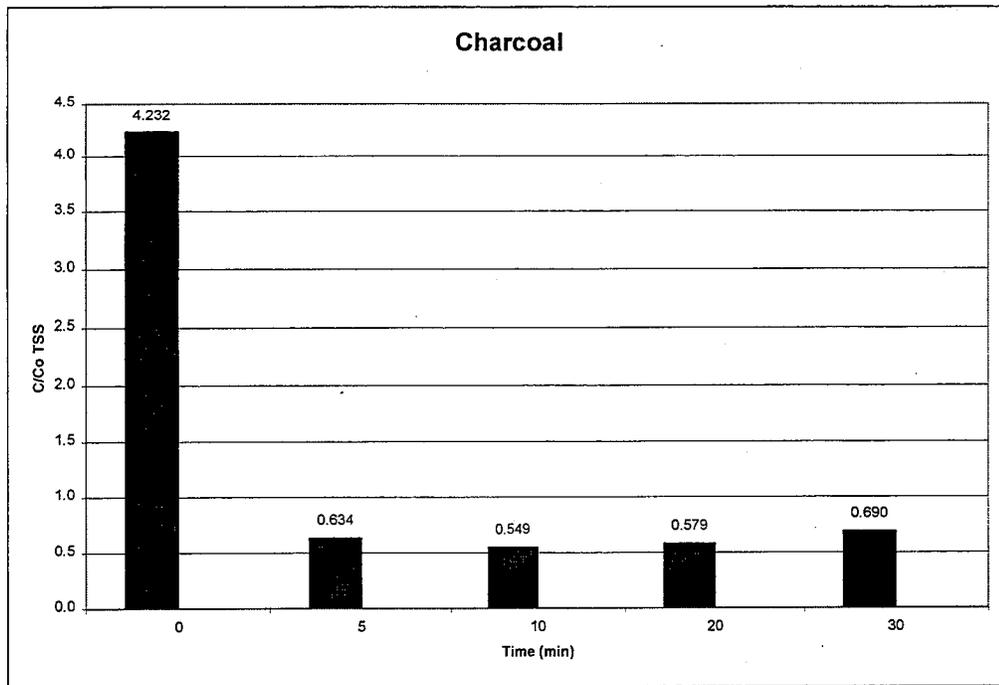


Figure 3.30 TSS Analysis of Charcoal Effluent

Table 3.10 Environmental Testing Results for Charcoal Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	87.9	121.5	984.1	484.0	0.602	0.015	145	6.25
0	196.0	283.6	1737.3	1096.2	1.656	0.060	613.6	6.58
5	65.2	72.9	919.3	349.8	0.677	0.023	92.0	6.92
10	--	--	--	--	0.903	0.020	78.6	6.82
20	72.8	103.5	1038.1	394.3	0.602	0.019	84.0	6.75
30	372.9	89.4	1004.4	372.9	0.677	0.019	100.0	6.70

3.6.3.4 Corn Cobs

The crushed corn cobs were purchased at a local pet store. The only packaging information is that they are a natural corn cob product. Figure 3.31 shows the corn cob grain size distribution. Metals concentration data is plotted in Figure 3.32. Only zinc exhibited a first flush in the 0 min time interval.

Cadmium was reduced by 90%, copper was reduced by 60%, and zinc was reduced by 80% at the 90 min sampling interval. Lead concentrations, however, remained high throughout the test period, and showed signs of breakthrough at the 60 min interval. Figure 3.33 shows that corn cobs were effective at removing greater than 80% of the nitrate from the synthetic stormwater. The 30 min sampling interval shows a large jump in nitrate concentration. The runoff water was changed at that time interval, but that should not have produced such a large increase in nitrate concentration since the results were reported as ratios. Figure 3.34 also shows a large increase in orthophosphate concentration at the 30 min interval. This suggests that the change in runoff water may have been responsible for the increases, however, Figures 3.32 and 3.35 do not show this same pattern. Recommendations that follow were based on the trend of the data, not on the apparent anomaly of this data point. All time intervals in Figure 3.34 show production of orthophosphate from the corn cob filter. Thus, this filter is effective at removing nitrate but not phosphate from runoff water. Figure 3.35 shows that approximately 75% of the TSS was removed with this medium. It should be noted that the medium swelled over the testing duration, thereby improving TSS removal, but making removal from the column difficult. Table 3.11 shows that the pH drops with initial contact with the corn cob filter, but then remains steady around 5.5. It should be noted that some of the corn cob material floated to the top of the 6 in head of water during the test period.

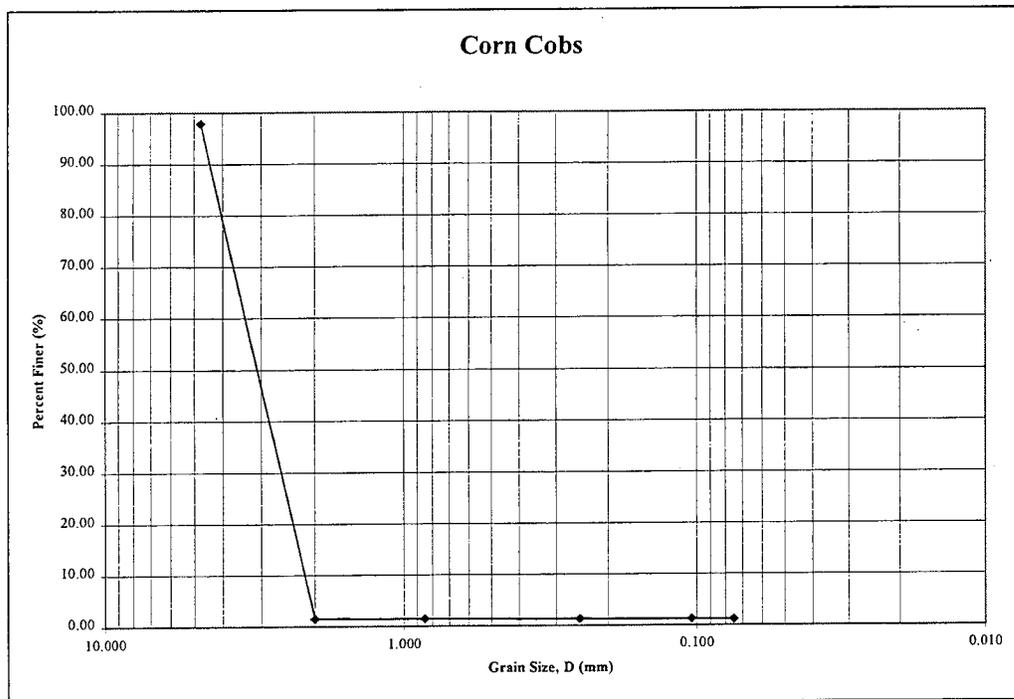


Figure 3.31 Sieve Analysis of Corn Cob Filter Medium

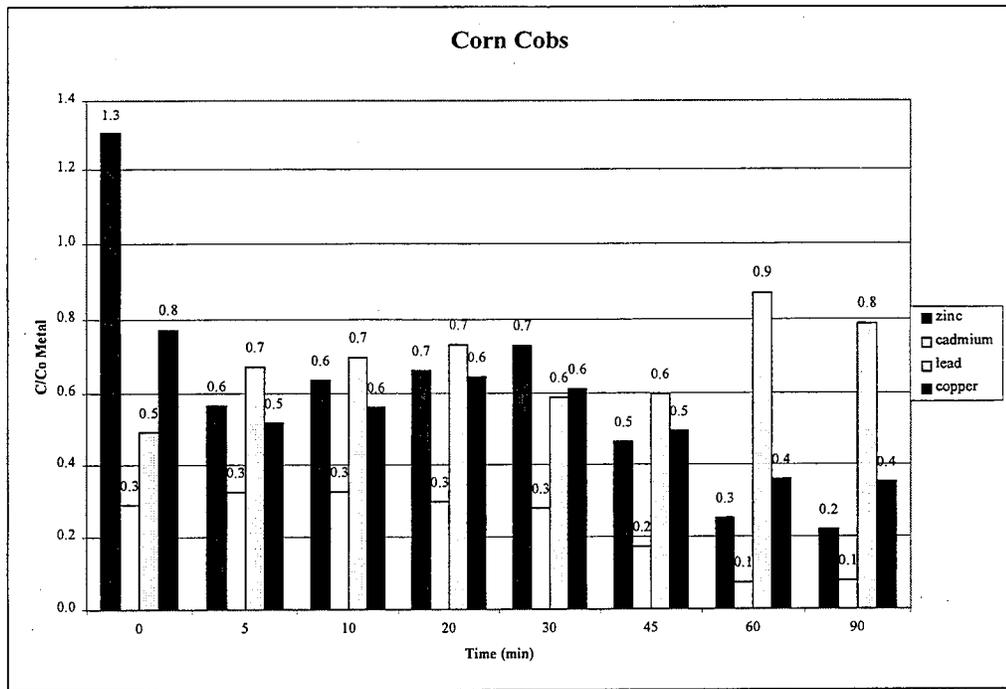


Figure 3.32 Metals Analysis of Corn Cob Effluent

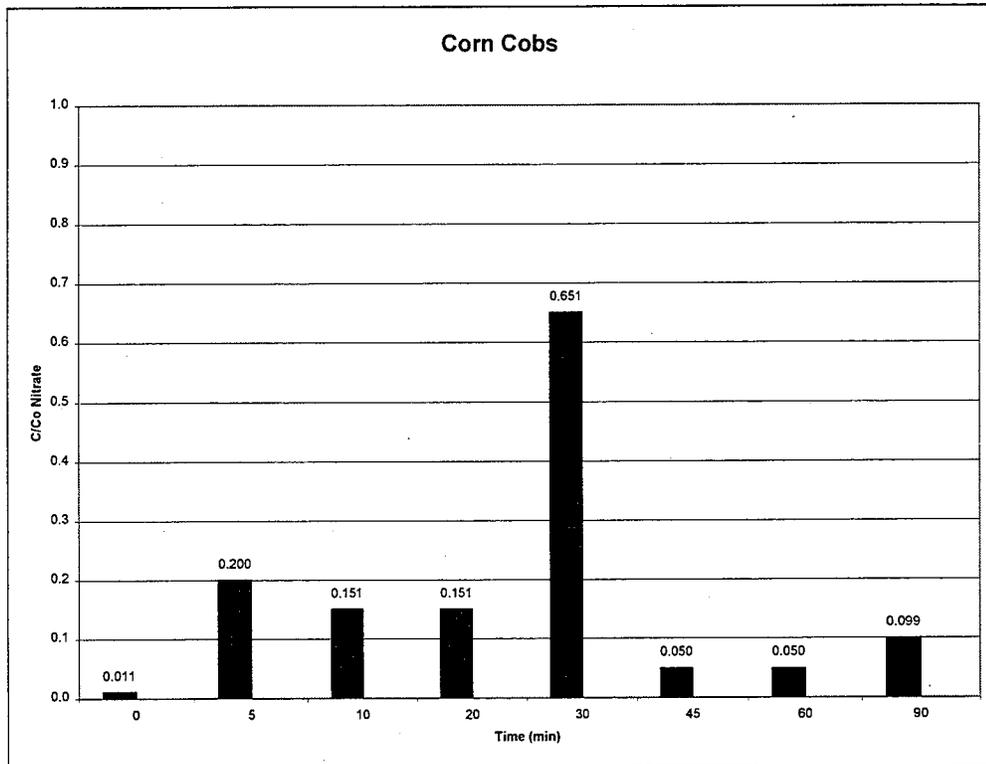


Figure 3.33 Nitrate Analysis of Corn Cob Effluent

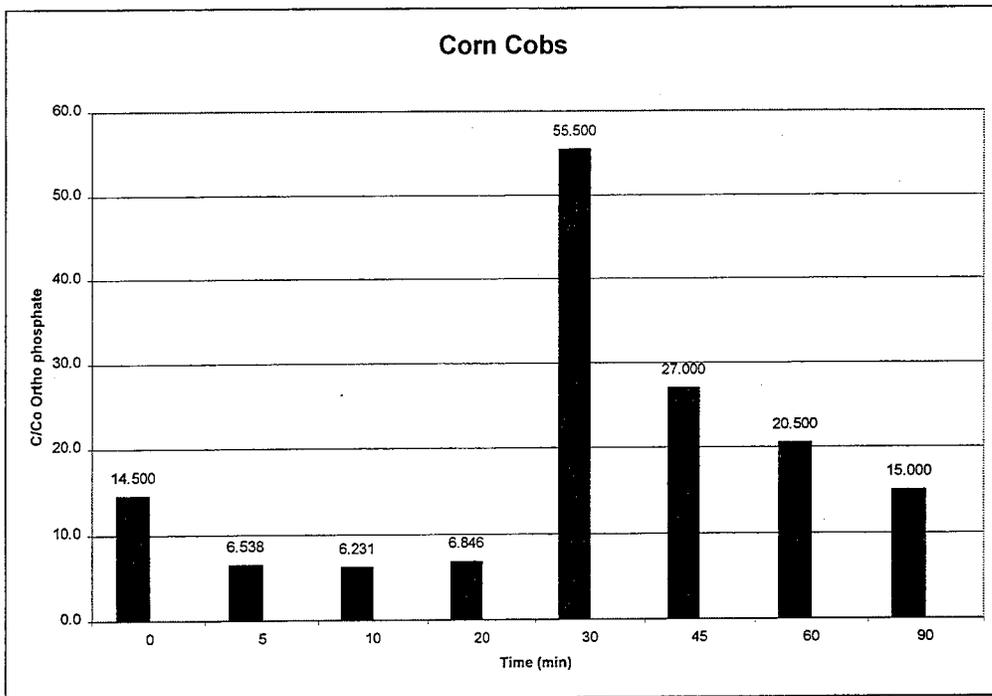


Figure 3.34 Phosphate Analysis of Corn Cob Effluent

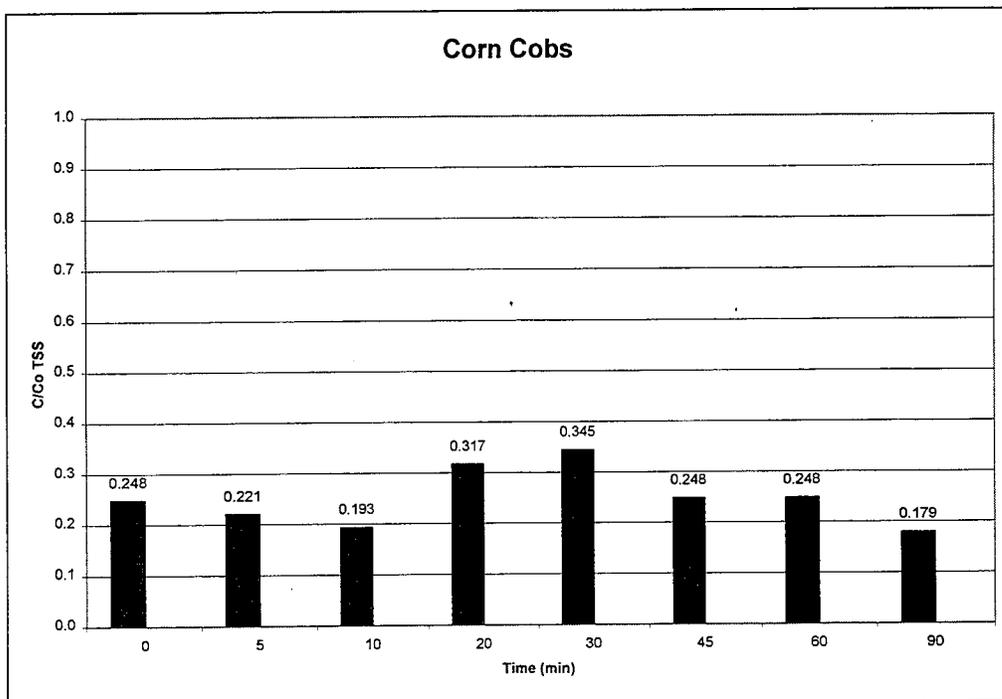


Figure 3.35 TSS Analysis of Corn Cob Effluent

Table 3.11 Environmental Testing Results for Corn Cob Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	78.3	96.1	773.8	474.0	0.704	0.052	145	5.35
0	22.7	74.3	380.3	618.7	0.008	0.754	36.0	4.72
5	25.4	49.7	521.2	267.9	0.141	0.340	32.0	5.71
10	25.5	53.9	540.8	301.4	0.106	0.324	28.0	5.66
20	23.3	62.0	566.9	314.0	0.106	0.356	46.0	5.54
Runoff	77.8	150.7	587.8	469.8	0.563	0.008	50.0	6.00
30	21.7	92.1	245.5	343.1	0.458	0.444	36.0	4.93
45	13.4	74.5	350.7	218.0	0.035	0.216	36.0	5.24
60	5.7	54.1	511.2	118.3	0.035	0.164	36.0	5.44
90	6.1	53.0	463.3	102.8	0.070	0.120	26.0	5.44

3.6.3.5 Garden Bark

The garden bark material was purchased at a local nursery. Its only packaging information is that it is made of mulch grade of conifer varieties. Figure 3.36 shows its grain size distribution. Metals removal is plotted in Figure 3.37. Zinc has an initial first flush at the 0 min time interval, but is 90% removed during the subsequent sampling intervals. Cadmium and copper concentrations also show reductions of 90% throughout the test period. Lead concentrations, however, remain essentially constant with only approximately 30% removed at each time interval. Figure 3.38 shows a large first flush of nitrate, nearly seven times the runoff concentration. Subsequent sampling intervals reveal only 20-30% nitrate removal with the garden bark filter. This general pattern is also present in the orthophosphate data presented in Figure 3.39. The 0 min time interval has 19 times the phosphate concentration as the synthetic stormwater. The concentration ratios are greatly reduced from 19 during the remainder of the test period, but each are significantly greater than 1.0, indicating production of phosphate from the garden bark column. The bark was effective at removing TSS, as shown in Figure 3.40. Eighty to 90% of solids were removed throughout the test period. Table 3.12 shows a large decrease in pH at initial contact with the garden bark. After 10 minutes, however, it increased and remained steady around 6.3. It should be noted that some of the garden bark material floated to the top of the 6 in head of water during the test period.

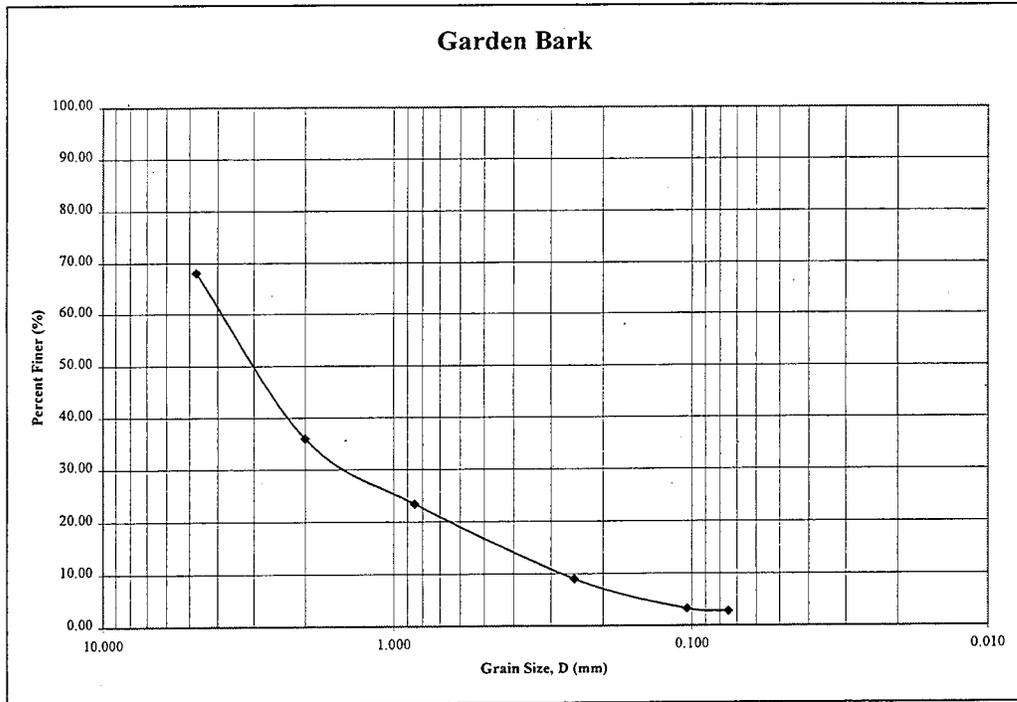


Figure 3.36 Sieve Analysis of Garden Bark Filter Medium

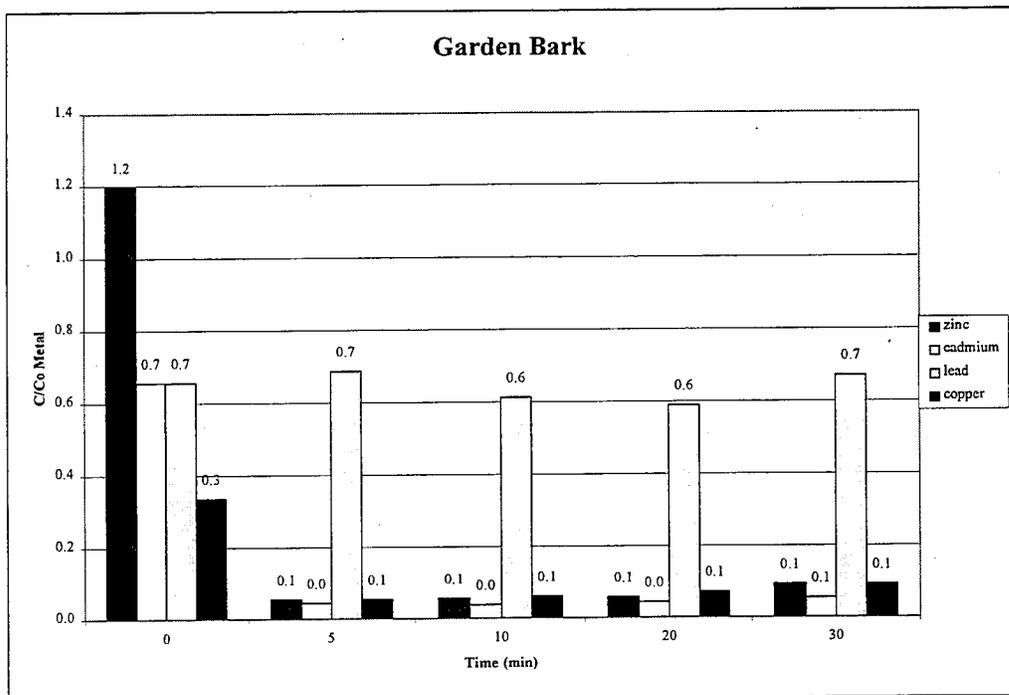


Figure 3.37 Metals Analysis of Garden Bark Effluent

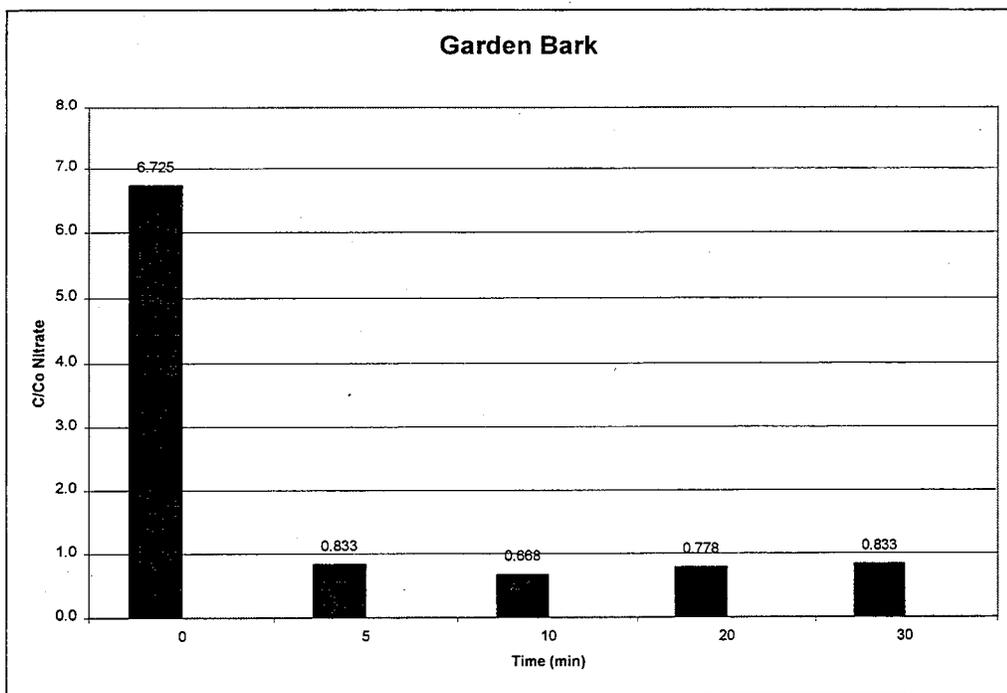


Figure 3.38 Nitrate Analysis of Garden Bark Effluent

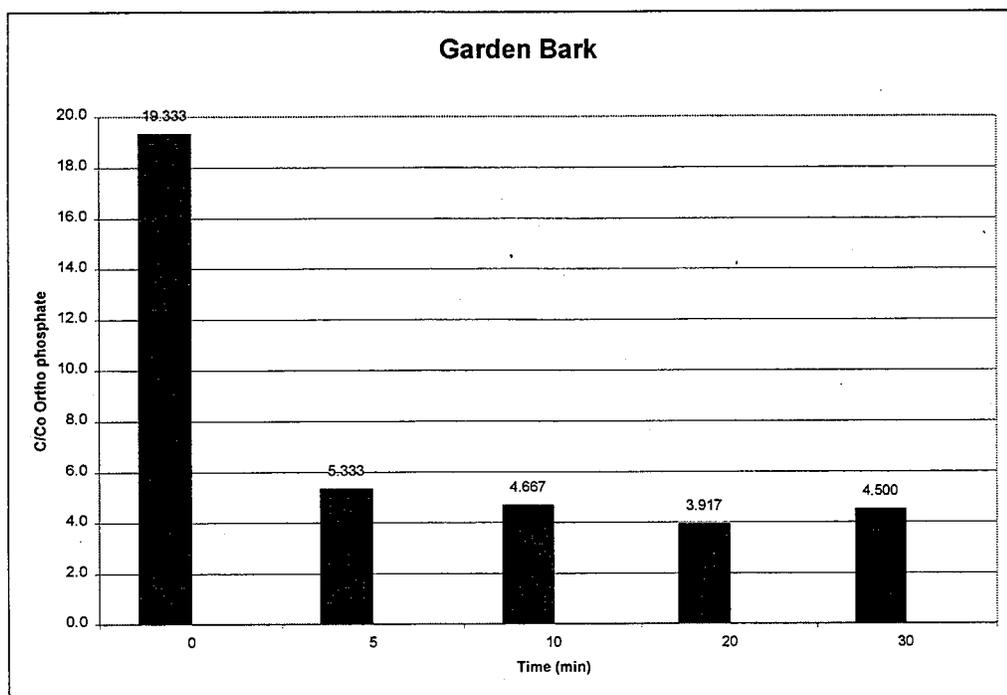


Figure 3.39 Phosphate Analysis of Garden Bark Effluent

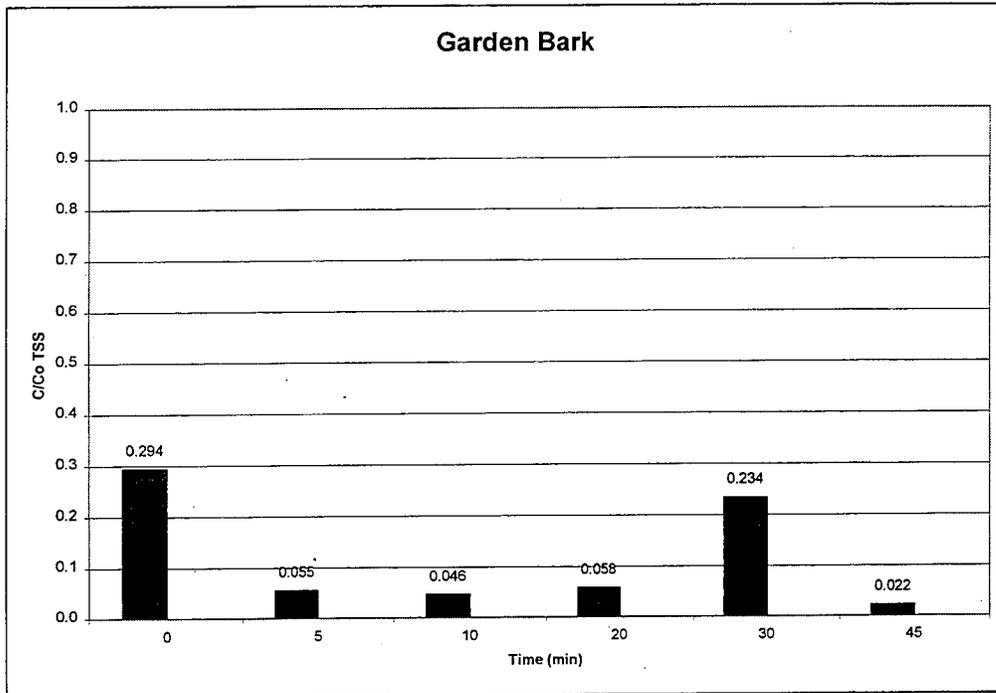


Figure 3.40 TSS Analysis of Garden Bark Effluent

Table 3.12 Environmental Testing Results for Garden Bark Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	72.8	215.8	847.1	530.0	0.677	0.012	145	7.07
0	47.8	72.7	556.0	634.6	4.553	0.232	42.67	3.40
5	3.2	11.7	581.6	28.9	0.564	0.064	8.00	5.70
10	2.8	13.1	518.8	29.7	0.452	0.056	6.67	6.10
20	3.1	15.6	499.9	30.4	0.527	0.047	8.40	6.23
30	4.0	19.9	568.9	49.3	0.564	0.054	34.00	6.26

3.6.3.6 Glass Beads

The glass beads filter material, used as a physical control, was purchased from the WSU laboratory supply store. They are uniform spheres with a 6 mm diameter. Figure 3.41 shows a large first flush of zinc, just over three times the concentration in the runoff water, and a small flush of copper. After the 0 min time interval, all metals concentrations remained very consistent for the duration of the test period. Very little metal, only 10-40% depending on the element, was removed with the glass beads filter. This was to be expected since the beads do not have adsorption sites on to which the metals can bind. Figure 3.42 shows the nitrate removal with the glass beads medium. The data point for the 0 min time interval was removed as an outlier based on the authors' engineering judgement. Surprisingly, because the glass was considered to be inert, nitrate was produced at each sampling interval. Orthophosphate concentrations, however, were decreased by approximately 30%, as shown in Figure 3.43. Figure 3.44 shows that the beads were effective at removing almost 80% of the TSS present in the synthetic stormwater. The increase in TSS concentration at the 60 min time interval, however, suggests the beginning of breakthrough for the solids. As shown in Table 3.13, the pH dropped 2.5 units upon entering the glass bead column, but quickly increased back to its original value. This may be explained by residual acid on the beads from the acid wash and deionized water rinse cleaning procedure.

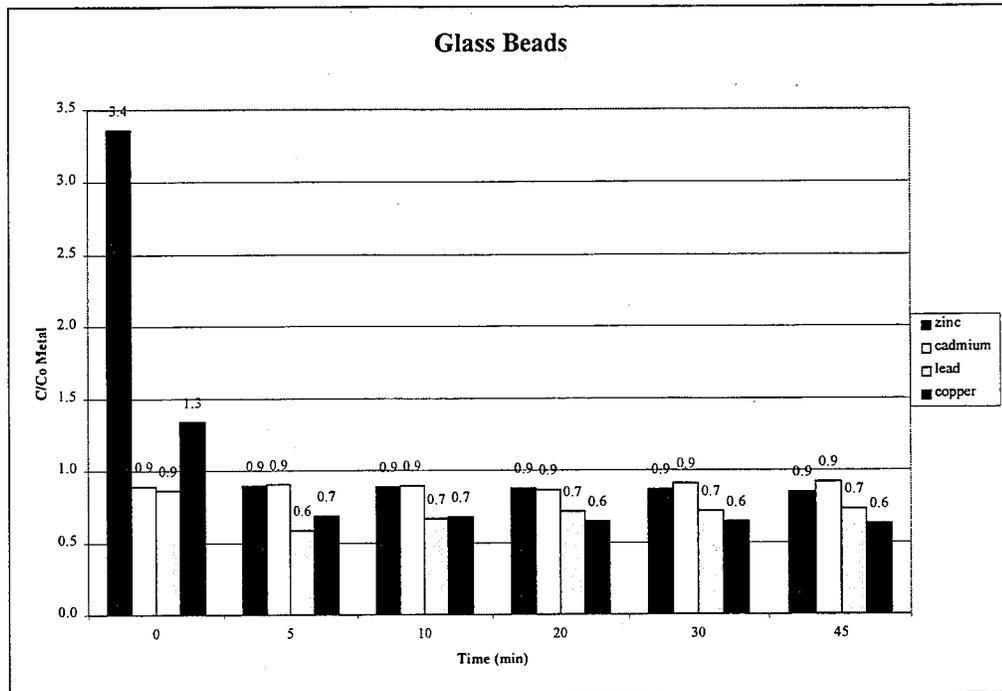


Figure 3.41 Metals Analysis of Glass Beads Effluent

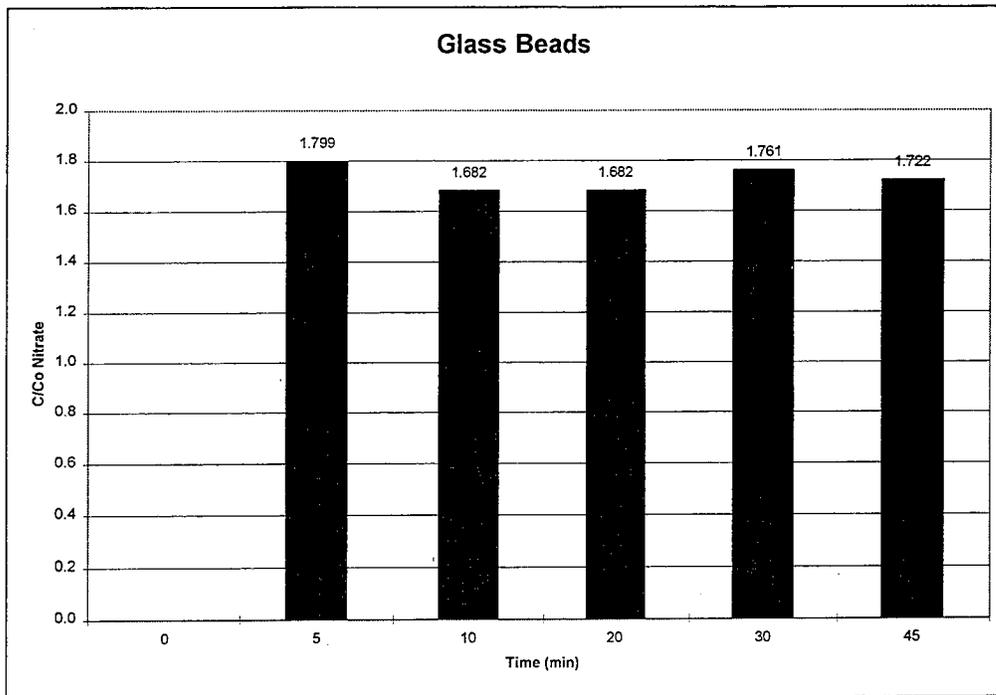


Figure 3.42 Nitrate Analysis of Glass Beads Effluent

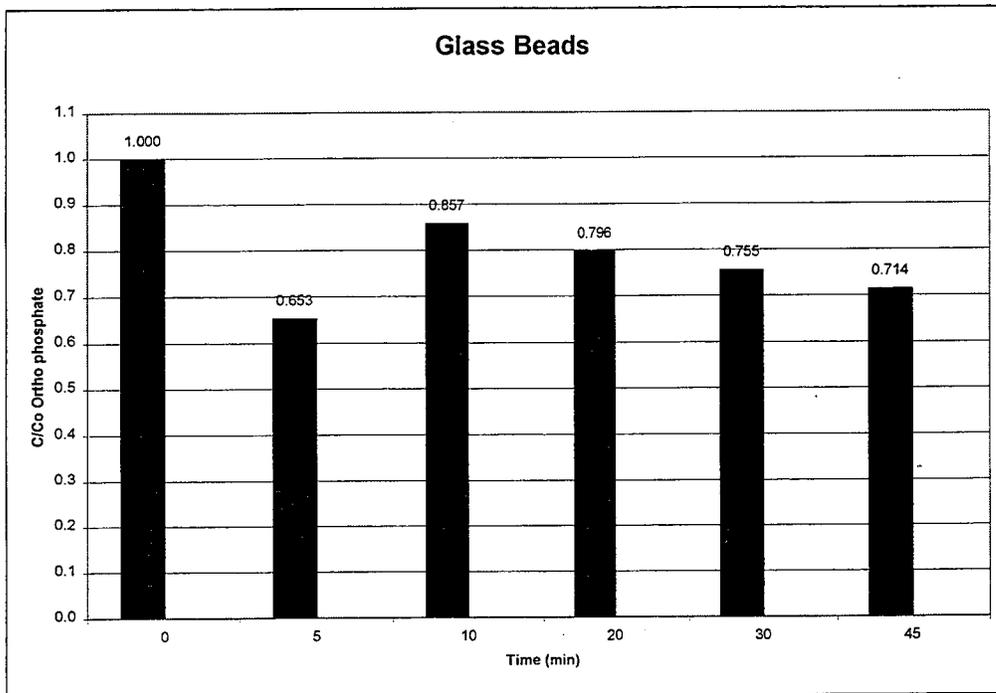


Figure 3.43 Phosphate Analysis of Glass Beads Effluent

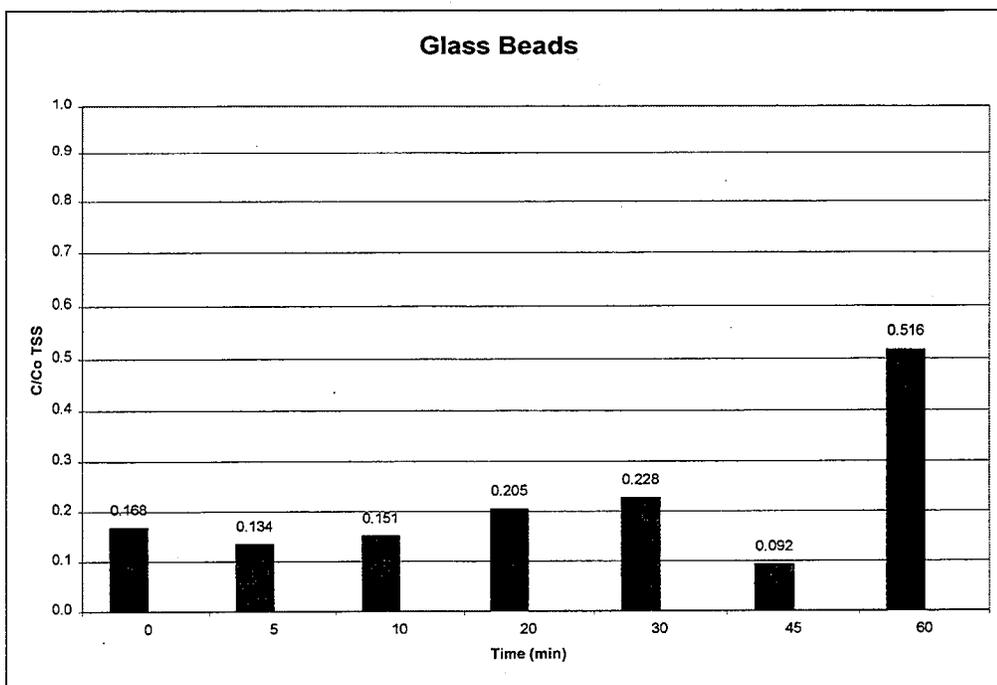


Figure 3.44 TSS Analysis of Glass Beads Effluent

Table 3.13 Environmental Testing Results for Glass Beads Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	81.4	127.3	946.0	506.8	0.528	0.049	145	5.48
0	72.6	170.6	815.8	1702.3	*	0.049	24.4	3.01
5	73.7	87.6	555.5	453.5	0.950	0.032	19.5	5.05
10	72.9	86.7	628.4	450.3	0.888	0.042	21.9	5.32
20	70.4	82.5	678.0	444.5	0.888	0.039	29.7	5.32
30	74.0	82.2	681.3	439.6	0.930	0.037	33.0	5.28
45	74.8	80.3	694.2	431.9	0.909	0.035	13.4	5.35
60	--	--	--	--	--	--	74.8	--

3.6.3.7 Kitty Litter

The generic kitty litter medium was purchased at Wal-Mart. The packaging information states that it is 99% dust free and made of ground natural clay. Figure 3.45 shows its grain size distribution. Kitty litter was envisioned as a good medium due to its absorbancy, however, it was so absorbant that hardly any water was able to pass through it during the testing period. It was therefore eliminated as a single medium possibility, but may be mixed with another medium to improve the filter matrix absorbancy.

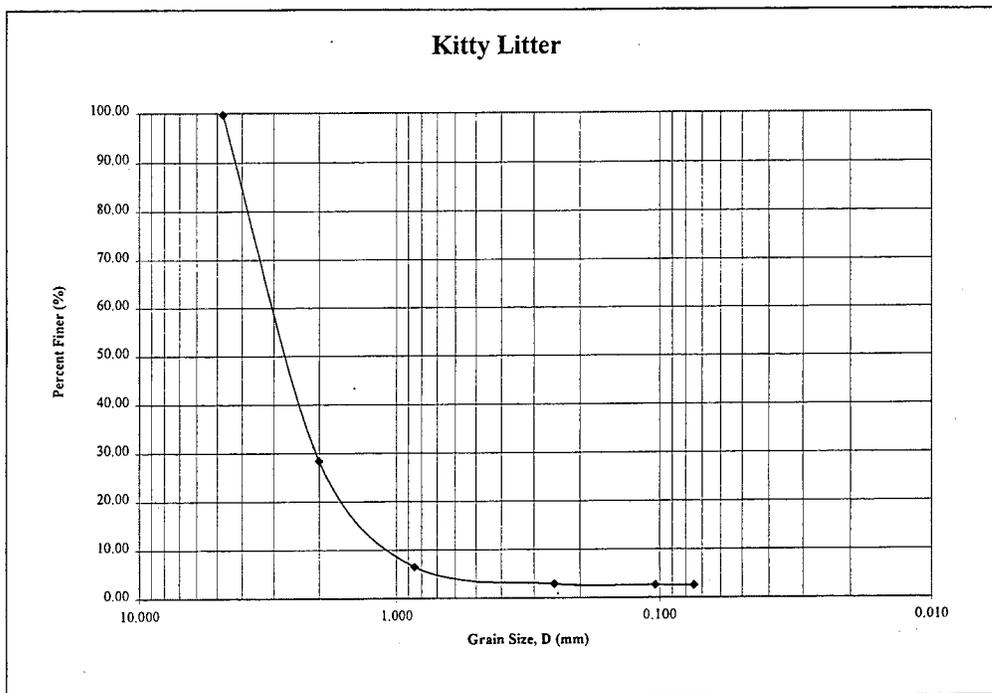


Figure 3.45 Sieve Analysis of Kitty Litter Filter Medium

3.6.3.8 Iron Oxide Coated Sand

The iron oxide coated sand (IOCS) was generously provided by Dr. Mark Benjamin of the University of Washington Civil Engineering Department. Figure 3.46 presents its grain size distribution. Figure 3.47 shows that IOCS is effective at removing metals from the synthetic stormwater. The 70 % removal of copper was a conservative result as copper concentrations were below the method detection limit, but their exact concentrations were not known. Lead concentrations were also below the detection limit, even for the synthetic stormwater, so an exact determination of removal efficiency was not possible. Zinc and cadmium concentrations were reduced by more than 90 % from the initial runoff water. Figure 3.48 shows that in general, IOCS is effective at removing orthophosphate from the runoff water. The 20-

minute time interval revealed a sharp increase in the effluent phosphate concentration, but that was considered an anomaly. All other time intervals yielded approximately a 70 % removal efficiency. Figure 3.49 illustrates that IOCS is effective at removing nearly 90 % of the TSS present in the synthetic stormwater. The small increases in TSS concentrations for the 30-minute and 45-minute time intervals suggests that breakthrough of solids may have begun to occur. Due to the small grain sizes of this sand, a 40-mesh screen was required on top of the TSS disk in order to prevent the sand column from washing out under the pressure of the 6 in head of water. Table 3.14 shows that the pH remained essentially constant throughout the testing period.

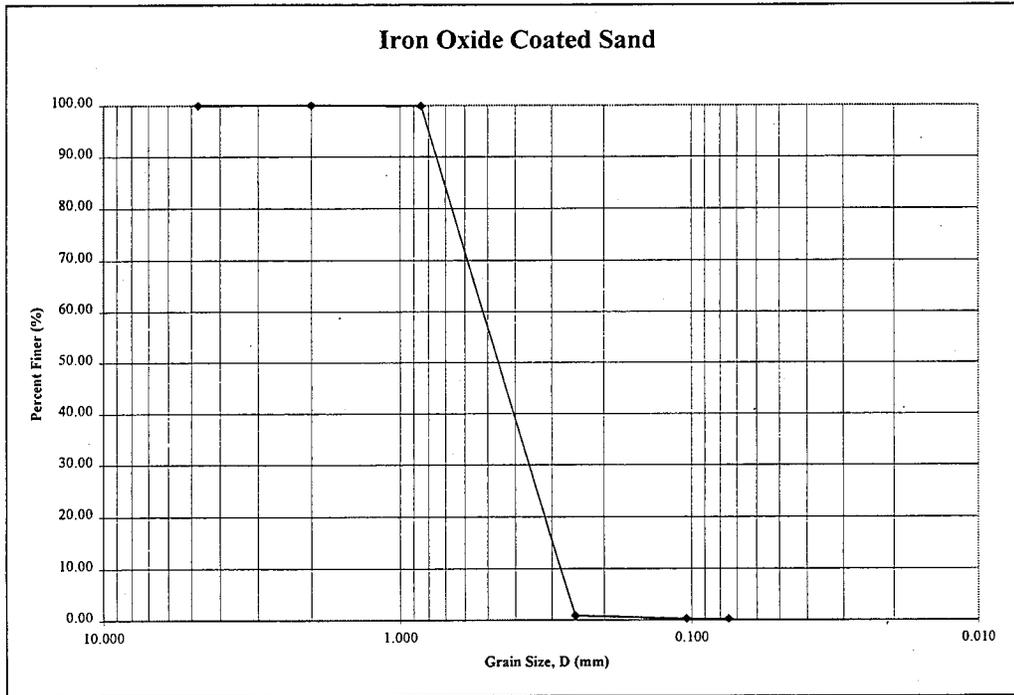


Figure 3.46 Sieve Analysis of Iron Oxide Coated Sand Filter Medium

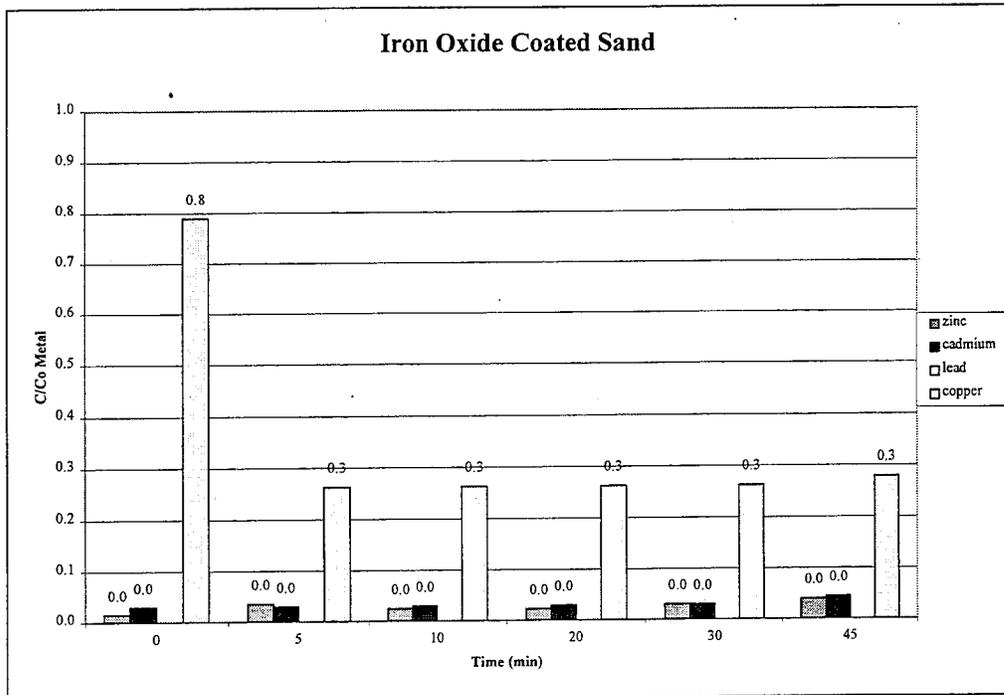


Figure 3.47 Metals Analysis of Iron Oxide Coated Sand Effluent

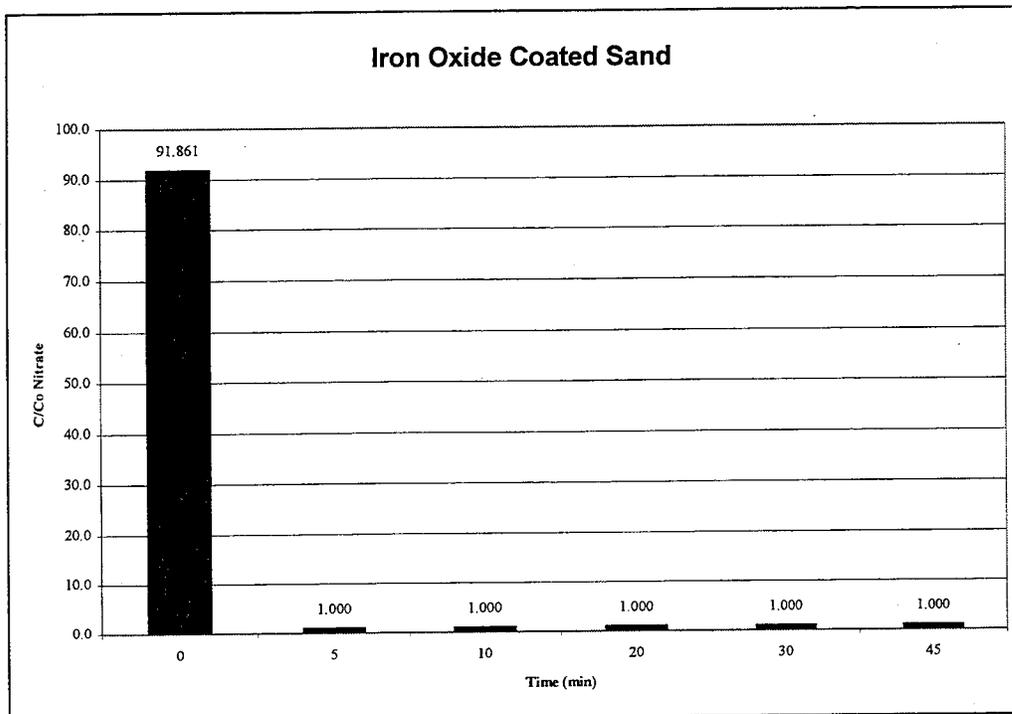


Figure 3.48 Nitrate Analysis of Iron Oxide Coated Sand Effluent

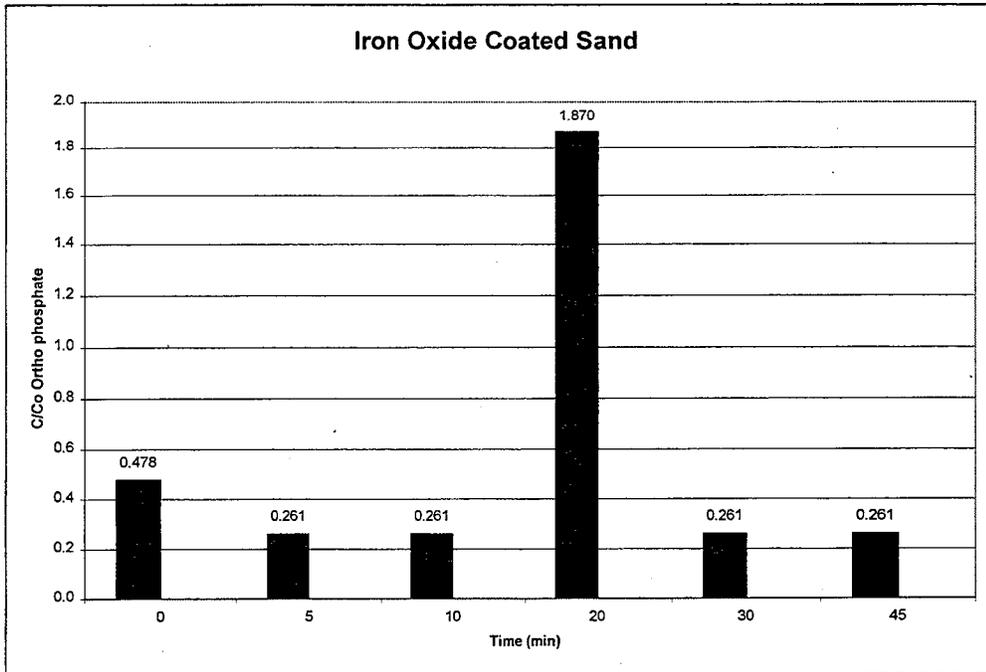


Figure 3.49 Phosphate Analysis of Iron Oxide Coated Sand Effluent

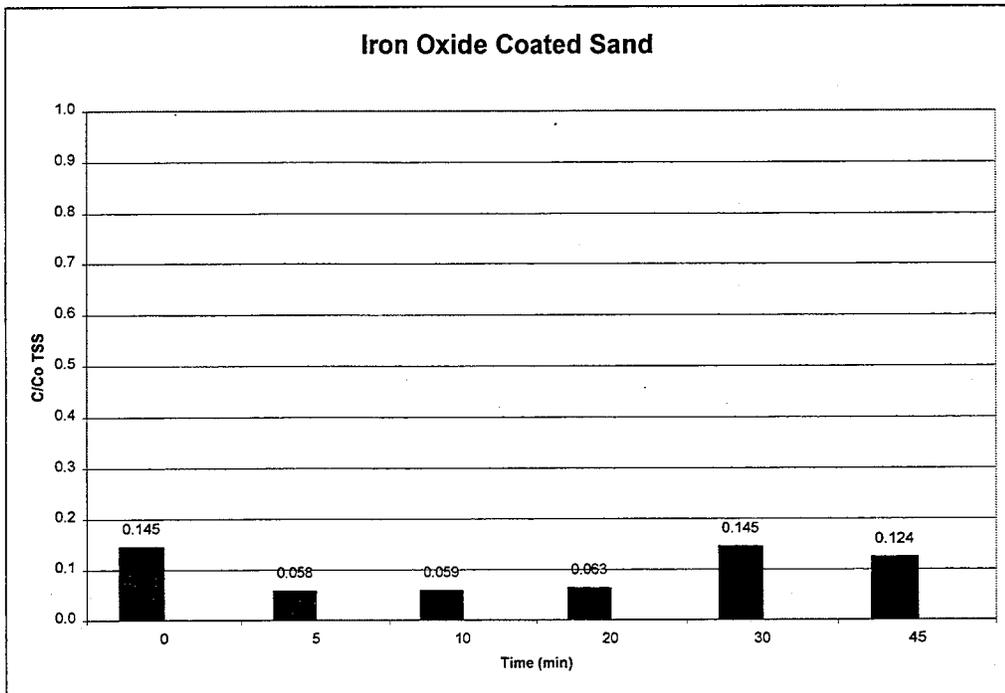


Figure 3.50 TSS Analysis of Iron Oxide Coated Sand Effluent

Table 3.14 Environmental Testing Results for Iron Oxide Coated Sand Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	67	19	<220	397	14.990	0.023	145.0	9.65
0	<2	15	<220	6.1	91.861	0.011	21.0	10.03
5	<2	<5	<220	14	14.990	0.005	8.4	9.90
10	<2	<5	<220	9	14.990	0.005	8.5	10.07
20	<2	<5	<220	9.1	14.990	0.043	9.2	9.65
30	<2	<5	<220	12	14.990	0.005	21.0	9.63
45	3	5.3	<220	16	14.990	0.005	18.0	9.75

3.6.3.9 Peat Moss

The peat moss medium is a horticultural sphagnum derived from peat bogs, purchased at Wal-Mart. Figure 3.51 shows its grain size distribution. Metals removal is plotted in Figure 3.52. The peat moss filter was effective at removing 80-90% of all the metals tested. Lead was the metal consistently removed the least. Figure 3.53 shows a large production of nitrate at each sampling interval, although the concentrations did decrease over the testing period. The 0 minute data point was eliminated as an outlier based on the judgement of the authors. Orthophosphate was also produced at each sampling interval, as shown in Figure 3.54. The phosphate data exhibited a first flush at the 0 minute time interval, but had no consistent trend during the testing period. The TSS data showed a longer first flush, lasting through the 10 min time interval, as illustrated in Figure 3.55. After the fines were eliminated from the column, the peat moss filter removed greater than 95% of the TSS in the runoff water. Table 3.15 shows that the pH remained consistent around 6.0 and 6.5 throughout the test period. It should be noted that some of the peat moss material floated to the top of the 6 in head of water during the test period.

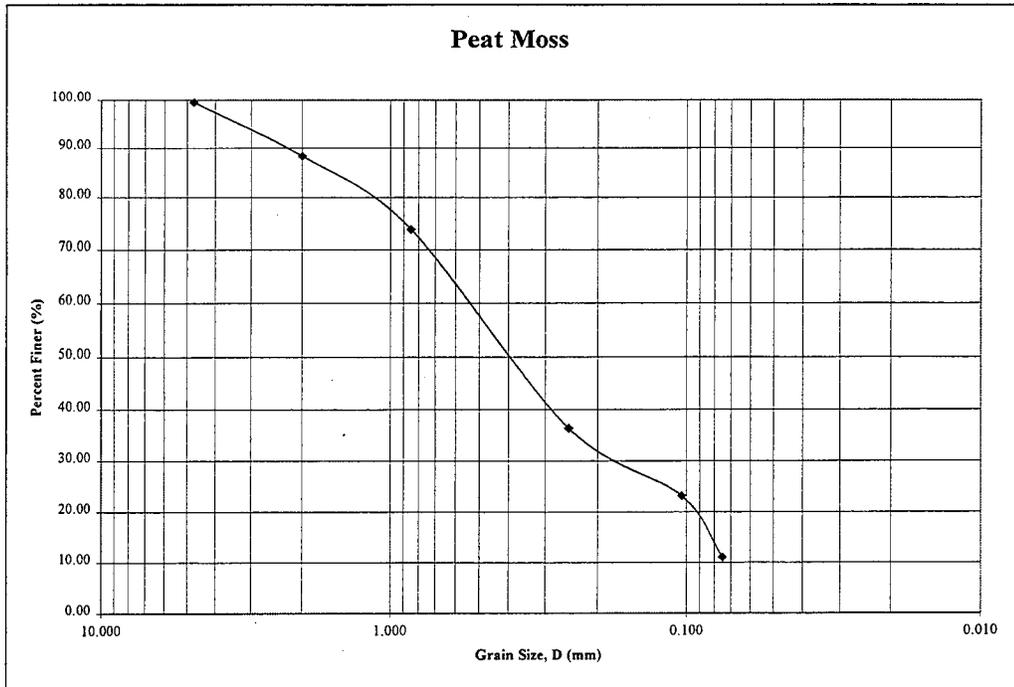


Figure 3.51 Sieve Analysis of Peat Moss Filter Medium

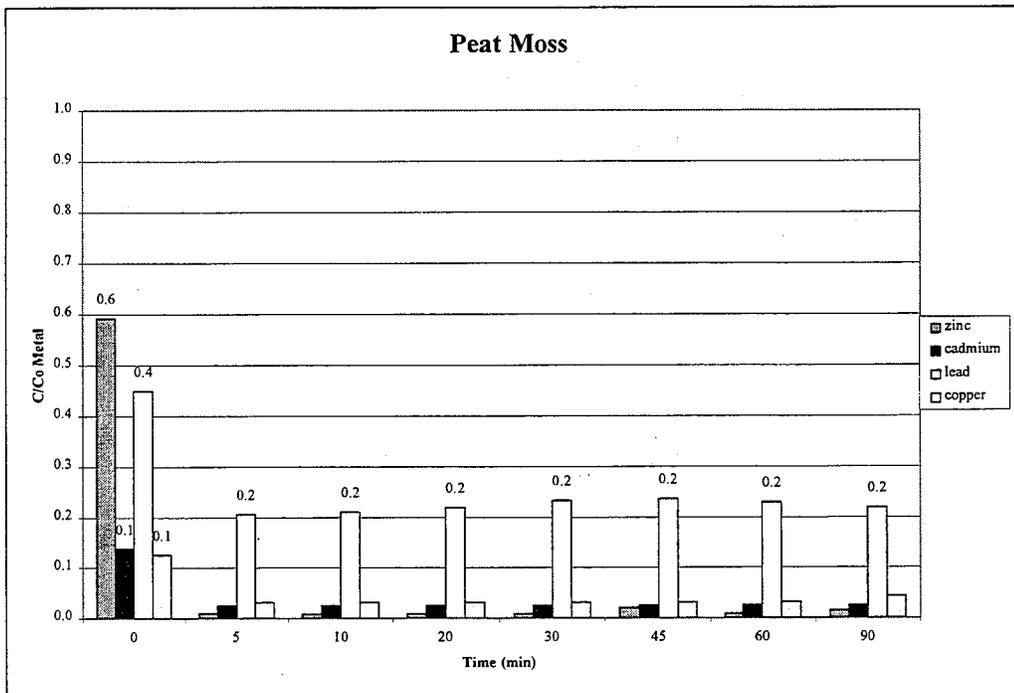


Figure 3.52 Metals Analysis of Peat Moss Effluent

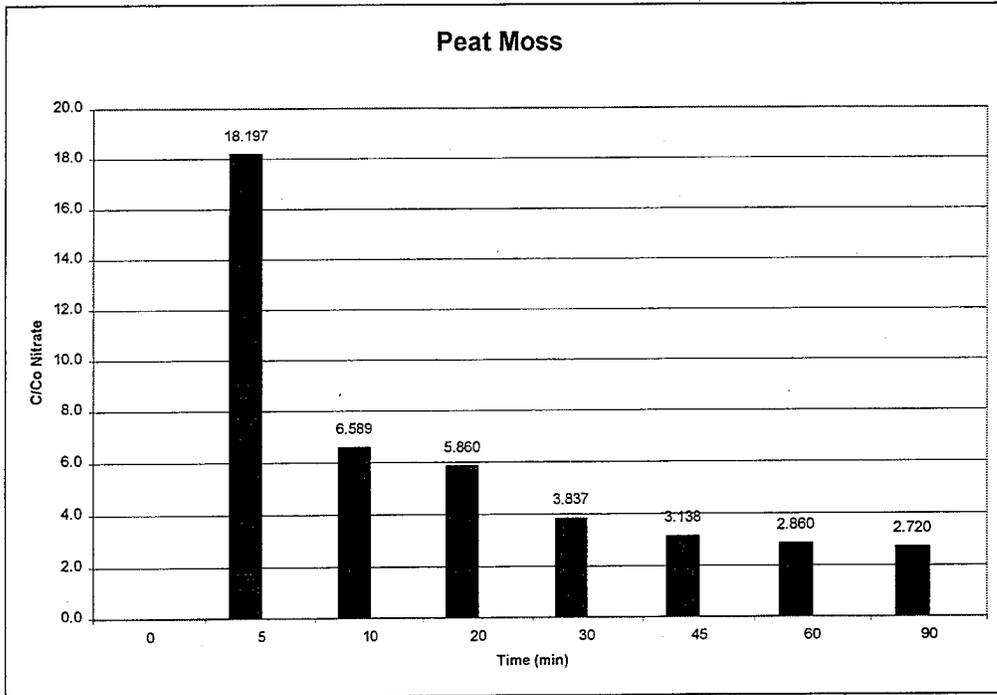


Figure 3.53 Nitrate Analysis of Peat Moss Effluent

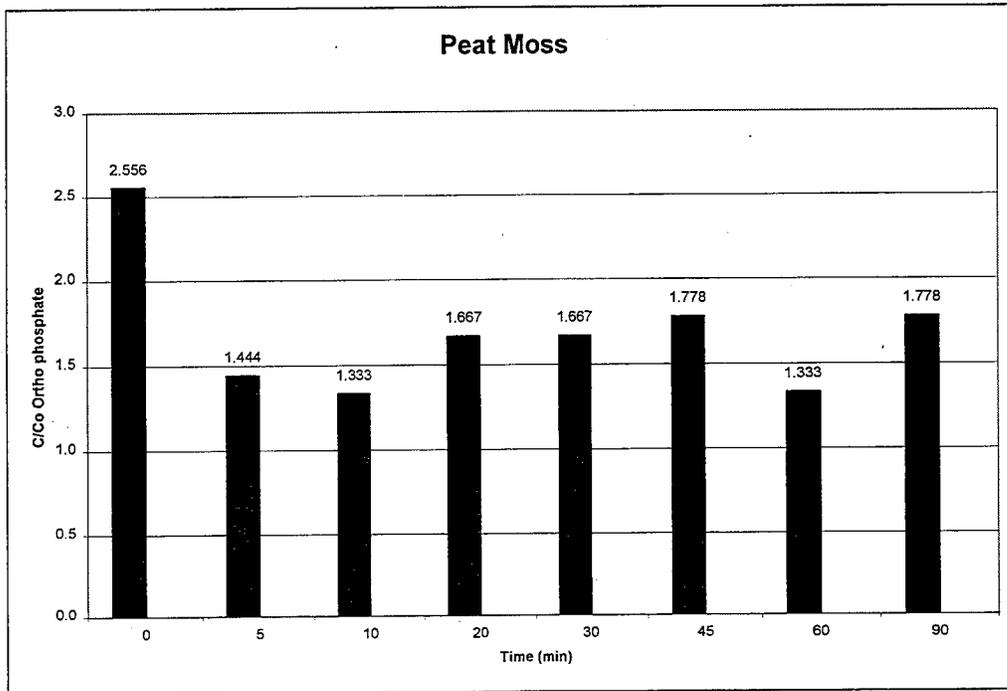


Figure 3.54 Phosphate Analysis of Peat Moss Effluent

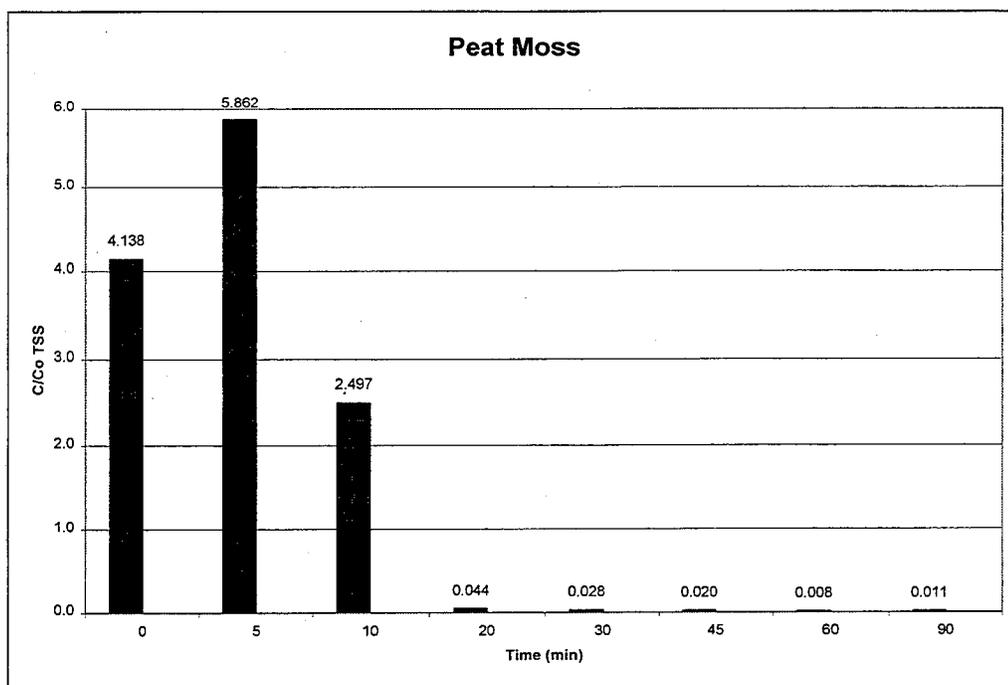


Figure 3.55 TSS Analysis of Peat Moss Effluent

Table 3.15 Environmental Testing Results for Peat Moss Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	79.9	126.1	775.4	460.5	0.528	0.009	145.0	7.17
0	11.0	15.9	348.5	272.9	*	0.023	600.0	4.52
5	<2	<4	160.0	4.6	9.608	0.013	850.0	5.65
10	<2	<4	167.9	<4	3.479	0.012	362.0	6.06
20	<2	<4	170.3	<4	3.094	0.015	6.4	6.13
30	<2	<4	181.2	<4	2.026	0.015	4.0	5.69
45	<2	<4	183.2	9.4	1.657	0.016	2.8	6.56
60	<2	<4	178.0	<4	1.510	0.012	1.2	6.46
90	<2	5.5	170.1	6.6	1.436	0.016	1.6	6.48

3.6.3.10 Persolite

The persolite was obtained from the Albrook Hydraulics Laboratory at WSU. It is used as an additive in concrete mixtures and contains perlite, a nuisance dust. Figure 3.56 shows its grain size distribution. Metal concentrations are plotted in Figure 3.57. The initial time intervals through 10 min, show effective removal of 80-90% for all metals. Sampling interval 20 min, however, marks the beginning of metals breakthrough for the persolite column. Zinc concentrations increase the most, followed by cadmium and copper. In contrast, lead concentrations continue the downward trend into the 90 min sampling interval. Figure 3.58 shows a first flush of nitrate at the 0 min time interval. The nitrate concentrations are significantly reduced from the initial high concentration, but continue to reveal production from the medium. Orthophosphate also exhibits a first flush at the 0 min time interval, but it is much less than that seen with nitrate, as shown in Figure 3.59. All subsequent sampling intervals shows approximately 70% phosphate removal. The first flush trend at the 0 min interval is also present in the TSS data plotted in Figure 3.60, but it is even more minimized than the phosphate data. All subsequent sampling intervals exhibit greater than 90% TSS removal from the synthetic stormwater. Table 3.16 shows an initial drop in pH as the runoff water comes in contact with the persolite. The pH then remains constant around 6.3 for the duration of the test period. It should be noted that some of the persolite material floated to the top of the 6 in head of water during the test period.

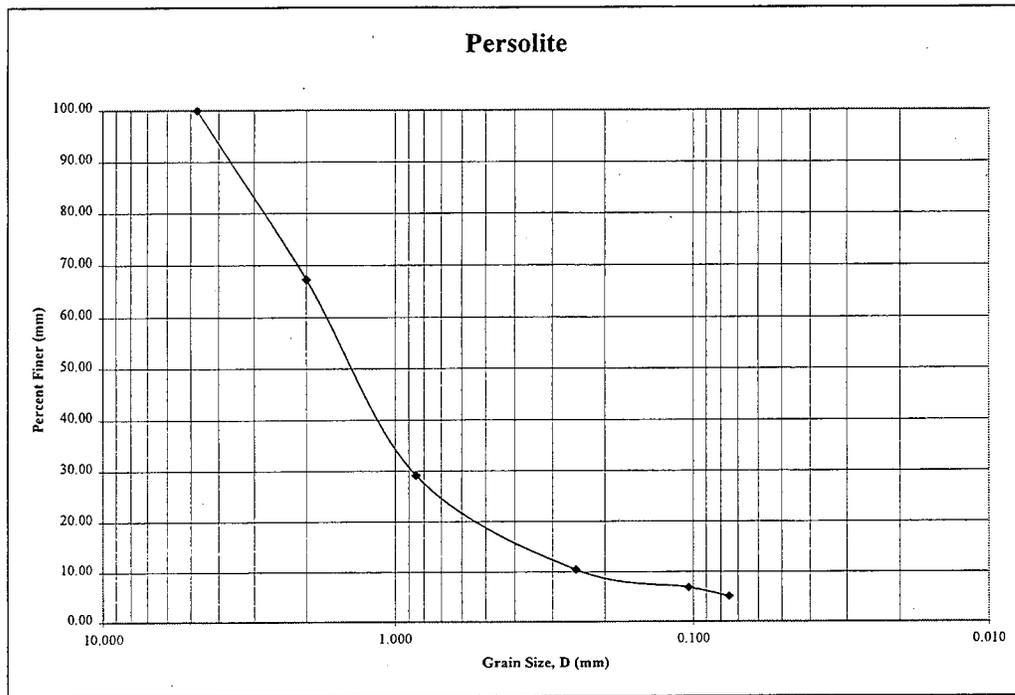


Figure 3.56 Sieve Analysis of Persolite Filter Medium

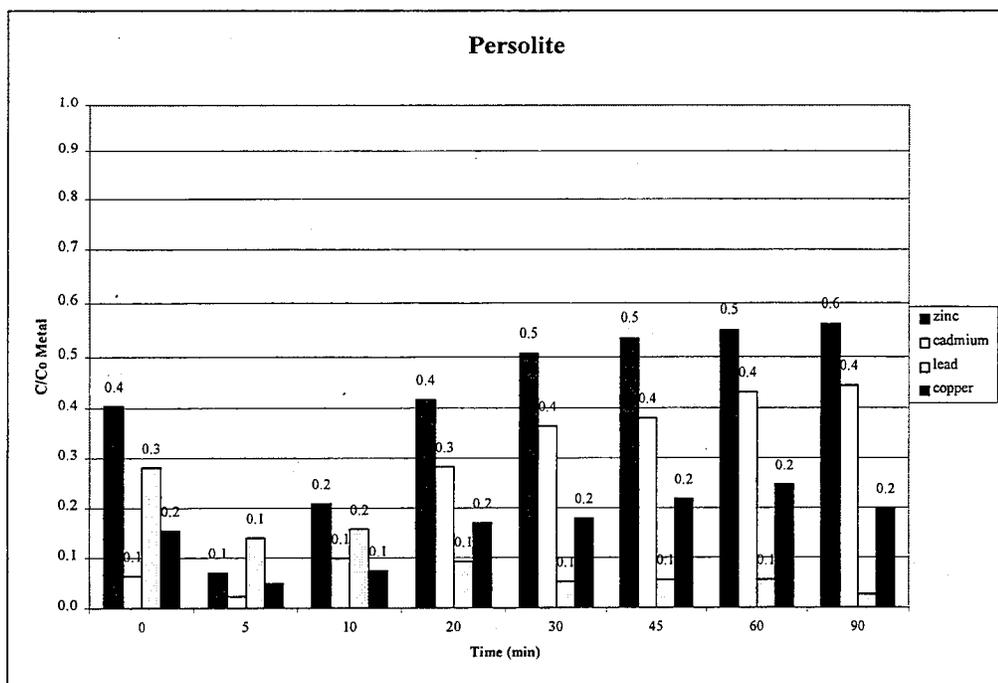


Figure 3.57 Metals Analysis of Persolite Effluent

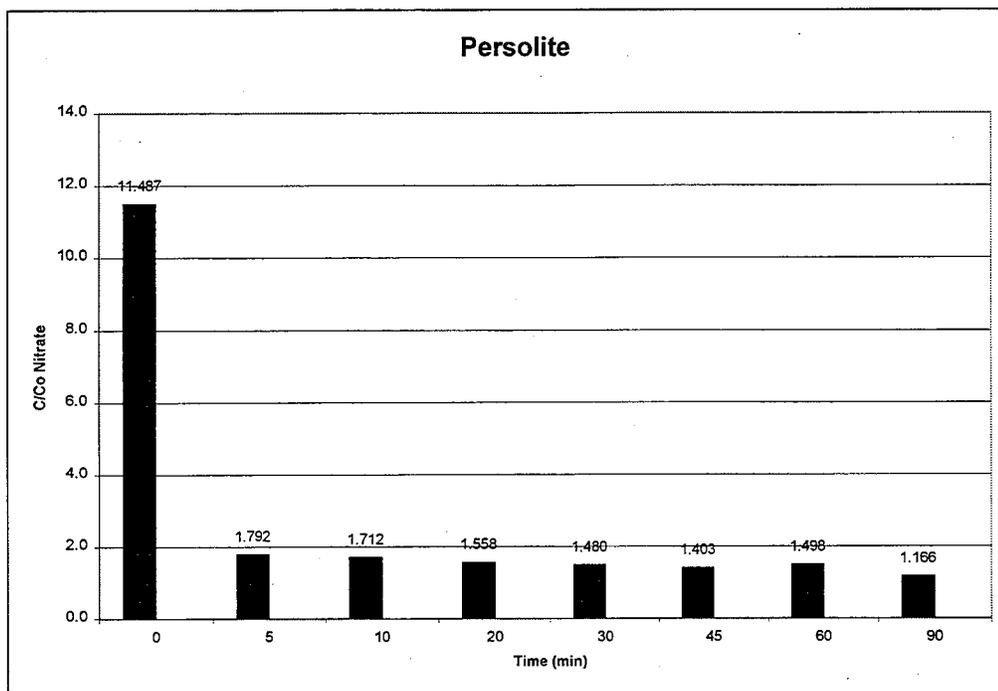


Figure 3.58 Nitrate Analysis of Persolite Effluent

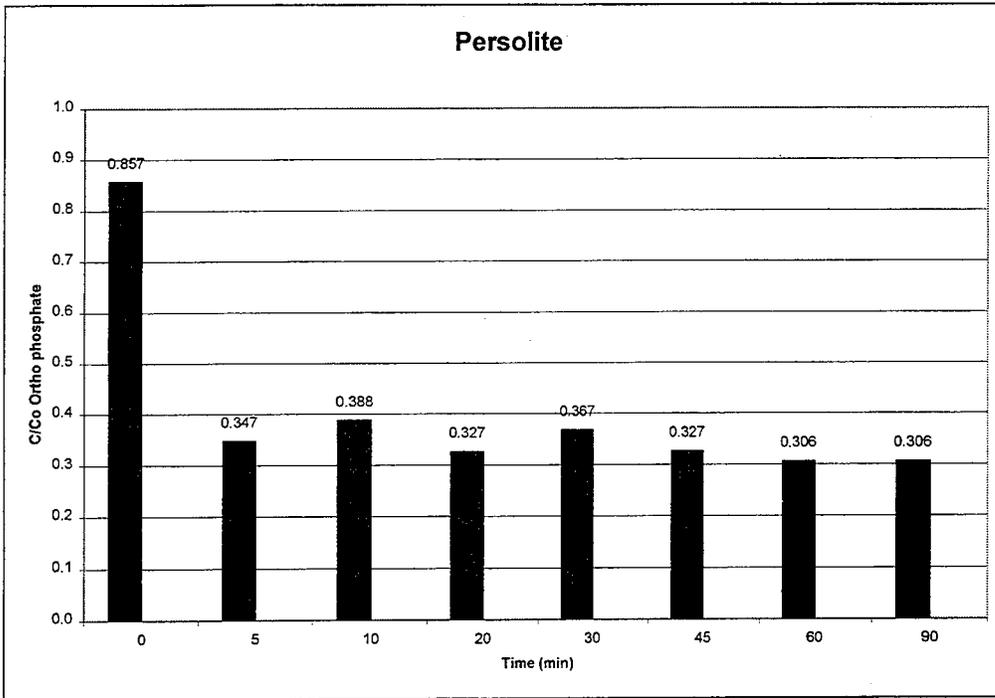


Figure 3.59 Phosphate Analysis of Persolite Effluent

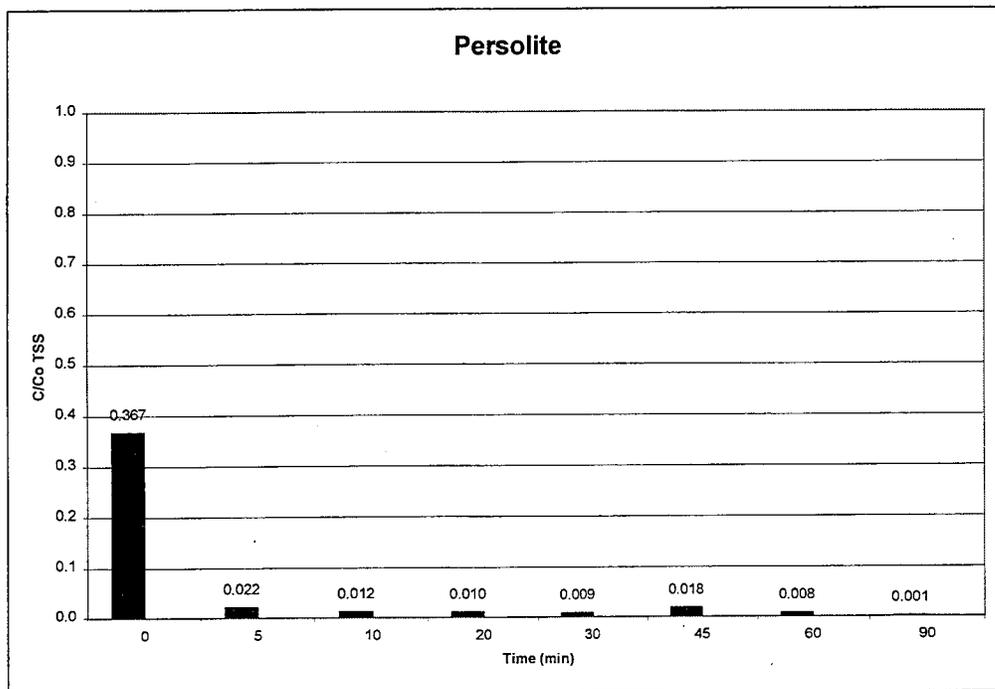


Figure 3.60 TSS Analysis of Persolite Effluent

Table 3.16 Environmental Testing Results for Persolite Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	83.2	115.9	1080.9	472.6	0.452	0.049	145.0	6.16
0	5.3	17.9	289.4	190.8	5.192	0.042	53.2	5.76
5	<2	5.7	144.2	33.0	0.810	0.017	3.1	6.32
10	8.2	8.6	161.8	98.5	0.774	0.019	1.7	6.28
20	23.5	19.7	94.8	196.9	0.704	0.016	1.4	6.26
30	30.3	20.7	54.2	239.1	0.669	0.018	1.2	6.26
45	31.6	25.3	57.3	252.8	0.634	0.016	2.6	6.20
60	35.9	28.6	57.4	259.9	0.677	0.015	1.1	6.35
90	37.0	23.1	27.7	265.2	0.527	0.015	0.2	6.30

3.6.3.11 Sand

The sand is an F series natural sand obtained from the Albrook Hydraulics laboratory at WSU. Figure 3.61 shows its grain size distribution. Figure 3.62 illustrates the metals concentration data. Except for copper, the sand effectively removes more than 90% of the metals from the initial 0-minute time interval. Copper is reduced to that level by the 5-minute time interval. Zinc, however, exhibits signs of breakthrough starting at the 20-minute sampling interval and continues to increase for the duration of the testing period. Cadmium follows the zinc trend starting at the 30-minute interval, and has completely broken through the column by the 45-minute time interval. Copper begins to breakthrough at the 45-minute interval. In contrast, lead concentrations remain consistent throughout the 90-minute test period. Figure 3.63 shows slight nitrate production at nearly every time interval. Figure 3.64 illustrates slight orthophosphate removal, around 30% through the first three sampling intervals, but then exhibits evidence of breakthrough starting with the 20-minute interval. Total suspended solids data is plotted in Figure 3.65. The sand filter is highly effective, removing more than 90% of the solids from the runoff water. The slight increase in TSS concentration at the latter time intervals may also be evidence of column breakthrough. As with the IOCS, a 40-mesh screen was required over the TSS disk to prevent the sand filter from washing out under the pressure of the 6 in head of water in the column. As shown in Table 3.17, the pH remained steady around 6.0, except at the 45-minute sampling interval. This may have been an instrument error.

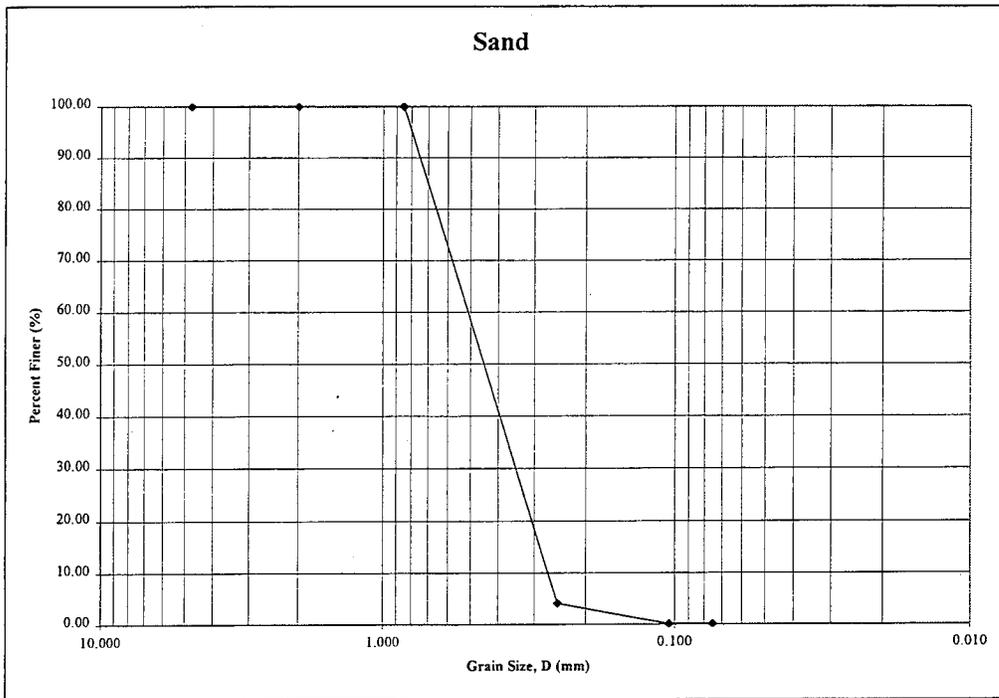


Figure 3.61 Sieve Analysis of Sand Filter Medium

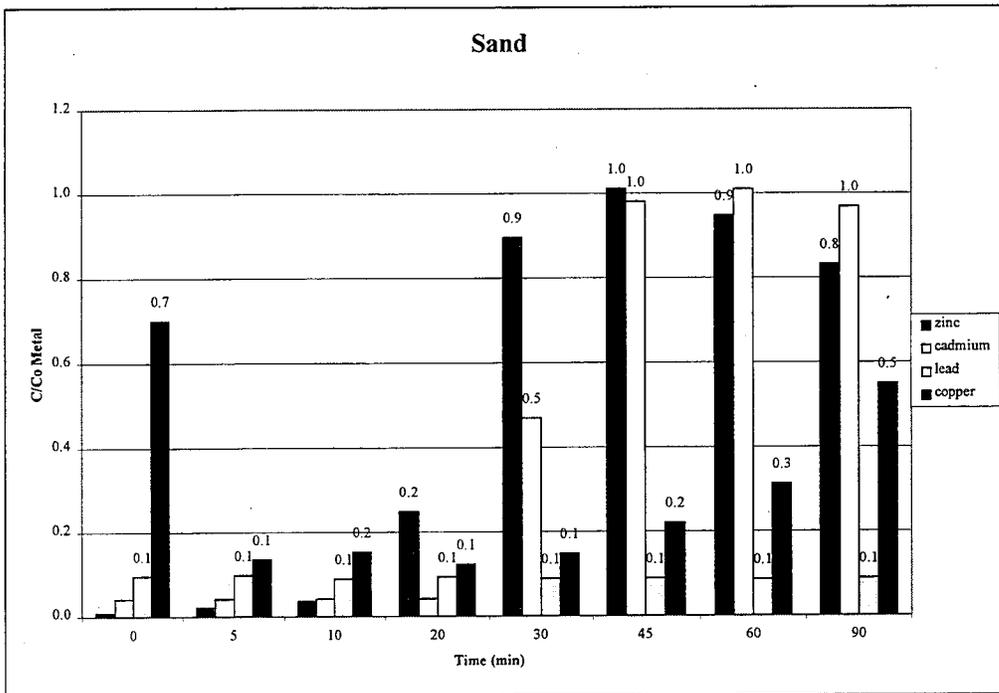


Figure 3.62 Metals Analysis of Sand Effluent

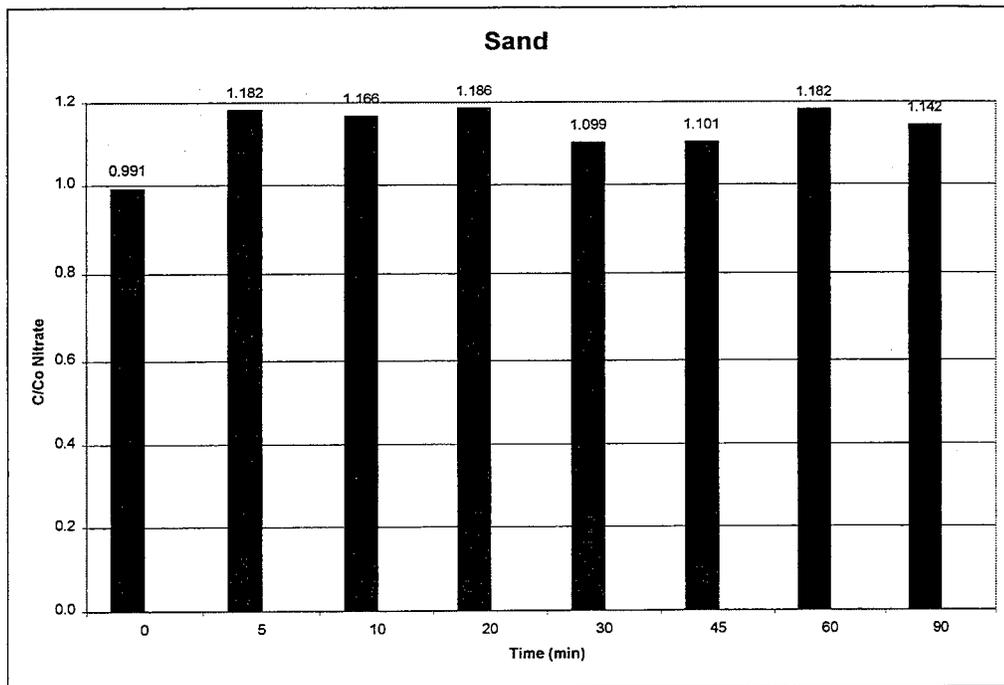


Figure 3.63 Nitrate Analysis of Sand Effluent

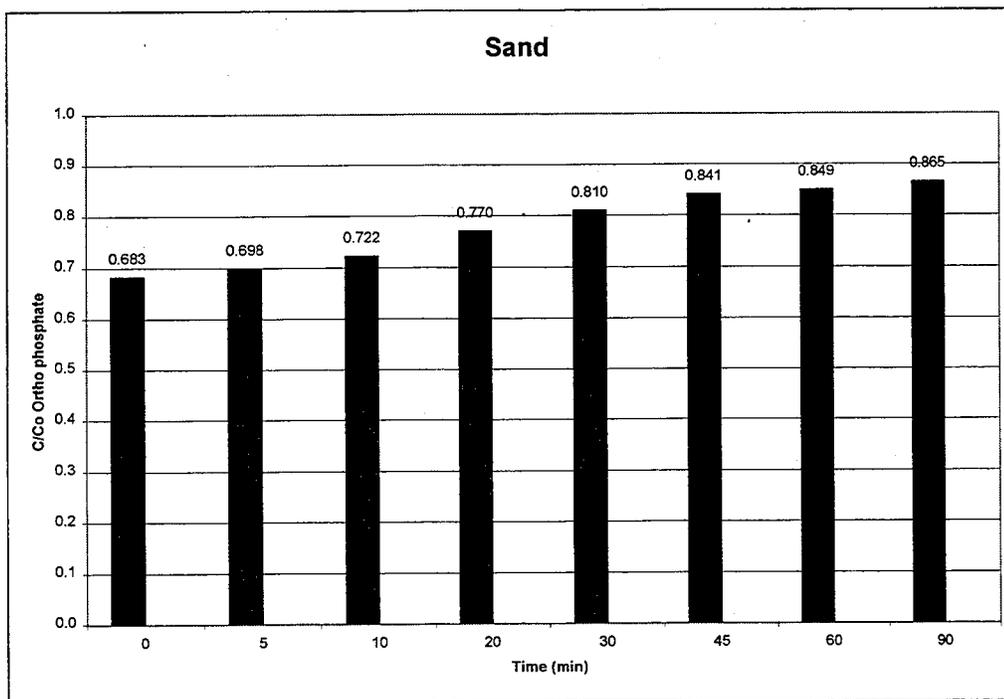


Figure 3.64 Phosphate Analysis of Sand Effluent

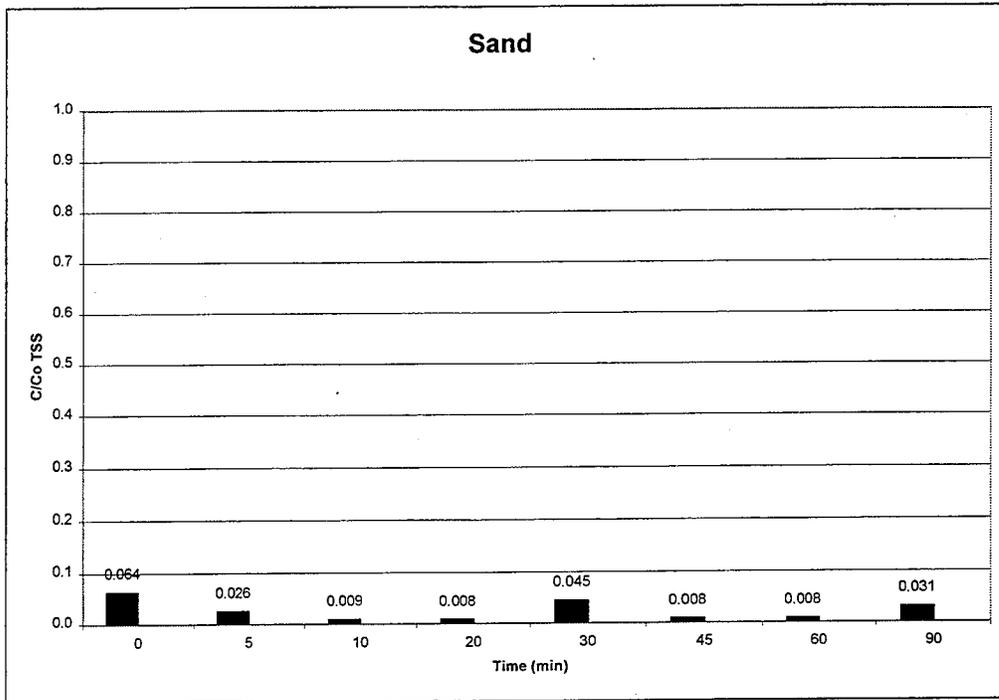


Figure 3.65 TSS Analysis of Sand Effluent

Table 3.17 Environmental Testing Results for Sand Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	48.3	72.2	806.9	457.3	0.705	0.126	145.0	5.52
0	<2	50.6	76.9	<4	0.699	0.086	9.2	6.12
5	<2	9.8	79.3	9.7	0.833	0.088	3.7	6.31
10	<2	11.0	71.9	16.3	0.822	0.091	1.2	6.22
20	2.0	8.9	74.9	113.6	0.836	0.097	1.2	6.18
30	22.7	10.7	71.8	410.0	0.775	0.102	6.5	6.15
45	47.4	15.9	71.6	462.9	0.776	0.106	1.2	7.90
60	48.8	22.6	69.7	433.5	0.833	0.107	1.2	6.13
90	46.8	39.7	72.0	380.5	0.805	0.109	4.4	6.09

3.6.3.12 Sand/Steel Wool

The sand described in Section 3.6.3.11 was combined with commonly available steel wool to form a layered column of media. The column was first loaded with 7.62 cm (3.0 in) of sand. A piece of steel wool cut to a square of length 5.08 cm (2.0 in) was placed on top of the sand. The piece of steel wool was 5.0 mm (0.2 in) thick and weighed 1.0 g (0.04 oz). Two more sand and steel wool layers were added to the column in the same manner. These three layers were topped off with one more 7.62 cm (3.0 in) layer of sand. Figure 3.66 shows a significant first flush of copper at the 0-minute timer interval. Through the 20 min sampling interval, the sand and steel wool filter removed greater than 60% of the metals present in the initial runoff. By the 30-minute interval, however, cadmium and zinc had broken through the column; copper broke through by the 90-minute sampling interval. Figure 3.67 illustrates a problem with the sand and steel wool mixture when it comes to nitrate removal. Essentially no nitrate is removed from solution. Figure 3.68 shows a large first flush of seven times the initial runoff concentration for orthophosphate at the 0-minute time interval. Subsequent sampling intervals reveal greatly reduced concentrations, but still indicate that the column is producing phosphate. The exception is the 90-minute sampling interval which shows approximately 60% phosphate removal. Total suspended solids removal is plotted in Figure 3.69. The sand and steel wool combination was very effective at removing more than 90% of the solids in the runoff water. As with the previous sand column materials, a 40-mesh screen was required over the TSS disk to prevent the sand filter from washing out under the pressure of the 6 in head of water in the column. Table 3.18 shows that the pH remained essentially constant throughout the testing period.

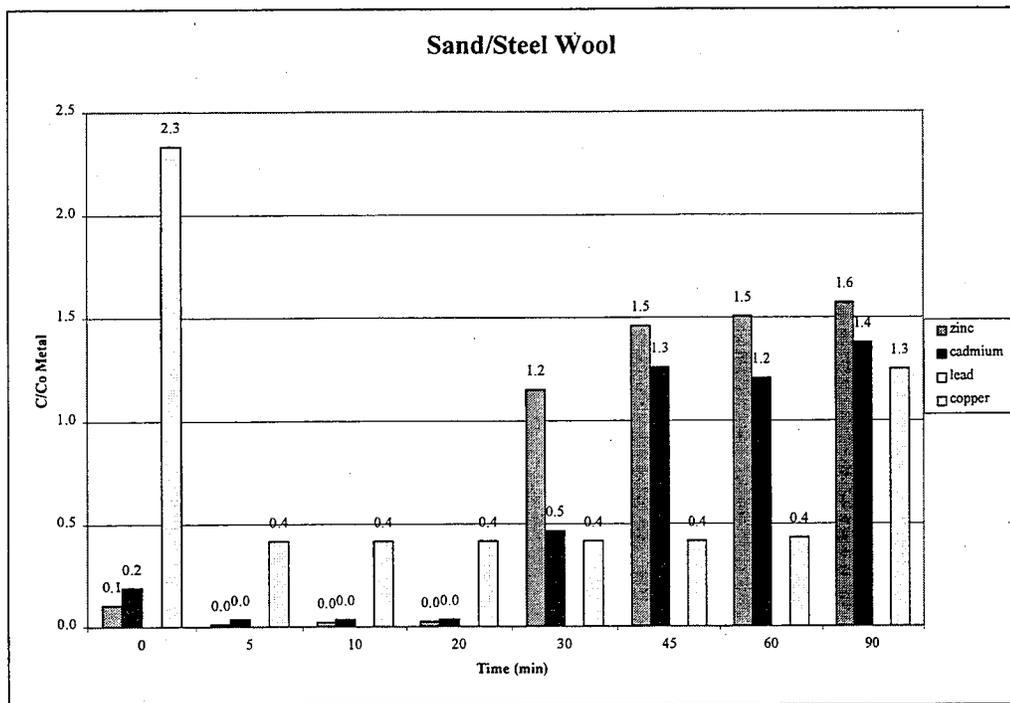


Figure 3.66 Metals Analysis of Sand/Steel Wool Effluent

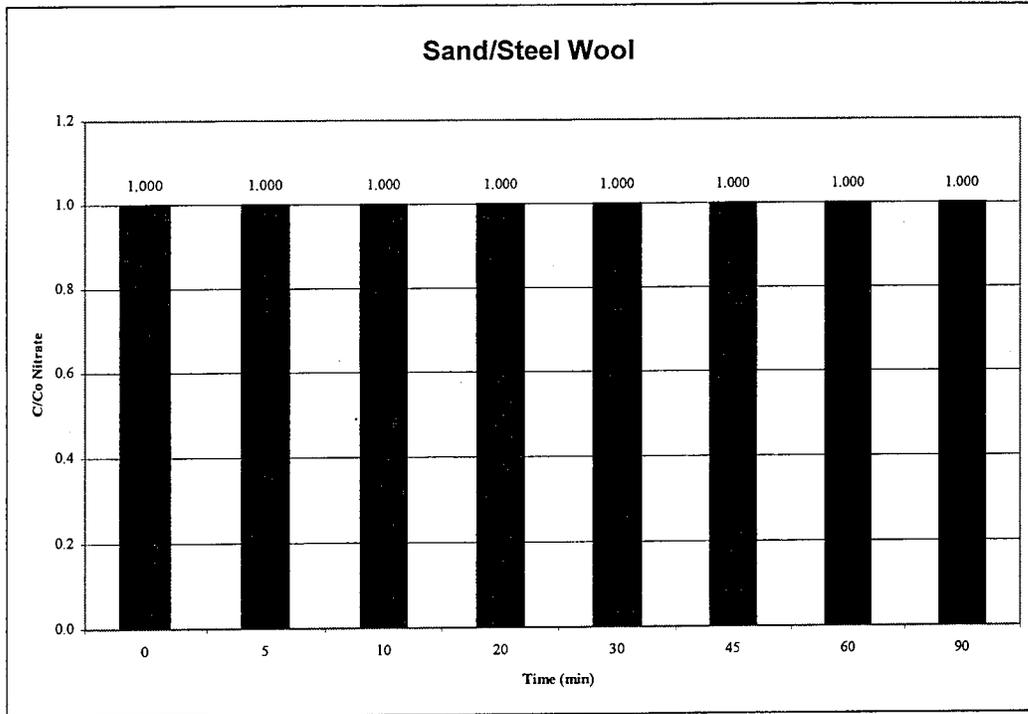


Figure 3.67 Nitrate Analysis of Sand/Steel Wool Effluent

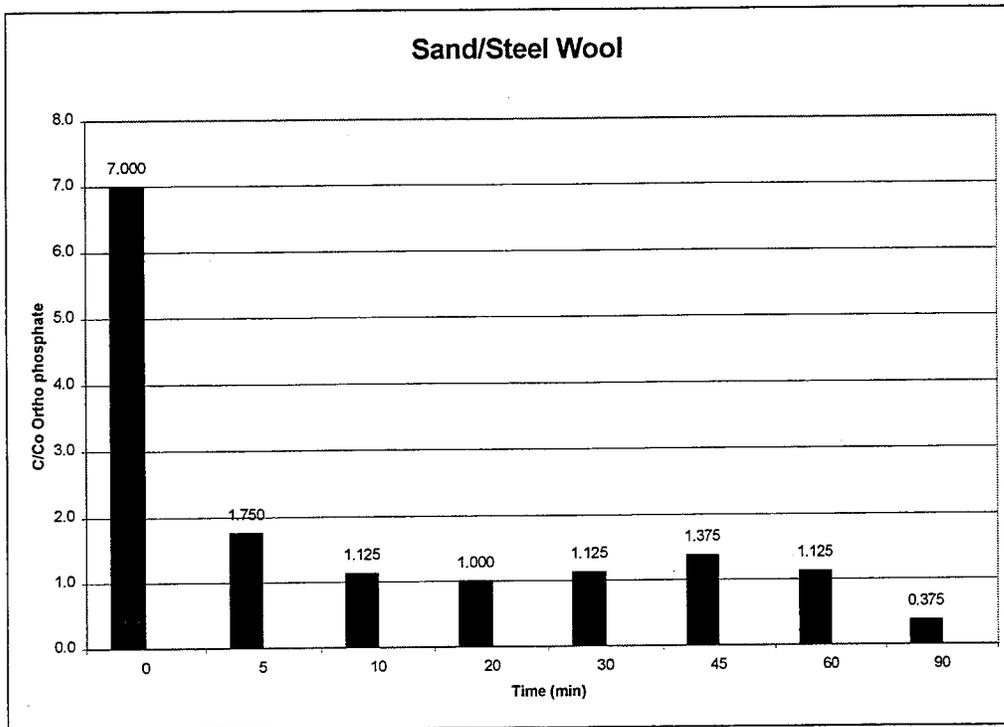


Figure 3.68 Phosphate Analysis of Sand/Steel Wool Effluent

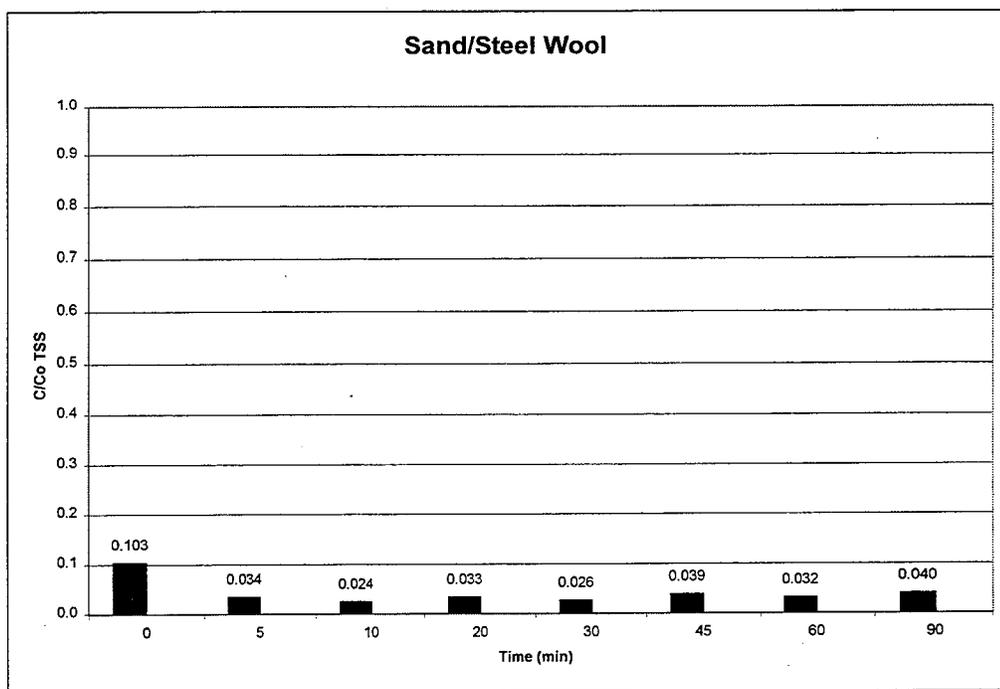


Figure 3.69 TSS Analysis of Sand/Steel Wool Effluent

Table 3.18 Environmental Testing Results for Sand/Steel Wool Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	58	12	<220	289	14.990	0.008	145.0	8.68
0	11	28	<220	30	14.990	0.056	16.0	9.54
5	<2	<5	<220	3	14.990	0.014	5.0	9.56
10	<2	<5	<220	6.3	14.990	0.009	3.5	9.57
20	<2	<5	<220	7.1	14.990	0.008	4.8	9.59
30	27	<5	<220	333	14.990	0.009	3.8	9.60
45	73	<5	<220	422	14.990	0.011	5.6	9.42
60	70	5.2	<220	435	14.990	0.009	4.6	8.86
90	80	15	<220	454	14.990	0.003	5.8	8.97

3.6.3.13 WSU Compost

The WSU compost is created on campus from a mixture of animal manure and bedding, ash, food waste, greenhouse potting mix, and yard trimmings. Figure 3.70 shows its grain size distribution. Figure 3.71 shows a small first flush at the 0 min time interval, especially for copper. Subsequent sampling intervals reveal significant metals removal for all metals tested. Zinc and cadmium were removed to below detection limits; lead and copper removals exceeded 90%. Figure 3.72 illustrates a large first flush, nearly 54 times the initial runoff water concentration for nitrate. Subsequent sampling intervals exhibited a downward trend of nitrate concentrations, but all leached nitrate from the column into the effluent water. Orthophosphate exhibited a longer first flush than did nitrate, as shown in Figure 3.73, although the concentrations were not as high as for nitrate. The WSU compost column produced phosphate at each sampling interval. Total suspended solids data is plotted in Figure 3.74. This medium produced two TSS flushes, one at the 0 min time interval and one at the 20 min time interval. The second flush may have been the result of overcoming initial preferential flow paths through the column. The first paths flushed out some of the fines. Then as the medium became more saturated, the remaining fines were eliminated from the column. Following the first flush, TSS concentrations were reduced almost 70%; after the second flush the concentrations were reduced nearly 90%. As listed in Table 3.19, the pH of the effluent is high and still rising at the 45 minute sampling interval. This is the result of the coal ash included in the WSU compost and should be taken into account for effluent discharge receiving waters. It should be noted that some of the WSU compost material floated to the top of the 6 in head of water during the test period.

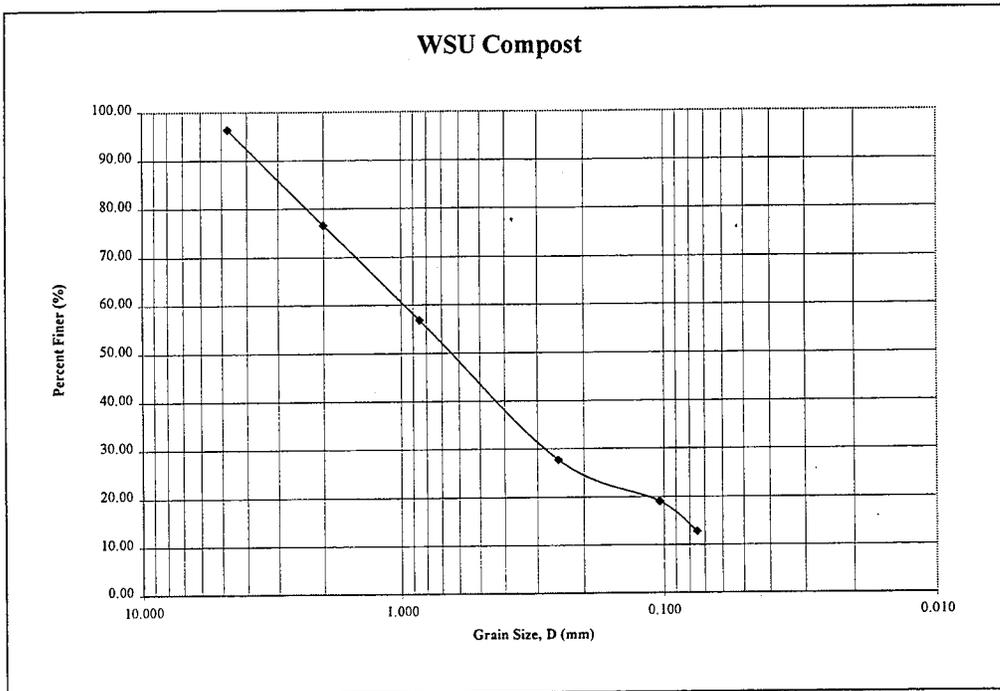


Figure 3.70 Sieve Analysis of WSU Compost Filter Medium

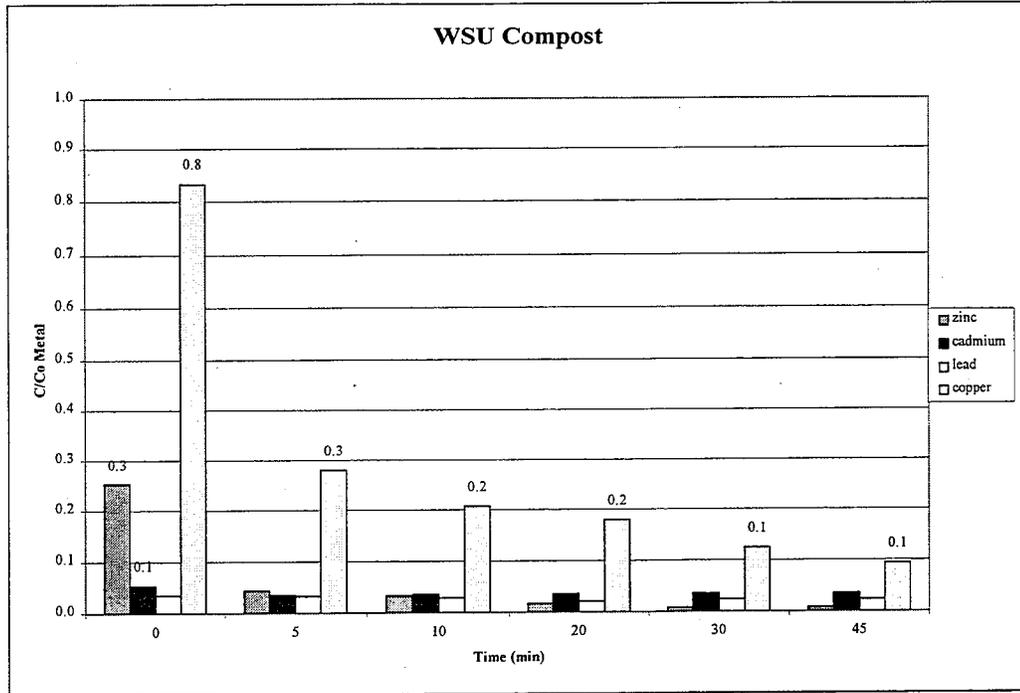


Figure 3.71 Metals Analysis of WSU Compost Effluent

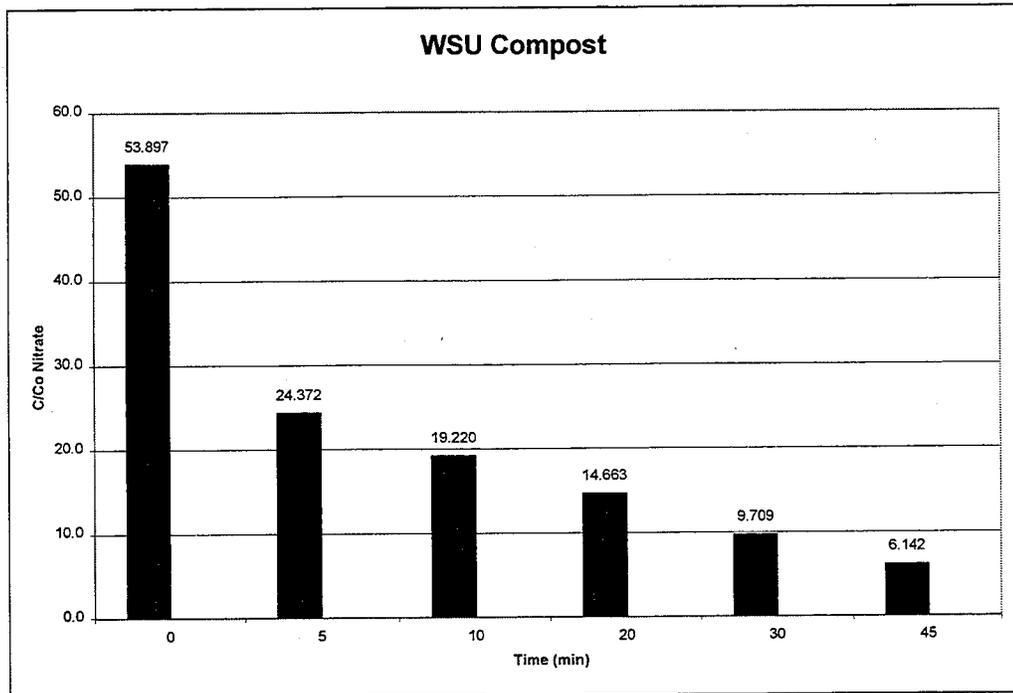


Figure 3.72 Nitrate Analysis of WSU Compost Effluent

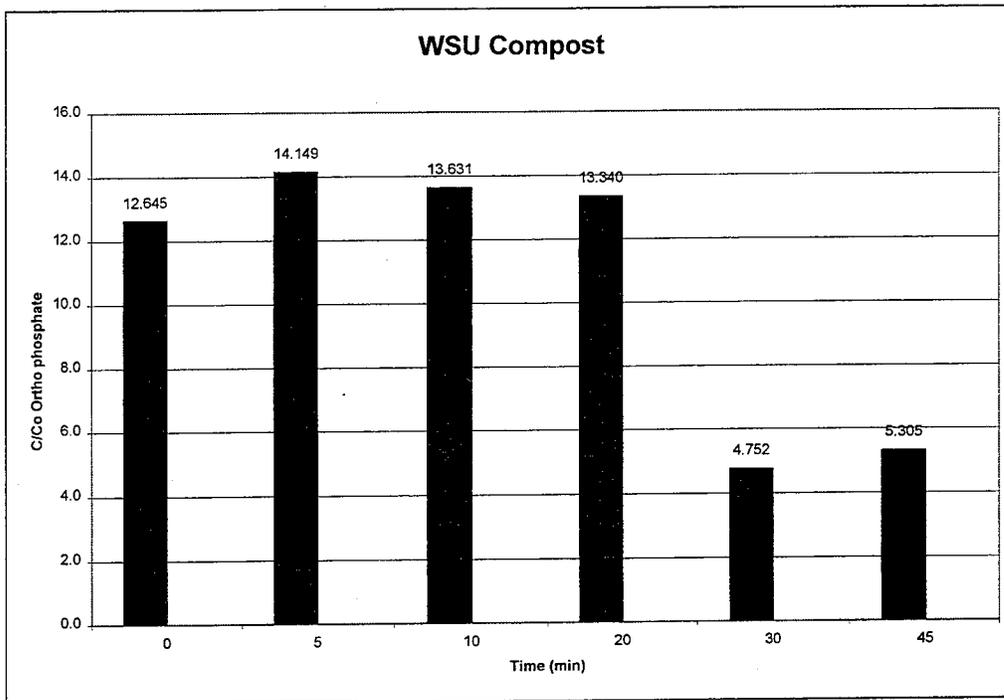


Figure 3.73 Phosphate Analysis of WSU Compost Effluent

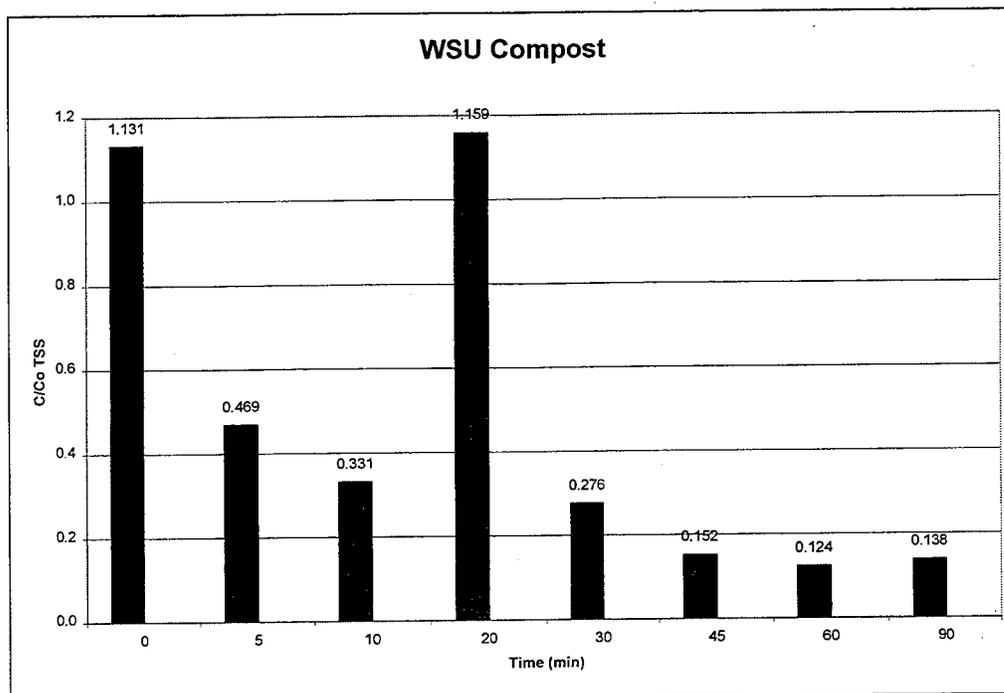


Figure 3.74 TSS Analysis of WSU Compost Effluent

Table 3.19 Environmental Testing Results for WSU Compost Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	55.8	104.6	1208.9	529.4	0.836	0.141	145.0	6.02
0	3.0	87.1	42.2	133.8	45.058	1.783	164.0	6.86
5	<2	29.3	40.1	22.9	20.375	1.995	68.0	7.74
10	<2	21.7	34.9	17.5	16.068	1.922	48.0	8.42
20	<2	18.8	25.0	8.8	12.258	1.881	168.0	8.85
30	<2	13.0	29.6	<4	8.117	0.670	40.0	9.16
45	<2	9.8	28.4	<4	5.135	0.748	22.0	9.64
60	--	--	--	--	--	--	18.0	--
90	--	--	--	--	--	--	20.0	--

3.6.3.14 CH Zeolite

The CH Zeolite was generously provided by Teague Mineral Products of Adrian, OR. It is considered a “hard” zeolite. Figure 3.75 shows its grain size distribution. Metals data is plotted in Figure 3.76. The 0-minute time interval shows a large first flush and production for all metals except cadmium. By the 5-minute interval, however, the filter removed more than 70% of the synthetic stormwater metal pollutants. Figure 3.77 illustrates an initial spike in nitrate concentration as the result of residual contamination of the zeolite. However, even after the initial washing is taken into account, the CH Zeolite was not effective in removing nitrate. The ratio never dropped below 1.0 at any time. Figure 3.78 shows that a significant amount of orthophosphate was leached from the column during the testing period. Although the general trend is toward decreasing concentrations, the smallest concentration is still more than 175 times greater than the initial runoff water. Figure 3.79 illustrates the TSS data for the CH zeolite. Again, the general trend is toward decreasing concentrations, however, the smallest concentration is almost three times greater than the synthetic stormwater concentration. Table 3.20 shows an initial decrease in pH as the runoff water comes in contact with the zeolite column. It then rises and remain fairly constant between 9.2 and 9.4.

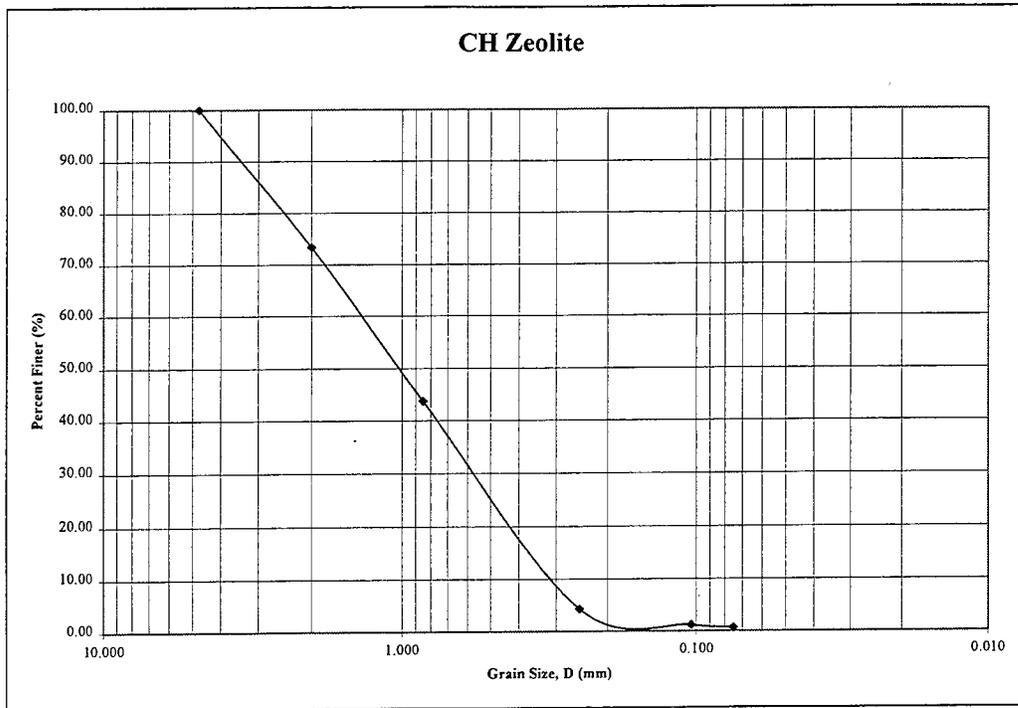


Figure 3.75 Sieve Analysis of CH Zeolite Filter Medium

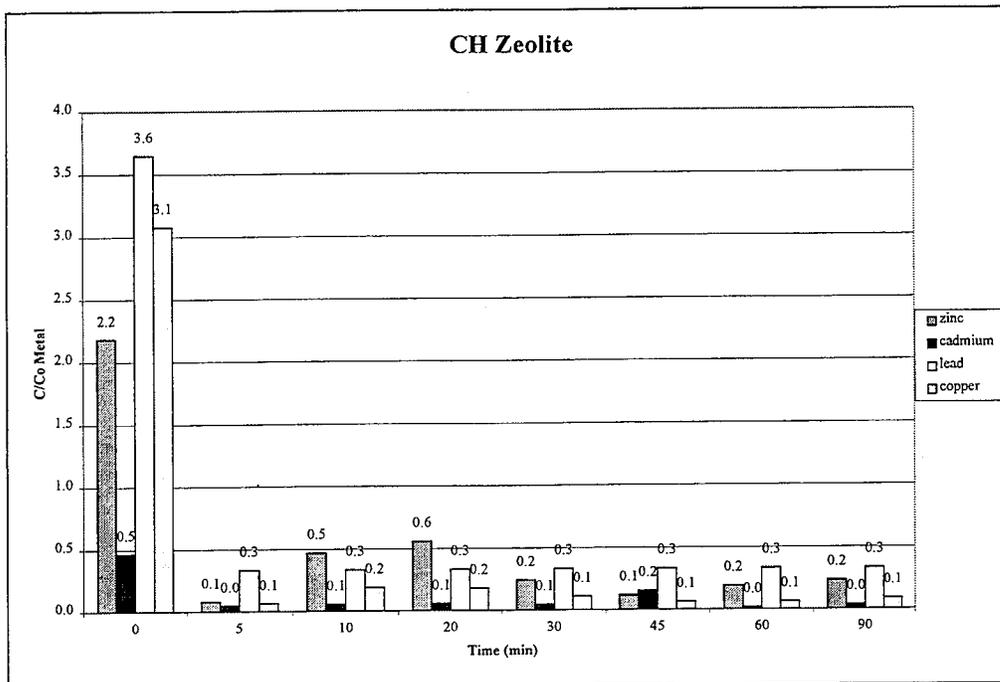


Figure 3.76 Metals Analysis of CH Zeolite Effluent

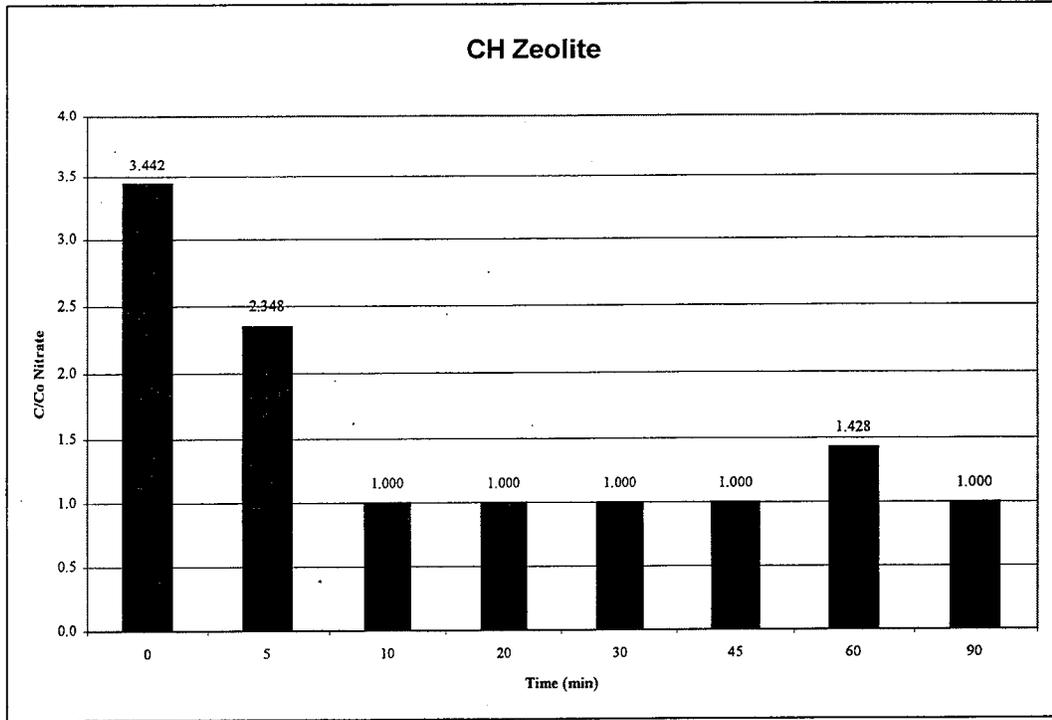
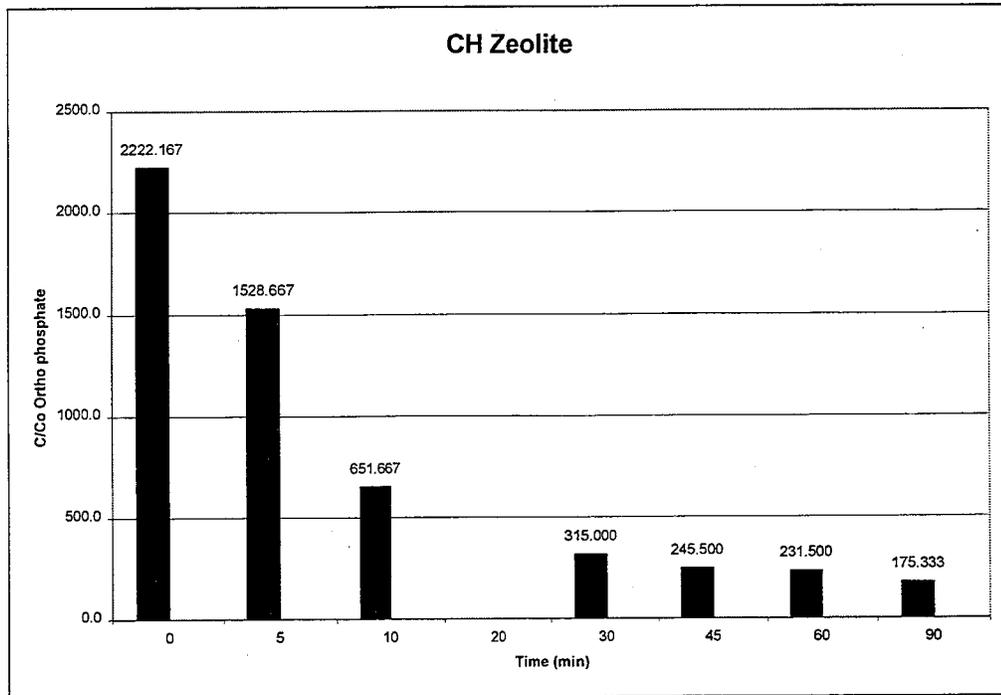


Figure 3.77 Nitrate Analysis of CH Zeolite Effluent



Note: Sample for 20 min was too turbid to analyze

Figure 3.78 Phosphate Analysis of CH Zeolite Effluent

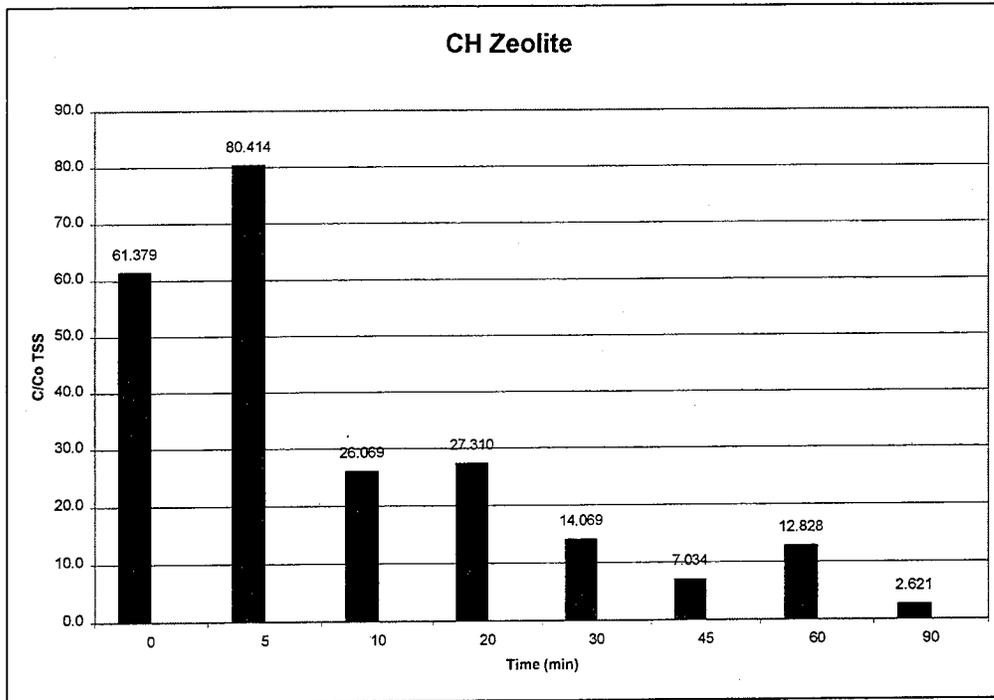


Figure 3.79 TSS Analysis of CH Zeolite Effluent

Table 3.20 Environmental Testing Results for CH Zeolite Effluent

Time (min)	Cd (ug/L)	Cu (ug/L)	Pb (ug/L)	Zn (ug/L)	NO ₃ (mg/L)	PO ₄ (mg/L)	TSS (mg/L)	pH
Runoff	103	77	653	609	14.990		145.0	8.68
0	48	237	2382	1329	51.596	13.333	8500.0	8.06
5	5	<5	<220	50	35.196	9.172	11660.0	8.36
10	6	15	<220	284	14.990	3.910	3780.0	8.81
20	6	14	<220	342	14.990	--	3960.0	9.18
30	5.2	8.6	<220	149	14.990	1.890	2040.0	9.22
45	16	<5	<220	74	14.990	1.473	1020.0	9.40
60	<2	<5	<220	118	21.406	1.389	1860.0	9.41
90	3.8	6.8	<220	144	14.990	1.052	380.0	9.22

3.6.3.15 XY Zeolite

The XY Zeolite was generously provided by Teague Mineral Products of Adrian, OR. It is considered a “soft” zeolite. Figure 3.80 shows its grain size distribution. As with the kitty litter, this filter medium proved to be too absorbant to be used in stormwater vaults. The column was filled with the standard 15.2 cm (6 in) head of synthetic runoff, but it produced no effluent after two hours. Based on this hydraulic property, the XY Zeolite was removed from further testing and consideration.

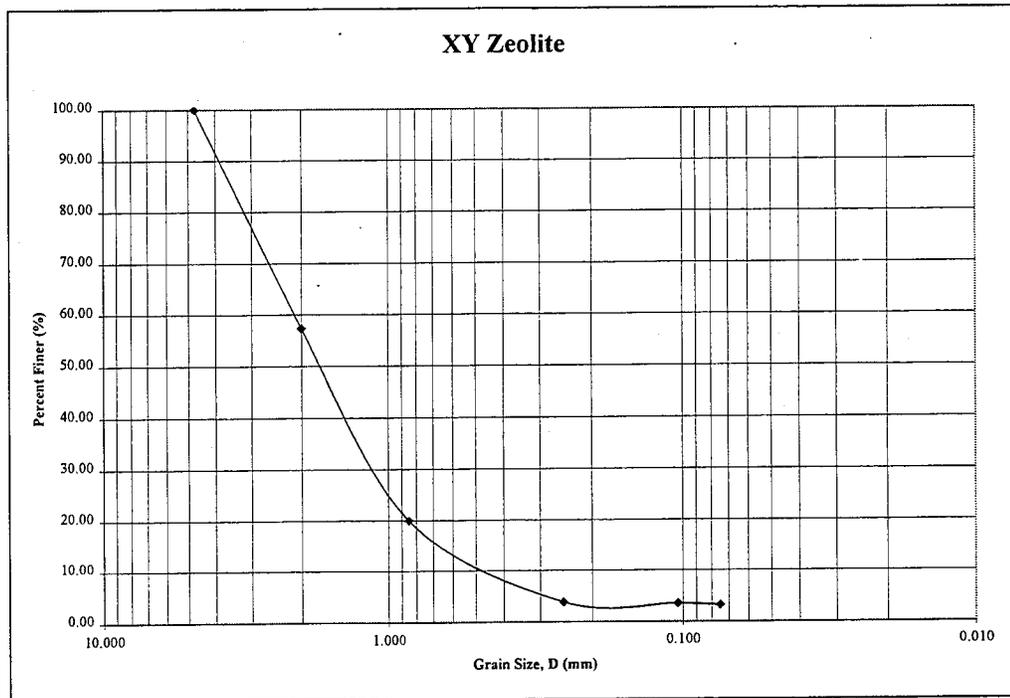


Figure 3.80 Sieve Analysis of XY Zeolite Filter Medium

3.6.4 Summary of Pollutant Removal Efficiencies

Table 3.21 provides a qualitative summary of the environmental analyses. The ratings of low, medium, and high correspond to the overall removal efficiencies for each type of pollutant tested. A high rating indicates that the medium removed greater than 75% of the contaminant; a medium rating is for removal of 50% to 75% of the contaminant; and a low rating is for removal of less than 25% of the contaminant. A medium would also have a low rating if it produced the contaminant, i.e. if the medium leached the pollutant, resulting in the effluent having a greater concentration than the influent synthetic runoff water.

Table 3.21 Summary of Removal Efficiencies for all Media

Media	Metals	Nitrate	Orthophosphate	TSS
Aquarium Rocks	Low	Low	Low	Medium
Cedar Bedding	Medium to High	Low	Low	High
Charcoal	Low	Low	Low	Low
Corn Cobs	Low to Medium	High	Low	Medium
Garden Bark	High	Low	Low	High
Glass Beads	Low	Low	Low	High
Iron Oxide Coated Sand	High		Medium	High
Peat Moss	High	Low	Low	High
Persolite	High	Low	Medium	High
Sand	High	Low	Low	High
Sand/Steel Wool	Medium to High		Low	High
WSU Compost	High	Low	Low	Medium to High
CH Zeolite	Medium		Low	Low

3.7 Implications for Design of Stormwater Vaults

When choosing a filter medium, two considerations are important: 1) can the medium hydraulically accommodate the runoff volume and 2) can the medium provide sufficient pollutant removal. Increased hydraulic capabilities can be achieved by using more vaults containing the same filter medium; increased pollutant removal is achieved by using a different medium or by combining more than one media. The following example illustrates how media are compared based on hydraulic performances. Table 3.21 can be used to determine an appropriate medium for pollutant removal.

Stormwater Vault Filter Media Calculations: Given a ferry dock located in Seattle with an area equal to 0.40 ha (1 ac), 100% imperviousness, determine the surface area of filter media required to accommodate a 6-month, 24-hour rain event.

Solution: The first step is to determine the 6-month, 24-hour storm event. WSDOT (1995) defines this event as 64% of the 2-year, 24-hour event. For Seattle, the 2-year, 24-hour event is 5.08 cm (2.0 in) (WSDOT, 1995). Therefore, the 6-month, 24-hour storm event (D) is:

$$D = 0.64 * 5.08 \text{ cm} = 3.25 \text{ cm} = 1.28 \text{ inches}$$

The next step is to determine the total runoff volume (V) per day (a 24-hour event) from the rain event using:

$$V = A * D * C$$

where: A is the area, D is the rain depth, and C is the runoff coefficient. Area is given in the problem in hectares so it must first be converted to units of square meters, where 0.40 ha (1 ac) is equal to 4047 m² (43560 ft²). The rain depth was calculated in the first step as 3.25 cm/day (1.28 in/day). Converting to meters for consistent units yields 0.03 m/day (0.11 ft/day). Because the ferry dock is 100% impervious, a conservative amount, the runoff coefficient is equal to 1.0; all of the rain becomes runoff as no infiltration is possible on paved ground. The total runoff volume per day from the entire ferry dock is:

$$V = 4047 \text{ m}^2 * 0.03 \text{ m/day} * 1.0 = 121.4 \text{ m}^3 / \text{day} = 4287 \text{ ft}^3 / \text{day}$$

The filter media surface area required to accommodate this rain event is determined by:

$$A = \frac{V * d_f}{k * h}$$

where: A is the surface area, d_f is the depth of filter medium, k is the coefficient of permeability, and h is the water head above the filter medium. Introducing the Infiltration Factor, I_f :

$$I_f = \frac{k * h}{d_f}$$

and substituting it into the surface area equation yields:

$$A = \frac{V}{I_f}$$

A list of permeability coefficients or infiltration rates for the filter media tested in this research was presented in Table 3.6. It should be noted that only when water head and filter medium depth are equal, will the Infiltration Factor be equal to the coefficient of permeability. In this study, they were not equal but were constant at 30.5 cm (1 ft) for d_f and 15.2 cm (6 in) for h . These experiments were designed to determine the critical infiltration level for stormwater vaults, making design calculations simpler. When k , h , and d_f are known, the Infiltration Factor is not required.

From Table 3.6, the infiltration rate or coefficient of permeability for garden bark is 0.648 cm/s (1837 ft/day). The Infiltration Factor is then:

$$I_f = \frac{0.648 \text{ cm / sec} * 15.2 \text{ cm}}{30.5 \text{ cm}} = 0.323 \text{ cm / sec} = 279 \text{ m / day} = 915 \text{ ft / day}$$

The required media surface area is:

$$A = \frac{121.4 \text{ m}^3 / \text{day}}{279 \text{ m / day}} = 0.44 \text{ m}^2 = 4.7 \text{ ft}^2$$

Therefore, a single stormwater vault should be sized to provide a surface area equal to 0.47 m² (4.7 ft²). If more than one vault is desired, they should be sized smaller such that the total surface area of all vaults is equal to 0.47 m² (4.7 ft²). Table 3.22 lists the surface area requirements for this same storm event for all tested filter media.

Table 3.22 Comparison of Filter Media Surface Area

Filter Medium	Required Surface Area (m ²)	Required Surface Area (ft ²)
Aquarium Rocks	0.33	3.55
Cedar Bedding	2.96	31.86
Charcoal	0.36	3.88
Corn Cobs	1.15	12.38
Garden Bark	0.47	5.06
Glass Beads	0.69	7.43
Iron Oxide Coated Sand	0.54	5.81
Peat Moss	10.78	116.03
Persolite	4.47	48.11
Sand	2.30	24.76
Sand/Steel Wool	2.04	21.96
WSU Compost	5.82	62.65
CH Zeolite	8.88	95.58

It should be noted that the equation for filter medium surface area does not include a safety factor. Variability in media grain sizes and sediment types, in vault shapes and designs, and in pollutant/trash loadings can increase or decrease the infiltration rates presented in this report. Consequently, care must be exercised by the designer when determining the required surface area.

Finally, maintenance schedules are also important to consider when choosing a filter medium. Although some of the media tested for this report reached the breakthrough point for pollutant removal within the 90 min testing period, the larger concern is loss of hydraulic capabilities as a result of filter clogging. To determine the expected filter replacement schedule, Figure 3.12 and Table 3.6 were analyzed for trends in the filter media discharge rates. In general, the clogging rates followed an exponential, first-order decay rate pattern. Numerically, this pattern is expressed as:

$$\frac{Q}{Q_0} = e^{-kt}$$

where Q is the flow rate for time t , Q_0 is the initial flow rate, k is the decay rate, and t is time. The decay rate or clogging rate is found by plotting the natural log of Q versus time (from Table 3.6); the decay rate is the slope of the resulting line. Table 3.23 lists the clogging rates for the nine filter media that follow this clogging pattern. Aquarium rocks, charcoal, glass beads, and CH zeolite are eliminated from this list because they showed no effects of clogging during the testing period. Theoretically this suggests that these media will never clog. Obviously this is untrue, but quantifying their clogging rates is not possible based on the laboratory column results.

Table 3.23 Filter Media Clogging Rate Constants

Filter Media	Clogging Rate Constant (min ⁻¹)
Cedar Bedding	0.0117
Corn Cobs	0.0267
Garden Bark	0.0103
Iron Oxide Coated Sand	0.0090
Peat Moss	0.0364
Persolite	0.0095
Sand	0.0121
Sand/Steel Wool	0.0086
WSU Compost	0.0144

Given the clogging rate constants, the time required for a given percent reduction in flow can be determined. For example, if it is assumed that the filter is effectively clogged when the flow is reduced to 20 percent of the original value ($Q = 0.2 Q_0$), then the clogging time can be computed as:

$$t = \frac{-\ln\left(\frac{Q}{Q_0}\right)}{k} = \frac{-\ln(0.2)}{k} = \frac{1.6094}{k}$$

From Table 3.23, the decay rate for the cedar bedding is 0.0117 min⁻¹ which means that the filter material will clog in approximately 138 minutes (1.6094/0.0117). This assumes a constant application rate that can be converted to an actual time by examining the amount and frequency of rainfall for a given location. However, this calculation will be extremely crude given the critical nature of time factor.

It must again be pointed out that maintenance schedules are difficult to determine due to the variability of sediment loading as illustrated in the literature. Given the importance of clogging in determining the overall feasibility of these filter methods, it is recommended that local field investigations be performed to determine loading rates.

4.0 Recommendations and Conclusions

The results of the column experiments provide conclusions regarding the hydraulic and pollutant removal performances of several potential stormwater vault and related confined spaces BMPs filter materials. Hydraulic performance is based on two media characteristics: infiltration rate and clogging potential. Slower infiltration rates can be compensated for by increasing the number of vaults installed at a particular site. Clogging potential is more difficult to address. Combinations of media or layers of media may be required to reduce the rate of filter clogging. The clogging of the filter material can not, and should not, be eliminated. As demonstrated in the column studies, the majority of pollutant removal comes from the filtering of pollutants adsorbed to sediments. This can be seen by the relatively poor removal of the dissolved nitrate concentration.

Because of the clogging potential, use of filter media approaches may not be appropriate for mountainous regions where snow and ice require the application of large amounts of sand and gravel. Pretreatment or pre-settling of suspended solids will greatly enhance the viability of several media types. However, experience has shown that in areas subject to extensive sanding operations, the pretreatment area would have to be enormous or frequently emptied.

Pollutant removal abilities varied greatly among the media tested. It should be pointed out that these results are based on a synthetic stormwater runoff applied at a constant rate. This is not the same as an actual precipitation event; field testing using actual runoff conditions are needed to evaluate the true efficiency of the various media. Nonetheless, based on the laboratory results, filter vaults show promise as a confined spaces BMP for reducing pollutant concentrations typically found in highway runoff.

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