REMOVAL OF HYDROCARBONS FROM URBAN STORMWATER RUNOFF BY GRAVITY SEPARATION

by

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(ABSTRACT)

Three rain events were sampled from a storm drain at Manassas Mall in Manassas, Virginia. The urban runoff samples obtained were placed into lab-scale Plexiglas® settling columns to monitor removal of total hydrocarbons (THC) by extended quiescent settling.

Samples were collected from the columns at specific depths and times over the 48-hour settling period. The samples were analyzed for total hydrocarbon content on a Horiba oil content analyzer. Hydrocarbon values were averaged at each column depth in order to construct average THC concentration and average THC percent removal profiles over settling time.

Maximum average THC removals were 77.8%, 32.5%, and 73.6%, respectively, for Storms #1, 2, and 3 after 48 hours of quiescent settling. These average removals corresponded to depths of -2 feet, -1 foot, and -3 feet in the 5-foot tall columns.

According to traditional sedimentation theory, pollutants settle out of water to the bottom of the container of interest. This did not appear to be solely the case in this hydrocarbon sedimentation study. It appeared that sedimentation was not the sole removal mechanism at work.

Some fractions of oil and grease seemed to reorganize into low-density sub-groups and float to upper regions of the column. Also, the majority of THC removal occurred within the first 18 hours of settling for two of the three storms sampled.

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CHAPTER I. INTRODUCTION

Urban stormwater runoff has gained increasing attention as a major source of water pollution, and pollutants found in urban stormwaters are diverse. It has been discovered that one of these pollutant constituents, hydrocarbons, needs more attention in the area of pollution control technologies. In many areas of the United States and other countries, urban stormwater runoff is untreated before being discharged to receiving water bodies. Therefore, some studies have chemically characterized stormwaters and focused on the effects that hydrocarbons and other pollutants have on aquatic life.

Many traditional stormwater treatment technologies utilize a detention basin, and sedimentation is the mechanism by which pollutant removal is accomplished. Two previous studies have attempted to quantify hydrocarbon removal by duplicating stormwater treatment on a lab-scale basis (Stenstrom *et al.*, 1984; Whipple and Hunter, 1981). Quiescent settling tests of urban runoff samples were conducted and hydrocarbon concentrations recorded over time. Results that were reported from the researchers' studies seemed limited, and in one case were inconclusive.

Based on the above discussion, the following objectives were set forth for the study contained within this thesis: 1) to determine the removal efficiencies possible for extended quiescent settling of hydrocarbons in several urban stormwater samples and 2) to evaluate the observed settling characteristics of hydrocarbons.

CHAPTER II. LITERATURE REVIEW

Introduction

Urban stormwater runoff is considered a very serious source of pollution in water resources of the United States. As a nonpoint source, urban runoff, gone untreated, has a more significant impact on water quality than some point sources, such as effluent from wastewater treatment plants (Randall *et al.*, 1978; Stenstrom *et al.*, 1984). In addition, wastewater effluents represent constant inputs to receiving waters, whereas stormwater flows are extremely variable in time, space, and pollutant load (Eganhouse and Kaplan, 1981).

Suspended solids and sediments are the primary forms of pollution found in urban runoff (ASCE, 1985; Randall *et al.*, 1982; Whipple *et al.*, 1983). In recent years, however, there has been a new focus on the occurrence of hydrocarbon contamination of waterways from oil and grease transported by these suspended solids in urban runoff. Stenstrom *et al.* (1984) found some concentrations of oil and grease in stormwater samples to be greater than the industrial discharge standard of 15 milligrams per liter (mg/L) for the San Francisco Bay area near where the study was conducted.

To avoid confusion, the terms "oil and grease" and "hydrocarbons" will be used interchangeably in this report. The common definition for the terms will be as given in *Standard Methods for the Examination of Water and Wastewater* (APHA, 1992): " 'Oil and grease' ["hydrocarbons"] is the material recovered as a substance soluble in the [extraction] solvent." This definition is related to methods used for analysis of oil and grease in runoff samples which will be discussed in a later chapter. Defined in this manner, oil and grease extracted from urban runoff includes petroleum hydrocarbons (primarily of anthropogenic origin). Stenstrom *et al.* (1984) stated that several different types of fatty acids (of biogenic origin) have been found in stormwaters, and these were included as oil and grease under the functional definition. One limitation is that other materials such as sulfur compounds, some organic dyes, and chlorophyll may also be extracted from acidified samples. This is simply a consequence of the method by which oils and greases are quantified.

Table 1 lists concentrations of total hydrocarbons (THC), biochemical oxygen demand (BOD), and total suspended solids (TSS) reported in several urban runoff studies. Schueler (1987), citing a 1982 Occoquan Watershed Monitoring Laboratory (OWML) report, discussed how studies have shown that trace metals may interfere with the BOD test to produce misleading results. Despite this potential problem, and given the highly variable nature of pollutant concentrations and quantity of runoff flow, a comparison of values reported in the literature is essential to having a basic understanding of the pollution aspects associated with urban stormwater. Subsequent sections include discussion on the sources of oil and grease in urban stormwater and potential removal techniques.

Table 1. Values reported for three water quality characteristics in urban stormwater runoff.

	CONCENTRATION	COMMENTS	REFERENCE
TOTAL HYDROCARBONS (mg/L)	< 30		Stenstrom *et al.*, 1982.
	3.69	Study in urban northern Philadelphia, PA area	Hunter *et al.*, 1979.
	13.1	Average conc. in Los Angeles River storm runoff study	Eganhouse and Kaplan, 1981.
	6-24	AHC* in Mercer Island Br., Seattle, WA	Wakeham, 1977.
BOD (mg/L)	10-20		Schueler, 1987.
	9	Urban site median EMC**	USEPA, 1983.
TOTAL SUSPENDED SOLIDS (mg/L)	100	or 0.1% by weight of the water inflow	Whipple *et al.*, 1983.
	715	Average conc. in Los Angeles River storm runoff study	Eganhouse and Kaplan, 1981.
	100	Urban site median EMC*	USEPA, 1983.

*AHC = aliphatic hydrocarbons

**EMC = event mean concentration = total mass of pollutant discharged divided by total quantity of water discharged during storm event

Sources of Hydrocarbons in Urban Runoff

Oil and Grease Origins

Hydrocarbons from oil and grease are a major pollutant found in urban stormwater runoff. Understanding the sources of runoff hydrocarbons is important in considering methods for control of pollutants entering the runoff, and ultimately, the receiving water body (Silverman and Stenstrom, 1989). Initially, pollutants sorb to raindrops falling through the atmosphere (Stahre and Urbonas, 1990). The literature is generally in agreement as to the major sources of hydrocarbons in urban runoff: crankcase oil drippings, combustion/exhaust products, intentional dumping of used oil, and other such petroleum-based lubricants leaking from automobiles (Hunter *et al.*, 1979; Novotny and Chesters, 1981; Stenstrom *et al.*, 1984; Whipple *et al.*, 1983). Naturally-occurring hydrocarbons are felt to contribute very little to the amounts found in urban stormwaters (Wakeham, 1977). Thus, it follows that high hydrocarbon concentrations are usually seen in runoff from roads, parking lots, gas stations and other impervious commercial areas (Schueler, 1987). Schueler (1987) also stated that atmospheric deposition of pollutants "equals or exceeds the total load exported in runoff." More than a billion pounds a year of material is deposited as automobile tires wear on roadways (Whipple *et al.*, 1983). This material deposits not only particles of rubber, but also zinc, oils and organic polymers which may exert an oxygen demand.

Factors Affecting Deposition of Hydrocarbons

Investigators have considered many factors that may affect the actual concentrations of oil and grease found in urban runoff. Differing opinions exist as to what parameter or combination of parameters has the greatest influence on hydrocarbon loads in urban runoff. Stenstrom *et al.* (1984) stated that land use is the overriding factor affecting oil and grease loads in urban runoff. They found concentrations of oil and grease in stormwater from commercial and parking areas three times that of stormwater from residential locales.

Stenstrom *et al.* (1982) instituted an extensive field sampling program that took place for seven storms during the winter of 1980-81 in the Richmond watershed of Contra Costa County, California. Findings from statistical studies performed on their results are listed below.

- Simple correlation coefficients showed no significant relationships of oil and grease concentrations to any of the other variables evaluated, which included 1) runoff flow rate, 2) total storm runoff, 3) days between storms, 4) time since storm beginning, 5) total storm rainfall, and 6) instantaneous rate of rainfall. Pearson correlation coefficients for all of the above comparisons were all below 0.1.

- Multivariate linear regressions indicated that less than 10% of the variability in oil and grease concentrations in the runoff could be explained by one to six of the variables when all data points were treated as an aggregate. The dependent variables examined by the linear regressions included 1) instantaneous flow rate, 2) total storm runoff, 3) days since previous storm, 4) time since storm beginning, 5) total storm rainfall, and 6) instantaneous rate of rainfall. Even when data from each station were analyzed separately by regression, no linear relationships were found between oil and grease concentrations and the above variables (except for one of the five sampling stations.)

- Analysis of variance (ANOVA) tests with three models produced two important results. For the first model, oil and grease concentration was the dependent variable with station number as a block, and seven variables were considered separately. Storm number was the factor that contributed the most variability in oil and grease concentration. In the second model, two independent variables were considered together and station number was blocked. The result was that time since storm beginning dictated variability in oil and grease concentration. For the third model, six independent variables were considered together with station number blocked. Again, time since storm beginning was tagged as contributing the greatest variability to oil and grease concentrations.

Stenstrom *et al.* (1982) concluded that the significance of the time since storm beginning may be related to the "first flush" phenomena, further discussed in the next section.

Hunter *et al.* (1979) studied the hypothesis that the time since the previous storm was most important in determining hydrocarbon loading. They found by linear regression analysis that only 17% of the variance in load was caused by variations in time since the previous storm. Another regression analysis resulted in a 16% variability of concentration being caused by time since the last storm. The authors attributed this effect to the degree of flushing attained by precipitation if pollutants are not completely removed by one storm. Hoffman *et al.* (1984) stated that mechanisms that determine the loading of polyaromatic hydrocarbons (PAHs) in runoff may be meteorological and not related to antecedent dry periods (i.e., time since the last storm). Potential mechanisms contributing to the loss of PAHs (and corresponding to decreased hydrocarbon loading) include wind blowing PAH-laden particles off surfaces, volatization, degradation, and photooxidation.

Herrmann (1981) found after extensive runoff sampling in the city of Bayreuth, Germany, that neither pollutant load, nor the 3,4-benzopyrene load was a function of time since the previous storm. Conversely, Herrmann found that maximum runoff was significantly correlated with pollutant load and the maximum load of 3,4-benzopyrene. This study confirmed that the limiting factor of the river basin in Bayreuth was transport, rather than the amassed pollutant load.

"First Flush" Effect

The first flush effect is related to the highly concentrated fraction of pollutants that are initially collected in urban stormwater runoff. This phenomenon occurs when the time-wise cumulative percentage of total storm pollutant load exceeds the time-wise cumulative percentage of total storm runoff flow. According to Whipple *et al.* (1983), detachment of particulate matter was noted as the removal mechanism at the beginning of surface washoff. The tendency for fine particulate matter (with sorbed hydrocarbons) to wash away early in a runoff event contributes to the initial high fraction of oil and grease in the first flush (Stenstrom *et al.*, 1982; Whipple *et al.*, 1983). Subsequent rainfall dilutes the pollutant concentrations in the storm sewer system (Stahre and Urbonas, 1990).

Hunter *et al.* (1979) noted a first flush during sampling in an urban northern Philadelphia area when the total hydrocarbon concentration increased to somewhat higher than 8 mg/L. Herrmann (1981) found that all but two of 13 storm events sampled in the Bayreuth, Germany study exhibited a first-flush effect. Accumulation of oil, grease, particulates, and other pollutants in the days preceding a storm would contribute to higher solubilization of oil and grease earlier in the storm event (Stenstrom *et al.*, 1982).

Hoffman *et al.* (1984) observed second and third flushes with storms sampled in Rhode Island. Figure 1 shows runoff constituents evaluated for a storm sampled on October 25, 1980, at an interstate highway. These graphs clearly indicated a response by total hydrocarbons and suspended solids to the second and third flush phenomena. Lack of a PAH response to a third flush was evidence of PAHs washing away earlier in the storm event.

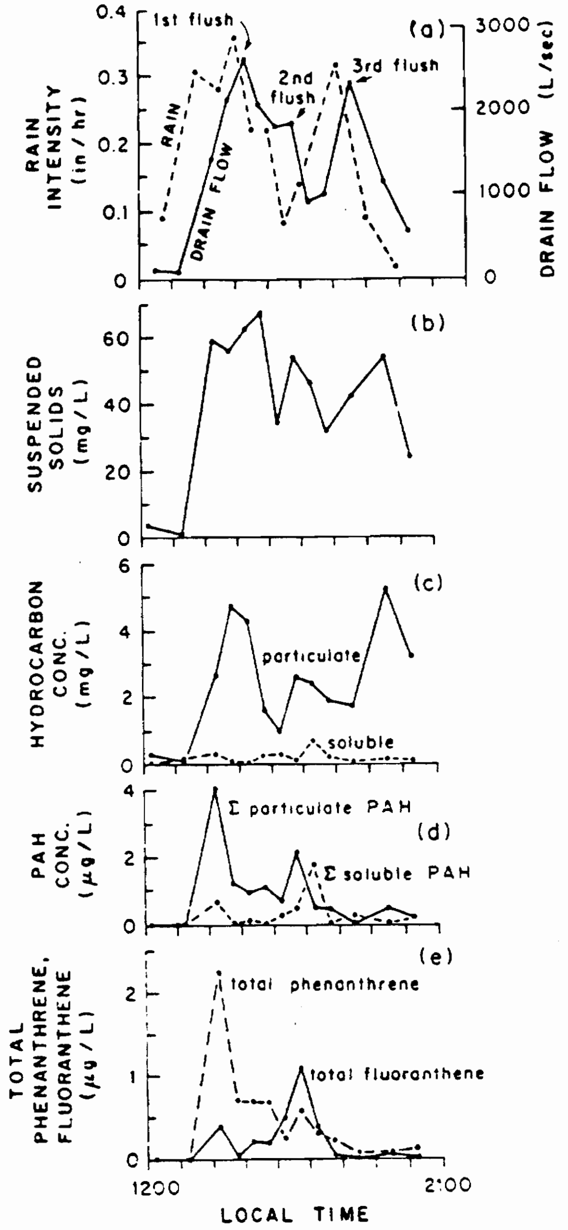

Figure 1. Runoff constituent variation for Oct. 25, 1980, storm as a function of local time.
(a) rain intensity and drain flow; (b) suspended solids; (c) particulate and soluble hydrocarbons; (d) particulate and soluble PAHs; (e) total fluoranthene and phenanthrene.
Source: Hoffman *et al.*, 1984.

Characteristics of Hydrocarbons in Stormwater Runoff

Oil and Grease Characteristics at Deposition

After deposition on pavement or other surfaces, the characteristics of hydrocarbons may alter before being washed away in stormwater runoff. For instance, the lower molecular weight, and thus more volatile, hydrocarbons may evaporate quickly during dry periods. Evaporation may be hindered if dissolution of hydrocarbons into asphalt void spaces occurs (Eganhouse *et al.*, 1981b). Hoffman *et al.* (1984) noted a lack of the more volatile PAHs in both urban runoff and atmospheric fallout, indicating analogous chemical composition. Also, instances of microbial degradation of hydrocarbons sorbed to soil particles represent a natural means of preventing some contaminants from being transported to receiving waters (Stenstrom *et al.*, 1982). Eganhouse *et al.* (1981b) found an abundance of normal and isoalkanes in the Los Angeles River samples, and added that this was evidence that little biodegradation of the hydrocarbons had occurred. The procession of petroleum compound degradation by microbes is generally in the following order: normals > branched > cyclics > aromatics (Eganhouse *et al.*, 1981b).

Cerniglia (1991) presented several processes that affect the fate of PAHs (see Figure 2). A portion of Cerniglia's studies focused on the isolation of a pyrene-degrading bacterium of the genus Mycobacterium. Within 48 hours of incubation, cultures of this bacterium degraded naphthalene

(59.5%), phenanthrene (50.9%), fluoranthene (89.7%), pyrene (63.0%), 1-nitropyrene (12.3%), 3-methylcholanthrene (1.6%) and 6-nitrochrysene (2.0%) to CO_2. Although this experiment was not intended to simulate an urban runoff-contamination situation, an objective was the identification of potential bacteria capable of bioremediation in contaminated sediments.

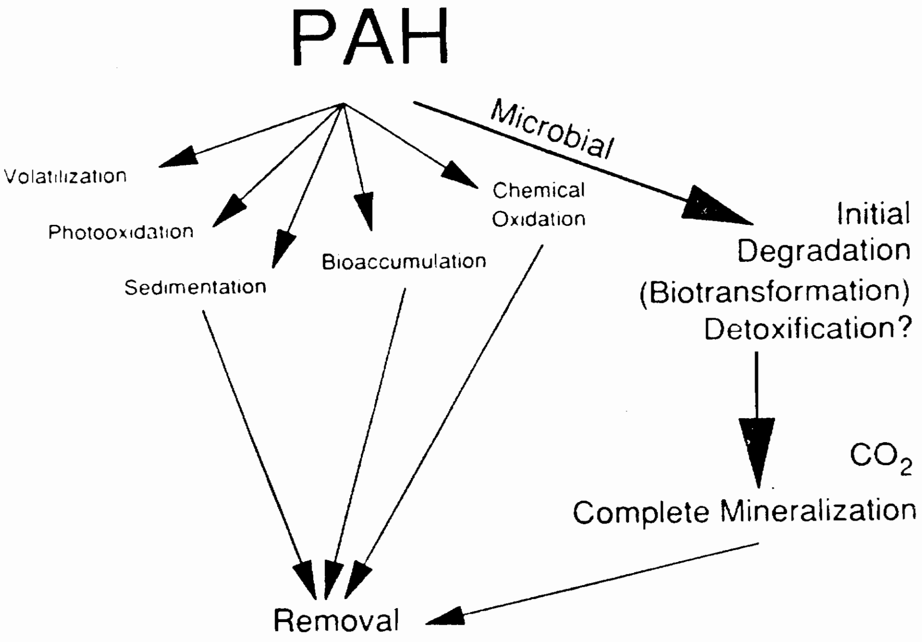

Figure 2. Diagram showing fate of polycyclic aromatic hydrocarbons.
Source: Cerniglia, 1991.

Behavior of Oil and Grease in Stormwater

Once mixed with water, oil and grease may form a surface layer, and hydrocarbons present will eventually attempt to sorb onto free particulate matter (Schueler, 1987). Stenstrom *et al.* (1982) found that hydrocarbons were consistently sorbed onto particulates, and indeed, other studies have determined that hydrocarbons have a great affinity for particulate matter (Cerniglia, 1991; Eganhouse and Kaplan, 1981; Hunter *et al.*, 1979; Randall *et al.*, 1982; Schueler, 1987; Stenstrom *et al.*, 1984; Whipple *et al.*, 1983). Stenstrom *et al.* (1982) also reported that about 85% of all hydrocarbons in urban runoff are associated with particulates and that this matter exists as either hydrocarbons sorbed to solid particle surfaces and/or clusters of oil droplets. In a comparable study, Hunter *et al.* (1979) found that 86.4% of the total hydrocarbons found in samples were in association with particulate matter. With respect to high molecular weight PAHs and total aromatics, an average of 79 to 93% were found particulate-associated (Hoffman *et al.*, 1984). Eganhouse and Kaplan (1981) stated that the "dissolved" fraction of hydrocarbons in samples was always below 15%, corresponding to an 85% or greater association of the remaining hydrocarbon fraction with particulate matter.

Identification of Compounds by Gas Chromatography

Some researchers have determined oil and grease content of storm runoff samples by chromatographic analyses. These studies have aided in the identification of specific compounds that survive the weathering process and go on to persist in the environment. In a runoff study of a watershed in Richmond, California, performed by Stenstrom *et al.* (1984), gas chromatography (GC) analyses of extracted samples were difficult due to the complex nature of storm runoff samples, i.e., the wide array of inputs to stormwater. Chromatogram peaks were found corresponding to anthracene and the C_{24} to C_{32} range in most samples analyzed. Also, a small number of samples were found to contain compounds with less than 10 carbons, and this was attributed to lack of using purge and trap analysis. Chromatograms produced by the researchers were found to be similar to those of other studies, i.e., a wide, unresolved envelope is typically seen beneath the peaks. Figure 3 gives a summary of the GC results obtained by Stenstrom *et al.* (1984).

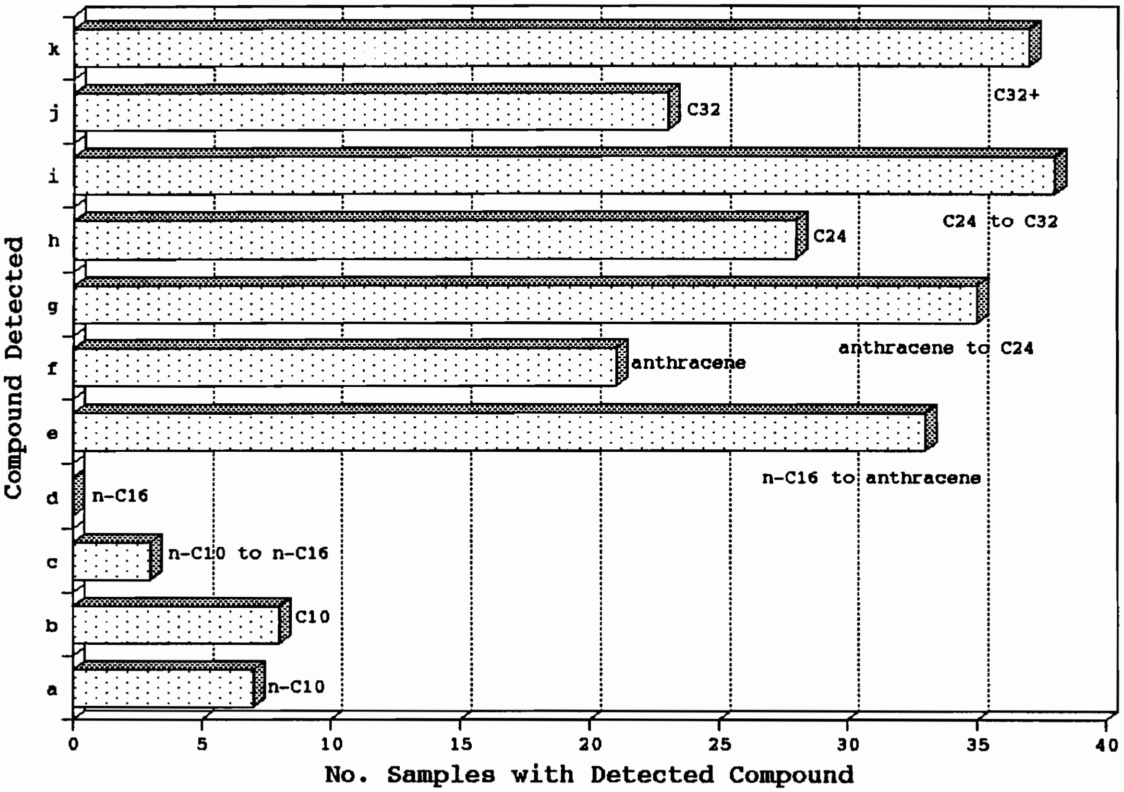

Figure 3. Results of GC analyses on 40 storm runoff samples. Source: Stenstrom *et al.*, 1984.

An extensive storm runoff study using gas chromatography was accomplished by Eganhouse *et al.* (1981b) on samples from the Los Angeles River. Sample-handling included the isolation of both bound and solvent-extractable fractions for total hydrocarbons, fatty acids, ketones, and polar compounds analyses. Discussion here will, of course, be limited to characterization of the total hydrocarbon fraction. Chromatographic characterization of the runoff samples revealed the presence of normal alkanes (n-alkanes), branched and aromatic hydrocarbons, cyclic compounds, as well as the unresolved species. All of the above were presumed to be of anthropogenic origin. Specific compounds that were tentatively identified in both bound and solvent-extractable fractions included naphthalene, phenanthrene/anthracene, fluoranthene, pyrene, chrysene, xanthene, and benzopyrene. Benzothiophene and dibenzothiophene were found only at trace levels in samples. Large unresolved envelopes in the n-C_{13} to n-C_{36}+ range constituting more than 80% of total hydrocarbons were seen on the chromatograms for every runoff sample (see Figure 4). Table 2 lists peak identifications for these chromatograms. The researchers also noted high-molecular weight n-alkanes (greater than n-C_{24}) with odd-to-even ratios greater than 1.0 as evidence of the presence of biogenic hydrocarbons (microbial and higher plant sources). This fraction was less than 2% of the total hydrocarbons for all samples, further indicating the predominance of anthropogenic

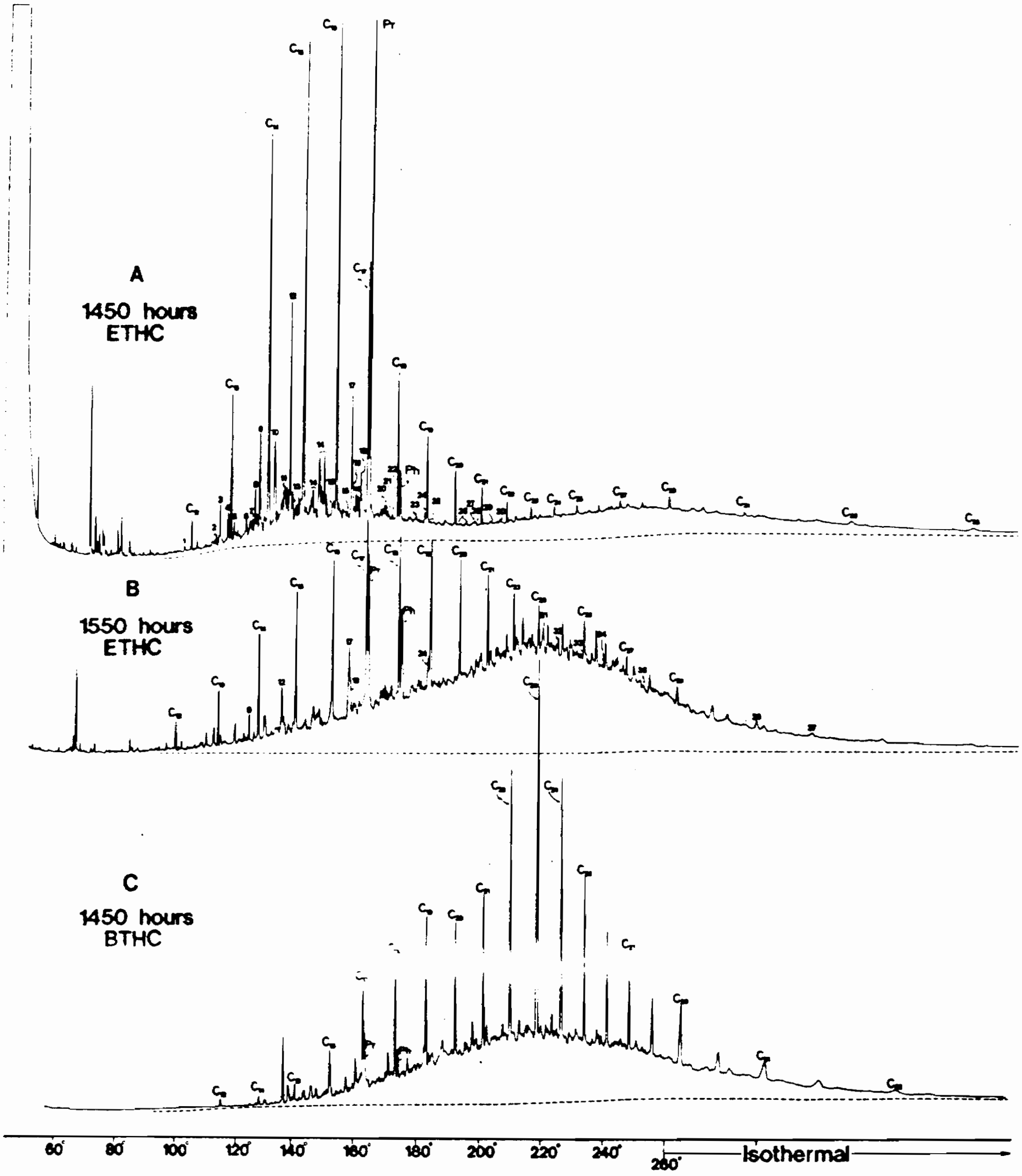

Figure 4. Total hydrocarbon gas chromatograms: (A) 1450 hours (unfiltered sample); (B) 1550 hours (unfiltered sample); (C) 1450 hours (particulates).
ETHC = solvent-extractable total hydrocarbons
BTHC = bound total hydrocarbons
Source: Eganhouse *et al.*, 1981b.

Table 2. Peak identifications for total hydrocarbon gas chromatograms in Figure 4.
Source: Eganhouse *et al.*, 1981b.

BRANCHED HYDROCARBONS

Peak No.	
2	2-methyldodecane (iso-C_{13})
3	2,6,10-trimethylundecane (isopr-C_{14})
8	2-methyltridecane (iso-C_{14})
9	2,6,10-trimethyldodecane (isopr-C_{15})
12	2,6,10-trimethyltridecane (isopr-C_{16})
17	2,6,10-trimethylpentadecane (isopr-C_{18})
24	2,6,10,14-tetramethylheptadecane (isopr-C_{21})

CYCLIC HYDROCARBONS

11	*n*-octylcyclohexane (C_{14})
18	*n*-decylcyclohexane (C_{16})
20	*n*-undecylcyclohexane (C_{17})
23	*n*-dodecylcyclohexane (C_{18})
28	*n*-tetradecylcyclohexane (C_{20})
30	*n*-pentadecylcyclohexane (C_{21})
31	$C_{23}H_{42}$ extended diterpane (structure I, $R = C_6H_{13}$)
32	$C_{24}H_{44}$ extended diterpane (structure I, $R = C_7H_{15}$)
33	$C_{25}H_{46}$ extended diterpane (structure I, $R = C_8H_{17}$)
34	$C_{26}H_{48}$ extended diterpane (structure I, $R = C_9H_{20}$)
35	$C_{28}H_{52}$ extended diterpane (structure I, $R = C_{11}H_{23}$)
36	17α(H),21β(H)-30-norhopane (structure II, $R = C_2H_5$)
37	17α(H),21β(H)-hopane (structure II, $R = C_3H_7$)

AROMATIC HYDROCARBONS

1	naphthalene
4	1-methylnaphthalene
5	2-methylnaphthalene
6	triisopropylbenzene (internal standard)
7	biphenyl
10	C_2 naphthalenes
13	C_1 biphenyls
14	C_3 naphthalenes
15	C_2 biphenyls
16	C_4 naphthalenes
19	C_5 naphthalenes

Table 2, continued.

Peak No.	*AROMATIC HYDROCARBONS - cont'd.*
21	C_3 biphenyls
22	phenanthrene or anthracene
25	C_1 phenanthrene/anthracenes
26	C_2 phenanthrene/anthracenes
27	pyrene
29	fluoranthene

hydrocarbons as the major source in stormwaters.

Storm runoff studies conducted by MacKenzie and Hunter (1979) in northern Philadelphia focused on identification of aromatic sulfur compounds. GC analyses indicated that naphthalenes and benzothiophenes were found in high concentrations in used crankcase oil, while these compounds were absent in runoff samples. Used crankcase oil was subjected to a 14-day weathering test, after which the aromatic fraction was found to be significantly reduced. Therefore, the lack of naphthalenes and benzothiophenes in stormwater samples was credited to natural weathering. Gas chromatograms of Delaware River sediment samples were similar to gas chromatograms of used crankcase oil and runoff samples. Also, high-boiling-point aromatic sulfur and hydrocarbon compounds were detected in the sediments, indicating that degradation was not a major factor in sediments. This may be important in predicting specific compounds that persist in the environment: the high-boiling-point aromatic sulfur compounds seem to be unaffected by short-term weathering and are readily deposited in sediments. Additionally, the researchers found dibenzothiophene and phenanthrene and/or anthracene in all samples (it was not possible to distinguish phenanthrene from anthracene on the column that was used). Again, large unresolved envelopes appeared on the chromatograms, as is typically seen in oil and grease analyses. MacKenzie and Hunter (1979) adopted the position taken in a 1965 paper by

Martin and Grant that the unresolved areas are evidence of four- and five-ring thiophenes in addition to aromatic sulfides, thiols, and thiaindans. Table 3 gives a summary of the hydrocarbon concentrations found in stormwater samples by the aforementioned researchers.

Table 3. Summary of hydrocarbon levels found in stormwater samples.
Source: MacKenzie and Hunter, 1979.

Storm Event Date	Hydrocarbon Type	Associated Hydrocarbons	
		Particulate mg/L	Soluble mg/L
4/3/75	aromatics	1.10	0.06
	total petroleum hydrocarbons	3.70	0.34
8/16/75	aromatics	1.65	0.07
	total petroleum hydrocarbons	5.06	0.24
11/12/75	aromatics	0.99	0.04
	total petroleum hydrocarbons	4.08	0.16

Priority Pollutants in Stormwater

Some hydrocarbon compounds identified in stormwater runoff are classified by the United States Environmental Protection Agency (USEPA) as priority pollutants. Results published from the Nationwide Urban Runoff Program (NURP) (USEPA, 1983) included a section that identified specific priority pollutant compounds detected in NURP samples. A total of 49 out of a possible 113 organic priority pollutants were detected in NURP samples. Monocylic and polycyclic aromatic compounds numbered 14 of the 49 organics detected (29%).

Table 4 summarizes information on these 14 aromatics that were detected. Emphasis was placed on benzene and toluene; which were two of six priority pollutant organic compounds found in 20% or more of the NURP samples. Table 5 lists those priority pollutant aromatics that were not detected in NURP samples. Note that all but one of the compounds detected (chlorobenzene) were "purely" of a hydrocarbon nature, while the majority of undetected compounds were of chlorinated benzene, and nitrogenated benzene and toluene composition.

Benzene and phenanthrene concentrations exceeded the USEPA human carcinogenic water quality criteria in at least 10% of the NURP samples. The exceedances for benzene at the 10^{-5}, 10^{-6}, and 10^{-7} risk levels were 3%, 34%, and 34% respectively, and for phenanthrene, 10%, 10% and 10%

Table 4. Priority pollutant aromatic compounds detected in NURP samples.
Source: USEPA, 1983.

Pollutant	Detection Frequency (%)	Range of Detected Concentrations (μg/L)
Monocyclic Aromatics		
Benzene	34	1 - 13
Benzene, chloro-	7	1 - 3
Benzene, ethyl-	12	1 - 3
Toluene	24	3 - 9
Polycyclic Aromatics		
Anthracene	6	1 - 5
Benzo(a)anthracene	3	1 - 3
Benzo(b)fluoranthene	1	2
Benzo(k)fluoranthene	1	4
Benzo(a)pyrene	3	1 - 2
Chrysene	6	0.6 - 4.5
Fluoranthene	7	0.3 - 12
Naphthalene	6	1 - 13
Phenanthrene	10	0.3 - 7
Pyrene	7	0.3 - 10

Table 5. Priority pollutant aromatic compounds not detected in NURP samples.
Source: USEPA, 1983.

Pollutant	Reported Limits of Detection* (μg/L)
Monocyclic Aromatics	
1,2-Dichlorobenzene	10
1,3-Dichlorobenzene	10
1,4-Dichlorobenzene	10
1,2,4-Trichlorobenzene	10
Hexachlorobenzene	10
Nitrobenzene	10
2,4-Dinitrotoluene	10
2,6-Dinitrotoluene	10
Polycyclic Aromatics	
Acenaphthene	10
Acenaphthylene	10
Benzo(g,h,i)perylene	10 - 25
Dibenzo(a,h)anthracene	10 - 25
Fluorene	10
Indeno(1,2,3-c,d)pyrene	10 - 25

*Where more than one detection limit is applicable because laboratory methodologies differed, a range is given.

respectively. It was felt that little risk would be posed to humans due to the concentrations of organic priority pollutants that were detected, with the potential exception of phenanthrene (and chloroform, not discussed here). Dilution during storm events and known fates and pathways of these organic compounds were listed as means by which risks to human health would be lessened. Also, fossil fuels combustion and gasoline consumption were given as the predominant sources of the frequently-detected compounds phenanthrene, benzene, ethylbenzene, and toluene.

Potential Consequences of Hydrocarbons in Receiving Waters

Toxicity Effects of Hydrocarbons on Aquatic Life

While oil and grease contamination in runoff constitutes low concentrations when compared to oil spills, even these low levels raise questions of toxicity to aquatic organisms (Stenstrom *et al.*, 1982). Whipple and Hunter (1981) listed petroleum hydrocarbons as the most common toxic pollutant in urban stormwater. Gavens *et al.* (1981) stated that mutations and cancers were caused in some organisms as a result of exposure to some PAHs. They also reported that the prevalence of long-chain aliphatic hydrocarbons seemed to mitigate toxicity effects, serving instead as an energy source.

Acute toxicity studies were performed on heterotrophic organisms, algae, salmon, and salmon eggs with a snowmelt runoff sample by Norwegian researchers (Gjessing *et al.*, 1984). The runoff sample yielded extracts containing about one third of the dissolved organic matter and two thirds of particulate-associated organic matter. GC characterization enabled only a fraction of these organics to be identified. Figure 5 shows the results of tests with varying concentrations (0 - 90%) of unfiltered runoff with bacteria, fungi, and protozoa. No negative effects were detected, and it was noted that an increased runoff concentration actually stimulated activity. Figures 6 and 7 depict results of the tests with the algae species Selenastrum capricornutum and Synedra acus using 50 and 100% filtered runoff concentrations and a control (0% runoff concentration). Figure 7 shows that a small stimulating effect was seen for both algae species with the 50% concentration. Acute toxicity of the 100% concentration was seen to be negligible. Other results revealed that undiluted runoff did not seem to negatively affect the salmon or salmon eggs. The researchers stressed that these tests were purely acute in nature, and that chronic effects and potential for bioaccumulation of the organics was not investigated.

Stenstrom *et al.* (1982) stated that the soluble petroleum hydrocarbon fractions (rather than dispersed droplets) may be the most detrimental to aquatic life. In general, the chemical form that the pollutant takes on as it enters the receiving water body will affect toxicity toward aquatic

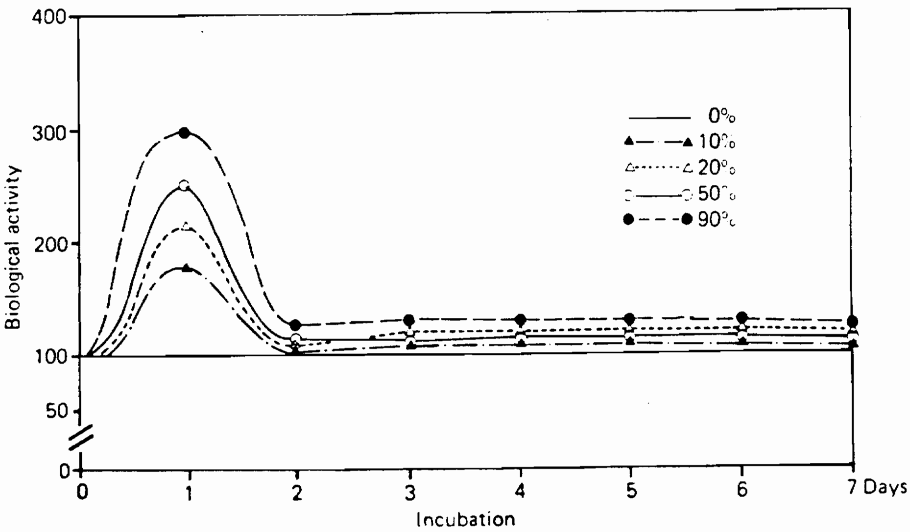

Figure 5. Results of acute toxicity tests on heterotrophic organisms using varying runoff concentrations. Source: Gjessing *et al.*, 1984.

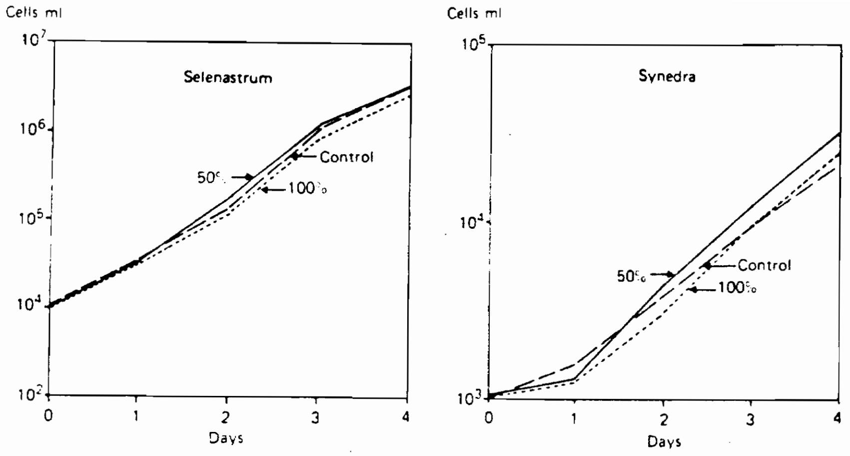

Figure 6. Results of acute toxicity tests on algae using 50 and 100% runoff concentrations.
Source: Gjessing *et al.*, 1984.

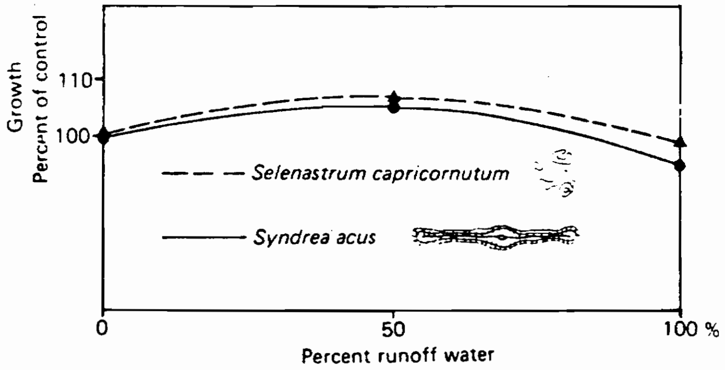

Figure 7. Dose/response curves using 50 and 100% runoff concentrations for the effect on the growth rate of algae.
Source: Gjessing *et al.*, 1984.

organisms (Jones, 1986). For instance, Jones (1986) cited one study from the 1982 and 1983 issues of the Water Pollution Control Federation (WPCF) *Annual Literature Review* that found crude oils and heavy metals to have less pathological influence than the more refined petroleum products such as lubricating oils.

Water Quality Effects of Pollutant Settling

Schueler (1987) stated that attention should be given not just to the water column, but to the sediment layer as well. Among other water quality impacts, the settling of suspended and particulate matter carries contaminants and probably contributes a sediment oxygen demand. Because a high fraction of hydrocarbons is concentrated in this layer due to sedimentation of particulates (Whipple *et al.*, 1983), benthic life may be at a higher risk than in other levels of the water column. Additionally, hydrocarbons in the sediments may not readily degrade over time (Stenstrom *et al.*, 1982) and are therefore available to be released back into the water column under suitable chemical conditions (Schueler, 1987).

Eadie *et al.* (1991) reported that partitioning of contaminants such as PAHs between the particulate and dissolved phases depends on inherent characteristics and chemical composition. Additionally, the researchers noted that, although poorly quantified, another exposure route of contaminants is through uptake by benthic life and subsequent food chain interactions.

Stormwater Runoff Treatment for Removal of Hydrocarbons

Settleability of Pollutants in Urban Runoff

A recent survey conducted by the American Society of Civil Engineers (ASCE, 1985) polled 150 stormwater management professionals, which included consulting engineers, government officials, and university professors. Responses from about 43% of those polled indicated that "hydraulic function was considered to be the most important design consideration [for] outlet structures... water quality design considerations were deemed relatively unimportant by most respondents but most felt that ponds improve water quality." Despite this survey, stormwater management theory seems to have now shifted to treating water quality control as important as water quantity control. The general goal of stormwater "pre-treatment" has been to trap and detain pollutants before they could be transported to receiving waters.

Because suspended solids are the primary form of pollution in urban runoff, it follows that sedimentation is useful in the removal of pollutants from urban runoff (Whipple *et al.*, 1983). Many researchers have conducted settling tests on urban runoff to assess settleability of specific pollutants. The following section will outline studies that have focused on the removal of hydrocarbons from urban stormwater.

Hydrocarbon Settleability Studies

One of the best-known settleability studies is that of Whipple and Hunter (1981). They focused on the removal of many pollutants (total phosphate, fecal coliform, suspended solids, BOD, nitrate, heavy metals, hydrocarbons, and ammonia), but discussion here will be limited to hydrocarbons. For samples taken at a shopping center in Lawrence Township of New Jersey on 9/21/79, the initial hydrocarbon concentration was just below 3.0 mg/L. After 36 hours of quiescent settling in a 6-foot deep column, the concentration was just below 1.0 mg/L. Further, Whipple and Hunter observed that the hydrocarbons tended to settle out almost as quickly as the total suspended solids, and that most of the settling occurred in 16 hours. They also noticed a time lag before appreciable THC removal began and attributed this phenomenon to sorption of the hydrocarbons to suspended particulates. These observations can be seen by comparing Figures 8 and 9, which show the total suspended solids and hydrocarbon settleability results from some of the storms the researchers sampled. The y-axes on these figures represent percent removal values of the constituents of interest. The authors stated that their results did not seem to support the hypothesis that pollutants settle out in proportion to the initial particulate concentrations. However, the data indicated that settling of oil and grease did occur over the 36-hour period of observation.

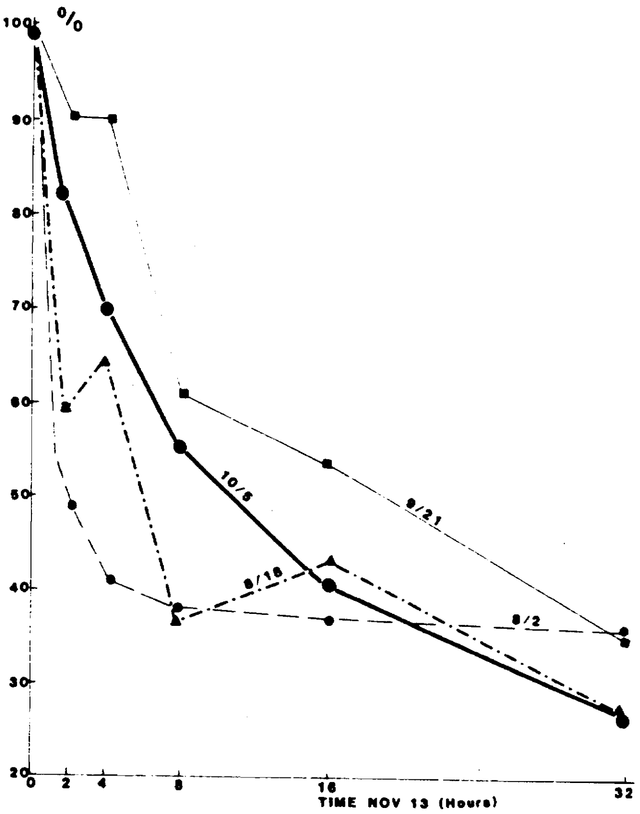

Figure 8. Total suspended solids settleability results.
Source: Whipple and Hunter, 1981.

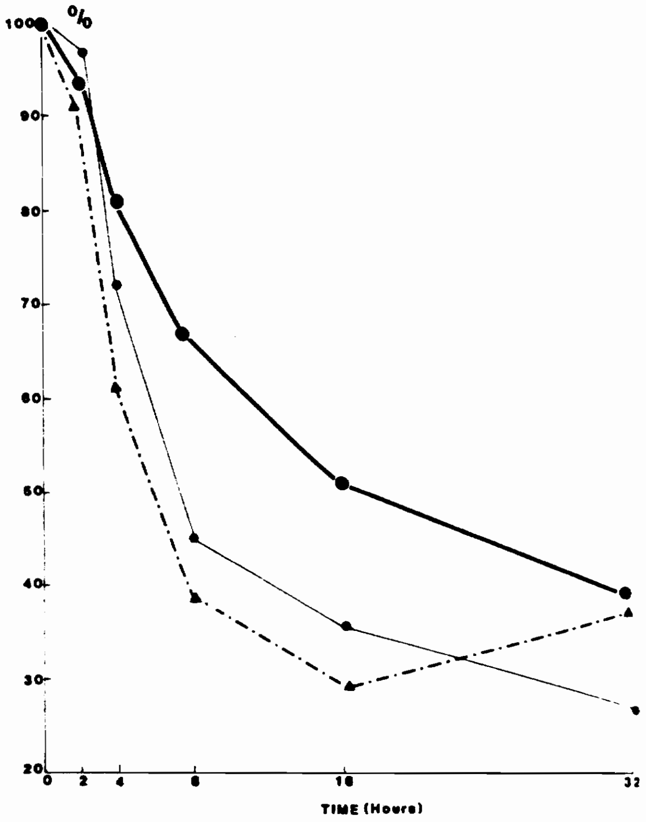

Figure 9. Hydrocarbon settleability results.
Source: Whipple and Hunter, 1981.

Stenstrom *et al.* (1984) studied oil and grease in urban runoff from a watershed in Richmond, California. They performed settling tests on samples collected from one of 7 storms sampled. Collected runoff was placed in a 1.6-meter high glass column. Samples were withdrawn from 3 ports in the column after 1, 2, 5, 10, and 30 minutes of settling. Additional 1-liter samples were taken from the water surface and column bottom after the 30-minute samples. The results indicated no real trend in sedimentation of oil and grease during the 30-minute settling time. A higher THC concentration was found in the bottom-layer sample, and this was attributed to rapidly-settling sediments with a sorbed fraction of oil and grease. The authors also noted a large amount of residual oil and grease forming a thin film on glassware used in their experiment, which may have accounted for less-than-actual hydrocarbon concentrations found in the runoff samples. This occurrence may illustrate the need to minimize the number of transfer vessels and/or sample collection containers used for this kind of work.

Pollution Control Measures for Hydrocarbons in Urban Runoff

Part of the study encompassed by NURP was a comprehensive review of control strategies for runoff quantity as well as quality (USEPA, 1983). Four groups were listed: detention devices, recharge devices, housekeeping practices, and other techniques (e.g., "living filter" approaches); some of the more popular techniques are discussed here.

One detention device, the catchbasin, is useful where sewer grades are not adequate to promote self-cleaning of accumulated sediments (Silverman and Stenstrom, 1989). These sediments are then manually cleaned out of the catchbasin on a regular basis.

NURP found wet detention basins to perform best in reducing urban runoff pollutants (USEPA, 1983). By keeping a continuous pool of water, the wet detention basin has an inherent detention time which allows pollutant settling to occur. No results were reported regarding the capability of the wet detention pond to remove hydrocarbons. Dry detention basins were reported by NURP to be incapable in pollutant-removal capabilities. Due to the fact that the primary function of the dry detention basin is only to control peak runoff flow rates, detention time for pollutant settling is not a factor in design.

Porous pavements (a form of recharge device) were reported by Silverman and Stenstrom (1989) to offer good potential for oil and grease removal from runoff. Paving stones that allow low vegetation to grow between the stones and asphalt pavements constructed with a fraction of fine particles may be effective porous pavements. Pollutant-laden runoff infiltrates through the surface where much of the load is detained, allowing the water to pass through to the underlying soil layer.

Mechanical street-sweeping is one of the most popular "housekeeping" methods. Many studies have suggested that it is also one of the most ineffective control strategies in practice (Silverman and Stenstrom, 1989). As oil and grease is known to sorb to fine particulate matter, Sartor *et al.* (1974) reported that most of these fines are not picked up by conventional street-sweeping. Silverman and Stenstrom (1989) theorized that a mix of water and biodegradable detergents sprayed on the pavement during sweeping may aid in solubilizing oil and grease.

Grassed swales or "greenbelts" are a popular control technology utilizing the "living filter" approach. Important design considerations for the grass swale, which provides modest pollutant removal, are slope, vegetation type and maintenance, and control of flow velocity and residence time (USEPA, 1983). The greenbelt concept is similar and employs an underlying gravel layer to drain the upper soil and vegetation layers and aid in distribution of percolating runoff water.

CHAPTER III. METHODS AND MATERIALS

This chapter describes the methods and laboratory equipment used for settling column tests conducted with stormwater runoff samples. It also outlines sampling and analytical procedures used to determine removal of hydrocarbons from the runoff samples.

Description of Sampling Site

Because urban stormwater was the focus of the study, a commercial storm drain was chosen in a parking lot at Manassas Mall in Manassas, Virginia. It was specifically located next to (not opening on) Rixlew Lane and was about 400 feet from the intersection of Rixlew Lane and Sudley Road (Route 234). Proximity of the site to OWML (a distance of about 2 miles) was also a factor in selection because studies with the samples were subsequently conducted at OWML.

The storm drain collected runoff from an urban area of approximately 23 acres. Runoff at this storm drain was comprised of drainage from the roof of the Hecht's Department Store (which flowed over the parking lot to the drain) and from parking lots and access roads in the immediate vicinity.

Runoff flowing into the storm drain was directed into a 42-inch reinforced concrete pipe, which eventually drained into nearby Flat Branch. The sampling location was deemed suitable for a runoff hydrocarbon study due to 1) large impervious/commercial areas, 2) relatively steady flow of automobile traffic through the area, and 3) the fact that large quantities of stormwater runoff (without prior pollutant removal) drained into a nearby creek.

Sampling Plan and Record-Keeping

Stormwater runoff samples were collected during three rain events. The samples were collected as grab samples by feeding a stainless steel bucket connected to a heavy rope into the center of the drain. After allowing the bucket to fill, a small amount was poured into a 7½-gallon plastic carboy, swirled, and emptied to rinse the carboy. The carboy was then filled and closed as fast as possible by retrieving grab samples with the bucket. This entire procedure was repeated until five of these carboys were completely filled to ensure enough runoff was collected.

After sample collection, the carboys were returned to the Occoquan Watershed Monitoring Laboratory in Manassas, Virginia. It was always an objective during sample handling and analysis to minimize sample transfer from one container to another in order to avoid possible analyte loss on container walls. Approximately 750 milliliters (mL) were taken from each carboy and thoroughly mixed in a beaker to obtain a composite sample. From this composite, 75 to 100 mL of sample were poured into a brown glass sample bottle and preserved as described below. Remaining samples in the carboys were poured into four Plexiglas® settling columns (except for the July 21 settling test which used only three columns.)

The columns were five feet high, six inches inside diameter, with quarter-inch walls. Filled to capacity, the columns held 7.5 gallons (28.4 liters) of sample. The columns were fitted with "ports" to enable sampling at specific levels and times in the water column. On three of the columns, the ports were at one, two, three, and four feet from the bottom. The fourth column had additional ports at 0.5, 1.5, and 2.5 feet from the bottom. All ports were fitted with Fisherbrand® 0.5-inch inside-diameter flexible clear plastic tubing and C-clamps to control the amount of sample taken from the column. The tops of the columns were kept covered with plastic lids to prevent possible evaporation of the analyte.

Glassware used for sample collection at the ports were Kerr 4-ounce square amber jars fitted with aluminum-lined lids. Before use, they were acid-washed with a 50% hydrochloric acid (HCl) solution, and then rinsed with reverse-osmosis treated water before being allowed to air-dry. Samples were taken from every port on a pre-determined schedule as shown in Table 6. The pH of random samples was measured using a Fisher Scientific (Pittsburgh, Pennsylvania) Accumet® pH Meter 925. Temperature was recorded for some samples with a standard mercury thermometer. All samples were then preserved to a pH less than two by adding 1:1 HCl, checking the pH with Fisherbrand® (Pittsburgh, Pennsylvania) Alkacid® Wide-Range Test Ribbon, and then refrigerating. For

Table 6. Sampling plan summary.

	No. columns used	Sample collection times
STORM #1 7/21/92	3	composite .75 hrs. 2 hrs. 18 hrs. 24 hrs. 48 hrs.
STORM #2 8/4/92	4	composite .75 hrs. 4 hrs. 18 hrs. 24 hrs. 48 hrs.
STORM #3 8/28/92	4	composite .5 hrs. 2 hrs. 18 hrs. 24 hrs. 48 hrs.

future reference in this report, the sample numbering scheme was as follows: e.g. for sample #21C24, the first digit ("2") indicated Storm #2, the second digit ("1") indicated Column #1, the letter indicated the port at -3 feet [columns #1 - 3: port A = -1 foot, port B = -2 feet, port D = -4 feet; column #4: port A = -1 foot, port B = -2 feet, port C = -2.5 feet, port D = -3 feet, port E = -3.5 feet, and port F = -4.5 feet], and the last numbers indicated the sampling time, 24 hours.

In addition to sample collection and preservation, it was also important to record other information specific to the storm events sampled. Equipment at the OWML recorded barometric pressure, outside and inside temperatures, windchill, windspeed, gustspeed, wind direction, and rainfall at the laboratory (contained in Appendix B). Rainfall and temperature data at Washington National and Dulles Airports were obtained from the National Weather Service (contained in Appendix C). Based on the proximity of the OWML to the sampling site, similar weather conditions were expected to occur at both locations. It was not feasible to set up meteorological or hydrologic recording equipment at the sampling site.

Sample Analysis

All samples taken from the column ports were analyzed for total oil and grease (hydrocarbons) on a Horiba (Irvine, California) OCMA-220 Oil Content Analyzer. Some information on the instrument has been provided in Table 7 because facts about it may be uncommon knowledge. A diagram of the analyzer may be seen in Figure 10. The instrument worked on the liquid-liquid extraction principle with infrared analysis and was based on Section 5520, Oil and Grease, in *Standard Methods for the Examination of Water and Wastewater* (APHA, 1992). It offered advantages including a reduction in the requirements for sample and extraction solvent volumes, glassware for extractions, and time needed. Additionally, it was operated on the 0 - 5 part per million (ppm) instrument range for all samples analyzed, except for a few of the Storm #1 samples. These samples were analyzed on the 0 - 20 ppm instrument range.

Trichlorofluoroethane ("freon") was the solvent used for extraction of oil and grease from stormwater samples. A Horiba (Kyoto, Japan) CR-200 Solvent Reclaimer (Figure 11) was used to purify spent solvent for reuse during analyses. One column of the two-column unit contained granulated carbon through which spent solvent was passed. After contacting the carbon, the purified solvent flowed to the reclaimer tube, where it was recovered by opening a valve and collecting it in a clean beaker. Due to the highly volatile nature of freon, analyses were conducted with the oil analyzer and solvent reclaimer under a fume hood.

Table 7. Horiba OCMA-220 oil content analyzer specifications.*
Source: Horiba Instruments, Inc., 1989.

REPEATABILITY**	± 4% of full scale ± 1 digit (on 3-digit panel)
SAMPLE VOLUME	20 mL per measurement
SOLVENT VOLUME	10 mL per measurement
CALIBRATION	oil/solvent standard for high calibration, pure solvent for zero calibration

*All specifications refer to 0 - 5 ppm instrument range.

**Interpretation of notation:

± 4% of 5 mg/L = 0.2 ± 1 digit on scale (0.1 - 0.3)

For example, a sample of 0.5 mg/L concentration could potentially read 0.2 - 0.8 mg/L on the instrument readout, or under optimum conditions, 0.4 - 0.6 mg/L.

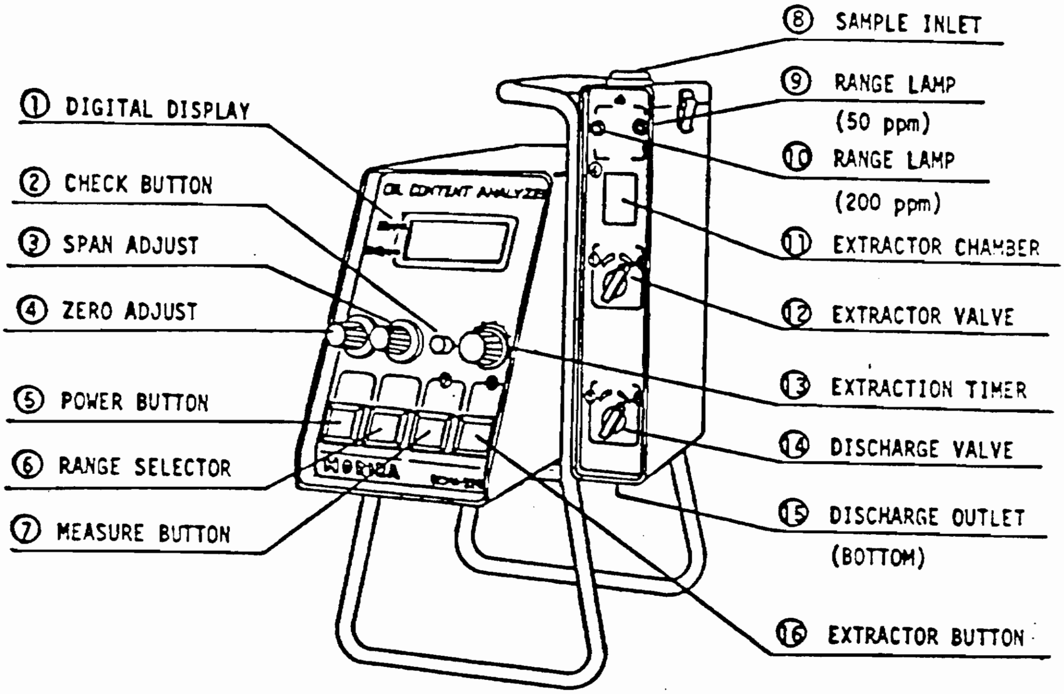

Figure 10. Horiba OCMA-220 oil content analyzer. Source: Horiba Instruments, Inc., 1989.

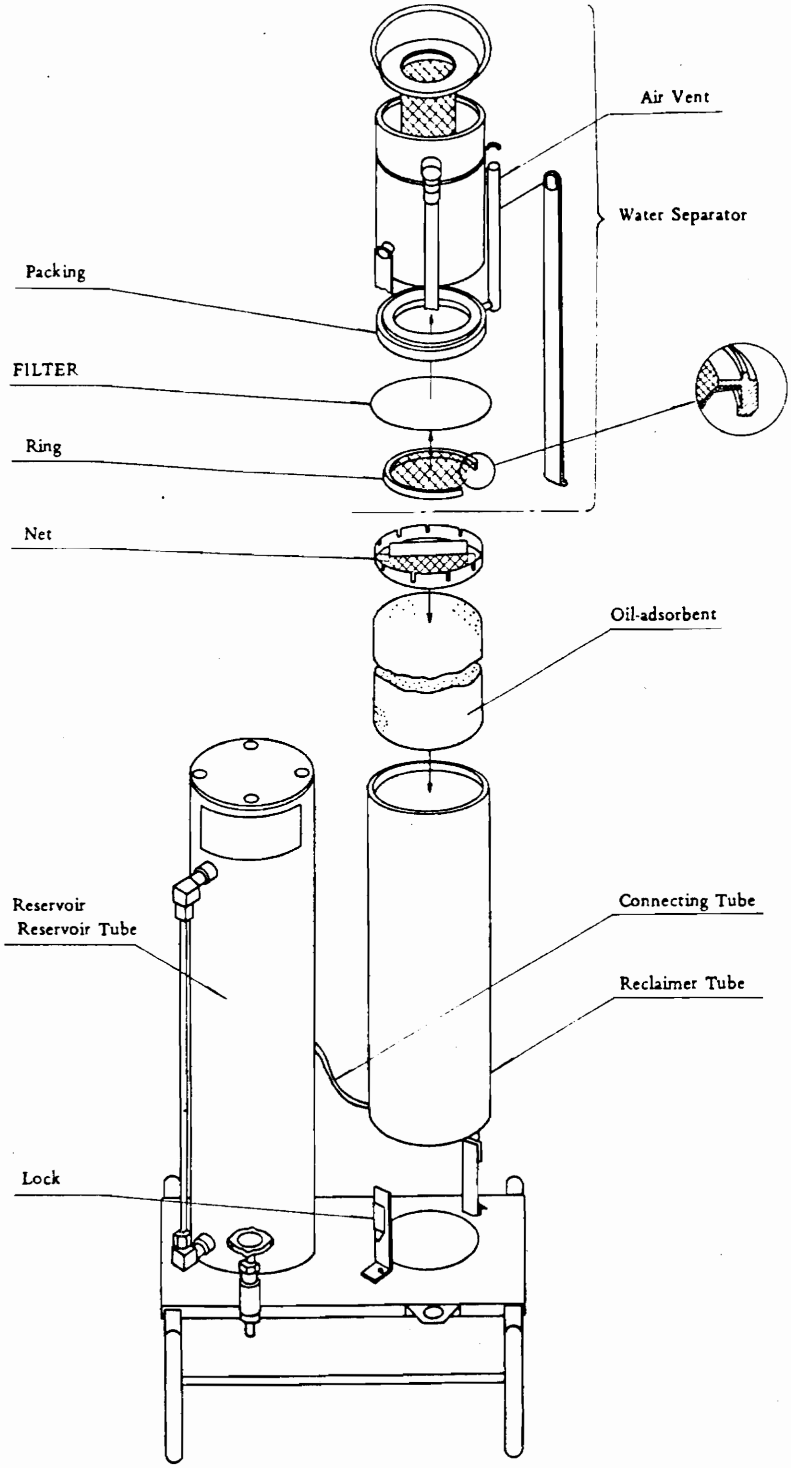

Figure 11. Horiba CR-200 solvent reclaimer.
Source: Horiba, Ltd. (no date)

The following is a general description of the method of operation for the Horiba oil analyzer (applies to the 0 - 5 ppm instrument range -- references to the 0 - 20 ppm instrument range are shown in parentheses):

- The sample bottle was placed on a magnetic stir plate to keep the sample completely mixed while pipetting a portion for analysis. Using a volumetric pipet, 20 mL (15 mL) of sample were measured and transferred into the extractor chamber through the sample inlet. Subsequently, 10 mL (15 mL) of freon were added to the extractor chamber. The lid was then shut on the sample inlet.

- The extractor was operated to mix the sample and freon for a period of 2 minutes. Time was allowed to view separation of the water and freon layers in the chamber.

- The extractor valve was manually turned to allow the solvent with extracted oil and grease to flow through a filter membrane and fill the analyzer sample cell. After closing the extractor valve, the discharge valve was opened to drain the solvent from the sample cell. This aliquot was used as a rinse through the sample cell to avoid contamination from previous samples. With the discharge valve closed, the extractor valve was again turned to fill the sample cell. Once the cell was filled, the measure button was depressed to activate the internal infrared analyzer. One minute was allowed to attain stabilization of the readout on the digital display. After the concentration was recorded, the measure button was depressed off. The discharge valve, and then the extractor valve were opened to allow remaining solvent and sample water to drain from the sample cell and extractor chamber, respectively, into a glass beaker.

Operating Principles of the Horiba Oil Analyzer

The internal infrared analyzer is a double-beam optical system. One beam is directed through the sample cell containing the freon and extracted oil and grease, while the other is directed through a sealed tube filled with a reference gas. Absorption of the infrared wavelengths by the oil and grease in the sample cell produces an energy differential between this cell and the reference cell. The beams are received into the dual-chambered detector. A diaphragm separating the chambers pulsates as the beams are blocked by a light chopper, thus producing a cyclical capacitance. The cyclical capacitance is converted to an electrical signal and then sent through a series of amplifiers, including the preamplifier, gain control potentiometer, AC amplifier, and finally the DC amplifier. The DC amplifier output to the digital display operates in direct proportion to the concentration of oil and grease in the sample, allowing the operator to make a reading from the front panel display.

Method Detection Limit Determination on Horiba Oil Analyzer

A method detection limit (MDL) study was undertaken and USEPA procedures were followed for the 0 - 5 mg/L (ppm) instrument scale. The standard used was a 4.6 mg/L solution, which was selected for ease of preparation because multiple reagents are used. This concentration also satisfied the USEPA criteria for selection of a standard for MDL determination. The result of the study was an MDL of 0.72 mg/L, although it was postulated that concentrations much less than this could accurately be detected. An MDL lower than 0.72 mg/L would have been produced if a standard less than the 4.6 mg/L solution was used. Maddalone *et al.* (1993) stated that for increasing concentrations, the standard deviation associated with measurement variability also increases, and vice versa. Therefore, a lower standard concentration would result in a smaller range of error in the measured values, (i.e., a lower standard deviation value), and hence a lower MDL is produced.

Therefore, another study was designed to verify the instrument's sensitivity over a range of low concentrations (OWML, 1992). Five dilutions of the 4.6 mg/L standard were prepared: 0.115, 0.23, 0.46, 0.76, and 0.92 mg/L. Note that three of these were below, and the other two were above the

USEPA MDL of 0.72 mg/L. After manual cleaning of the instrument sample cell, followed by optical alignment and gain adjustment, three replicates of each standard were analyzed.

The results (contained in Appendix E) indicated that low levels of hydrocarbons could be detected with consistent repeatability. Most important, the 0.1 mg/L standard was recovered as 0.1 mg/L for three out of four replicates, and was clearly differentiated from the 0.2 mg/L standard. This study confirmed that the Horiba oil analyzer can reliably detect concentrations lower than the USEPA MDL of 0.72 mg/L on the 0 - 5 mg/L scale.

Data Analysis

Initial attempts to use the total hydrocarbon data to construct "flow-through curves" (i.e., treating the sedimentation columns as ideal settling basins) were not successful. It was impossible to construct contour lines showing percent incremental removal of hydrocarbons in the traditional manner of flow-through curve analysis. Therefore, this type of evaluation was abandoned for a more straightforward approach utilizing concentration and percent removal profiles plotted against column depth and settling time.

Average THC concentration and average THC percent removal values were calculated from the raw sample data. Additionally, the ranges of percent THC removal achieved were determined from the data. All of the above are graphically presented in the Results chapter and subsequently evaluated in the Discussion chapter.

In-depth statistical analyses on the hydrocarbon concentration and percent removal data were not performed. The database was not of a sufficient size to warrant statistical evaluation. For example, at one column depth and one sampling time, a maximum of four data points (one from each column) was possible. Instead, the focus was on using the given repeatability specifications to clearly differentiate the hydrocarbon concentrations presented on the graphs. Distinctions had to be made between trends in the data that truly indicated settling and/or other behavior of oil and grease, and potential areas where "violations" of the allowed range of repeatability were occurring. A brief discussion addressing repeatability as it related to analyses of sample duplicates is contained in Appendix F.

CHAPTER IV. RESULTS

Graphical results of the column studies completed for three stormwater runoff events are presented in this chapter. Table 8 summarizes the constituents measured in the column samples, and these raw data are contained in Appendix A. Meteorological data associated with the rain events sampled were recorded by monitoring equipment at OWML and are contained in Appendix B.

Introduction

Table 9 summarizes general information related to rainfall and THC concentrations in the runoff samples collected. The THC values are the concentrations of total hydrocarbons in the composite samples that were obtained as described in the Methods and Materials chapter. Total rainfall and rainfall intensity values were calculated from the data contained in Appendix B. Note the comparatively high total rainfall and intensity of Storm #2 relative to the other two storm events. Because of problems incurred immediately before samples from Storms #1 and 2 were collected, personnel were not able to be present at the sampling site when runoff commenced. Also, Storm #3 was part of a storm system in Northern Virginia that was formed by the remnants of Hurricane Andrew, which had ravaged South Florida and parts of Louisiana earlier in the week.

Table 8. Summary of water quality constituents measured in column samples.

Total hydrocarbons (mg/L)
Water temperature (°C) [random samples]
pH [random samples]

Table 9. General summary of storms sampled.

	STORM #1 7/21/92	**STORM #2** 8/4/92	**STORM #3** 8/28/92
# days of antecedent dry weather	6	3	10
total rainfall (in.)	0.14	0.80	0.13
rainfall intensity (in/hr)	0.19	0.64	0.07
THC (mg/L)	1.8	1.0	3.5

Hydrocarbon Concentrations

Figures 12, 13, and 14 show the average hydrocarbon concentration profiles in the columns for the three storm events. Figures 15 and 16 show the THC concentrations in only Column #4 for Storms #2 and 3. These figures were included to view the concentration and removal profiles at intermediate depths (-2.5, -3.5 and -4.5 feet) not afforded by the other three columns. Only three dashed lines connecting the data points on Figure 15 were included so as not to obscure the data from the viewer's eye.

Samples from Storms #1 and 3 clearly indicated a decrease in average THC over time at all column depths. No consistent trends were seen in the Storm #2 average THC data. Storm #1 runoff samples had a THC concentration of 1.8 mg/L, which was reduced over 48 hours in three columns to an average of 0.4 mg/L at the -2 and -4 foot depths. Storm #2 runoff samples had a THC concentration of 1.0 mg/L, which was reduced over 48 hours in four columns to an average of 0.7 mg/L at the -1 and -3 foot depths. Storm #3 runoff samples had a THC concentration of 3.5 mg/L, which was reduced over 48 hours in four columns to an average of 0.9 mg/L at the -3 foot depth.

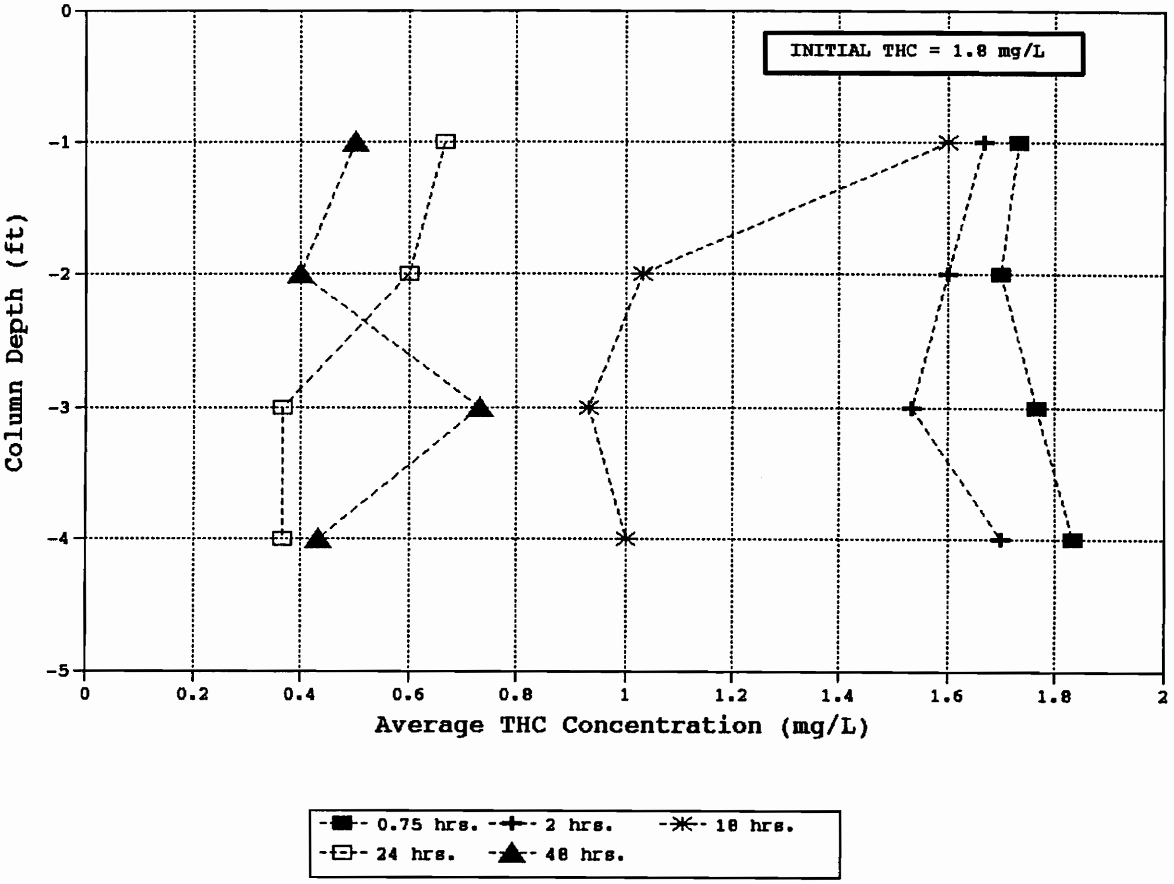

Figure 12. Storm #1: Average THC concentration profiles for columns #1 - 3.

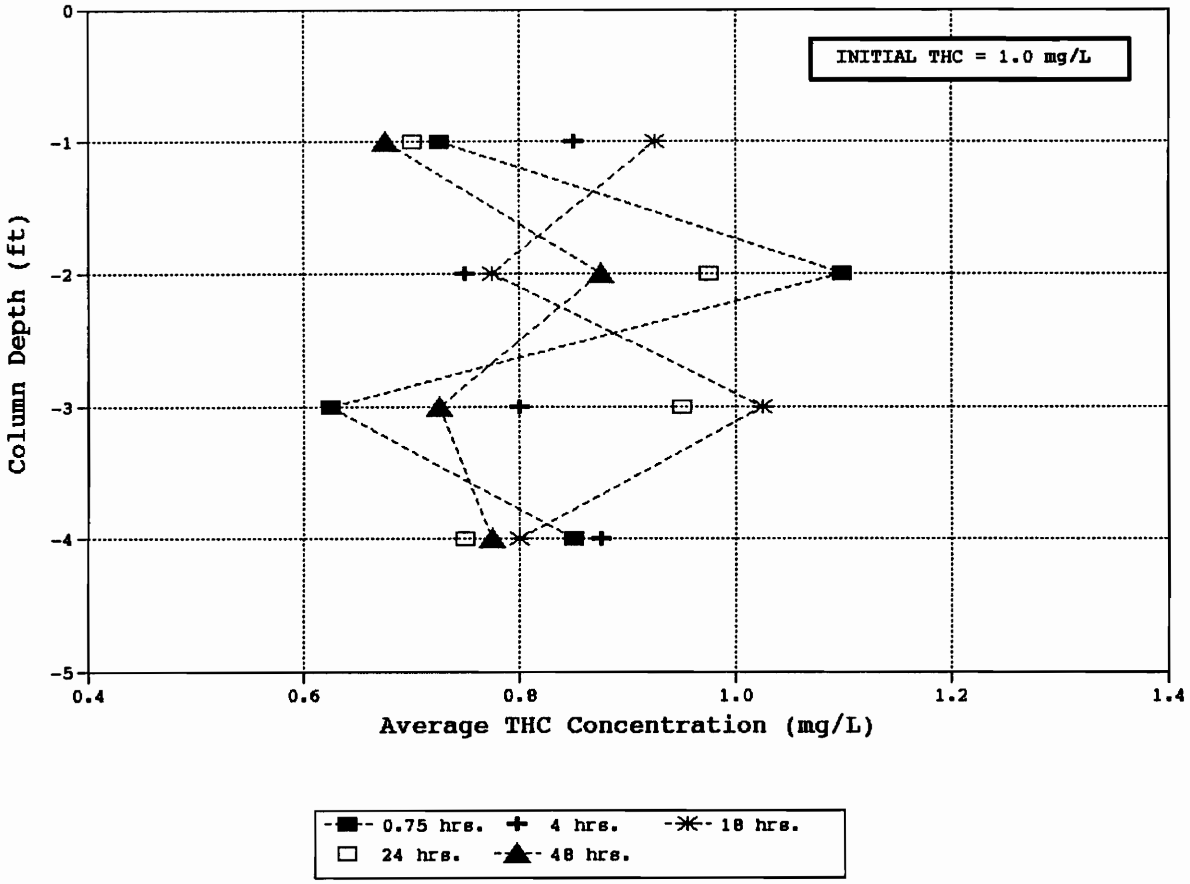

Figure 13. Storm #2: Average THC concentration profiles for columns #1 - 4.

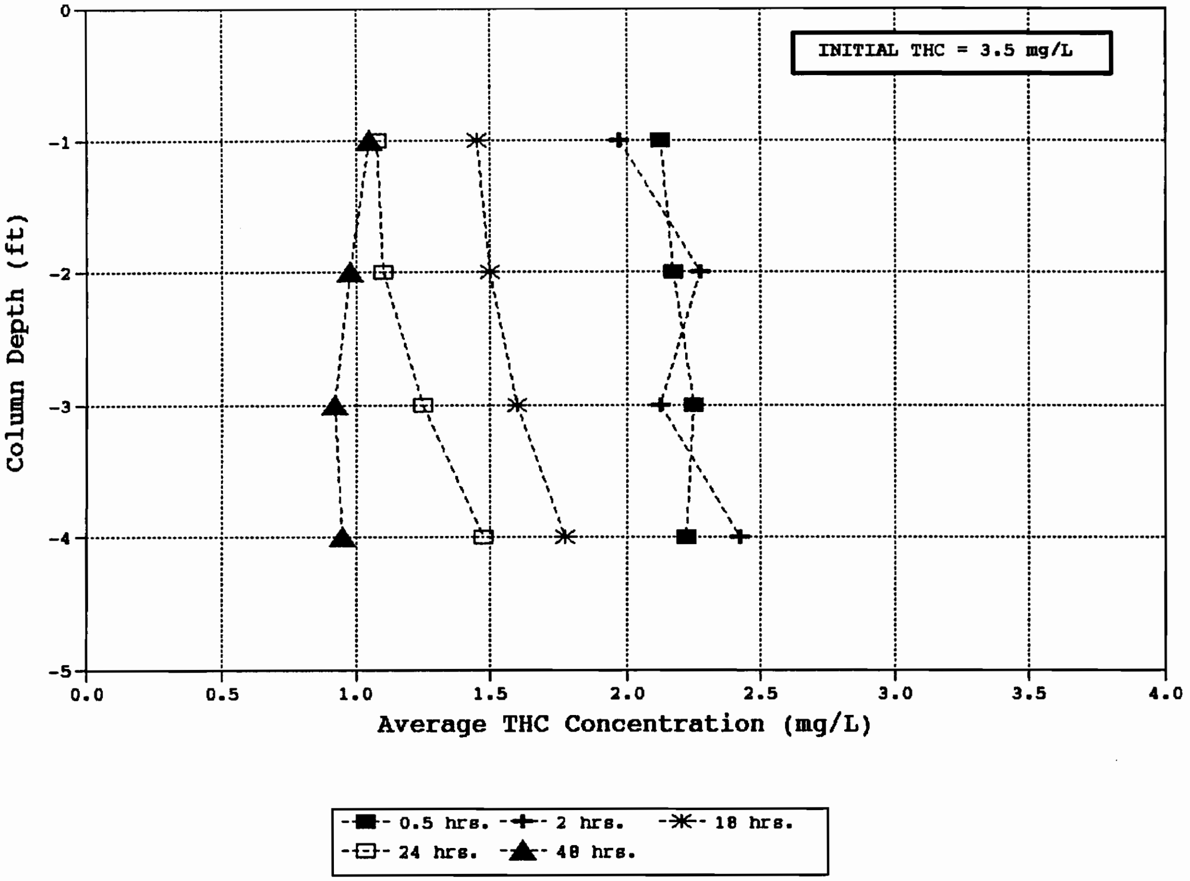

Figure 14. Storm #3: Average THC concentration profiles for columns #1 - 4.

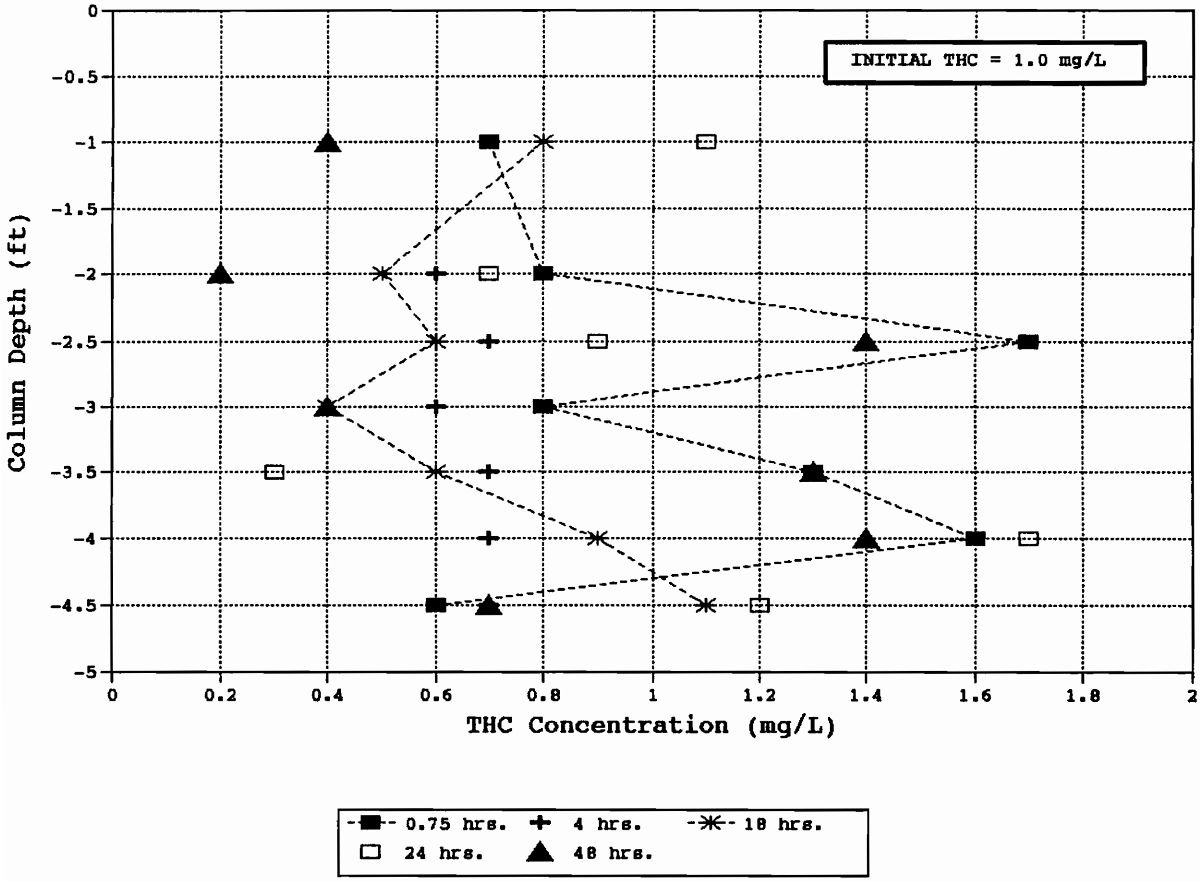

Figure 15. Storm #2: THC Concentration profiles for column #4 only.

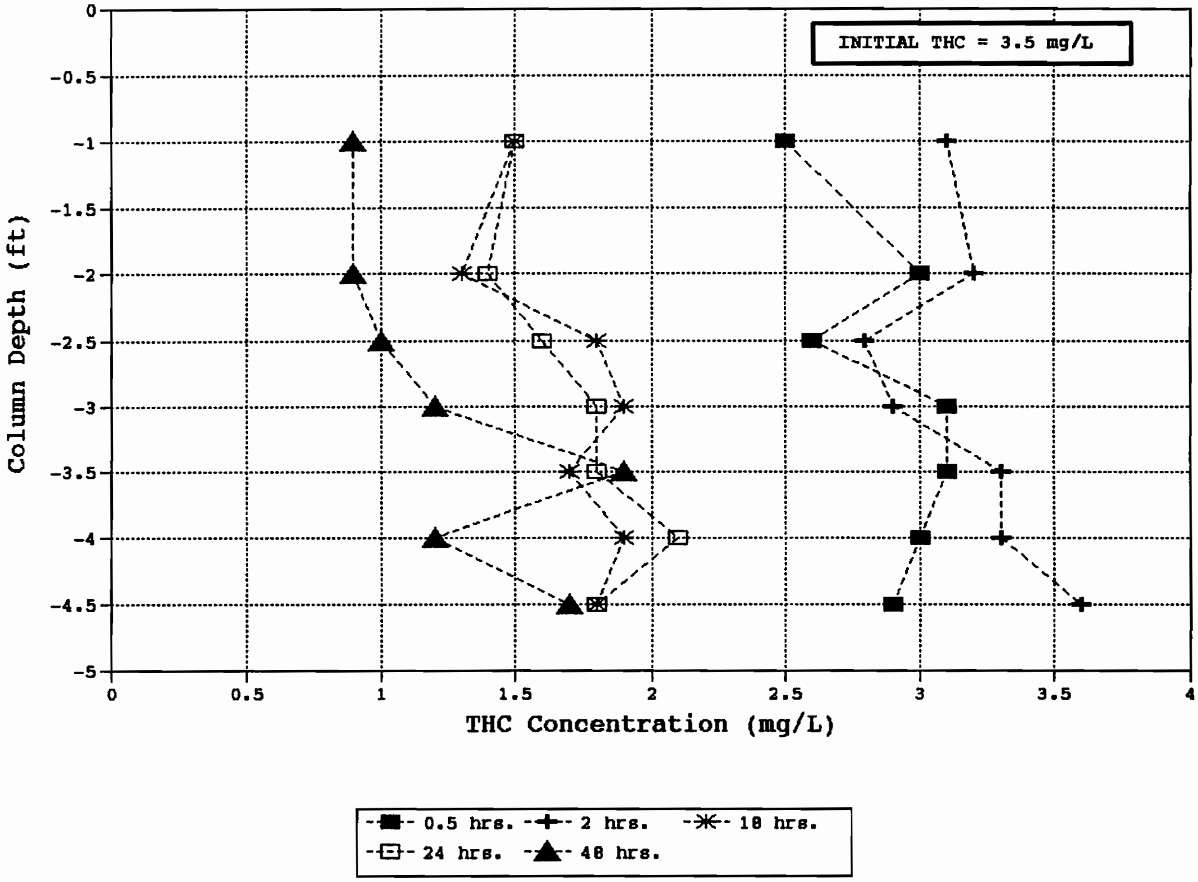

Figure 16. Storm #3: THC Concentration profiles for column #4 only.

Percent THC Removals Achieved

Figures 17, 18, and 19 show the average THC percent removal obtained during the column studies for the three storm events. Figures 20 and 21 show Storms #2 and 3 THC percent removal profiles for column #4 only. Again, only three dashed lines were placed on Figure 20 to help guide the viewer's eye.

A 77.8% average THC removal at the -2 foot depth was achieved over 48 hours of settling with the Storm #1 samples. In the Storm #2 samples, a 32.5% average THC removal at the -1 foot depth was achieved over 48 hours of settling. In the Storm #3 runoff samples, a 73.6% average THC removal at the -3 foot depth was achieved over 48 hours of settling. Areas on the Storm #1 and 2 profiles (Figures 17 and 18) represented by "negative removal" values may indicate regions of concentration (agglomeration) of hydrocarbons, and will be described in the Discussion chapter.

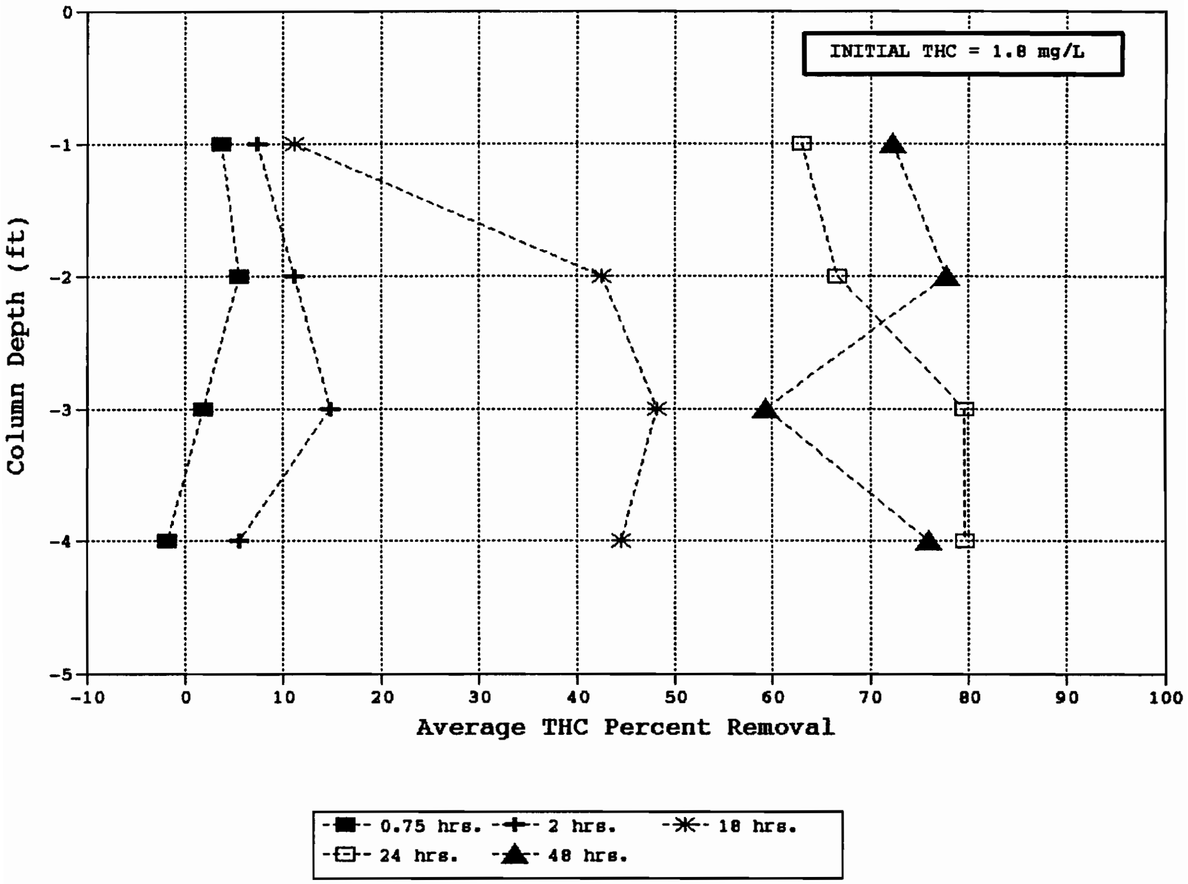

Figure 17. Storm #1: Average THC percent removal profiles for columns #1 - 3.

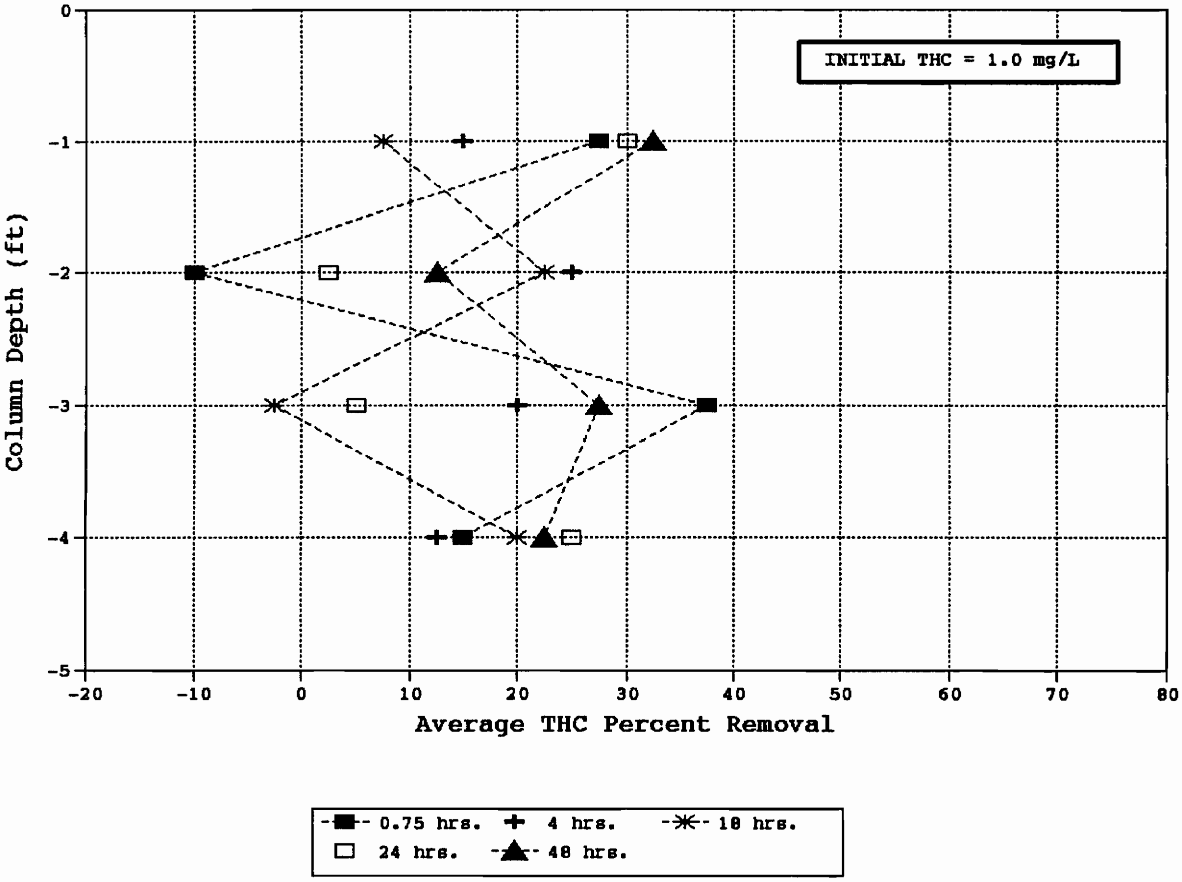

Figure 18. Storm #2: Average THC percent removal profiles for columns #1 - 4.

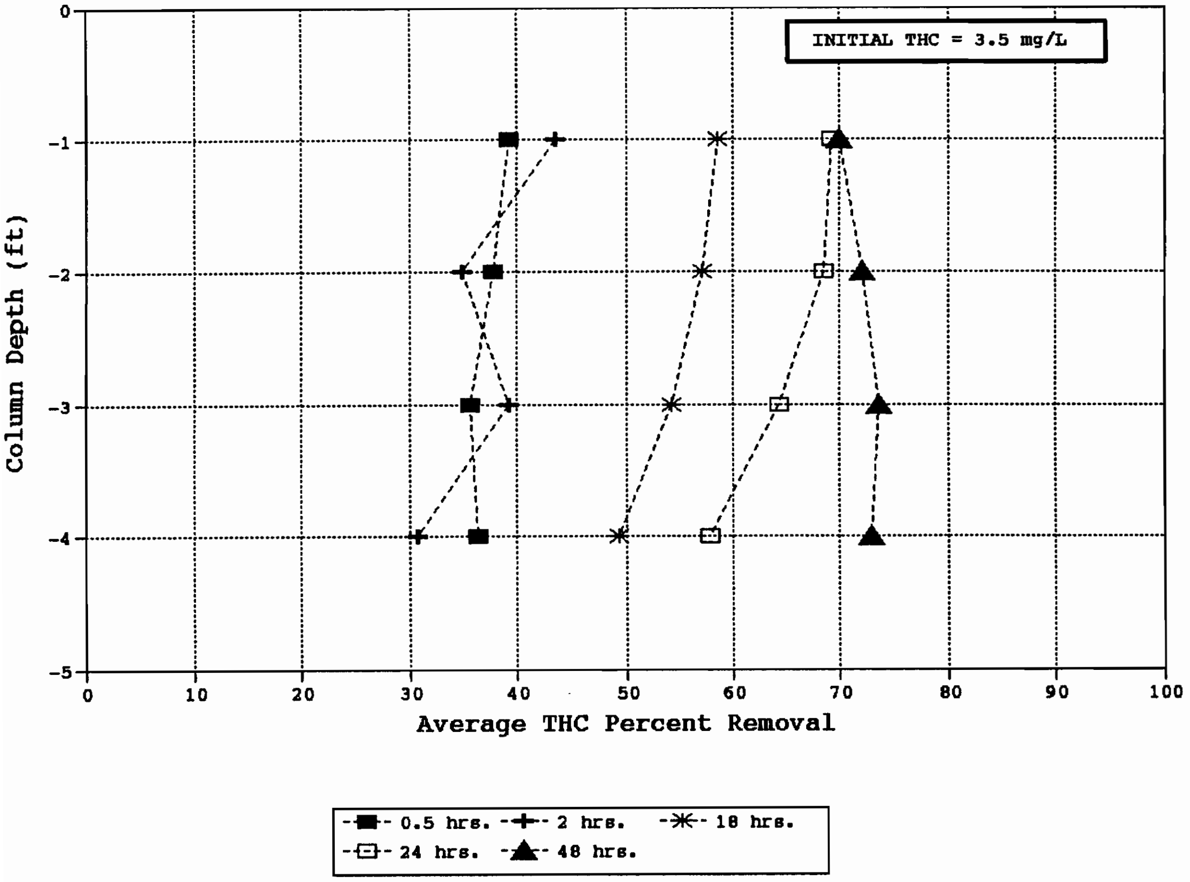

Figure 19. Storm #3: Average THC percent removal profiles for columns #1 - 4.

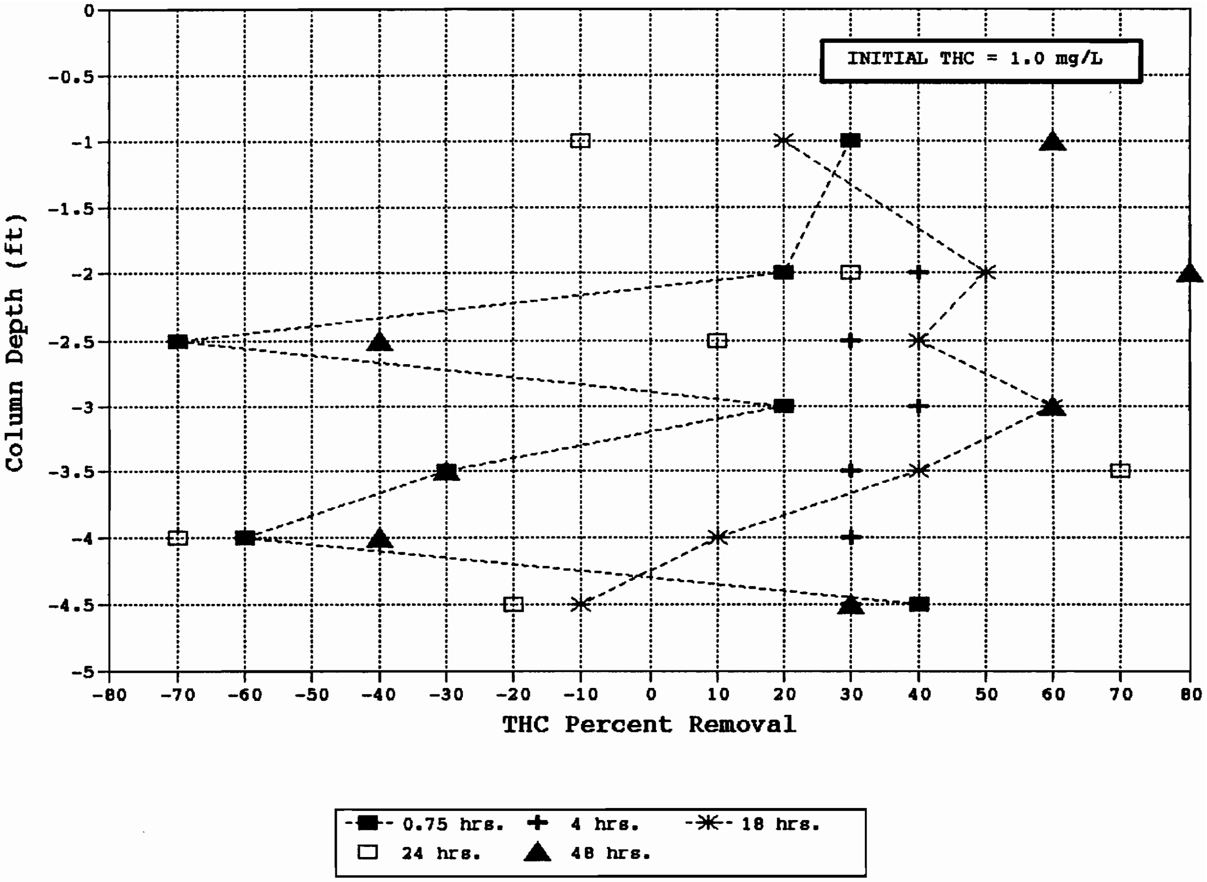

Figure 20. Storm #2: THC percent removal profiles for column #4 only.

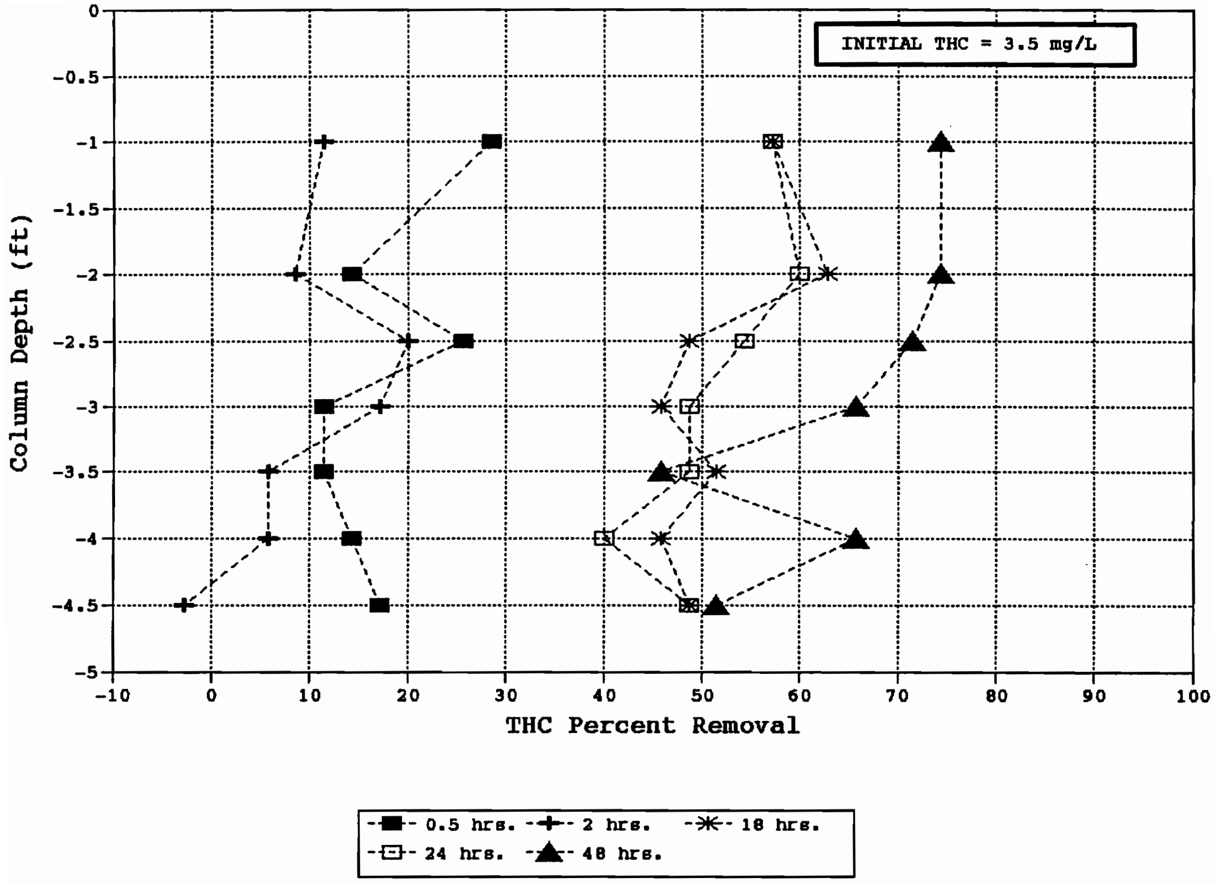

Figure 21. Storm #3: THC percent removal profiles for column #4 only.

Range of Removals Achieved

Figures 22, 23, and 24 display the percent THC removal ranges achieved for the three storm events sampled. The maximum and minimum THC removal percentages are represented by the tops and bottoms, respectively, of the vertical bars on the graphs. These values are the maximum and minimum removal percentages that occurred at each of the four column depths across the three or four columns. Again, negative percent removal values on the y-axes of Figures 22 and 23 indicate potential areas of oil and grease accumulation.

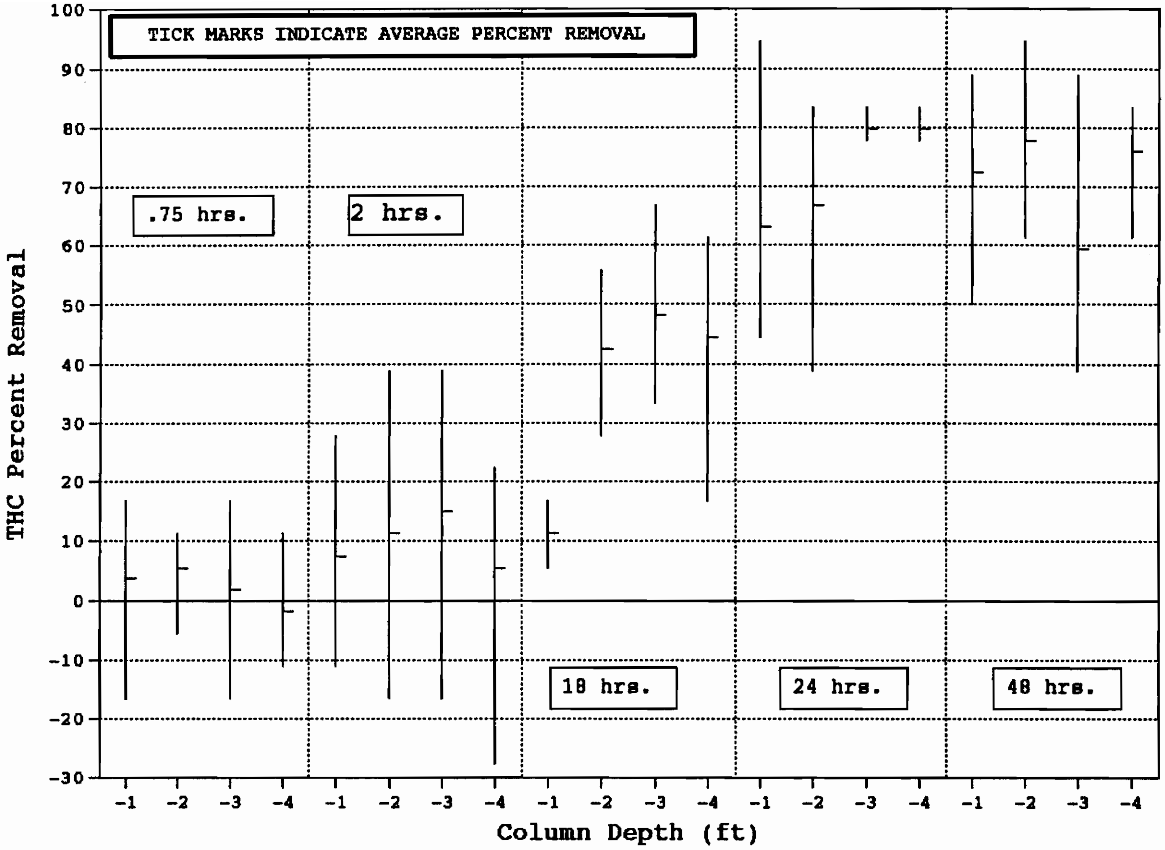

Figure 22. Storm #1: Percent THC removal ranges for columns #1 - 3.

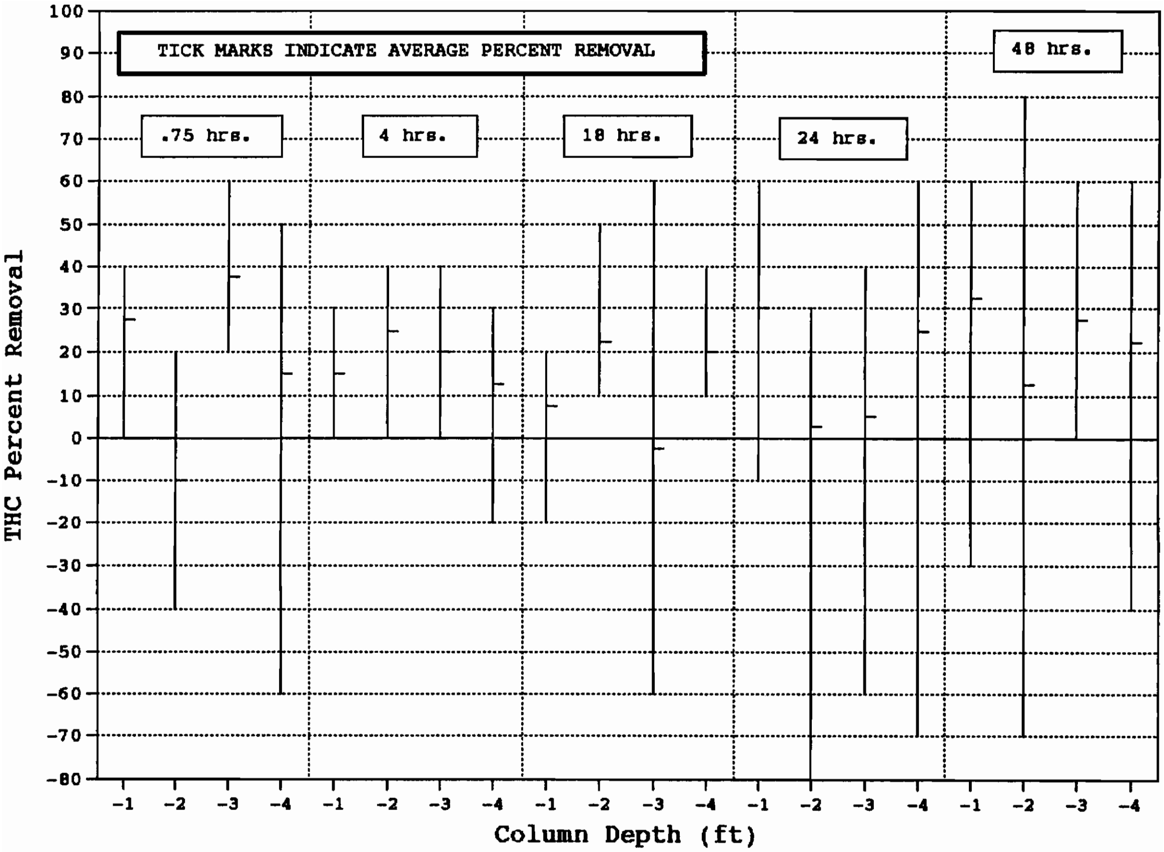

Figure 23. Storm #2: Percent THC removal ranges for columns #1 - 4.

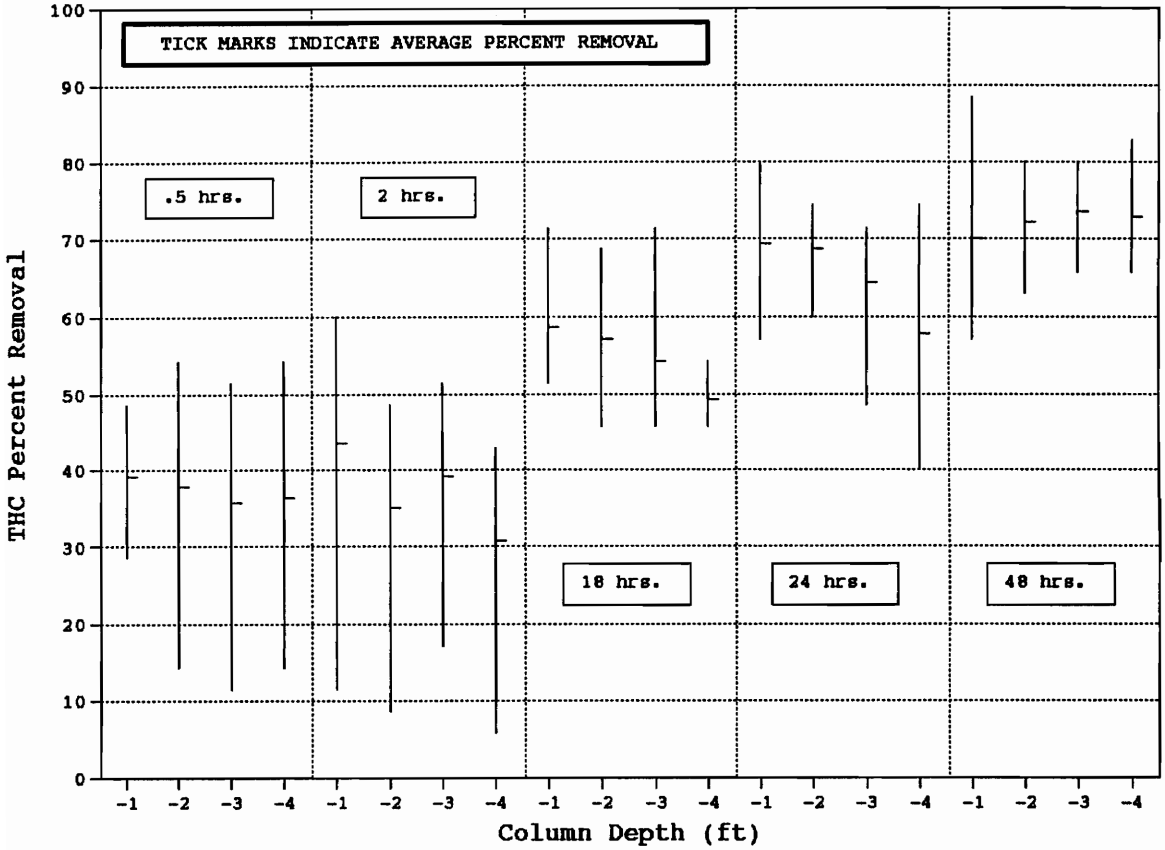

Figure 24. Storm #3: Percent THC removal ranges for columns #1 - 4.

Column Observational Data

During the column studies for the three storms sampled, visual assessments were made of the runoff samples in the columns. Initially, the water in the columns was turbid from being poured to completely mix the sample. After quiescence was attained, close observation revealed a suspension of extremely fine particulates in the water columns. Over the 48-hour study period, settleable particulates formed a fine, thin film at the bottom of the columns for all three storms. For Storm #3, the quantity of suspended solids was such that some accumulation of the particles was observed on the column walls. This was visible over the 5-foot column depth and may have occurred because of charge effects of the column Plexiglas® material on the particulates in the water. Additionally, inspection of the water column surfaces revealed that, for all three storms sampled, some had a fine "rainbow-like" sheen characteristic of a surface accumulation of oil and grease. This surface film did not completely cover the water surfaces in all the columns, and sometimes varied in visual "intensity" during the 48-hour tests, based on interactions that occurred between hydrocarbons and suspended solids.

Oil and Grease Separator Studies

One element of the Metropolitan Washington Council of Governments (MWCOG) hydrocarbon study was the long-term characterization of constituents in oil and grease separators. Nineteen existing oil and grease (single- and dual-chambered) separators in Washington, D.C., and Montgomery County, Maryland, were sampled by OWML staff for water and sediments. Total suspended solids, total organic carbon, and total hydrocarbons characterizations from the water sample analyses are included in Appendix D. Total hydrocarbon analyses were performed on a Horiba oil content analyzer. The results of this study have been included with this thesis to illustrate typical concentrations of TSS, TOC and THC seen in oil and grease separators.

CHAPTER V. DISCUSSION

Hydrocarbon Concentrations

Appearance of Profiles

One of the most significant features of the average THC concentrations for Storms #1 and 3 was the slight curvature of the profiles. Higher average THC concentrations were generally seen in the upper and lower depths of the columns, which gave the profiles their curved shape. Also prevalent was the apparent randomness of the profiles for Storm #2.

Effects of Storm Characteristics on Settling

Recalling storm properties (Table 9 in Results), it was possible that the rainfall amount and intensity influenced the settling aspects and/or concentrations of oil and grease in the runoff samples collected. The relatively lower rainfall and intensity of Storms #1 and 3 produced runoff samples with higher THC concentrations, and therefore, more resolved concentration profiles. The much higher rainfall, intensity, and lower antecedent dry period associated with Storm #2 produced a runoff sample with a lower THC concentration, and therefore, less-resolved concentration profiles. Although reliability of the oil analyzer at lower concentrations was confirmed (as discussed in the Methods and Materials chapter) it still is possible that the THC concentration of this storm (1.0 mg/L) may have been susceptible to instrument "noise", making it difficult to successfully conduct column studies. Also, due to the great intensity of this storm, most oil and grease on the pavement surface probably washed away early in the rain event.

The number of days of antecedent dry weather may also have had an impact on the storm samples and column studies. The higher number of dry-weather days (6 and 10) were associated with the well-resolved profiles of Storms #1 and 3, respectively, while only 3 days of dry weather preceded Storm #2. These observations may be discounted by the fact that Stenstrom *et al.* (1982) found no correlation of oil and grease concentrations in runoff with days between storms or total storm rainfall. Additionally, ANOVA tests conducted by Stenstrom *et al.* determined that time since storm beginning was a contributor to variability of oil and grease concentrations. Therefore, the time at which samples were collected during the storms may have been a factor in the settling behavior of oil and grease. It should be noted, however, that approximately 71% of the 2.5-square-mile (1626-acre) Richmond Watershed studied by Stenstrom *et al.* (1982) was identified as single-family residential land use. This represented a much larger basin area and more diverse land usage as compared to the 23-acre study site of concern in this thesis.

Column #4 Profiles for Storms #2 and 3

The Column #4 THC concentration profiles for Storm #2 exhibited as much variability as the average concentration profiles for all four columns. The 4-hour profile exhibited the most uniform concentration with depth for the Storm #2 study. The Storm #3 THC concentration profiles for Column #4 are comparable to those of the average profiles for all four columns. The 2-hour concentration at -4.5 feet exceeded the storm THC concentration of 3.5 mg/L. This is probably evidence that rapidly-settling sediments carried enough oil and grease to accumulate in this region in concentrations greater than 3.5 mg/L. Further discussion on these graphs is offered in the next section.

Percent THC Removals Achieved

Time Lag Between Profiles

The average THC percent removal profiles were simply "mirror images" of the average THC concentration profiles. In analyzing the data, the focus is on the actual percentage of the storm THC concentration that has been removed. On the Storms #1 and 3 removal graphs, only low removal percentages were seen for the early samples (.75 and .5 hours) which agreed with the observations of Stenstrom *et al*. (1984) during their 30-minute study period. A time lag preceding an appreciable amount of THC removal was seen between the 2-hour and 18-hour sample profiles, a phenomenon that was also recorded by Whipple and Hunter (1981) during hydrocarbon settling studies. It is hypothesized that during this time the oil and grease was sorbing to suspended matter, which acted as the vehicle of sedimentation. In this same time period, approximately 50% THC removal occurred. Whipple and Hunter (1981) reported that most settling took place during the first 16 hours; Storms #1 and 3 column studies were also warranted by this observation.

Negative Percent "Removals"

The areas on the Storms #1 and 2 graphs represented by negative removal percentages indicated that the THC concentration at that point in time was greater than the storm THC concentration. Therefore, an average accumulation (about -2%, or an average concentration slightly greater than 1.8 mg/L) of oil and grease occurred at the -4 foot column depth at .75 hours of settling for Storm #1. As earlier discussed, this may have been evidence of rapid settling of suspended material carrying enough oil and grease to the lower column depths to exceed the storm THC concentration detected. Similarly, hydrocarbon accumulations occurred at -2 feet at .75 hours (-10%), and at -3 feet at 18 hours (-2.5%) during the Storm #2 column test. Much more variability in the THC removal percentages was seen for Storm #2, but the values still seem to indicate that agglomeration was a factor in slight removal of oil and grease.

Storm #1: General Discussion

The best THC removal was consistently at the -2 and -3 foot depth region for the first 18 hours of the test. This could indicate that during this period, mechanisms other than sedimentation alone influenced oil and grease removal. Some amounts of oil and grease may have floated with the aid of small bubbles entrained when the runoff samples were poured into the columns. Also, it appears that other fractions of oil and grease settled rapidly (below the -3 foot mark) after the water column became quiescent. These movements therefore accounted for optimum removal taking place at mid-column. At 24 hours, the average THC removal peaked at about 80% at the -3 and -4 foot depths. The 48-hour removal profile indicates what may be a skew point at -3 feet. One of the samples analyzed at this depth and time (#13C48) satisfied the allowable range of instrument repeatability, although at the maximum difference of 0.6 mg/L (refer to Appendix F). Also, the THC concentration detected in sample #12C48 (1.1 mg/L) seemed slightly elevated, but no duplicate sample was analyzed to support or refute this theory. Therefore, inaccurate analysis of one or both of these samples may have contributed to the skew point on the 48-hour profile.

Storm #2: General Discussion

Due to irregularity of the percent removal data, it was difficult to draw firm conclusions on these results. At .75

hours, the profile "oscillated" between about 30% average THC removal and -10% average THC removal (i.e., 10% average THC accumulation). The low concentration of hydrocarbons present may have been highly influenced by interactions with suspended materials, thereby producing inconsistent profiles such as this one. Some fractions of oil and grease that were accumulated at .75 hours and -2 feet may have risen to the -1 foot level during the next 3 hours. This would explain the average 25% removal suddenly achieved at -2 feet, and the decreased removal (about 15%) at -1 foot at the 4-hour mark. A time lag in THC removal between the 4-hour and 18-hour profiles is not discernable as on the Storms #1 and 3 graphs.

Near the end of the test, the 24- and 48-hour profiles indicate that the most hydrocarbon-free water is roughly at the top and bottom regions of the columns. This is the opposite of what occurred with the Storms #1 and 3 studies, where optimum THC removal happened at about mid-column. The lower THC concentration associated with Storm #2 samples seemed to have erratic effects on the settling and/or floating patterns of the oil and grease. This was also exemplified by the inconsistent THC removal profiles of Column #4. Even at the intermediate depths (-2.5, -3.5, and -4.5 feet) the removal data oscillated such that it was difficult to identify trends in floating or settling.

Storm #3: General Discussion

A noticeable aspect of these profiles is the THC removal (about 30%) that occurred almost immediately. This may be due to the THC concentration being almost twice that of the THC concentration for Storm #1. A large fraction of oil and grease immediately settled and/or floated after quiescence was attained. One limitation of the study was that surface (0 to -1 foot depth) and extreme bottom (-4.5 to -5 foot depth) samples were not obtained since the initial assumption was that sedimentation was the sole removal mechanism. After the time lag (between 2 and 18 hours), optimum removal is consistently at the upper- to mid-column regions out to 48 hours. As with the Storm #1 samples, this may have been accomplished by the combination of some oil and grease fractions settling below -3 feet, and other fractions floating above the -2 foot mark.

These events further indicate that the properties of oil and grease within the water column were non-uniform. Throughout the water column, the oil and grease seemed to reorganize into sub-groups having similar properties such as solubility and density. Presence of suspended material was an essential element to which the oil and grease preferentially sorbed instead of solubilizing into water, as previously discussed in the Methods and Materials chapter. Therefore, the denser hydrocarbon fractions settled down while the less dense fractions may have migrated up the water column under quiescent conditions.

The Column #4 THC percent removal profiles demonstrated similar trends (time lag and profile curvature) to those seen on the average removal profiles for all four columns. One noticeable feature on the Column #4 graph was the convergence of the 18-, 24-, and 48-hour profiles at the -3.5 foot depth. This seems to be a region where oil and grease had concentrated, and where sub-groups of hydrocarbons subsequently floated and settled such that optimum removal was achieved in the middle section of the column.

Range of Removals Achieved

The percent THC removal range graphs reinforced the fact that each of the columns acted as its own THC removal experiment within each of the three independent studies. The wide ranges of maximum and minimum THC percent removal demonstrated the variability of movement of oil and grease in the columns.

The removal ranges for Storm #1 showed accumulations to almost 30% occurring for the first 2 hours. After the time lag between 2 and 18 hours, the removal ranges shifted up on the graph. The average percent removals showed a steady increase after 18 hours, and seemed to level out at the 24- and 48-hour marks.

Nothing surpassed the variability seen in the removal ranges for Storm #2. Accumulations as much as 80% occurred throughout the entire 48-hour test period. As expected, no trend was readily seen in the average percent removal marks.

The Storm #3 ranges indicated early THC removal in substantial amounts as on the average percent removal profiles, however, no accumulations were documented in this study. The time lag before an escalation in additional removal was also prevalent on the graph, and a general upward trend in average percent removal was apparent. The 18- and 24-hour ranges demonstrated that optimum average removal was at the higher column depths. At 48 hours, a leveling-off of the average percent removals occurred, and peak removal emerged at mid-column.

CHAPTER VI. CONCLUSIONS

After conducting column studies to determine hydrocarbon removal efficiencies on urban runoff samples from three storm events, the following conclusions seem warranted:

1. Sedimentation may not be the only mechanism involved in removal of hydrocarbons from urban stormwater runoff. Movements of oil and grease in the water column did not appear to be unidirectional. Some hydrocarbon fractions sorbed to particulate matter and settled, while other fractions agglomerated into globules which floated. This was observed for two of the three storms sampled in which the -2 and -3 foot column depths seemed to be a region where oil and grease reorganized into mobile sub-groups.

2. Conventionally-designed stormwater detention basins may not successfully function for the removal of hydrocarbons from stormwater runoff. According to the major results of this study, hydrocarbons are "removed" to the upper and lower depths of the water column under quiescent conditions, leaving the most hydrocarbon-free water at mid-column. This implies that all hydrocarbons are not settled and removed by manual cleaning or sediment transport; some fraction of oil and grease remains in the water column and may eventually affect aquatic life if the basin effluent flows into a stream or river.

3. This study confirmed that although runoff in each of the columns behaved independently, increasing THC removal with time was observed over 48 hours of quiescent settling for two of the three storms sampled.

4. Highly-resolved average THC concentration and percent removal profiles resulted from two storms that were characterized as low-rainfall, low-intensity, and higher THC events. Conversely, less-resolved average THC concentration and percent removal profiles resulted for the third storm, which was characterized as a high-rainfall, high-intensity, lower THC event. This low THC concentration was highly susceptible to fluctuations during the course of 48 hours of quiescent settling. The results were difficult, if not impossible to interpret, and no consistent trends in THC removal were identified.

5. This study found that the majority of THC removal occurred within the first 18 hours. This was observed for two of the storms sampled. During this time period, hydrocarbons in the runoff seemed to be sorbing to suspended particulate matter, such that a sharp increase in THC removal was observed at 18 hours. Only 20 to 30% additional THC removal occurred during the following 30 hours of quiescent settling.

CHAPTER VII. RECOMMENDATIONS

Based on the results of the research presented in this thesis, recommendations for related future experimentation are as follows:

1. Along with quantifying total hydrocarbons, total suspended solids may also be measured in all column samples. This is absolutely necessary if the partitioning of hydrocarbons between the soluble ("dissolved") and particulate-bound phases during separation is to be evaluated.

2. Surface grab samples and column bottom samples may be collected over the study period. This would facilitate quantification of hydrocarbons in the upper and lower levels of the water column, where floatable globules and settleable agglomerates of oil and grease may be detected, respectively.

3. To further aid in "capturing" and quantification of floating hydrocarbons, an inverted, closed funnel-type apparatus may be positioned over a sample port in the column. The apparatus should not span the entire column width such that settling oil and grease is obstructed. A suitable space between the apparatus and column wall would serve a dual purpose: to allow continual settling of hydrocarbons from above, while minimizing "loss" of floating hydrocarbons through this gap. A column retro-fitted with this device could be used solely to monitor floating hydrocarbons at

varying depths with time.

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APPENDIX A

HYDROCARBON SEDIMENTATION DATA

Table A-1. Storm #1: Settling Column #1 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
11A0	7/21/92	0.75	11.6	1.6	-1	11.1
11B0	7/21/92	0.75	23.4	1.6	-2	11.1
11C0	7/21/92	0.75	35.3	1.5	-3	16.7
11D0	7/21/92	0.75	47.1	2.0	-4	-11.1
11A2	7/21/92	2	10.9	1.7	-1	5.6
11B2	7/21/92	2	22.7	1.6	-2	11.1
11C2	7/21/92	2	34.5	1.1	-3	38.9
11D2	7/21/92	2	46.4	2.3	-4	-27.8
11A18	7/22/92	18	9.8	1.7	-1	5.6
11B18	7/22/92	18	21.6	1.3	-2	27.8
11C18	7/22/92	18	33.4	1.2	-3	33.3
11D18	7/22/92	18	45.3	1.5	-4	16.7
11A24	7/22/92	24	9.0	0.9	-1	50.0
11B24	7/22/92	24	20.8	0.4	-2	77.8
11C24	7/22/92	24	32.6	0.4	-3	77.8
11D24	7/22/92	24	44.4	0.4	-4	77.8
11A48	7/23/92	48	8.2	0.9	-1	50.0
11B48	7/23/92	48	20.0	0.7	-2	61.1
11C48	7/23/92	48	31.8	0.2	-3	88.9
11D48	7/23/92	48	43.6	0.3	-4	83.3

Table A-2. Storm #1: Settling Column #2 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
12A0	7/21/92	0.75	11.7	2.1	-1	-16.7
12B0	7/21/92	0.75	23.6	1.9	-2	-5.6
12C0	7/21/92	0.75	35.3	2.1	-3	-16.7
12D0	7/21/92	0.75	47.1	1.9	-4	-5.6
12A2	7/21/92	2	10.9	2.0	-1	-11.1
12B2	7/21/92	2	22.7	2.1	-2	-16.7
12C2	7/21/92	2	34.5	2.1	-3	-16.7
12D2	7/21/92	2	46.3	1.4	-4	22.2
12A18	7/22/92	18	10.1	1.6	-1	11.1
12B18	7/22/92	18	22.0	1.0	-2	44.4
12C18	7/22/92	18	33.6	1.0	-3	44.4
12D18	7/22/92	18	45.3	0.8	-4	55.6
12A24	7/22/92	24	9.1	0.1	-1	94.4
12B24	7/22/92	24	20.9	1.1	-2	38.9
12C24	7/22/92	24	32.8	0.4	-3	77.8
12D24	7/22/92	24	44.5	0.3	-4	83.3
12A48	7/23/92	48	8.3	0.2	-1	88.9
12B48	7/23/92	48	20.0	0.4	-2	77.8
12C48	7/23/92	48	31.8	1.1	-3	38.9
12D48	7/23/92	48	43.5	0.7	-4	61.1

Table A-3. Storm #1: Settling Column #3 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
13A0	7/21/92	0.75	12.6	1.5	-1	16.7
13B0	7/21/92	0.75	23.4	1.6	-2	11.1
13C0	7/21/92	0.75	35.2	1.7	-3	5.6
13D0	7/21/92	0.75	47.0	1.6	-4	11.1
13A2	7/21/92	2	11.8	1.3	-1	27.8
13B2	7/21/92	2	22.6	1.1	-2	38.9
13C2	7/21/92	2	34.4	1.4	-3	22.2
13D2	7/21/92	2	46.1	1.4	-4	22.2
13A18	7/22/92	18	10.8	1.5	-1	16.7
13B18	7/22/92	18	21.6	0.8	-2	55.6
13C18	7/22/92	18	33.4	0.6	-3	66.7
13D18	7/22/92	18	45.2	0.7	-4	61.1
13A24	7/22/92	24	9.9	1.0	-1	44.4
13B24	7/22/92	24	20.8	0.3	-2	83.3
13C24	7/22/92	24	32.5	0.3	-3	83.3
13D24	7/22/92	24	44.3	0.4	-4	77.8
13A48	7/23/92	48	9.0	0.4	-1	77.8
13B48	7/23/92	48	19.8	0.1	-2	94.4
13C48	7/23/92	48	31.4	0.9	-3	50.0
13D48	7/23/92	48	43.2	0.3	-4	83.3

Table A-4. Storm #1: Average Hydrocarbon Removal for Columns #1 - 3.

SETTLING TIME (hr)	AVG. TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	AVERAGE PERCENT REMOVAL	HIGH REMOVAL PERCENTAGE	LOW REMOVAL PERCENTAGE
0.75	1.7	-1	3.7	16.7	-16.7
0.75	1.7	-2	5.6	11.1	-5.6
0.75	1.8	-3	1.9	16.7	-16.7
0.75	1.8	-4	-1.9	11.1	-11.1
2	1.7	-1	7.4	27.8	-11.1
2	1.6	-2	11.1	38.9	-16.7
2	1.5	-3	14.8	38.9	-16.7
2	1.7	-4	5.6	22.2	-27.8
18	1.6	-1	11.1	16.7	5.6
18	1.0	-2	42.6	55.6	27.8
18	0.9	-3	48.1	66.7	33.3
18	1.0	-4	44.4	61.1	16.7
24	0.7	-1	63.0	94.4	44.4
24	0.6	-2	66.7	83.3	38.9
24	0.4	-3	79.6	83.3	77.8
24	0.4	-4	79.6	83.3	77.8
48	0.5	-1	72.2	88.9	50.0
48	0.4	-2	77.8	94.4	61.1
48	0.7	-3	59.3	88.9	38.9
48	0.4	-4	75.9	83.3	61.1

Table A-5. Storm #1: Sample Temperature and pH Data.

SAMPLE #	DATE SAMPLED	TEMP. (deg. C)	pH
11A0	7/21/92	28	6.3
11A24	7/22/92	27	5.73

Table A-6. Storm #2: Settling Column #1 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
21A0	8/4/92	0.75	11.8	1.0	-1	0.0
21B0	8/4/92	0.75	23.5	1.4	-2	-40.0
21C0	8/4/92	0.75	35.1	0.4	-3	60.0
21D0	8/4/92	0.75	46.8	0.5	-4	50.0
21A4	8/4/92	4	10.6	0.8	-1	20.0
21B4	8/4/92	4	22.3	1.0	-2	0.0
21C4	8/4/92	4	34.0	1.0	-3	0.0
21D4	8/4/92	4	45.8	1.2	-4	-20.0
21A18	8/5/92	18	9.5	1.2	-1	-20.0
21B18	8/5/92	18	21.3	0.9	-2	10.0
21C18	8/5/92	18	33.0	1.2	-3	-20.0
21D18	8/5/92	18	44.8	0.6	-4	40.0
21A24	8/5/92	24	8.5	0.8	-1	20.0
21B24	8/5/92	24	20.2	1.8	-2	-80.0
21C24	8/5/92	24	31.9	1.6	-3	-60.0
21D24	8/5/92	24	43.6	0.4	-4	60.0
21A48	8/6/92	48	7.3	0.6	-1	40.0
21B48	8/6/92	48	19.1	0.7	-2	30.0
21C48	8/6/92	48	30.7	0.8	-3	20.0
21D48	8/6/92	48	42.4	0.4	-4	60.0

Table A-7. Storm #2: Settling Column #2 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
22A0	8/4/92	0.75	11.7	0.6	-1	40.0
22B0	8/4/92	0.75	23.4	0.8	-2	20.0
22C0	8/4/92	0.75	35.1	0.5	-3	50.0
22D0	8/4/92	0.75	46.8	0.6	-4	40.0
22A4	8/4/92	4	10.6	0.9	-1	10.0
22B4	8/4/92	4	22.4	0.7	-2	30.0
22C4	8/4/92	4	34.1	0.9	-3	10.0
22D4	8/4/92	4	45.9	0.8	-4	20.0
22A18	8/5/92	18	9.6	0.8	-1	20.0
22B18	8/5/92	18	21.3	0.8	-2	20.0
22C18	8/5/92	18	33.0	1.6	-3	-60.0
22D18	8/5/92	18	44.8	0.8	-4	20.0
22A24	8/5/92	24	8.4	0.5	-1	50.0
22B24	8/5/92	24	20.3	0.7	-2	30.0
22C24	8/5/92	24	31.8	0.6	-3	40.0
22D24	8/5/92	24	43.4	0.5	-4	50.0
22A48	8/6/92	48	7.1	0.4	-1	60.0
22B48	8/6/92	48	18.8	0.9	-2	10.0
22C48	8/6/92	48	30.4	1.0	-3	0.0
22D48	8/6/92	48	42.1	0.8	-4	20.0

Table A-8. Storm #2: Settling Column #3 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
23A0	8/4/92	0.75	12.6	0.6	-1	40.0
23B0	8/4/92	0.75	23.3	1.4	-2	-40.0
23C0	8/4/92	0.75	35.1	0.8	-3	20.0
23D0	8/4/92	0.75	46.8	0.7	-4	30.0
23A4	8/4/92	4	11.5	1.0	-1	0.0
23B4	8/4/92	4	22.3	0.7	-2	30.0
23C4	8/4/92	4	33.9	0.7	-3	30.0
23D4	8/4/92	4	45.6	0.8	-4	20.0
23A18	8/5/92	18	10.4	0.9	-1	10.0
23B18	8/5/92	18	21.1	0.9	-2	10.0
23C18	8/5/92	18	32.8	0.9	-3	10.0
23D18	8/5/92	18	44.5	0.9	-4	10.0
23A24	8/5/92	24	9.2	0.4	-1	60.0
23B24	8/5/92	24	19.9	0.7	-2	30.0
23C24	8/5/92	24	31.6	0.8	-3	20.0
23D24	8/5/92	24	43.3	0.4	-4	60.0
23A48	8/6/92	48	7.9	1.3	-1	-30.0
23B48	8/6/92	48	18.6	1.7	-2	-70.0
23C48	8/6/92	48	30.3	0.7	-3	30.0
23D48	8/6/92	48	41.9	0.5	-4	50.0

Table A-9. Storm #2: Settling Column #4 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
24A0	8/4/92	0.75	11.6	0.7	-1	30.0
24B0	8/4/92	0.75	23.3	0.8	-2	20.0
24C0	8/4/92	0.75	29.0	1.7	-2.5	-70.0
24D0	8/4/92	0.75	34.7	0.8	-3	20.0
24E0	8/4/92	0.75	40.4	1.3	-3.5	-30.0
24F0	8/4/92	0.75	46.1	1.6	-4	-60.0
24G0	8/4/92	0.75	51.9	0.6	-4.5	40.0
24A4	8/4/92	4	9.5	0.7	-1	30.0
24B4	8/4/92	4	21.3	0.6	-2	40.0
24C4	8/4/92	4	27.0	0.7	-2.5	30.0
24D4	8/4/92	4	32.8	0.6	-3	40.0
24E4	8/4/92	4	38.6	0.7	-3.5	30.0
24F4	8/4/92	4	44.3	0.7	-4	30.0
24G4	8/4/92	4	50.1	0.7	-4.5	30.0
24A18	8/5/92	18	7.6	0.8	-1	20.0
24B18	8/5/92	18	19.4	0.5	-2	50.0
24C18	8/5/92	18	25.1	0.6	-2.5	40.0
24D18	8/5/92	18	30.8	0.4	-3	60.0
24E18	8/5/92	18	36.6	0.6	-3.5	40.0
24F18	8/5/92	18	42.3	0.9	-4	10.0
24G18	8/5/92	18	48.0	1.1	-4.5	-10.0
24A24	8/5/92	24	5.6	1.1	-1	-10.0
24B24	8/5/92	24	17.4	0.7	-2	30.0
24C24	8/5/92	24	23.1	0.9	-2.5	10.0
24D24	8/5/92	24	28.8	0.8	-3	20.0
24E24	8/5/92	24	34.6	0.3	-3.5	70.0
24F24	8/5/92	24	40.3	1.7	-4	-70.0
24G24	8/5/92	24	46.1	1.2	-4.5	-20.0
24A48	8/6/92	48	3.8	0.4	-1	60.0
24B48	8/6/92	48	15.5	0.2	-2	80.0
24C48	8/6/92	48	21.3	1.4	-2.5	-40.0
24D48	8/6/92	48	26.9	0.4	-3	60.0
24E48	8/6/92	48	32.6	1.3	-3.5	-30.0
24F48	8/6/92	48	38.3	1.4	-4	-40.0
24G48	8/6/92	48	44.1	0.7	-4.5	30.0

Table A-10. Storm #2: Average Hydrocarbon Removal for Columns #1 - 4.

SETTLING TIME (hr)	AVG. TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	AVERAGE PERCENT REMOVAL	HIGH REMOVAL PERCENTAGE	LOW REMOVAL PERCENTAGE
0.75	0.7	-1	27.5	40.0	0.0
0.75	1.1	-2	-10.0	20.0	-40.0
0.75	0.6	-3	37.5	60.0	20.0
0.75	0.9	-4	15.0	50.0	-60.0
4	0.9	-1	15.0	30.0	0.0
4	0.8	-2	25.0	40.0	0.0
4	0.8	-3	20.0	40.0	0.0
4	0.9	-4	12.5	30.0	-20.0
18	0.9	-1	7.5	20.0	-20.0
18	0.8	-2	22.5	50.0	10.0
18	1.0	-3	-2.5	60.0	-60.0
18	0.8	-4	20.0	40.0	10.0
24	0.7	-1	30.0	60.0	-10.0
24	1.0	-2	2.5	30.0	-80.0
24	1.0	-3	5.0	40.0	-60.0
24	0.8	-4	25.0	60.0	-70.0
48	0.7	-1	32.5	60.0	-30.0
48	0.9	-2	12.5	80.0	-70.0
48	0.7	-3	27.5	60.0	0.0
48	0.8	-4	22.5	60.0	-40.0

Table A-11. Storm #2: Sample Temperature and pH Data.

SAMPLE #	DATE SAMPLED	TEMP. (deg. C)	pH
21A0	8/4/92	26	6.1
21A18	8/5/92	24	5.4
21A24	8/5/92	25	5.5
21A48	8/6/92	25	5.4
22A18	8/5/92	N/D	5.4
22A24	8/5/92	N/D	5.2
22A48	8/6/92	N/D	5.2
23A18	8/5/92	N/D	5.6
23A24	8/5/92	N/D	5.2
23A48	8/6/92	N/D	5.2
24A18	8/5/92	N/D	5.5
24A24	8/5/92	N/D	5.2
24A48	8/6/92	N/D	5.2

N/D = not determined

Table A-12. Storm #3: Settling Column #1 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
31A0	8/28/92	0.5	11.8	2.4	-1	31.4
31B0	8/28/92	0.5	23.5	1.8	-2	48.6
31C0	8/28/92	0.5	35.2	1.9	-3	45.7
31D0	8/28/92	0.5	46.8	1.6	-4	54.3
31A2	8/28/92	2	10.4	1.6	-1	54.3
31B2	8/28/92	2	22.1	1.9	-2	45.7
31C2	8/28/92	2	33.8	1.7	-3	51.4
31D4	8/28/92	2	45.5	2.1	-4	40.0
31A18	8/29/92	18	9.3	1.6	-1	54.3
31B18	8/29/92	18	20.9	1.7	-2	51.4
31C18	8/29/92	18	32.6	1.7	-3	51.4
31D18	8/29/92	18	44.3	1.8	-4	48.6
31A24	8/29/92	24	8.0	1.0	-1	71.4
31B24	8/29/92	24	19.8	1.0	-2	71.4
31C24	8/29/92	24	31.5	1.0	-3	71.4
31D24	8/29/92	24	43.2	1.5	-4	57.1
31A48	8/30/92	48	6.9	1.5	-1	57.1
31B48	8/30/92	48	18.6	1.3	-2	62.9
31C48	8/30/92	48	30.3	1.0	-3	71.4
31D48	8/30/92	48	42.0	1.0	-4	71.4

Table A-13. Storm #3: Settling Column #2 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
32A0	8/28/92	0.5	11.6	1.8	-1	48.6
32B0	8/28/92	0.5	23.2	1.6	-2	54.3
32C0	8/28/92	0.5	34.9	1.7	-3	51.4
32D0	8/28/92	0.5	46.6	2.1	-4	40.0
32A2	8/28/92	2	10.3	1.4	-1	60.0
32B2	8/28/92	2	22.0	1.8	-2	48.6
32C2	8/28/92	2	33.8	1.8	-3	48.6
32D2	8/28/92	2	45.5	2.0	-4	42.9
32A18	8/29/92	18	9.1	1.7	-1	51.4
32B18	8/29/92	18	20.8	1.9	-2	45.7
32C18	8/29/92	18	32.5	1.8	-3	48.6
32D18	8/29/92	18	44.2	1.8	-4	48.6
32A24	8/29/92	24	7.9	0.7	-1	80.0
32B24	8/29/92	24	19.6	0.9	-2	74.3
32C24	8/29/92	24	31.3	1.1	-3	68.6
32D24	8/29/92	24	43.1	0.9	-4	74.3
32A48	8/30/92	48	6.8	1.4	-1	60.0
32B48	8/30/92	48	18.4	1.0	-2	71.4
32C48	8/30/92	48	30.1	0.7	-3	80.0
32D48	8/30/92	48	41.9	0.6	-4	82.9

Table A-14. Storm #3: Settling Column #3 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
33A0	8/28/92	0.5	12.8	1.8	-1	48.6
33B0	8/28/92	0.5	23.4	2.3	-2	34.3
33C0	8/28/92	0.5	35.1	2.3	-3	34.3
33D0	8/28/92	0.5	46.8	2.2	-4	37.1
33A2	8/28/92	2	11.5	1.8	-1	48.6
33B2	8/28/92	2	22.2	2.2	-2	37.1
33C2	8/28/92	2	33.9	2.1	-3	40.0
33D2	8/28/92	2	45.6	2.3	-4	34.3
33A18	8/29/92	18	10.3	1.0	-1	71.4
33B18	8/29/92	18	21.0	1.1	-2	68.6
33C18	8/29/92	18	32.8	1.0	-3	71.4
33D18	8/29/92	18	44.4	1.6	-4	54.3
33A24	8/29/92	24	9.1	1.1	-1	68.6
33B24	8/29/92	24	19.8	1.1	-2	68.6
33C24	8/29/92	24	31.6	1.1	-3	68.6
33D24	8/29/92	24	43.3	1.4	-4	60.0
33A48	8/30/92	48	7.9	0.4	-1	88.6
33B48	8/30/92	48	18.6	0.7	-2	80.0
33C48	8/30/92	48	30.3	0.8	-3	77.1
33D48	8/30/92	48	42.0	1.0	-4	71.4

Table A-15. Storm #3: Settling Column #4 Data.

SAMPLE #	DATE SAMPLED	SETTLING TIME (hr)	DEPTH BELOW WATER SURFACE (in.)	TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	PERCENT REMOVAL
34A0	8/28/92	0.5	11.5	2.5	-1	28.6
34B0	8/28/92	0.5	23.3	3.0	-2	14.3
34C0	8/28/92	0.5	28.9	2.6	-2.5	25.7
34D0	8/28/92	0.5	34.6	3.1	-3	11.4
34E0	8/28/92	0.5	40.4	3.1	-3.5	11.4
34F0	8/28/92	0.5	46.0	3.0	-4	14.3
34G0	8/28/92	0.5	51.7	2.9	-4.5	17.1
34A2	8/28/92	2	9.4	3.1	-1	11.4
34B2	8/28/92	2	21.1	3.2	-2	8.6
34C2	8/28/92	2	26.8	2.8	-2.5	20.0
34D2	8/28/92	2	32.6	2.9	-3	17.1
34E2	8/28/92	2	38.3	3.3	-3.5	5.7
34F2	8/28/92	2	44.0	3.3	-4	5.7
34G2	8/28/92	2	49.7	3.6	-4.5	-2.9
34A18	8/29/92	18	7.3	1.5	-1	57.1
34B18	8/29/92	18	19.0	1.3	-2	62.9
34C18	8/29/92	18	24.8	1.8	-2.5	48.6
34D18	8/29/92	18	30.4	1.9	-3	45.7
34E18	8/29/92	18	36.2	1.7	-3.5	51.4
34F18	8/29/92	18	41.9	1.9	-4	45.7
34G18	8/29/92	18	47.6	1.8	-4.5	48.6
34A24	8/29/92	24	4.9	1.5	-1	57.1
34B24	8/29/92	24	16.6	1.4	-2	60.0
34C24	8/29/92	24	22.3	1.6	-2.5	54.3
34D24	8/29/92	24	28.0	1.8	-3	48.6
34E24	8/29/92	24	33.8	1.8	-3.5	48.6
34F24	8/29/92	24	39.4	2.1	-4	40.0
34G24	8/29/92	24	45.3	1.8	-4.5	48.6
34A48	8/30/92	48	2.9	0.9	-1	74.3
34B48	8/30/92	48	14.5	0.9	-2	74.3
34C48	8/30/92	48	20.2	1.0	-2.5	71.4
34D48	8/30/92	48	25.9	1.2	-3	65.7
34E48	8/30/92	48	31.6	1.9	-3.5	45.7
34F48	8/30/92	48	37.3	1.2	-4	65.7
34G48	8/30/92	48	42.9	1.7	-4.5	51.4

Table A-16. Storm #3: Average Hydrocarbon Removal for Columns #1 - 4.

SETTLING TIME (hr)	AVG. TOTAL HYDROCARBONS (mg/L)	COLUMN DEPTH (ft)	AVERAGE PERCENT REMOVAL	HIGH REMOVAL PERCENTAGE	LOW REMOVAL PERCENTAGE
0.5	2.1	-1	39.3	48.6	28.6
0.5	2.2	-2	37.9	54.3	14.3
0.5	2.3	-3	35.7	51.4	11.4
0.5	2.2	-4	36.4	54.3	14.3
2	2.0	-1	43.6	60.0	11.4
2	2.3	-2	35.0	48.6	8.6
2	2.1	-3	39.3	51.4	17.1
2	2.4	-4	30.7	42.9	5.7
18	1.5	-1	58.6	71.4	51.4
18	1.5	-2	57.1	68.6	45.7
18	1.6	-3	54.3	71.4	45.7
18	1.8	-4	49.3	54.3	45.7
24	1.1	-1	69.3	80.0	57.1
24	1.1	-2	68.6	74.3	60.0
24	1.3	-3	64.3	71.4	48.6
24	1.5	-4	57.9	74.3	40.0
48	1.1	-1	70.0	88.6	57.1
48	1.0	-2	72.1	80.0	62.9
48	0.9	-3	73.6	80.0	65.7
48	1.0	-4	72.9	82.9	65.7

Table A-17. Storm #3: Sample Temperature and pH Data.

SAMPLE #	DATE SAMPLED	TEMP. (deg. C)	pH
31A0	8/28/92	27	5.24
31A2	8/28/92	26	5.08
31A24	8/29/92	25	N/D
31A48	8/29/92	24	N/D
32A0	8/28/92	N/D	5.26
32A2	8/28/92	N/D	5.32
33A0	8/28/92	N/D	5.48
33A2	8/28/92	N/D	5.41
34A0	8/28/92	N/D	5.41
34A2	8/28/92	N/D	5.34

N/D = not determined

APPENDIX B

METEOROLOGICAL AND RAINFALL DATA RECORDED AT OWML

Table B-1. Storm #1: Meteorological and rainfall data recorded at OWML on 7/21/92.

TIME	BAROMETER (in. Hg)	TEMPA (°F)	TEMPB (°F)	WCHILL (°F)	WSPEED (mph)	GSPEED (mph)	WDIRECT (°)	RAIN (in)
00:00	30.53	79.6	75.1	79.6	0	0	112	0.00
00:30	30.53	79.0	75.0	79.0	0	2	112	0.00
01:00	30.53	77.8	74.9	77.8	0	0	270	0.00
01:30	30.52	77.4	74.8	77.4	0	0	67	0.00
02:00	30.51	76.3	74.7	76.3	0	0	67	0.00
02:30	30.51	75.9	74.9	75.9	0	0	67	0.00
03:00	30.51	75.4	74.5	75.4	0	0	67	0.00
03:30	30.51	74.4	74.4	74.4	0	0	67	0.00
04:00	30.51	74.3	74.4	74.3	0	0	67	0.00
04:30	30.52	74.1	74.2	74.1	0	0	67	0.00
05:00	30.52	74.1	74.2	74.1	0	0	67	0.00
05:30	30.52	76.6	74.1	76.6	0	0	67	0.00
06:00	30.52	80.9	74.0	80.9	0	0	67	0.00
06:30	30.53	86.0	74.4	86.0	0	0	67	0.00
07:00	30.55	88.7	74.5	88.7	0	0	67	0.00
07:30	30.56	90.4	74.9	90.4	0	0	360	0.00
08:00	30.56	91.1	75.4	91.1	0	3	360	0.00
08:30	30.57	93.1	76.3	93.1	0	3	360	0.00
09:00	30.58	95.1	75.7	95.1	0	2	360	0.00
09:30	30.58	96.5	75.6	96.5	0	3	360	0.00
10:00	30.57	97.2	75.7	97.2	0	3	360	0.00
10:30	30.58	97.9	76.0	97.9	0	4	360	0.00
11:00	30.58	99.0	76.1	99.0	0	6	360	0.00
11:30	30.58	99.1	76.1	99.1	0	4	360	0.00
12:00	30.58	97.7	76.4	97.7	0	2	292	0.00
12:30	30.56	96.1	76.3	96.1	0	4	360	0.00
13:00	30.56	95.0	77.5	95.0	2	5	360	0.00
13:30	30.56	96.8	78.3	96.8	1	3	360	0.00
14:00	30.62	83.6	78.6	82.4	7	16	360	0.03
14:30	30.61	74.3	78.6	73.6	3	10	360	0.14
15:00	30.61	79.7	78.4	79.1	3	8	360	0.14
15:30	30.60	83.1	77.8	83.0	1	6	360	0.14
16:00	30.57	83.9	77.7	83.8	2	7	360	0.14
16:30	30.56	84.3	77.8	84.0	3	8	360	0.14
17:00	30.56	83.8	77.7	83.6	2	5	360	0.14
17:30	30.59	82.7	77.9	82.7	0	3	360	0.14
18:00	30.60	82.8	77.3	82.7	2	7	360	0.14
18:30	30.57	80.9	76.6	80.9	1	6	360	0.14
19:00	30.59	82.6	77.0	82.6	1	5	45	0.14
19:30	30.59	80.4	75.5	80.4	0	3	45	0.14
20:00	30.59	79.5	76.1	79.5	0	5	45	0.14

Table B-1, Continued.

TIME	BAROMETER (in. Hg)	TEMPA (°F)	TEMPB (°F)	WCHILL (°F)	WSPEED (mph)	GSPEED (mph)	WDIRECT (°)	RAIN (in)
20:30	30.61	77.6	76.7	77.6	0	0	112	0.14
21:00	30.61	76.7	76.3	76.7	0	0	112	0.14
21:30	30.61	76.4	75.4	76.4	0	0	247	0.14
22:00	30.61	76.2	75.2	76.2	0	3	360	0.14
22:30	30.60	75.7	75.4	75.7	0	3	360	0.14
23:00	30.60	75.0	75.6	75.0	0	0	360	0.14
23:30	30.60	75.0	75.0	75.0	0	0	360	0.14

"TEMPA" = temperature outside OWML
"TEMPB" = temperature inside OWML
"WCHILL" = windchill
"WSPEED" = wind speed
"GSPEED" = gust speed
"WDIRECT" = wind direction
"RAIN" = rainfall amount

Table B-2. Storm #2: Meteorological and rainfall data recorded at OWML on 8/4/92.

TIME	BAROMETER (in. Hg)	TEMPA (°F)	TEMPB (°F)	WCHILL (°F)	WSPEED (mph)	GSPEED (mph)	WDIRECT (°)	RAIN (in)
00:00	30.42	74.5	73.3	74.5	0	0	22	0.00
00:30	30.40	74.0	73.6	74.0	0	2	22	0.00
01:00	30.39	73.0	73.8	73.0	0	1	22	0.00
01:30	30.39	72.6	73.6	72.6	0	0	202	0.00
02:00	30.39	72.0	73.7	72.0	0	0	202	0.00
02:30	30.39	71.2	73.3	71.2	0	0	202	0.00
03:00	30.38	71.1	73.6	71.1	0	0	202	0.00
03:30	30.38	71.2	74.2	71.2	0	0	202	0.00
04:00	30.37	71.3	73.8	71.3	0	0	67	0.00
04:30	30.37	71.5	73.6	71.5	0	0	180	0.00
05:00	30.37	71.2	73.0	71.2	0	0	180	0.00
05:30	30.37	71.4	72.9	71.4	0	0	45	0.00
06:00	30.38	72.2	73.2	72.2	0	3	45	0.00
06:30	30.38	73.4	73.0	73.4	0	4	225	0.00
07:00	30.39	76.7	74.4	76.6	0	5	270	0.00
07:30	30.39	78.0	73.6	78.0	0	3	270	0.00
08:00	30.40	78.0	74.6	78.0	1	3	360	0.00
08:30	30.41	79.2	74.0	79.2	0	0	247	0.00
09:00	30.41	82.1	73.9	82.1	0	2	360	0.00
09:30	30.42	86.0	74.1	86.0	0	0	360	0.00
10:00	30.41	90.7	74.1	90.7	0	2	45	0.00
10:30	30.43	92.6	74.9	92.6	0	3	360	0.00
11:00	30.43	93.8	74.6	93.8	1	4	225	0.00
11:30	30.43	93.4	75.0	93.4	1	3	180	0.00
12:00	30.42	90.9	75.6	90.9	0	3	360	0.00
12:30	30.41	90.2	76.1	90.2	1	5	360	0.00
13:00	30.45	71.6	76.1	71.5	0	17	360	0.51
13:30	30.45	71.5	74.9	71.5	0	2	360	0.76
14:00	30.43	73.1	74.9	73.1	0	1	157	0.80
14:30	30.44	79.6	74.9	79.6	0	3	45	0.80
15:00	30.43	81.3	74.0	81.2	1	5	90	0.80
15:30	30.43	82.6	75.3	82.6	1	6	45	0.80
16:00	30.43	83.4	75.4	83.4	0	3	90	0.80
16:30	30.43	83.3	75.3	83.3	0	2	67	0.80
17:00	30.44	83.2	75.3	82.9	2	9	360	0.80
17:30	30.43	81.7	75.1	81.3	2	10	360	0.80
18:00	30.45	80.2	74.8	80.1	2	7	360	0.80
18:30	30.46	79.1	75.0	78.8	2	7	360	0.80
19:00	30.47	77.3	74.3	77.3	2	5	360	0.80
19:30	30.48	76.2	74.3	76.1	1	5	360	0.80
20:00	30.50	75.5	74.5	75.5	0	4	360	0.80

Table B-2, Continued.

TIME	BAROMETER (in. Hg)	TEMPA (°F)	TEMPB (°F)	WCHILL (°F)	WSPEED (mph)	GSPEED (mph)	WDIRECT (°)	RAIN (in)
20:30	30.51	74.3	73.9	74.3	0	0	360	0.80
21:00	30.52	73.1	73.9	73.1	0	0	360	0.80
21:30	30.51	72.3	73.4	72.3	0	3	360	0.80
22:00	30.51	71.0	73.1	71.0	0	0	45	0.80
22:30	30.51	70.5	73.6	70.5	0	0	45	0.80
23:00	30.52	69.4	73.6	69.4	0	2	360	0.80
23:30	30.52	69.3	73.1	69.3	0	0	360	0.80

"TEMPA" = temperature outside OWML
"TEMPB" = temperature inside OWML
"WCHILL" = windchill
"WSPEED" = wind speed
"GSPEED" = gust speed
"WDIRECT" = wind direction
"RAIN" = rainfall amount

Table B-3. Storm #3: Meteorological and rainfall data recorded at OWML on 8/28/92.

TIME	BAROMETER (in. Hg)	TEMPA (°F)	TEMPB (°F)	WCHILL (°F)	WSPEED (mph)	GSPEED (mph)	WDIRECT (°)	RAIN (in)
00:00	30.36	65.9	77.5	65.9	0	4	225	0.00
00:30	30.40	74.2	79.1	74.1	1	4	45	0.00
01:00	30.38	73.4	79.1	73.4	1	4	67	0.00
01:30	30.38	74.4	79.1	74.4	1	5	90	0.00
02:00	30.38	73.5	79.1	73.3	2	5	22	0.00
02:30	30.38	71.9	79.1	71.9	0	3	67	0.00
03:00	30.37	71.8	79.0	71.8	0	4	112	0.00
03:30	30.37	71.5	79.0	71.5	0	3	157	0.00
04:00	30.36	71.6	78.9	71.6	1	4	45	0.00
04:30	30.35	70.9	78.9	70.9	0	3	67	0.00
05:00	30.34	71.3	78.7	71.3	1	4	45	0.00
05:30	30.34	71.9	78.5	71.8	1	4	90	0.00
06:00	30.34	72.0	77.9	71.9	1	4	67	0.00
06:30	30.34	73.2	78.2	73.1	1	4	45	0.00
07:00	30.34	73.1	78.9	72.8	2	5	45	0.00
07:30	30.34	73.8	79.0	73.6	2	5	90	0.00
08:00	30.34	74.0	79.1	73.8	1	7	67	0.00
08:30	30.35	76.1	79.1	75.7	3	6	45	0.00
09:00	30.34	81.5	79.6	80.9	4	9	45	0.00
09:30	30.34	83.7	80.1	83.2	4	10	45	0.00
10:00	30.34	83.2	80.6	82.6	4	12	67	0.00
10:30	30.33	83.2	80.9	82.5	5	12	45	0.00
11:00	30.32	83.4	81.0	82.6	6	12	67	0.00
11:30	30.29	85.0	81.0	84.5	5	11	67	0.00
12:00	30.29	84.1	81.0	82.8	8	17	45	0.00
12:30	30.29	83.4	81.7	82.0	8	17	45	0.00
13:00	30.27	84.2	82.5	82.9	9	16	45	0.00
13:30	30.25	83.9	82.8	82.2	10	18	67	0.00
14:00	30.23	81.1	82.9	79.3	8	16	67	0.00
14:30	30.21	77.8	82.8	74.4	11	17	67	0.03
15:00	30.20	76.5	82.8	75.8	3	13	90	0.09
15:30	30.19	75.8	81.8	75.5	2	6	67	0.12
16:00	30.19	75.3	81.0	74.1	4	15	202	0.13
16:30	30.20	74.9	80.9	74.1	4	7	225	0.13
17:00	30.21	75.5	80.6	75.1	3	9	225	0.13
17:30	30.22	74.9	80.2	74.9	0	4	225	0.13
18:00	30.24	74.0	80.0	74.0	0	2	225	0.13
18:30	30.25	72.9	79.2	72.9	0	0	225	0.13
19:00	30.26	72.4	79.1	72.4	0	2	247	0.13
19:30	30.28	71.5	79.1	71.5	0	1	270	0.13
20:00	30.29	71.1	79.0	71.1	0	1	292	0.13

Table B-3, Continued.

TIME	BAROMETER (in. Hg)	TEMPA (°F)	TEMPB (°F)	WCHILL (°F)	WSPEED (mph)	GSPEED (mph)	WDIRECT (°)	RAIN (in)
20:30	30.30	71.1	78.9	71.1	0	2	337	0.13
21:00	30.31	71.5	78.9	70.7	2	9	360	0.13
21:30	30.33	71.6	78.8	70.3	5	11	270	0.13
22:00	30.34	69.7	78.4	69.2	3	6	292	0.13
22:30	30.35	68.2	78.0	67.8	2	6	247	0.13
23:00	30.35	67.3	77.7	67.0	2	5	247	0.13
23:30	30.36	66.0	77.5	65.9	0	5	225	0.13

"TEMPA" = temperature outside OWML
"TEMPB" = temperature inside OWML
"WCHILL" = windchill
"WSPEED" = wind speed
"GSPEED" = gust speed
"WDIRECT" = wind direction
"RAIN" = rainfall amount

APPENDIX C

WEATHER DATA FOR STORMS SAMPLED

Table C-1. Weather data for storm events sampled.
Source: National Weather Service, 1992.

	STORM #1 7/21/92	**STORM #2** 8/4/92	**STORM #3** 8/28/92
		RAINFALL	
*	.62 in.(d)	.50 in.(d)	.20 in.(d)
*	2.00 in.(m)	.50 in.(m)	2.48 in.(m)
*	18.80 in.(y)	22.64 in.(y)	24.62 in.(y)
WASHINGTON NATIONAL AIRPORT		TEMPERATURE	
*	96°F max.	85°F max.	85°F max.
*	73°F min.	67°F min.	69°F min.
*	85°F mean	76°F mean	77°F mean
*	+6 dep.	-3 dep.	n/r
		RAINFALL	
*	1.06 in.(d)	.01 in.(d)	.14 in.(d)
*	1.84 in.(m)	.01 in.(m)	1.33 in.(m)
*	19.31 in.(y)	24.71 in.(y)	26.03 in.(y)
DULLES AIRPORT		TEMPERATURE	
*	94°F max.	85°F max.	82°F max.
*	64°F min.	60°F min.	63°F min.
*	79°F mean	73°F mean	73°F mean
*	+3 dep.	-3 dep.	n/r

Notation: (d) = daily rainfall
(m) = monthly rainfall total
(y) = yearly rainfall total
dep. = departure from mean
n/r = not recorded

APPENDIX D

MWCOG OIL AND GREASE SEPARATOR CHARACTERIZATIONS

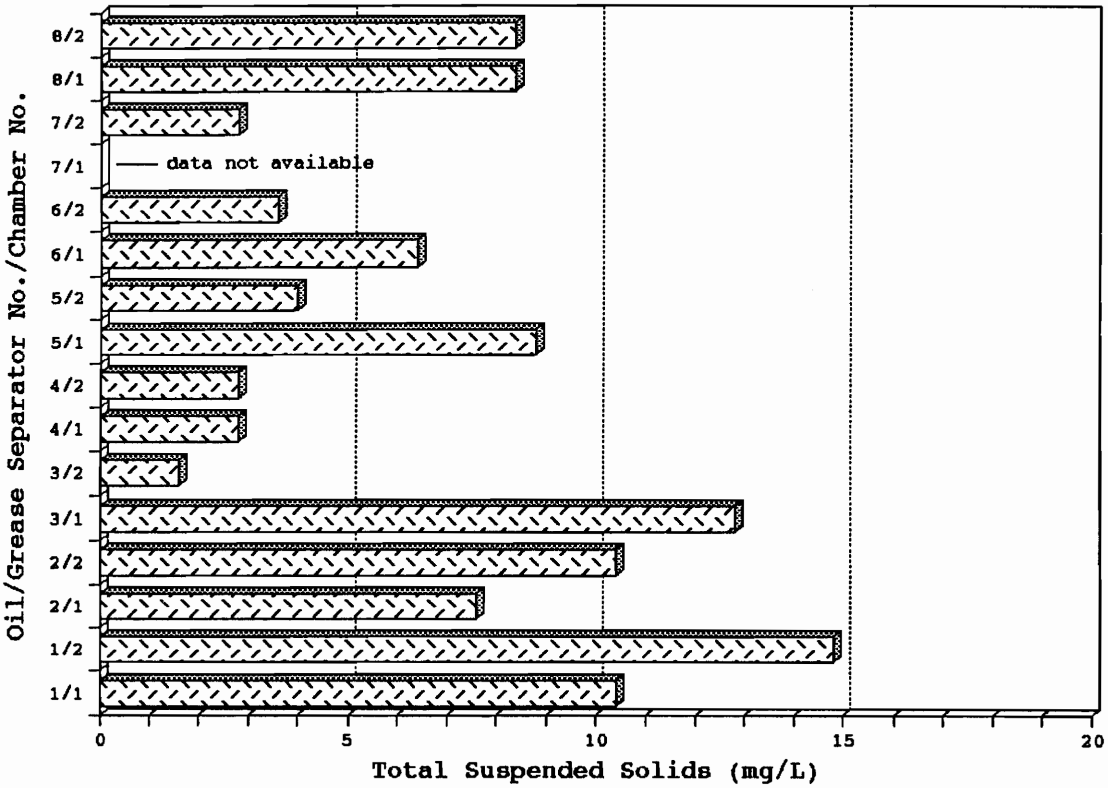

Figure D-1. TSS concentrations in water samples from oil and grease separators #1 - 8.

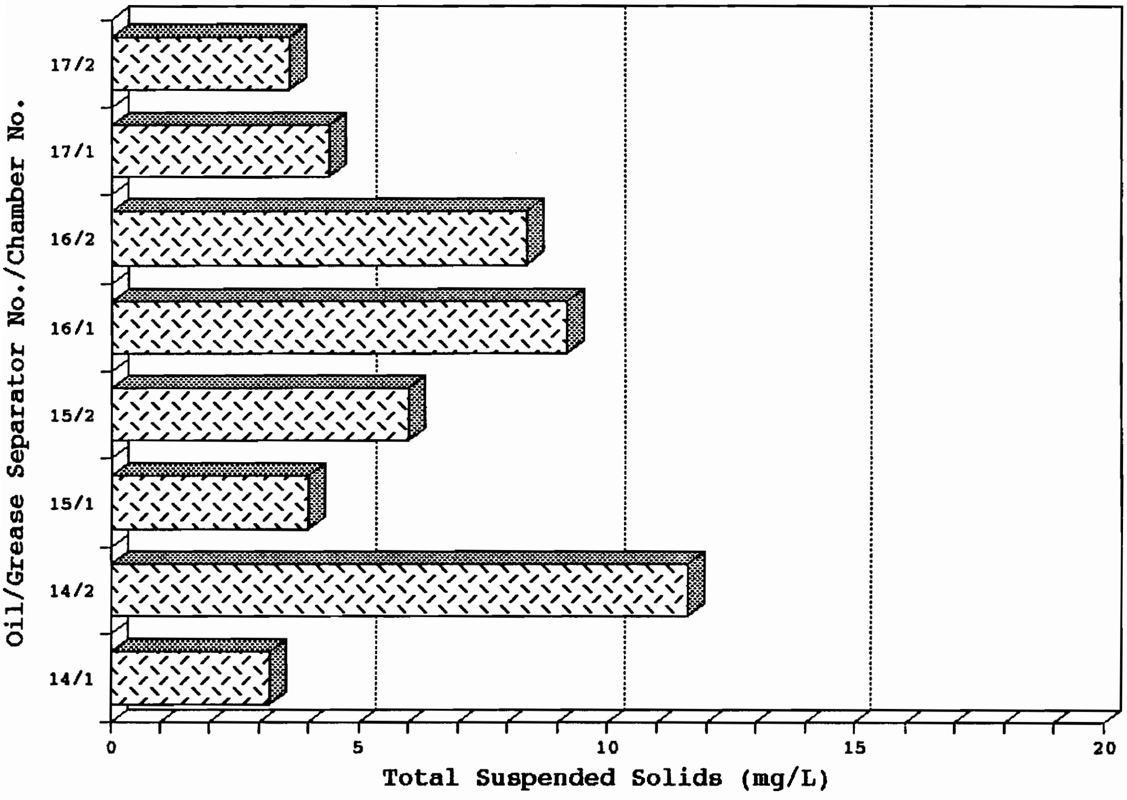

Figure D-2. TSS concentrations in water samples from oil and grease separators #14 - 17.

Note: TSS concentration data not available for oil and grease separators #9 - 13 and #18 and 19.

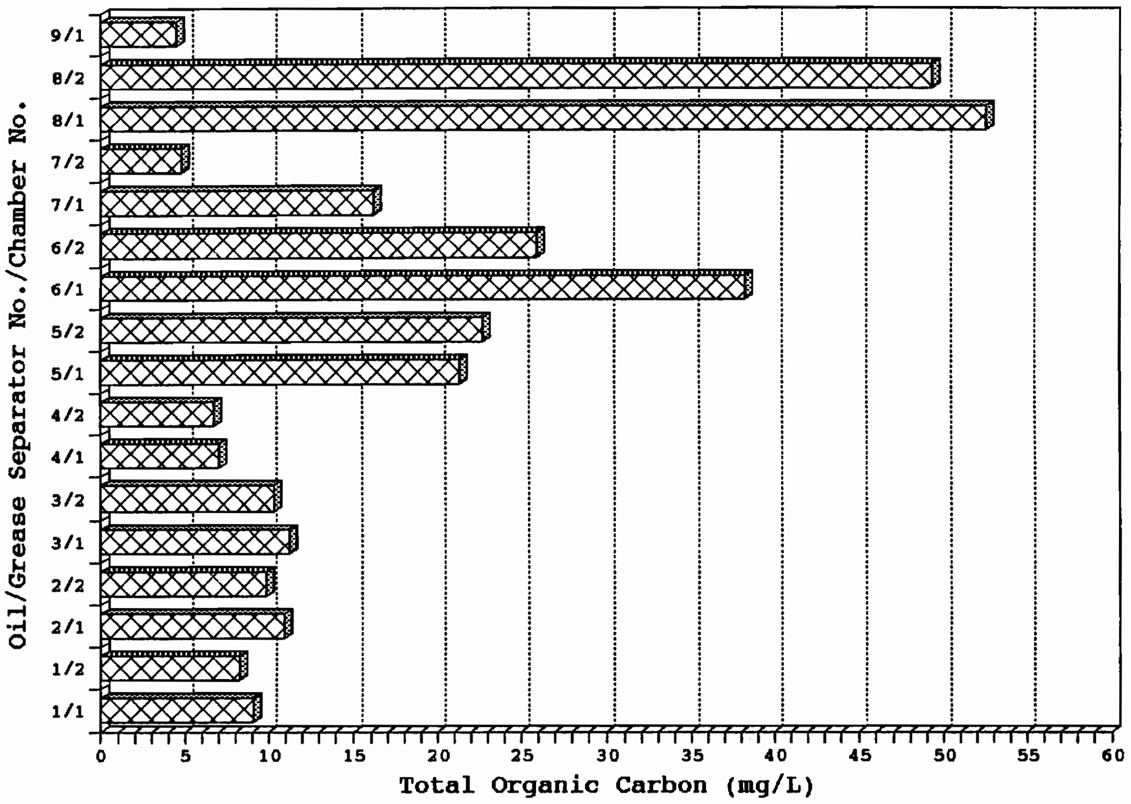

Figure D-3. TOC concentrations in water samples from oil and grease separators #1 - 9.

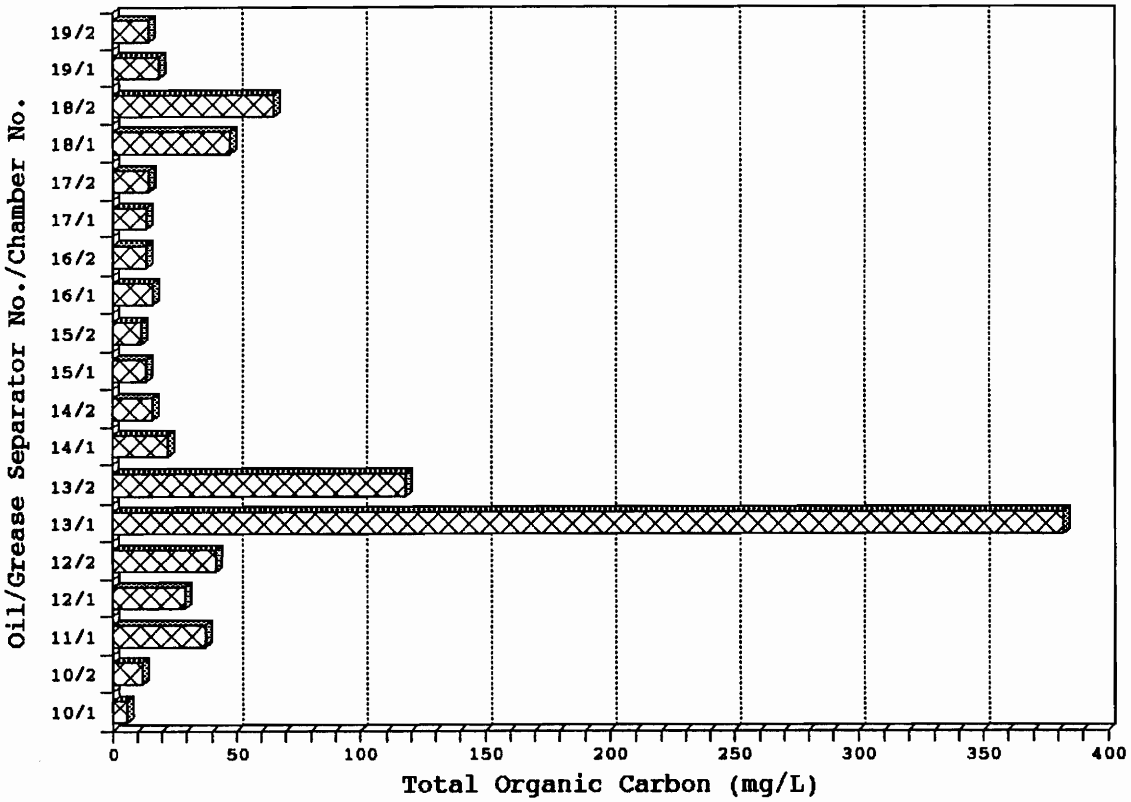

Figure D-4. TOC concentrations in water samples from oil and grease separators #10 - 19.

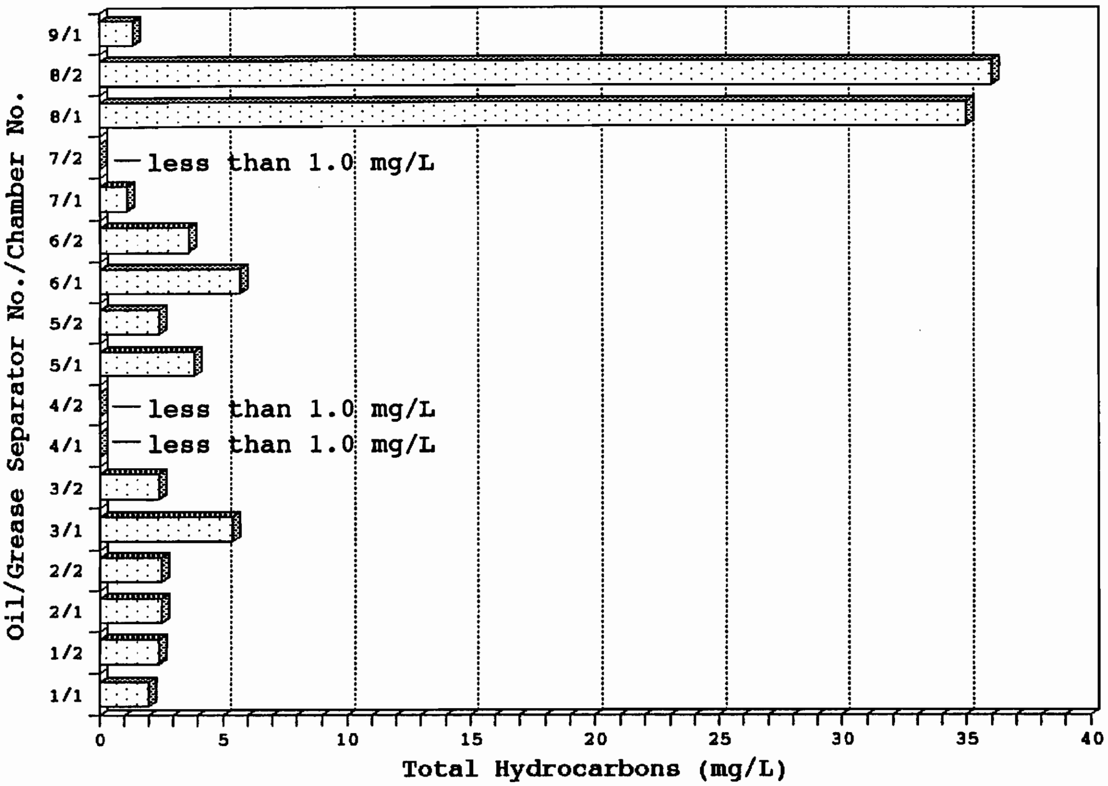

Figure D-5. THC concentrations in water samples from oil and grease separators #1 - 9.

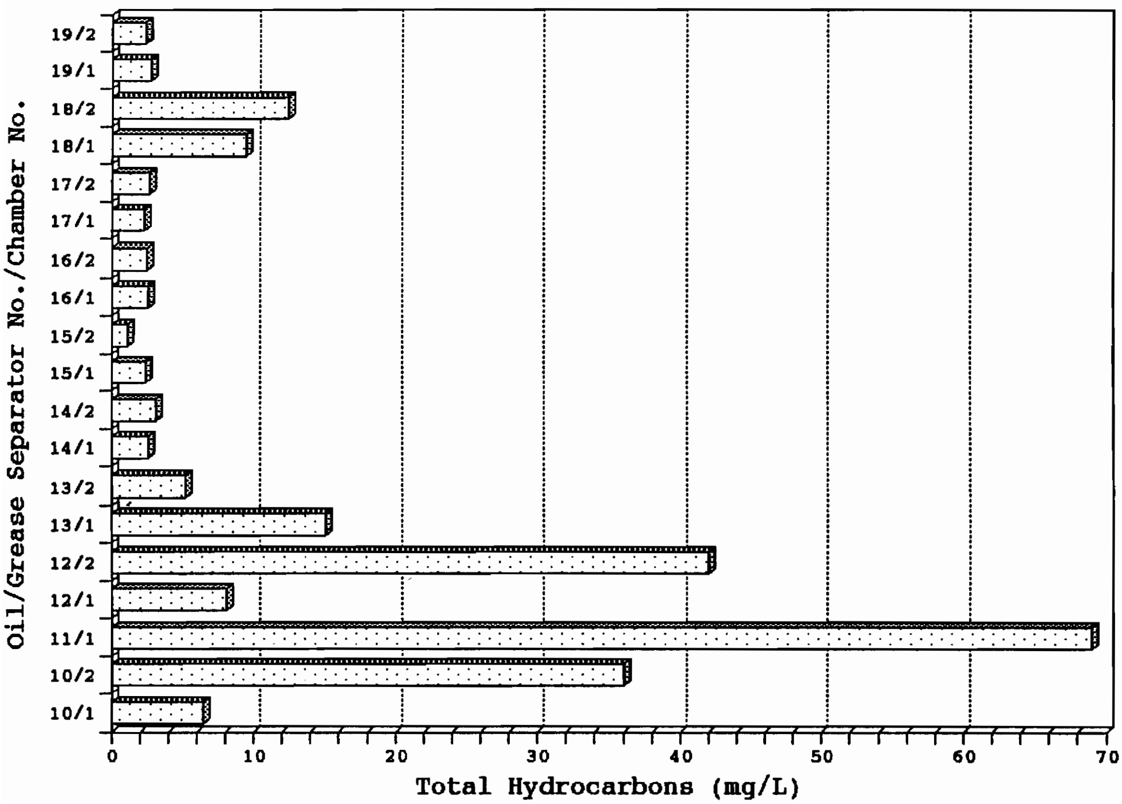

Figure D-6. THC concentrations in water samples from oil and grease separators #10 - 19.

APPENDIX E

RESULTS OF OWML SECONDARY MDL STUDY

Table E-1. Results of secondary MDL study conducted on Horiba oil analyzer.
Source: OWML, 1992.

STANDARD (mg/L)	INSTRUMENT READINGS (mg/L)	FINAL RESULT (AVERAGE) (mg/L)
0.92	1.1	0.9
	0.9	
	0.7	
0.766	0.8	0.8
	0.9	
	0.7	
0.46	0.6	0.55
	0.6	
	0.5	
	0.5	
0.23	0.4	0.25
	0.2	
	0.2	
	0.2	
0.115	0.1	0.15
	0.3	
	0.1	
	0.1	

APPENDIX F

SAMPLE AND DUPLICATE THC CONCENTRATIONS
AND
DISCUSSION ON INSTRUMENT REPEATABILITY

Table F-1. List of sample and duplicate sample THC concentrations.

SAMPLE #	THC CONCENTRATION (mg/L)
12C2	2.1
12C2-DUP.	1.9
11C24	0.4
11C24-DUP.	0.3
13C48	0.9
13C48-DUP	0.3
13D48	0.3
13D48-DUP.	0.3
24G0	0.6
24G0-DUP.	0.4
21A18	1.2
21A18-DUP.	1.0
21B24	1.8
21B24-DUP.	0.9
21C48	0.8
21C48-DUP.	0.8
24G48	0.7
24G48-DUP.	0.7
34F0	3.0
34F0-DUP.	2.7
34F2	3.3
34F2-DUP.	3.3
34F18	1.9
34F18-DUP.	1.8
34F24	2.1
34F24-DUP.	1.5
34F48	1.2
34F48-DUP.	1.2

DISCUSSION: Given that the repeatability specification for the Horiba oil analyzer is the range ±(0.1 - 0.3 mg/L) as described in the Methods and Materials chapter, the acceptable maximum difference between readings for a sample and its duplicate is 0.6 mg/L. The only sample pair that violated this limit was sample #21B24/#21B24-DUP as listed in Table F-1. The difference in concentrations read was 0.9 mg/L, or 0.3 mg/L over the allowable range. The difference read with two sample pairs (#13C48/#13C48-DUP. and #34F24/#34F24-DUP.) was exactly 0.6 mg/L. Therefore, less than 10% of the samples for which duplicates were analyzed violated the specified repeatability range of the instrument.

VITA

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