OIL AND GREASE IN STORMWATER RUNOFF

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ABSTRACT

This study, conducted as part of the regional planning mandated by the Federal Water Pollution Control Act of 1972 (PL92-500), section 208, provides a tool for management of oil and grease runoff from urban areas to the San Francisco Bay. A field sampling program undertaken to determine the nature and source of oil and grease. A literature review was performed to evaluate available mitigation techniques, and the available techniques were ranked as favorable, marginally favorable, and unfavorable. Literature reviews were also conducted to examine previous studies of sources, chemical characteristics, and environmental fate of oil and grease in urban storm waters, and to examine potential biological effects of oil and grease inputs on estuarine environment.

The field sampling program was performed during seven storms in the winter of 1980-1981 in a watershed in Richmond, Contra Costa County, California. The Richmond watershed was selected for study because it included industrial, commercial, residential and undeveloped properties--typical of many areas bordering the San Francisco Bay. Oil and grease concentration and runoff flow rate was determined for samples collected at the mouth of the watershed and at four other sampling stations, each representative of a land use type, at regular intervals during each storm. Gas chromatography was performed on selected samples to identify chemical characteristics of the oil and grease.

The results of the field sampling program indicate the the oil and grease contribution to urban storm water runoff is highly dependent upon the land use type. Mean oil and grease concentration in runoff flow ranged from 4.13 mg/l (upstream residential area) to 15.25 mg/l (parking lot). Another parameter, hydrocarbon load factor, as calculated as an index of comparison of the potential oil and grease contribution from each land use category under uniform conditions of rainfall. These values ranged from 142 lb./sq. mi.-in. rainfall (upstream residential area) to 3452.59 l./sq. mi.-in. rainfall (parking lot). Oil and grease concentration was found to show little relationship to individual storm characteristics such as days between storms, rate of rainfall, or runoff flow rate. However, a moderate "first flush" effect was observed in this study. Automobile crankcase oil and automobile exhaust particulates appeared to be important sources of oil and grease in runoff flow, as indicated by gas chromatography analysis of the runoff samples. Evidence of spills was also found in several samples.

Favorable mitigation techniques included non-structural control methods such as oil recycling programs and improved automobile emissions control as well as several structural control measures--porous pavement, green belts improved street and parking lot cleaning, biological end-of-pipe systems such as wetlands or marshes, sorption systems for manholes and gutter entrances, and disperson devices. The applicaton of these mitigation techniques were found to be highly site specific. Most treatment systems were marginally favorable or poor.

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CHAPTER I

INTRODUCTION

One of the most significant sources of pollution to natural waters is non-point source pollution, such as pollution from diverse origin such as contaminated urban storm waters. Storm waters contain a large variety of contaminants, including oil and grease. Oil and grease has long been recognized as a pollutant which may cause significant environmental damage. To control non-point source pollution, Public Law 92-500 provided for area-wide planning in section 208. The goal of area-wide planning is a systematic way to provide for treatment plants, regulation of land use, and the overall control of pollution at minimum costs. This study is in response to the planning mandated by PL92-500. The results of this study are intended to provide a basis for a pilot program of oil and grease control in urban stormwater in the San Francisco Bay area.

Oil and grease from urban stormwaters represents a low level, chronic release of oil and grease, as opposed to oil spills. Unfortunately, very little research has been performed on the environmental effects of low level discharges. Oil spills are commonly large scale point sources of oil and grease release which are aesthetically displeasing and obvious sources of pollution. In contrast to spills, oil and grease in urban runoff may originate from a myriad of small, non-point sources: vehicle exhaust, crankcase oils, fuel oils, gas stations, fried chicken stands. There is no obvious single source of oil and grease runoff pollution and often no visible sign of this pollution in the runoff. Yet substantial quantities of oil and grease may be released into the Bay exclusive of spills.

To put the hydrocarbon input into the Bay in perspective, one must examine the major inputs into the Bay. In 1972, a dry water year, total stormwater runoff into the Bay was approximately 1,110,000 acre-feet, with waste effluent roughly 900,000 acre-feet. The outflows from the delta dwarfed these contributions, consisting of approximately 9,500,000 acre-feet. Delta outflows and variability of outflow, although presently reduced from historic level through the use of upstream reservoirs, has ranged from about 4,000,000 acre-feet during the 1931 drought to greater than 50,000,000 acre-feet in 1938. Tidal action flushes about 6 percent of the Bay volume with each tidal cycle, and is a major mechanism for Bay pollutant removal (California, State of, 1979).

While water quantity derived from runoff and treated effluent comprises only a relatively small percentage of total Bay effluent, pollutant contributions from these sources appear very significant. Approximately one-half of the pollutant sources of BOD, heavy metals, total nitrogen and total phosphorus enter the Bay from point sources and surface runoff with a greater contribution predicted for the future (Russell, et. al., 1980). A similar comprehensive examination of oil and grease sources into the Bay has not been performed. However, for comparative purposes, an integrated petroleum refinery the size of the 350,000 bbl/day plant in Richmond could legally discharge an average of about 500 kg/day of oil and grease/day into the Bay. Using the East Bay Municipal Utility District's (EBMUD) estimate of about 10 mg/l oil and grease in their effluent, domestic waste could account for an additional 15,000 kg/day of oil and grease discharged into the Bay. Projecting from the oil and grease concentrations observed in this study, it is estimated that stormwater contributes approximately 22,000 kg/day of oil and grease to the Bay. The effects of stormwater pollution are aggravated because the discharge of pollutants occur during brief time periods.

Runoff normally enters the Bay along the shorelines, often in areas not subject to rapid dilution or flushing. This is particularly true in the South Bay, where fresh water flushing is only common during periods of large storms. An estuarine system like the Bay offers one of the most productive of all types of habitat, with spawning grounds and nurseries for many kinds of fish and shellfish, and vital habitats for waterfowl using the Pacific Flyway. Along the shorelines exist shellfish beds and areas vital to successful fish spawning, feeding and migration. These areas also harbor much of the vegetative life responsible for the high level of productivity. Microcrustaceans and microorganisms providing the necessary link between the primary producers and many of the larger organisms also exist predominately along the shorelines. Since it is at the shorelines that most of the runoff enters the Bay, it is the shoreline that appears most vulnerable to contamination. Shoreline contamination could result in severe consequences affecting large areas of the Bay.

Objectives of this study were to determine the potential benefits and favorable techniques for managing oil and grease in stormwater. It was hoped that the results of the study would be generally applicable to urban areas, as opposed to a site-specific result which would only be relevant to the study area. Therefore the approach was structured to relate the findings to quantitative aspects of the land-use types, storm characteristics, and oil and grease characteristics.

To accomplish these objectives a 2.5 square mile watershed in the city of Richmond, California was selected as the study area. This watershed was chosen because it included industrial, commercial, undeveloped, and residential properties, which is typical of many areas bordering San Francisco Bay. Within the study area, five sampling locations were chosen, and an experimental program was designed to analyze urban storm waters for oil and grease during seven storms in the winter of 1980-1981. Samples were collected during storms on a regular basis and were analyzed for oil and grease concentration. Selected samples were also analyzed using gas chromatography in the hopes of determining the nature and source of the oil and grease. An analysis of variance and a regression analysis were applied to the resulting data.

To ascertain the importance of land use pattern on the watershed's total oil and grease budget, a simple modeling and simulation study was performed. Using this model, the effects of potential treatment methods were simulated for each land use pattern. Growth scenarios were also simulated. Finally, incorporating the modeling results with the data and the literature review allowed the development of a set of recommended treatment techniques.

CHAPTER 2

OIL AND GREASE IN URBAN STORMWATER RUNOFF: ITS CHEMICAL CHARACTERIZATION, POTENTIAL SOURCES, AND ENVIRONMENTAL FATE

Introduction

Hydrocarbons enter the marine environment from a number of natural and man-made sources. As shown in Table 2-1, marine transportation is the largest single contributor of hydrocarbons to the oceans. Most of these emissions occur during normal operations, with accidents accounting for only a small fraction of the total. The contribution of urban runoff is comparable to that from natural seepage, especially when it is considered that some of the input from river runoff is the result of upstream urban stormwater runoff. Large spills of oil cause extensive obvious disruption of the environment. In low concentrations, hydrocarbons are of interest as pollutants chiefly due to their toxicity. Point sources of hydrocarbon pollution, such as refineries or tanker loading terminals, can be and are monitored and regulated rather easily. Pollution from non-point sources, due to its diffuse nature, is much more difficult to study and to regulate.

There is a large body of literature on general non-point source pollution of urban stormwater runoff (Browne, 1978; Browne, 1980; Field and Cibik, 1980). Information on hydrocarbon pollution of these waters is much less extensive. It is estimated that about 5% of the total hydrocarbons entering the ocean come from urban stormwater runoff (NAS, 1975). As contributions from other sources decrease due to tighter controls and better technology, the importance of urban stormwater as a hydrocarbon source will increase. As an example of the increasing importance of urban storm water, estimates of present and future contributions of hydrocarbon source will increase. As an

TABLE 2-1 BUDGET OF PETROLEUM HYDROCARBONS INTRODUCED INTO THE OCEANS

Source	Input Rate (mta)[a] Best Estimate	Input Rate (mta)[a] Probable Range	Reference
Natural seeps	0.6	0.2-1.0	Wilson et al (1973)
Offshore production	0.08	0.08-0.15	Wilson et al (1973)
Transportation			
LOT tankers	0.31	0.15-0.4	Results of workshop panel deliberations
Non-LOT tankers	0.77	0.65-1.0	
Dry docking	0.25	0.2-0.3	
Terminal operations	0.003	0.0015-0.005	
Bilges bunkering	0.5	0.4-0.7	
Tanker accidents	0.2	0.12-0.25	
Nontanker accidents	0.1	0.02-0.15	
Coastal refineries	0.2	0.2-0.3	Brummage (1973a)
Atmosphere	0.6	0.4-0.8	Feuerstein (1973)
Coastal municipal wastes	0.3	-	Storrs (1973)
Coastal, Nonrefining, industrial wastes	0.3	-	Storrs (1973)
Urban runoff	0.3	0.1-0.5	Storrs (1973), Hallhagen (1973)
River runoff	1.6	-	Storrs (1973), Hallhagen (1973)
TOTAL	6.113		

[a] mta, million metric tons annually (N.A.S., 1975).

example of the increasing importance of urban storm estimates of present and future contributions of hydrocarbons to the Delaware Estuary are presented in Table 2-2.

Sources and Patterns of Hydrocarbon Pollution

Hydrocarbons in urban runoff can come from accidental spills or deliberate dumping of lubricating oils or fuel oils; from emissions of engines during normal operation, such as vehicle exhaust particulates or drippings of crankcase oil; from dustfall or rainout of atmospheric particulates; from spilling of crude or refined petroleum products during production, processing and transportation; from leached or eroded pavement; from natural seepage on land or erosion of organic bearing sedimentary rocks; or from natural biogenic sources (Eganhouse and Kaplan, 1981b; Hunter et al, 1979; Wakeham, 1977). Wakeham (1977) shows that natural hydrocarbons are only a minor contribution to most urban runoff. Of the other sources, used crankcase oil has been identified by gas chromatography studies as the most probably major contributor (Hunter et al, 1979; MacKenzie and Hunter, 1979; Wakeham, 1977). However, vehicular particulate emissions have a similar GC profile so that differentiating between these two highly probably sources is difficult.

Values for hydrocarbon concentration in urban stormwater as measured by various investigators are presented in Table 2-3. As is explained in the previous section, great care must be taken in comparing these results due to the diverse experimental and analytical methods used to derive them. Hydrocarbons associated with storm water runoff have been found to be predominantly aliphatic. Eganhouse and Kaplan (1981a) measure 88% aliphatics while Hunter et al (1975, 1979) measure about 70% aliphatics average. Hunter et al (1979) found aromatics formed 31.6% of the particulate fraction and only

TABLE 2-2 ESTIMATED PETROLEUM POLLUTION, DELAWARE ESTUARY (Whipple and Hunter, 1979)

	1975 (lb/day)	Future (lb/day)
Spills	6,000	6,000
Municipal Effluent	7,800-15,600	2,000
Refinery Effluent	24,000	1,900
Other Industrial Effluent	8,900	6,200
Urban runoff	10,500	10,700
TOTAL (rounded)	57,000-65,000	26,800

TABLE 2-3 MEASURED VALUES OF HYDROCARBON CONCENTRATION

PLACE	DESCRIPTION	HYDROCARBON FRACTION	CONCENTRATION (mg/l) High	Low	Mean
Philadelphia, PA (1)	Urban runoff	Aliphatic			
		Particulates	3.41	1.12	2.28
		Soluble	.50	.12	.29
		Aromatic			
		Particulates	1.65	.49	1.01
		Soluble	.19	.04	.11
Seattle, Wash. (2)	Bridge runoff	Aliphatic	24.0	6.0	12.0
	Urban runoff	Aliphatic	7.5	.2	1.2
	Bridge runoff	Total	96.0	0.0	27.0
	Urban runoff	Total	16.0	1.0	10.0
	Freeway runoff	Total	60.0	10.0	44.0
Stockhom, Sweden (3)	Terrace houses	Total			
	Suburban	Total			
	Highway	Total			
	Mixed	Total			
Los Angeles, CA (4)	River	Aliphatic			11.5
		Aromatic			1.6

(1) Hunter et al, 1979
(2) Wakeham, 1977
(3) Soderlund and Lehtinen, 1972
(4) Eganhouse and Kaplan, 1981a

26.1% of the soluble fraction. Conversely, Eganhouse and Kaplan (1981a) report the aliphatic to aromatic ratio to be 11.5 for particulates and only 2.9 for the dissolved phase, meaning that aromatics are proportionately more common in the dissolved phase.

Hydrocarbons are consistently found to be predominantly associated with particulates. Determinations of the average proportion of hydrocarbons found on particulates are: 81% (Shaheen, 1975), 96.4% (Hunter et al, 1979) and greater than 85% (Eganhouse and Kaplan, 1981a). Eganhouse and Kaplan (1981a) determined that the most of the hydrocarbons are found on finer particulates (Shaheen, 1975; Sartor et al, 1974). This could be a surface to volume effect, smaller particulates having more surface area for adsorption of hydrocarbons per unit of weight than do larger particulates. It has not been determined if the hydrocarbon distribution is uniform within any individual particle size category, nor is the degree of saturation of the particles known.

Patterns of hydrocarbon pollution vary with watershed and storm characteristics. The effects of watershed topography, size, and shape on runoff distribution are well known in hydrology. The concentration of hydrocarbons in urban runoff is a function of the degree of urbanization and types of land uses in the watershed (Whipple and Hunter, 1979; Soderlund and Lehtinen, 1972; Rimer et al, 1978).

Due to the inherently intermittent nature of storms, runoff waters can contribute sudden sharp peaks of pollutant to receiving bodies. This shock loading can increase the effects of pollutants on life forms if the pollutant concentrations are high during the early part of a storm. These high concentrations which fall off quickly are termed the "first flush". Hunter et al (1979) suggest that this effect is due to the washing off of easily transported hydrocarbons. Soderlund and Lehtinen (1972) observe no such effect with suspended solids. The actual pollutant at any time during a storm appears to be a function of the flow at that time. Figures 2-1 to 2-3 show this effect (Hunter et al, 1979). Peaks in flow are matched by peaks in hydrocarbon load. The correlation coefficient between flow and hydrocarbon load is quite low, however, indicating that they are not linearly related (Eganhouse and Kaplan, 1981a)

Hunter et al (1979) found that the total hydrocarbon load for a storm is a function of the total rainfall during the storm. The particulate fraction of the load rises exponentially with increase in total rainfall, as shown in Figure 2-4. Load cannot continue to increase exponentially indefinitely, and more data for larger storms are required for further definition of this function. There is disagreement in the literature as to the importance of the time period between storms in determining hydrocarbon pollutant levels.

Some sources consider this factor to be important (Huber et al, 1975; Metcalf and Eddy, Inc., 1971; Shaheen, 1975) and others do not (Whipple et al, 1977; Hunter et al, 1979). It is possible that where rainfall patterns are roughly constant throughout the year the time between storms may not be as important a parameter as in watersheds with long dry seasons. The effects of time period between storms will be discussed further in the section on transport mechanisms.

Chemical Characterization of Urban Stormwater Runoff-Previous Studies

Very few studies looking at the oil and grease content of urban stormwater runoff using gas chromatography (GC) or gas chromatography in combination with mass spectroscopy (GC/MS) have been undertaken to date. The few studies which have been done have attempted to identify oil and grease

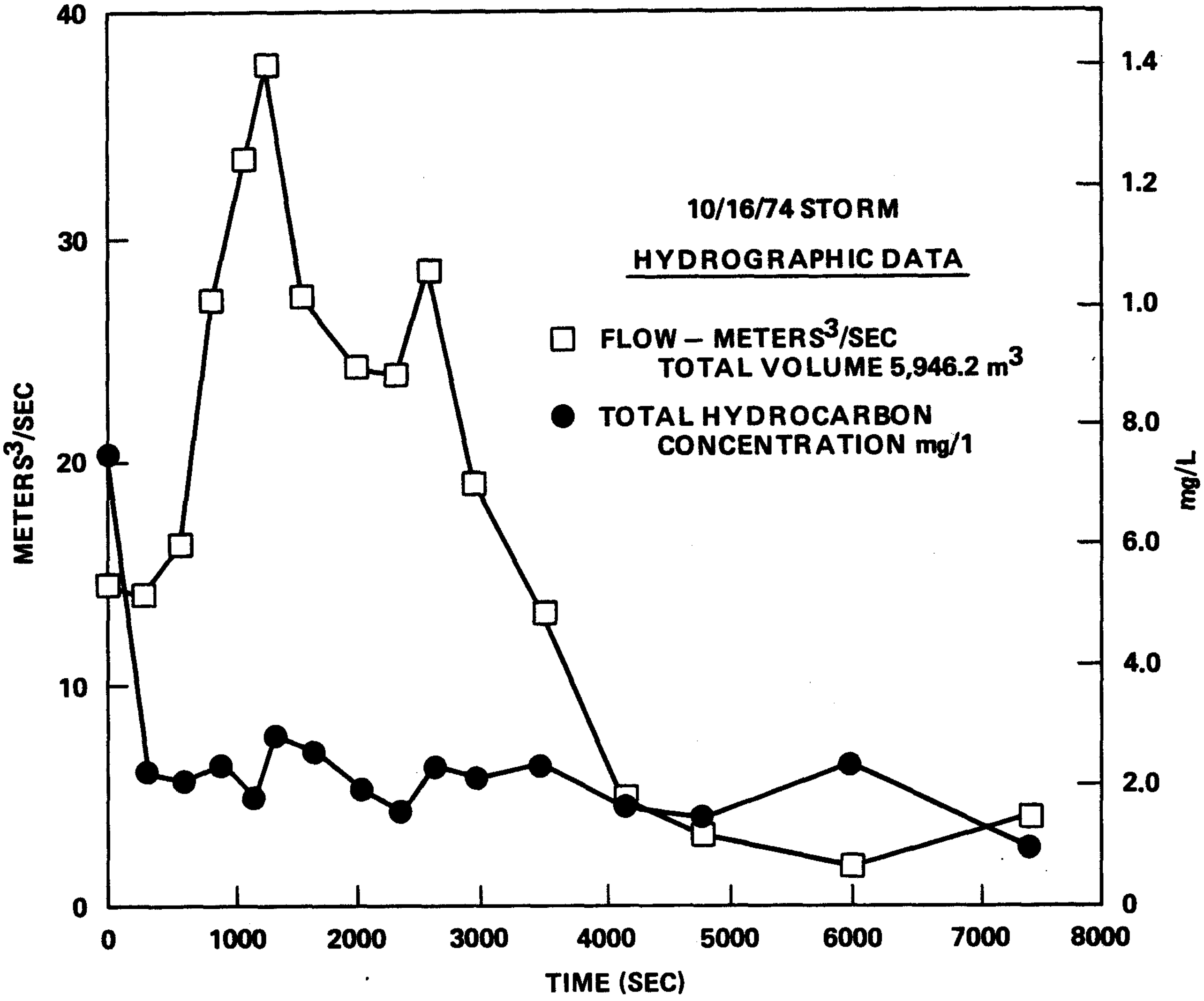

Figure 2-1 Hydrograph-pollutograph of October 16, 1974, storm event (Hunter et al, 1979)

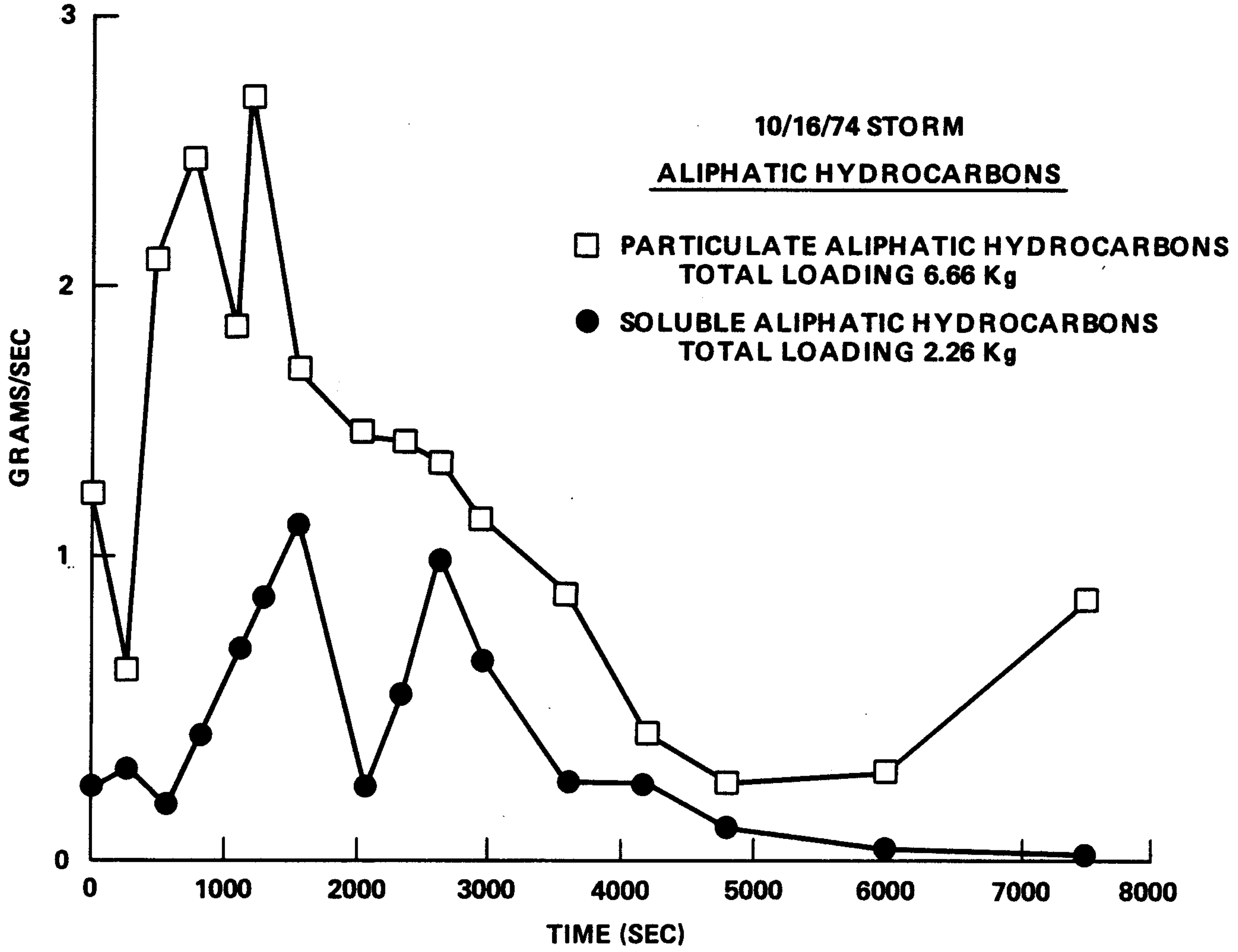

Figure 2-2 Mass loading rate pollutograph of aliphatic hydrocarbons in October 165, 1974, storm event (Hunter, et. al., 1979)

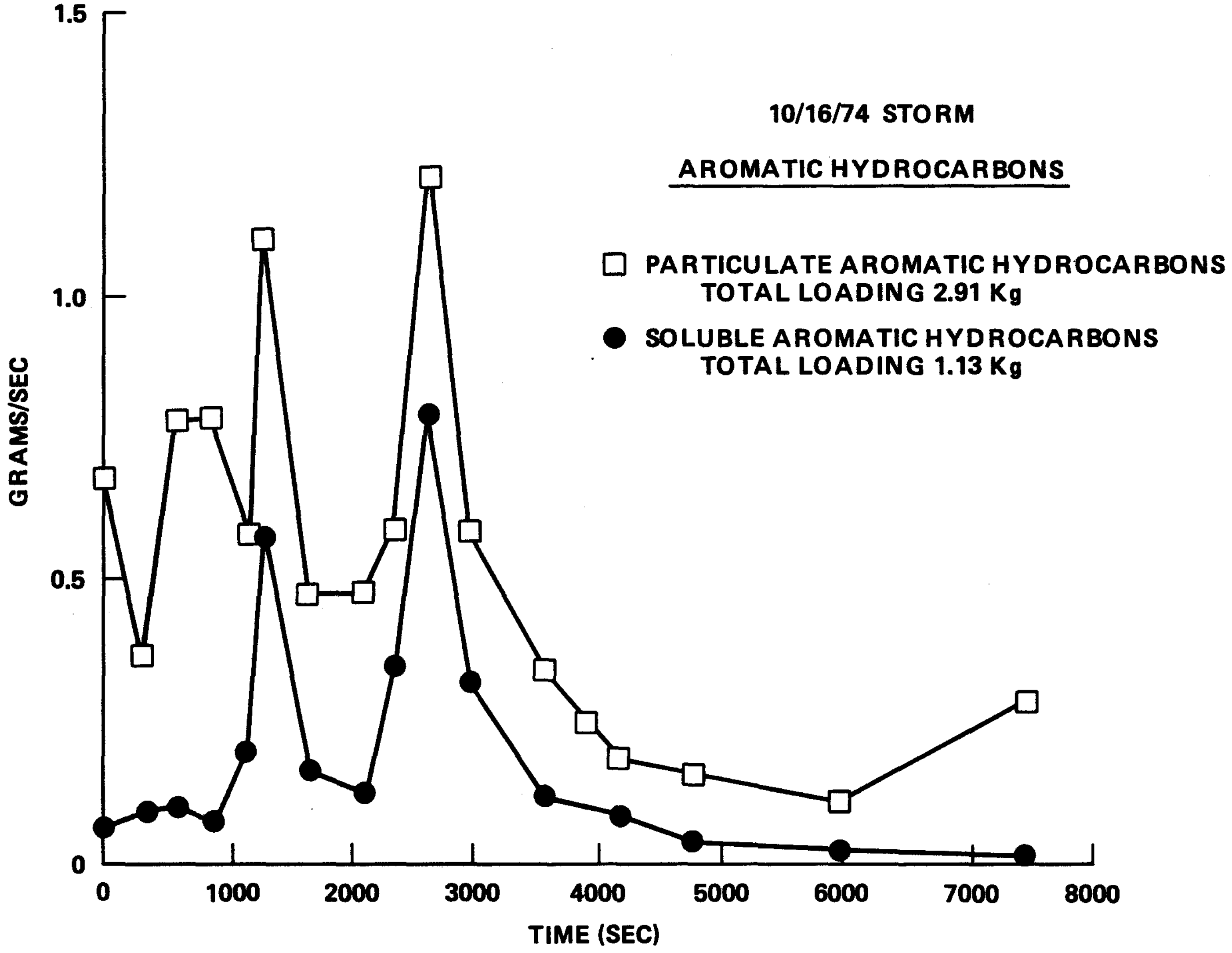

Figure 2-3 Mass loading rate pollutograph of aromatic hydrocarbons in October 16, 1974, storm event. (Hunter et al, 1979).

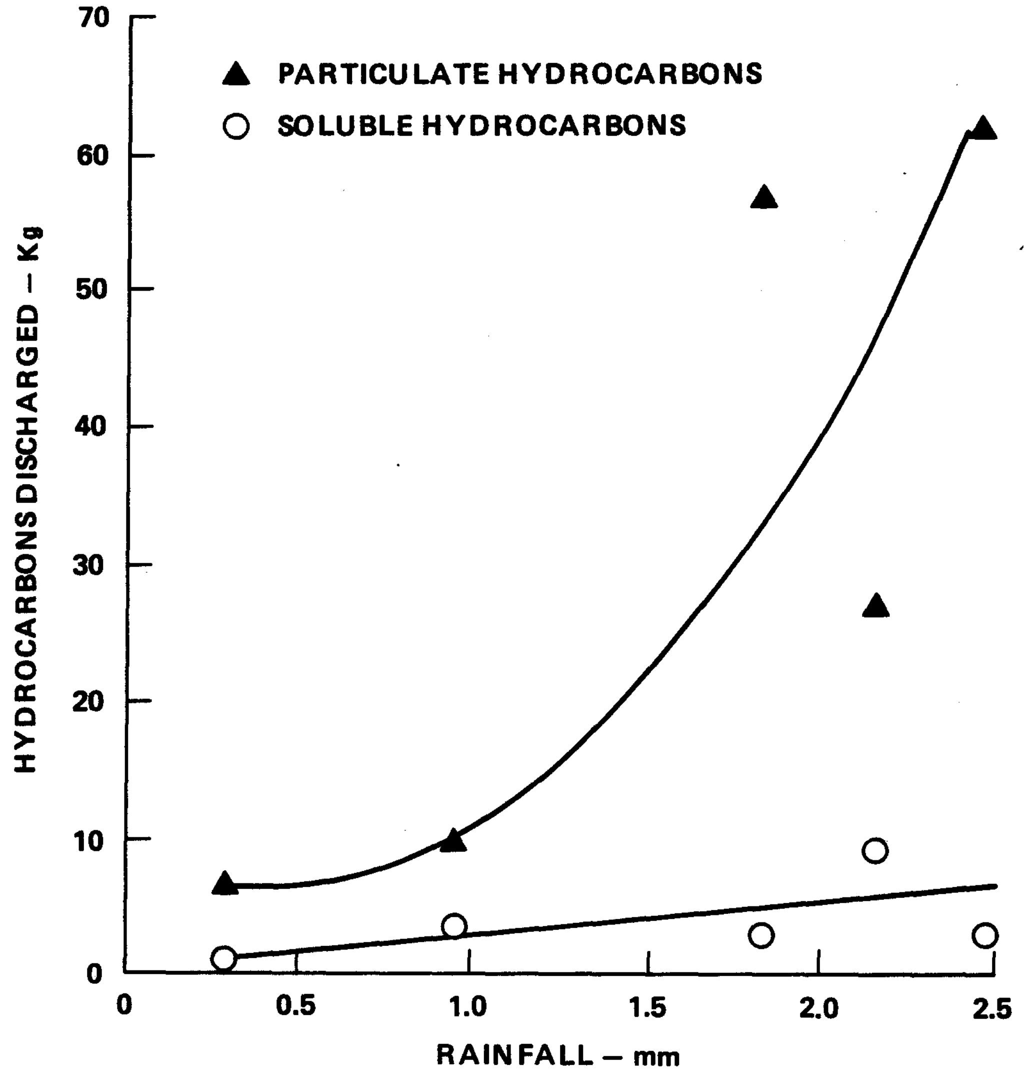

Figure 2-4 Effect of amount of rainfall on total hydrocarbons discharged from storm sewer. (Hunter et al, 1979)

sources by comparing gas chromatograms of the stormwater to gas chromatograms of potential oil and grease sources and have looked for individual marker compounds in stormwater which would be indicative of a particular source. Comparisons of gas chromatograms from potential sources (e.g. used crankcase oil) with the gas chromatograms of stormwater runoff are made difficult by the weathering of oil and grease components in the environment. For example, MacKenzie and Hunter (1979) show that the lower boiling component (e.g. benzothiophenes and naphthalenes) of used crankcase oil may be absent from stormwater due to weathering. It has also been demonstrated that petroleum compounds can be degraded by microbial action, generally in the sequence of normals, branched, cyclics, and aromatics (Ehrhardt and Blumer, 1972; Reed, 1977). Since petroleum products appear to account for a substantial portion of the oil and grease in urban stormwater runoff, weathering of petroleum can be an important factor determining the pattern of the stormwater gas chromatogram and can be a confounding factor when trying to identify specific oil and grease sources. Identification of individual compounds using GC/MS has, in some cases, provided additional evidence in source identification by indicating the presence of source-specific marker compounds and has indicated the presence of potentially harmful (e.g. carcinogenic) compounds in stormwater runoff.

The following discussion describes the methods which have been used in previous studies attempting to identify the sources of oil and grease compounds in urban stormwater runoff. Because the sampling and fractionation schemes used were different in each study, a brief description of each is also included. For detailed descriptions of the sampling methods, fractionation schemes and GC operating conditions, the reader is referred to the individual studies cited.

The most extensive characterization of the organics in stormwater runoff undertaken to date was performed by Eganhouse et al (1981). This group used gas chromatography and gas chromatography/mass spectroscopy combined with thin layer chromatography (TLC) to characterize the water soluble and particle-bound organics. They then commented on the possible sources (e.g. anthropogenic or biogenic) of the identified compounds and compound classes.

Samples of Los Angeles River stormwater runoff were collected at 11 intervals during one storm on November 21, 1978. In preparation for chemical analysis, the collected samples were separated into (1) unfiltered samples, (2) filtered samples (Whatman GF/A glass-fiber filters), and (3) gravity-settled particulates. Successive liquid/liquid extracts were then performed on the filtered and unfiltered samples using hexane (added as a preservative) followed by three portions of $CHCl_3$. Following concentration of the combined extract from each sample, drying, and removal of elemental sulfur; total extractable organics were measured gravimetrically. The particulates were extracted exhaustively with $CHCl_3$ to remove the extractable organics and then saponified to isolate the bound constituents (Eganhouse, Simoneit, and Kaplan, 1981).

Separation of the total extractable organics from the filtered and unfiltered samples was then performed using thin-layer chromatography. Separation of the bound organics was similarly achieved following methylation of the fatty acids. The three sets of samples were separated into four fractions for molecular analysis: (1) total hydrocarbons (THC), (2) fatty acids, (3) ketones, and (4) polar compounds.

Separated fractions were examined by high-resolution, glass-capillary gas chromatography using flame ionization detectors and gas chromatography/mass spectrometric analysis. (See Eganhouse et al, 1981, for a detailed description method and equipment). Tentative compound identifications are based on gas chromatographic retention times and/or analysis of data from the mass spectrometer coupled to the gas chromatograph. Quantitative result for the total hydrocarbon and fatty acid fractions were achieved by comparing samples with external standards.

Following analysis of the total hydrocarbon elute, Eganhouse et al concluded that the hydrocarbons were primarily derived from petroleum residues. They also observed that hydrocarbons constituted roughly 60 percent of the total-extractable organics in the stormwaters of the Los Angeles River and that approximately 94 percent of the hydrocarbons were associated with particulate matter. Molecular evidence cited by Eganhouse et al in support of their conclusion that the stormwater hydrocarbons are primarily of petroleum origin include the following:

(1) A broad envelope of unresolved species (see Figure 2-5) extending from n-C_{13} to n-C_{36} and comprising >80 percent of the total hydrocarbons (Ehrhardt and Blumer, 1972).

(2) A homologous series of normal alkanes (n-C_{13-24}) with odd-even predominance (EOP) about equal to 1.0 (Ehrhardt and Blumer, 1972).

(3) Abundant branched homologues including isoprenoids, iso- and anteiso-alkanes (Johns et al, 1966 and Bendoraitis et al, 1963).

(4) Multiple homologous series of alicyclic and polycyclic compounds such as the alkyl cyclohexanes, steranes, diterpanes, and triterpanes.

(5) A variety of parent polynuclear aromatic compounds in association with alkyl substituted homologue assemblages.

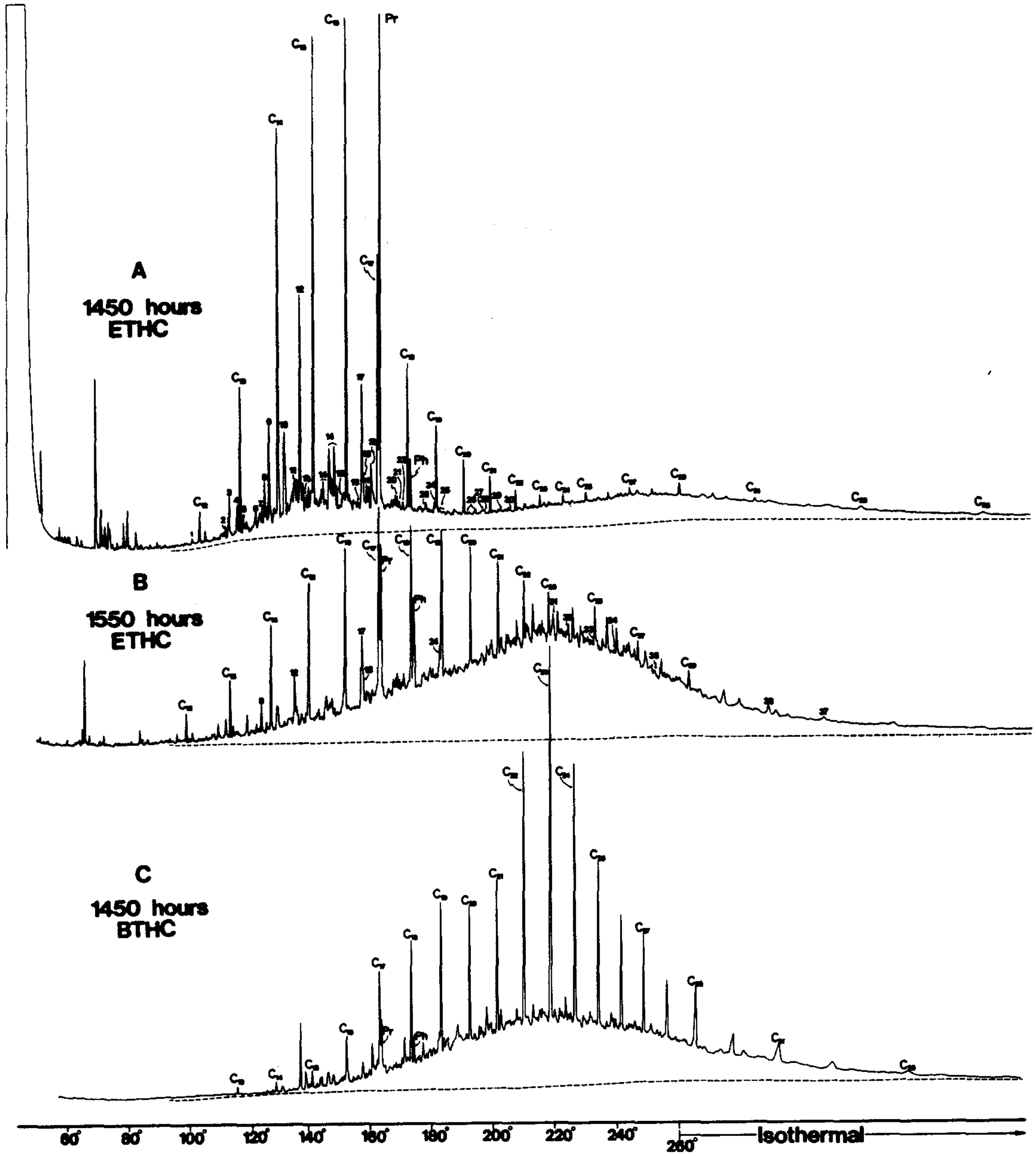

Figure 2-5 Gas chromatograms of total hydrocarbon fractions in storm runoff: (A) 1450 hours (unfiltered sample); (B) 1550 hours (unfiltered sample); (C) 1450 hours (particulates). (Eganhouse et al, 1981).

(6) The ancient character of the hydrocarbons as evidenced by the absence of the 17 α (H)-hopane isomers and the distribution of the 17 α (H)-hopane isomers $>C_{30}$ (Dastillung and Albrecht, 1976).

(7) The presence of a molecule, 17 α(H), 18a(H), 21 βH-28, 30-bisnorhopane, which has been identified as a major terpenoid constituent of California crude oils (Seifert et al, 1978).

Eganhouse et al noted that the petroleum hydrocarbons could have come from several different sources but did not specify any single source as the predominant or most likely origin. One of the potential sources was automobile exhaust particulates, which are distributed as an unresolved complex mixture ranging from n-C_{22} to n-C_{34}+ and maximizing at n-C_{29} (Boyer and Laitinen, 1974). Eganhouse et al reported a pattern similar to this in their sample, particularly in the later stages of the storm. Dewaxed lubricating and transmission oils are also generally characterized by a high molecular weight, unresolved complex mixture with no detectable normal alkanes (Dell'Acqua et al, 1975). As can be seen in Figure 2.5, however, the stormwater hydrocarbons collected from the Los Angeles River include a substantial proportion of n-alkanes. Eganhouse et al (1978) concluded that the high molecular weight fraction of the unresolved complex mixture could have come from a combination of sources.

The presence of high molecular weight n-alkanes ($>$N-C_{24}) with OEP values >1.0 suggests the presence of biogenic hydrocarbons, presumably derived from the epicuticular waxes of higher plant (Eglington and Hamilton, 1967). Hydrocarbons fitting this pattern were identified by Eganhouse et al in their stormwater samples, but they never comprised more than 1.6 percent of the total hydrocarbon fraction. In addition, because bacteria displays little or no carbon preference in metabolically synthesized n-alkanes (Han and Calvin, 1969; Jones, 1969), Eganhouse et al stated that they could not exclude the possibility that minor amounts of bacterial hydrocarbons might also be present in stormwater runoff.

As alluded to above, many individual compound were identified in the hydrocarbon fraction, including normal alkanes, and a wide variety of branched, unsaturated, and cyclic compounds. Among the compounds identified were several polynuclear aromatic hydrocarbons, including several homologous series such as napthalene plus C_{1-5} homologues, biphenyl plus C_{1-4}, and phenanthrene/anthracene plus C_{1-2} homologues. Other tentatively identified PNA's included fluroanthene, pyrene, chrysene, xanthene, and benzopyrene. Benzothiophene and dibenzothiophene (plus alkylated homologues), found abundantly in Philadelphia stormwaters (MacKenzie and Hunter, 1979), were only found at trace levels in Los Angeles River stormwater by Eganhouse et al (1981).

Since petroleum contains only a minor amount of long-chain carboxylic acids (Seifert, 1975), Eganhouse et al (1981) concluded that fatty acids found in stormwater are almost entirely biogenic. The ketone fraction only comprised 4.3 percent of the total solvent-extractable organics in stormwater. Eganhouse et al (1981) believed the sources of some of the ketones to be anthropogenic (possibly petroleum), but exact sources were not identified. Most of the compounds identified in the polar fraction were believed by Eganhouse et al to be of biological origin, although they also acknowledged that some of the material could be petroleum-derived polar heteroatomic material (i.e., N-S-O compound) or other anthropogenic intermediate oxidation products.

Hunter et al. (1979) looked at stormwater in Philadelphia with the objective of determining the actual loadings of petroleum hydrocarbons to the environment by urban stormwater runoff. During this study five separate storms were sampled by taking 20 ℓ grab samples at 5-minute intervals during the flow period. Samples from two of the storms were analyzed separately, but the samples from the other three storms were composited on a flow proportionate basis in order to reduce analysis time.

The fractionation method used is illustrated in Figure 2-6. In this scheme, the sample was separated by centrifugation such that particles down to 1-μm were removed. The aqueous portion was then passed through an activated carbon column, and the particulates were further dried. Both fractions were then treated identically, including successive extractions with hexane, benzene, and chloroform in a soxhlet apparatus. To separate the petroleum hydrocarbons in the six resulting extracts from other extractable material, a silica gel chromatographic procedure was used. In this step, the extracts were evaporated to dryness on silica gel which was subsequently charged to a chromatograph column and eluted with the following elutropic series: hexane, to elute aliphatic hydrocarbons; benzene to elute aromatic hydrocarbons; and chloroform/methanol (1/1), to elute oxy-polar compounds.

Infrared spectra were obtained on each elute as a screening procedure to judge the efficiency of the silica gel separation and to give an indication to the compound types present (Hunter et al, 1978). Each elute was then analyzed with a gas chromatograph using both flame ionization and flame photometric detectors allowing simultaneous detection of both hydrocarbon and sulfur-containing compounds.

Chemical analysis of crankcase oil processed with the chromatographic procedure described above revealed it to be composed of about 63 percent aliphatic and 37 percent aromatic hydrocarbons. Hunter et al felt this was similar enough to the hydrocarbons in their stormwater samples (70% aliphatic

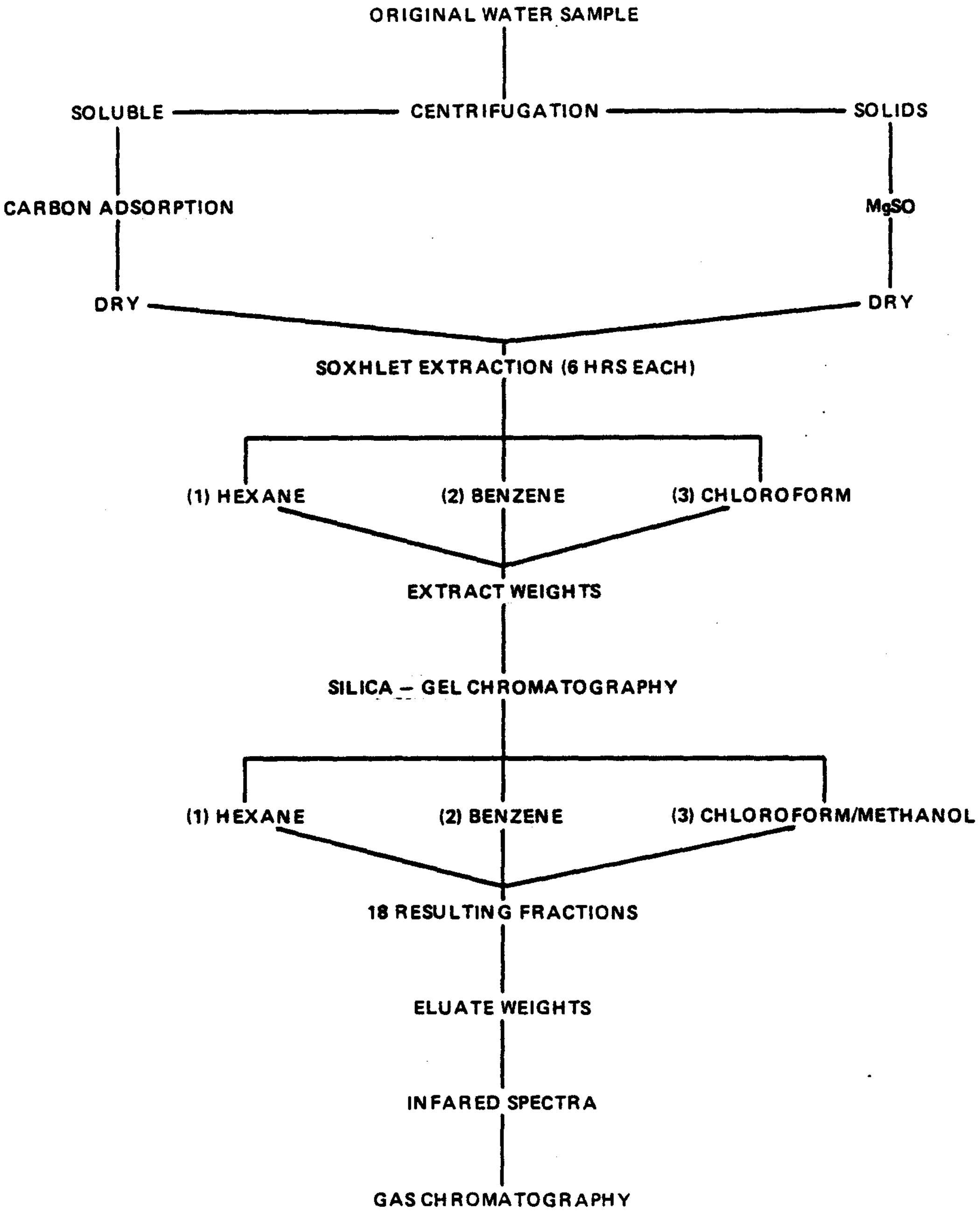

Figure 2-6 Analytical scheme (Hunter et al, 1979)

and 30% aromatic) to warrant further investigation. Accordingly, several petroleum products were fractionated and analyzed. The major features of the gas chromatograms of the aliphatic eluates are shown in Table 2-4. The similarity of the chromatograms of the aliphatics from used crankcase oil and stormwater runoff can be seen in Figure 2-7. The characteristic unresolved hydrocarbon envelopes of the used crankcase oils are very similar to that of the stormwater runoff with respect to retention time and peak area. The presence of an unresolved envelope of sulfur compounds in both the crankcase oil and stormwater runoff samples further suggests a causal relationship. On the basis of the information described above, Hunter et al (1979) tentatively concluded that the primary source of the described hydrocarbons was crankcase oil and stated that further research would be needed for confirmation.

MacKenzie and Hunter (1979) analyzed stormwater runoff from three of the storms in the Philadelphia drainage basin which were just discussed in the previous study by Hunter et al (1979). This second study involving MacKenzie and Hunter was directed toward the characterization, source, and probable fate of aromatic sulfur compounds and petroleum oils from stormwater runoff. Fractionation in this study was virtually identical to the previously described scheme used by Hunter et al, as can be seen by comparing Figures 2-6, 2-7 and 2-8; however, gas chromatographic analysis in this study was performed on the aromatic rather than the aliphatic eluates. Flame ionization and sulfur-specific flame photometric detectors were used. Identification and quantification of individual compounds (e.g. benzothiophene, dienzothiophene and the triaromatics) was based on GC retention times and mass spectometry.

The sources of the stormwater hydrocarbons were established by comparing the gas chromatograms of the aromatic fractions of various refined petroleum

TABLE 2-4 COMPARATIVE GAS CHROMATOGRAPHIC RESULTS OF ALIPHATIC HYDROCARBONS IN STORMWATER PARTICULATES AND STANDARD OILS (Hunter et al, 1979)

Source	Envelope Peak (Retention time, min)	Carbon Range Envelope Peak	Sulfur Envelope
No. 2 Fuel	6	C6-C20	Absent
No. 4 Fuel	8	C11-C22	Absent
No. 6 Fuel	10	C8-C34	Absent
Hydraulic	15,18	C16-C40	Absent
Lubricating	18	C20-C40	Absent
Crankcase 1	17.5	C17-C40	Present
Crankcase 2	17	C18-C40	Present
9/3/74 storm	17	C17-C40	Present
1/16/75	17.5	C-16-C40	Present
4/3/75	17.5	C-15-C40	Present

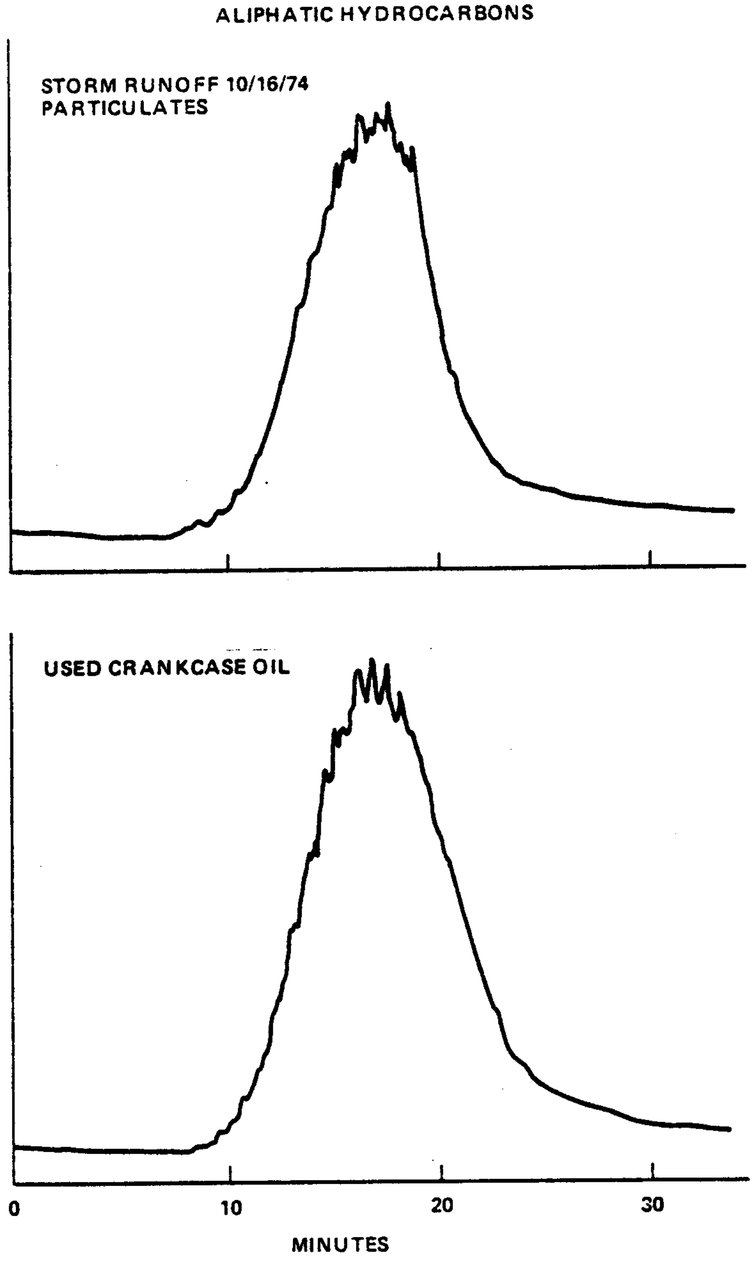

Figure 2-7 Fingerprint chromatograms of aliphatic hydrocrabons in stormwater particulates and used crankcase oil by FID. Chromatographic conditions: 3% SP-2100 80 to 100 mesh Supelcoport, programmed 100 to 300°C, 10°C/min (Hunter, et. al., 1979).

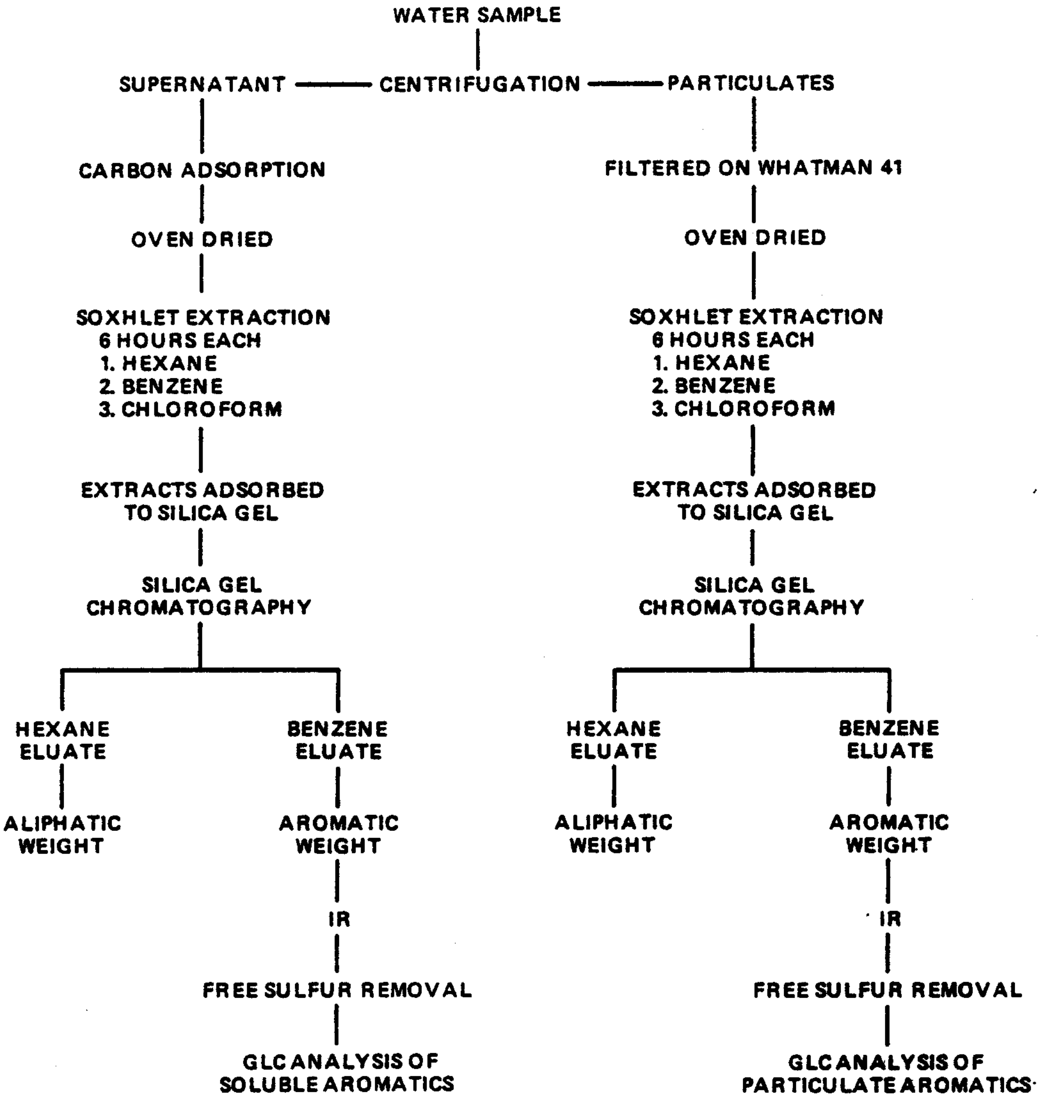

Figure 2-8 Analytical Scheme (MacKenzie and Hunter, 1979)

products to the gas chromatograms of the aromatic fractions of the particle associated hydrocarbons from stormwater runoff. The particulate phase was chosen for fingerprint analysis because it contained about 95 percent of the total aromatics. Figure 2-9 shows the gas chromatograms of the aromatic hydrocarbons associated with the stormwater particulates in the Delaware River sediments and in some refined petroleum products using a flame ionization detector (FID). Figure 2-10 shows the simultaneous response with a sulfur-specific flame photometric detector (FPD) system.

The source of the aromatic hydrocarbons in the stormwater sample is not obvious based on the FID fingerprint (Figure 2-9). The FPD fingerprints, however, are distinct, and the similarity between the stormwater and crankcase oil fingerprints can be seen. On the basis of this information, Hunter and MacKenzie concluded that while the high boiling, high molecular weight components of several petroleum products may have contributed to the oil pollution in urban runoff, used crankcase oil appeared to be the most likely contributor.

All samples contained dibenzothiophene and phenanthrene and/or anthracene. The average concentration of dibenzothiophene in the three storms sampled ranged from 44.2 to 62.3 ng/l. Phenanthrene and anthracene could not be differentiated on the column used (MacKenzie and Hunter, 1979). The large unresolved envelopes are thought to be composed primarily of four and five-ring thiophenes as well as aromatic sulfides, thiols, and thianidans according to Martin and Grant (1965).

Another study which examined oil-and-grease-type compounds in urban runoff was performed by Wakeham (1978). The purpose of this study was to determine the contributions of petroleum hydrocarbons from several suspected sources to Lake Washington. Among the suspected sources investigated were

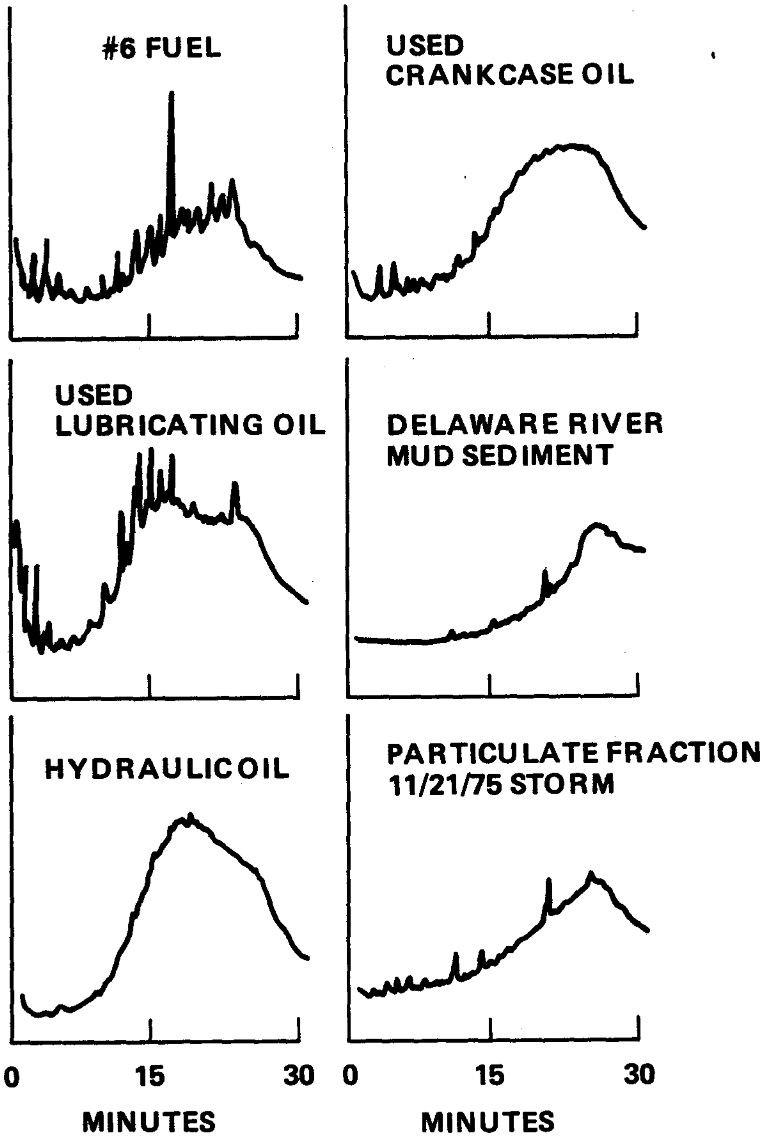

Figure 2-9 Gas Chromatograms of Aromatic Hydrocarbons Using a Flame Ionization Detector (MacKenzie and Hunter, 1979)

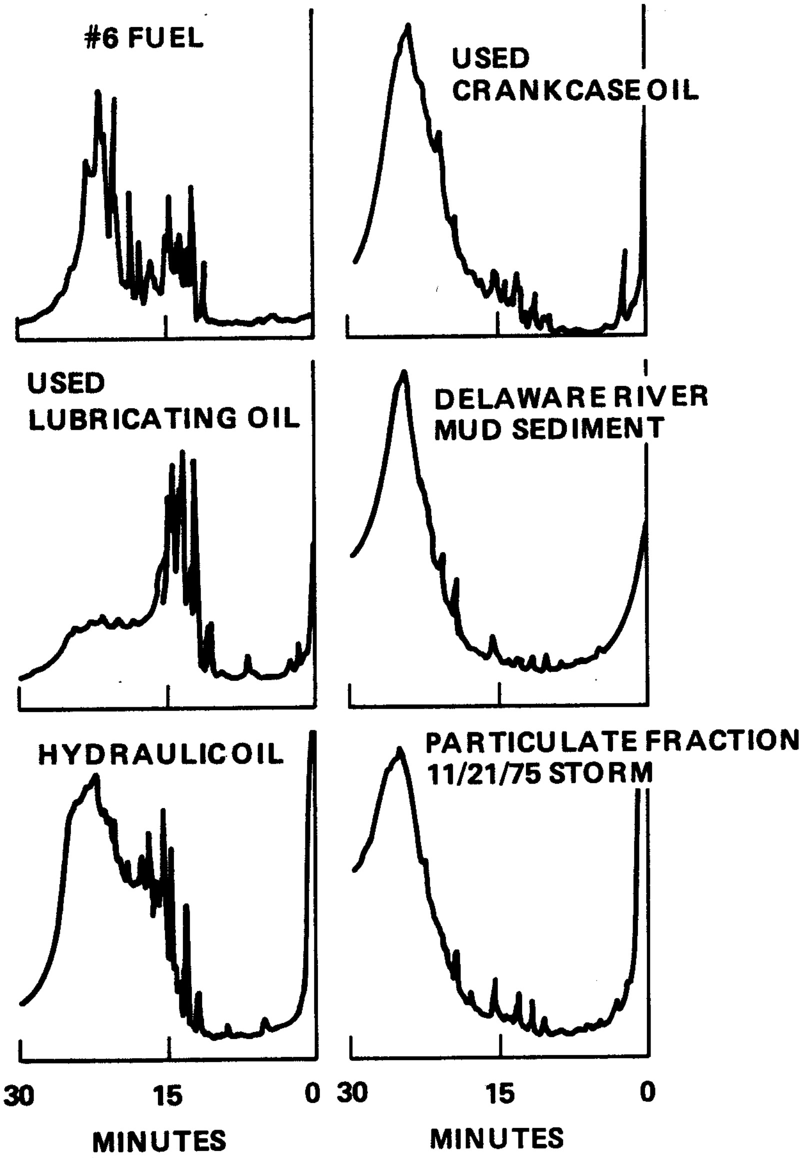

Figure 2-10 Gas Chromatograms of Aromatic Hydrocarbon Fractions Using a Flame Photometric Detector-Sulfur Mode (MacKenzie and Hunter, 1979)

urban stormwater runoff from Seattle (3 sampling sites) and the runoff from two freeway bridges which cross Lake Washington. Fifty stormwater samples were collected over a 15-month period.

The bridge and urban stormwater runoff was collected in stainless steel buckets and transferred to glass bottles prior to returning to the lab for extraction and analysis. No attempt was made to collect samples at beginnings of storms. Samples were extracted three times with pentane, and the pentane extractables were subsequently charged to columns of alumina packed over silica gel. The columns were then eluted with pentane. Following evaporation of the pentane solvent, the elutes were weighed on an electrobalance. The molecular composition of the aliphatic hydrocarbons was then analyzed by gas chromatography using flame ionization detectors.

Wakeham (1978) observed that the chromatograms of urban and bridge runoff water show primarily a large unresolved complex mixture of cyclic and branched saturated hydrocarbons. In addition, he notes that odd-carbon chain length paraffins are present in nearly equal concentrations as are paraffins with even-carbon chain lengths. The presence of these two features are generally indicative of petroleum-type hydrocarbons (Wakeham, 1978). Wakeham also cites the radio-carbon age (35,000 yrs) of the hydrocarbons as further evidence of their petroleum origin.

Wakeham (1978) suggests that the petroleum hydrocarbons are due to discharges of lubricating oils from automobiles. The evidence which he cites as suggesting this source is the gas chromatogram pattern of a large unresolved envelope coupled with small paraffin peaks (indicative of dewaxed lubrication oils). He notes the similarity of the chromatograms of used motor oil and stormwater runoff, as shown in Figure 2-11.

Transport Mechanisms

Between the time of the initial release of hydrocarbon pollutants at their source and their final deposition by stormwater runoff into receiving waters, chemical and physical processes take place that change the character of the pollutant. One obvious change that occurs is the rapid evaporation of lighter hydrocarbon fractions, making weathered hydrocarbon samples sharply depleted in the low carbon range as compared to unweathered samples. Some degradation of the hydrocarbon may occur at the original release site, but this is essentially a slow process and depends strongly on the environment of release. Hydrocarbons absorbed by soils may be completely degraded by bacteria and never reach receiving waters. Hydrocarbons deposited on roadways will undergo little or no degradation before transport to receiving waters.

The physical state of the hydrocarbons in stormwater is important because it determines the fate of the pollutant in the environment and thus determines its potential environmental effects. The design of mitigation measures is also determined by the state of the hydrocarbons at the time of treatment. Hydrocarbons in storm water can exist as free oil on the surface of the water or adsorbed onto particles; or as dissolved or colloidal oil mixed with the water itself. Free oil can be skimmed from the surface, and particulates settle out to be deposited in bottom sediments. Dissolved or colloidal oil is difficult to remove, requiring some form of chemical intervention to separate it out. Dissolved and colloidal hydrocarbons are also most hazardous environmentally since they are most easily available for uptake by marine organisms.

As has been previously stated, about 85% of all hydrocarbons in urban stormwater runoff are in association with particulates. These particulates are separated from solution by filtering or by some gravimetric process such as centrifugation. They therefore include either agglomerations of oil droplets, or solid particles with hydrocarbons adsorbed to their surfaces, or most probably some mixture of the two. These two types of particulates are indistinguishable with respect to their physical behavior although they are chemically different.

It is not clear how the hydrocarbons come to be in conjunction with particulates. Several mechanisms are possible. The hydrocarbons may drip onto a surface and associate there with pre-existing particulates. They may be originally emitted in conjunction with particulates as in emissions from automobile tailpipes or from stationary furnaces burning hydrocarbon fuel. Agglomerations of hydrocarbons may form on dry surfaces and be picked up by stormwater, or the agglomerations may form within the runoff stream. Similarly, free or dissolved hydrocarbons can adsorb onto particle surfaces during transport by storm water. Probably several, if not all, of these mechanisms operate on the hydrocarbons found in urban storm water runoff.

Whatever the mechanism of association, it is clear that most hydrocarbons in urban runoff are associated with particulates and therefore an understanding of the transport dynamics of particulates is vital to an explanation of the transport of hydrocarbons. A Washington D.C. study (Shaheen, 1975) determined that the street dust and dirt fraction (particles less than 3.35 mm in diameter) is composed primarily of local minerals and materials abraded from the road surface. 95% of this material is insoluble and inorganic. Traffic dependent rates of deposition onto roads of total dust and dirt (2.38×10^{-3} lb/axle-mile) were determined by this same study. While these deposition rates are constant, the actual accumulation of pollutants on roadways does not proceed at a constant rate but levels off after a time, as shown in Figure 2-12. Shaheen (1975) determined the ratio of pollutant loadafter three days deposition to pollutant load after one day. The ratio

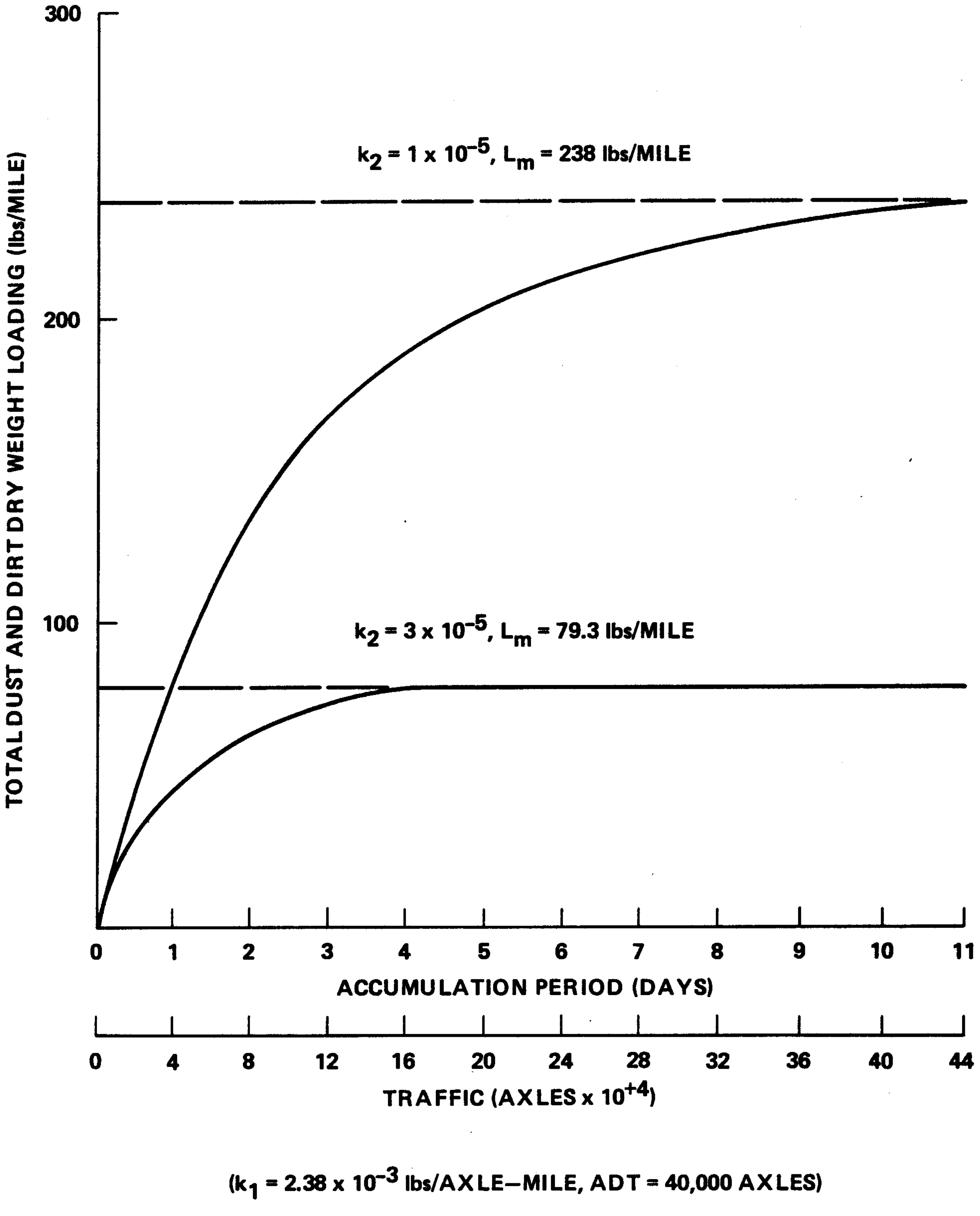

Figure 2-12 Total Dust and Dirt Dry Weight Accumulations (Shaheen, 1975)

for particulates was 1.43, and that for oil and grease was 1.42. The close similarity of these ratios supports the evidence that hydrocarbons are primarily associated with particulates. This leveling off of pollutant load on roadways takes place in the absence of street sweeping or flushing by storms. It is caused by removal of particulates from the road by winds and by traffic action. Thus it appears that road surfaces have a saturation level for particulates, and hence for hydrocarbons, since hydrocarbons are found primarily in conjunction with particulates.

Sartor et al (1974) obtain similar results as shown in Figure 2-13, but they interpret their data as showing a loading rate which decreases with time to a small constant non-zero value. Thus the pollutant load would continue to increase slowly, and surfaces would not saturate. There is insufficient data at this time to decide between these two interpretations of the data.

The experimentally observed leveling off of pollutant load has various effects on general storm water pollution. If the material blown off the road is transported to another surface with a high runoff coefficient K, such as a sidewalk or a parking lot, no net reduction in runoff pollution occurs. However, if the particles end up on a low K surface such as a green belt, the particles may be retained through storm events, yielding a net decrease in pollution.

The tendency for particulate loading and thus for hydrocarbon loading to level off with time makes it less likely that the time between storms will be proportional to hydrocarbon pollutant levels. It is possible that the particulates on roadways will become more saturated with hydrocarbons as the time between cleaning or storm events increases. This seems consistent with the theory that total storm pollutant load is independent of the time since the previous storm, but that the degree of concentration of hydrocarbons in

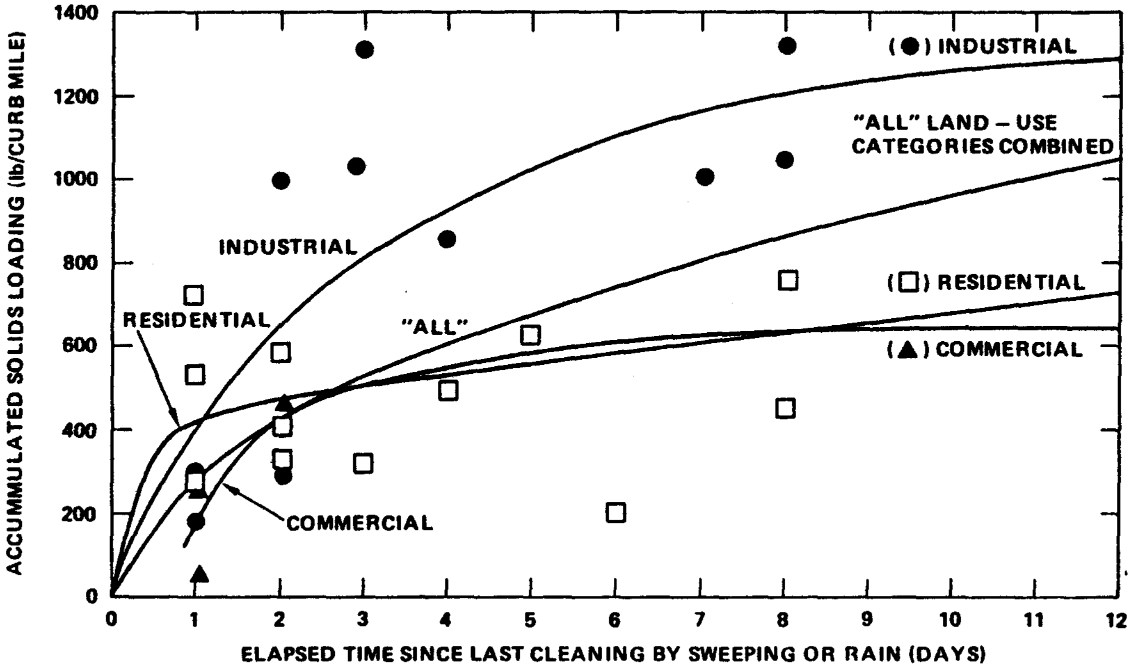

Figure 2-13 Accumulation of Pollutants by Land Use (Sartor et al, 1974)

the first flush is a function of the length of the antecedent dry period (Weibel, 1964). Highly saturated surface particulates from roadways would probably be strongly represented in the first flush waters.

The dynamics of particulate transport would allow extraneous factors to influence particulate concentration and hence hydrocarbon concentration in storm waters. Consider two identical storms preceded by the same number of dry days. If one storm is preceded by high winds that blow hydrocarbon bearing particulates out of the area, or off of high K surfaces, such as roads, and onto low K surfaces such as open land, the runoff waters from that storm will have lower hydrocarbon concentrations. Hydrocarbon concentration can easily be influenced by winds since the smallest particulate fraction, which are most vulnerable to wind transport, contain the greatest proportion of hydrocarbons.

Oil and grease accumulation rates for various land uses were estimated for the EPA's Storm Water Management Model (SWMM) (Huber et al, 1975; Metcalf and Eddy Inc., 1971). These rates, which are based on engineering judgement and not on experimental data, are presented in Table 2-5. Shaheen (1975) reports that land use does indeed affect accumulation rates. The SWMM estimated rates are constant and do not include the leveling off with time which is experimentally measured by Shaheen (1975) and Sartor et al (1974). For this reason accumulation is taken to be proportional to the time since the previous storm.

Road characteristics also have an effect on pollutant loads. Shaheen (1975) reports that high curbs allow larger concentrations of particulates by acting as wind shields. Figure 2-14 shows his results. Where curbs are lower the particulate distribution contains fewer smaller particles which are more

TABLE 2-5 GREASE ACCUMULATION

(Metcalf and Eddy Inc., 1971)

Type	Land Use	mg/dry day/100 ft-curb
1	Single family residential	318
2	Multiple family residential	1,044
3	Commercial	1,498
4	Industrial	2,088
5	Undeveloped or park	681

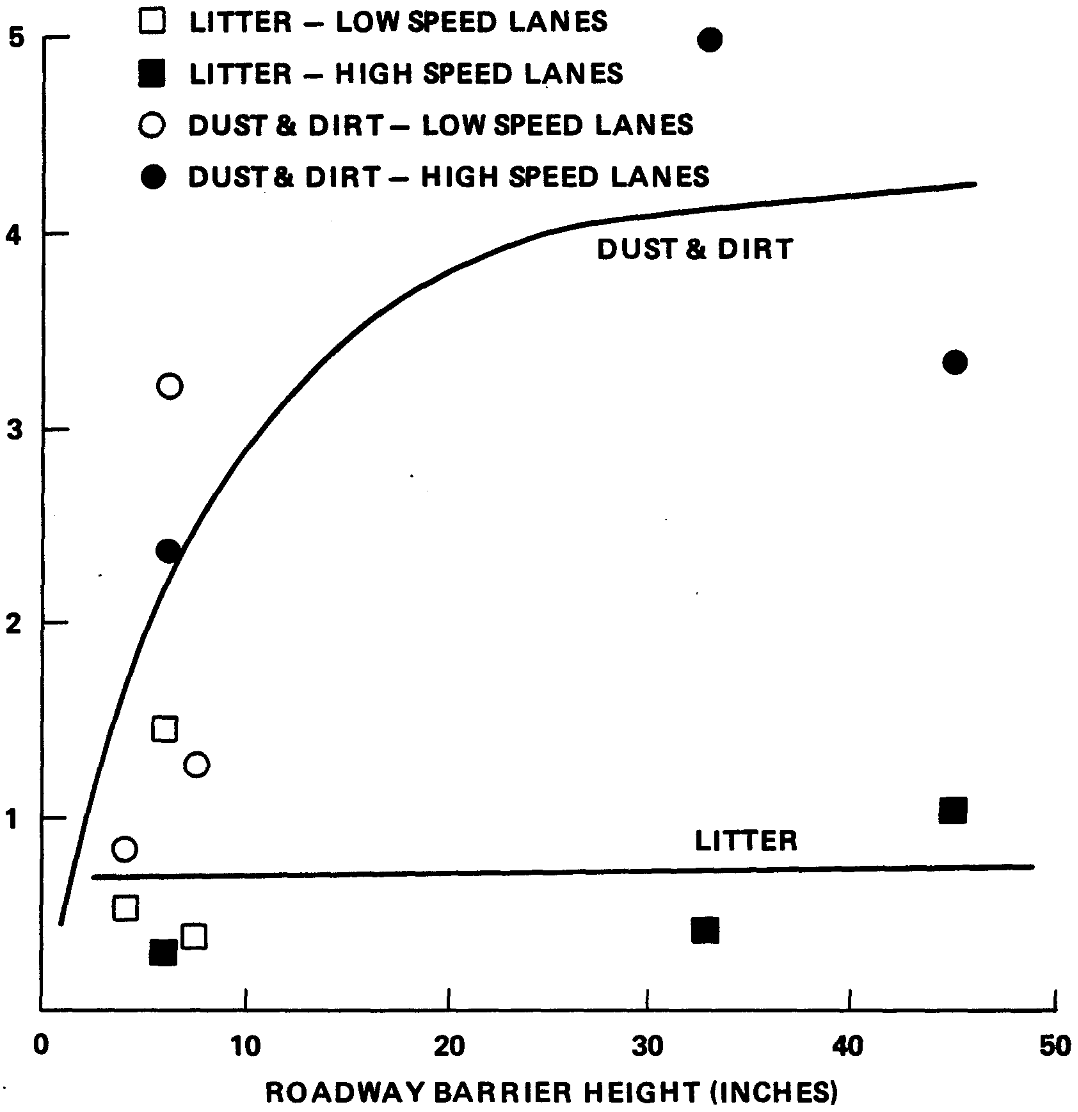

Figure 2-14 Per Axle Dry Weight Loading vs. Roadway Barrier Height (Shaheen, 1975)

easily transported over the barrier by winds. For any curb height, the greatest concentration of pollutants is found near the curb (Sartor et al., 1974). Shaheen (1975) proposes two alternate ways in which this effect may be utilized. Roadways could be built without curbs to allow wind transport of particulates to adjoining greenbelts. Conversely, high curbs could be built to trap particulates, especially the smaller size fractions that carry the most hydrocarbons. These roadways would then be mechanically cleaned periodically. A difficulty with this concept is that if cleaning were not frequent enough, the roadways with their high curbs would provide a very efficient system for transportation of hydrocarbons to receiving waters during storms. Also it is known (Shaheen, 1975; Sartor et al, 1974) that street sweeping efficiency falls off greatly for smaller particulates. Thus the particles most likely to be left behind by traditional mechanical cleaning methods are precisely those it is most important to remove.

Road surfacing material also influences the degree of particulate pollution (Russell and Blois, 1980; Sartor et al, 1974), with concrete surfaces contributing fewer particulates and hence less hydrocarbons than does asphalt. Road surface condition is cited as an important criterion in some studies (Sartor et al, 1974), and is considered unimportant in others (Russell and Blois, 1980). Poor road surfaces can provide local areas for high production and retention of particulates, producing high hydrocarbon content in storm runoff.

Summary

Hydrocarbons in urban stormwater runoff are found mostly in association with particulates. Since particulates are a major pollutant in stormwater runoff (Sartor et al, 1974; Sonderlund and Lehtinen, 1972), perhaps hydrocarbon removal can best be accomplished in conjunction with particulate removal. More work is required to identify the percentage contributions of the various hydrocarbon sources to pollution. Crankcase oil has been identified as a major contribution, and the consistently higher contributions from roadways than from residential sites implies that emissions during vehicle operation either from engine leakage or crankcase drippings are a more important source than illegal dumping. Since the GC profile of tailpipe exhaust so closely resembles that of crankcase oil, further study is required to differentiate between these sources to better determine source control measures.

CHAPTER 3

BIOLOGICAL EFFECTS OF OIL AND GREASE

Introduction

In the past decade, interest in the biological effects of hydrocarbons on marine organisms has increased as efforts have been made to control significant pollutant releases into the marine environment. A large body of literature on the effects of hydrocarbon pollution on marine organisms has been published and several recent review articles (NAS, 1975; Anderson, 1979; AIBS, 1976; Malins et al, 1977; API, 1977) have summarized the results of recent studies and assessed the current state of knowledge on the effects of oil pollution.

Most of the work done on the biological effects of oil on marine life has been in response to oil spills. However, petroleum-derived hydrocarbons are regularly released into estuarine environments in proportion to surrounding urbanization and technological developments (Di Salvo et al, 1975). Both the quantity and the quality of oil from spills may differ significantly from that in urban runoff, resulting in substantially different effects on the marine environment. Spills expose marine life to much higher concentrations at any one time than oil and grease from surface runoff.

Oil Types

The types of petroleum or petroleum products most commonly released into the marine environment are crude oils, Bunker C or No. 6 fuel oils, diesel or No. 2 fuel oils, and light petroleum products such as kerosenes or gasolines (NAS, 1975). The composition of these oils are significantly different. Bunker C fuel oils are the heaviest distillate fractions of petroleum. The great majority of compounds in Bunker C oil in the C_{30}+ range, and typically consist of 15% paraffins, 45% naphthenes, 25% aromatics, and 15% polar NSO compounds.

No. 2 fuel oils represent a middle distillate fraction of petroleum composed almost entirely of hydrocarbons in the range C_{12} to C_{25}. By molecular type, 30% are paraffins, 45% are naphthenes, and 25% are aromatics.

Light petroleum products are made up of virgin and cracked components. Kerosene contains hydrocarbons in the C_{10} to C_{12} molecular weight range, typically 35% paraffins, 50% naphthenes, and 15% aromatics. Gasoline contains hydrocarbons in the range C_5 to C_{10}, typically 50% paraffins, 40% naphthenes, and 10% aromatics for virgin gasoline and 20 to 30% aromatics in blended gasoline (NAS, 1975).

Oil in Urban Runoff

The predominant contributor to oil and grease in urban runoff is most likely used automotive crankcase oil, a refined distillate petroleum product. Wakeham (1977) attempted to characterize the sources of petroleum hydrocarbons in Lake Washington and collected data suggesting that hydrocarbons from urban stormwater runoff come from discharges of lubricating oils from automobiles. Whipple and Hunter (1979) concluded that petroleum hydrocarbons in urban runoff resemble used crankcase oil and contain toxic chemicals such as the polynuclear hydrocarbons, naphthene, pyrene, fluoranthene, chrysene, and benzo (a)-pyrene.

Once released into the environment, crankcase oils may undergo considerable modifications before they enter the marine environment. Oils exposed to the atmosphere may become extensively "weathered" which primarily involves the evaporative loss of lower molecular weight hydrocarbons from the oil- water mixture, leaving behind the heavier molecular weight component (Garza and Muth, 1974; MacKenzie and Hunter, 1979).

Crankcase oils have different components than crude oils and fuel oils. Crude oils and fuel oils contain homologous series of n-alkanes and branched alkanes, napthenes, aromatic hydrocarbons, and non-hydrocarbon components, (Farrington and Quinn, 1973). Lubricating oils, however, are usually dewaxed, that is the n-alkanes and branched alkanes are removed (Farrington and Quinn, 1973; Blumer et al, 1970).

Oil Toxicity

The soluble fractions of petroleum are probably the most harmful to marine organisms. Discharges into estuaries may be especially damaging since they pollute shallow water areas that serve as nursery areas for many coastal marine biota (NAS, 1975). Toxicity may vary widely among different types of oil because the composition and concentration of individual hydrocarbons present in the oil varies. Anderson et al (1974) found that the water soluble fractions of crude oils were richer in light aliphatics and single-ring aromatics than the water soluble fractions of refined oils, which contained higher concentrations of naphthalenes. In general, the water solubility of hydrocarbons drops drastically as one goes to higher carbon numbers. Solubility can also change with degradative processes; for example, naphthalene (solubility, 32 pm) can be oxidized to d-naphthol (solubility, 740 ppm) (NAS, 1975). Ric~~h~~e et al (1977) have made a number of observations on the comparative toxicity of oils:

1. Toxicity of crude and refined oils depends on the concentration of toxic compounds in the oil and on physical factors, such as the temperature and

viscosity of the oil, which affect transport of petroleum hydrocarbons into the water.

2. Refined oils are generally considered more toxic than crude oils because they often have higher concentrations of aromatic hydrocarbons and are usually less viscous than crude oils.
3. Oil toxicity is apparently due to the soluble compounds in the water rather than dispersed droplets.
4. Toxicity of aromatic hydrocarbons increases with the number of rings and with the degree of alkyl substitution. Solubility decreases with these factors so that the relative importance of individual aromatic hydrocarbons to toxicity of water soluble fractions is unknown. Mono- and dinuclear aromatics probably account for most of the toxicity in water soluble fractions.

Recent results suggest that aromatics, in particular naphthalene and naphthalene type compounds, are probably the most toxic (De Vries, 1979).

Table 3-1 summarizes the data from several studies on the comparative toxicity of different aromatic hydrocarbons. The results are quite consistent for the six species tested. Mono-aromatics are the least toxic; acute toxicity increases with increasing molecular size up to the four-and five-ring aromatic compounds which have very low water solubility. Increasing the number of side chains on the aromatic nuclears (alkylation) of one, two, and three-ring compounds, such as benzenes and naphthalenes, results in higher toxicity. The position of side chains may also influence the toxicity of aromatics (Caldwell et al 1977).

To a certain degree, it is possible to predict the toxicity of a given oil based on the relative concentration of toxic aromatics present in the oil. For example, No. 2 fuel oil is more toxic than crude oils since it

TABLE 3-1 COMPARATIVE TOXICITY OF DIFFERENT AROMATIC HYDROCARBONS, EXPRESSED IN 96-HR LC_{50}'S WITH CONCENTRATIONS IN PPM. ASTERISK (*) INDICATES THAT TOXIC CONCENTRATIONS WERE ABOVE SOLUBILITY LIMITS (Rice et al, 1976).

AROMATIC H.C.	96-hr LC_{50}'s in ppm					
	POLYCHAETE[1]	SHRIMP[2]	CRAB LARVAE[3]	SHRIMP[4]	BASS[5]	GOLDFISH
Benzene	--	27	108	20	5.8-10.9	--
Toluene	--	95	28	4.3	7.3	22.8
Ethyl benzene	--	--	13	0.5	4.3	--
Tri-methyl benzene	--	5.4	5.1	--	--	12.5
Xylene	--	7.4	--	--	--	16.9
m-	--	--	12	3.7	9.2	--
o-	--	--	6	1.3	11.0	--
p-	--	--	--	2.0	2.0	--
Naphthalene	3.8	2.4	>2			
Methyl naphthalene	--	1.1	1.6			
Di-methyl naphthalene	2.6	0.7	0.60			
Tri-methyl naphthalene	2	--	--			
Phenanthrene	0.6	--	--			
Methyl phenanthrene	0.3	--	--			
Fluorene	1	--	--			
Fluoranthrene	0.5	--	--			
Chrysene	*	--	--			
Benzo-(a)-pyrene	*	--	--			
1,2,5,6-Dibenzanthracene	*	--	--			

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[1] Neff et al (1976). Neanthes araenaceodentata

[2] Neff et al (1976). Palaemonetes pugio

[3] Caldwell et al (This symposium). Cancer magister, Stage I larvae

[4] Benville and Korn (In press). Crago fraciscorum

[5] Benville and Korn (In press). Morone saxatilis

[6] Brenniman et al (1975). Carassius auratus

contains more aromatics (NAS, 1975). Crankcase oils have been shown to be particularly toxic to aquatic organisms. Virgin crankcase oils contains relatively high concentrations of polycyclic aromatics (PAH) as a result of considerable refining and processing (Neff, 1976).

PAH (naphthalenes and phenanthrenes) have high toxicity and persistence in the marine environment (Linden et al, 1979). The presence and concentration of specific PAH in oil are influenced by a number of factors including the composition of the crude oil from which the petroleum product is derived, and refining conditions such as temperature and catalysts. Carcinogenicity observed in human or in experimental animals following exposure to some materials derived from fossil fuels appear to be partly due to polycyclic aromatic hydrocarbons (Bingham and Yolk, 1969).

Payne et al (1978) have tested the mutagenicity of crude oils and both new and used crankcase oil fractions toward Salmonella typhimurium strain TA-98. Positive results were obtained only with used crankcase oils; however, it appears that compounds other than benzopyrene or benzanthracene (which are produced in automobile engines) are the major mutagenic sources. Previous work had demonstrated that fish taken from sites with a history of oil contamination had elevated AHH (aromatic hydrocarbon hydroxylases) levels. AHH are enzymes involved in the bioactivation of aromatic compounds to mutagens in mammalian systems and are known to occur in most marine organisms. In some mammalian systems there is a relationship between AHH activity and susceptibility to hydrocarbon-induced cancers. This may have implications for human health since hazards to humans could come from eating oil-contaminated seafood, particularly if carcinogens such as polycyclic aromatic hydrocarbons (PAH) are present (NAS, 1975).

Petroleum hydrocarbons that combine with other organic and inorganic substances in water and sediments such as pesticides, PCBs, and chlorine compounds may be considerably more toxic than each substance by itself (Blumer et al, 1977; Laughlin et al, 1978). The synergistic effects of these combined products may also result in greater fat solubility and high bioaccumulation potential. The photooxidation of oils may produce toxic hydrocarbon products or increase the toxicity of oil constituents (Payne et al, 1978).

Petroleum Hydrocarbons in Water and Sediments

The fate of petroleum hydrocarbons released into the marine environmental is not completely understood. However, transient storage compartments include water, marine organisms, and sediments, with sediments probably being the most significant long-term storage site (Di Salvo *et al* , 1975). Losses of hydrocarbons from the system may occur through evaporation, tidal and riverine flushing, and microbial degradation. Farrington and Quinn (1973) have provided some evidence for these processes in the marine environment with their analysis of hydrocarbons in surface sediments and clams (*Mercenaria mercenaria*) in Narrangansett Bay.

In another study, clam (*Tapes japonica*, *Mya arenaria*) and mussel (*Mytilus edulis*) samples from around the Bay Area were found to be contaminated with different concentrations of hydrocarbons (Guard, 1981). Hydrocarbon tissue contents, analyzed by thin layer chromatography, ranged between 20 ppm to 220 ppm, from the cleanest to dirtiest point. Interestingly, the majority of the unsaturated fraction of hydrocarbons seemed to be composed of highly alkylated mono- and di-aromatics. Previous work by MacKenzie and Hunter (1979) reported a disappearance of diaromatics through weathering in urban runoff. This could suggest that the hydrocarbons found in clams and mussels analyzed might come from oil directly spilled into the bay rather than from automotive lubricative oil in stormwaters.

Other studies have also shown that petroleum hydrocarbons can accumulate in bottom sediments. Often, these accumulated hydrocarbons undergo little breakdown and are released into the water column over an extended period of time. Thus, polluted sediments are a major source of chronic hydrocarbon pollution.

Blumer (1970) found that essentially unaltered No. 2 fuel oil was present in sediments two months after a major spill and that various components of the oil were being released into the water. MacKenzie and Hunter (1979) and Wakeham (1977) found that river and lake bottom sediment accumulated petroleum hydrocarbons from storm-water runoff and that little degradation of the most toxic oil fractions had occurred. The major contributing pollutant in these studies was found to be used crankcase oils. Petroleum hydrocarbons tend to accumulate in sediments for the following reasons:

1. Hydrocarbons adsorbed to particulate matter settle out of the water column as they become heavier and less soluble.
2. Petroleum hydrocarbon degrading bacteria preferentially attack low molecular weight, straight chain hydrocarbons, leaving other oil constituents behind, and
3. As oil components are degraded, oxygen is depleted in the sediments, preventing further breakdown (Farrington and Quinn, 1973) ; MacKenzie and Hunter, 1979).

Oil pollutants in sediments can concentrate fat-soluble poisons by acting as "partitioners" to retain substances which have a low solubility in water but a higher solubility in petroleum hydrocarbon mixtures. Oil pollutants may adsorb to particulate matter containing toxic organic compounds such as DDT or

PCBs and chemically interact with these and other adsorbed constitutents (Blumer et al, 1970; MacKenzie and Hunter, 1979). Hydrocarbons may also combine with chlorine compounds to produce chlorinated hydrocarbons (Whipple and Hunter, 1979). Hartung and Linger (1970) found that combined levels of chlorinated hydrocarbons in river sediments approached levels similar to insecticide applications and that such polluted areas were devoid or very deficient in benthic arthropods. Numerous investigations have shown that bacteria preferentially metabolize n-alkanes and branched alkanes relative to naphthenic and aromatic hydrocarbons (Farrington and Quinn, 1973). Bacterial degradation has little effect on the less soluble aromatics and higher molecular weight compounds (Tanacredi, 1977). Since hydrocarbon in urban runoff appears to consist primarily of used crankcase oils which contain relatively high concentrations of higher molecular weight compounds especially if weathered, bacterial decomposition is not likely to be extensive. Wakeham (1977) found that hydrocarbons entering Lake Washington from urban runoff are not rapidly dispersed or degraded by microorganisms but they are being incorporated in increasing concentrations in lake sediments.

Effects on Marine Organisms

The toxic effects of oil pollution may be acute or sublethal. Although sublethal effects do not kill an organism outright, they may reduce the ability of marine organisms to survive and reproduce in their normal environment (Linden et al, 1979), effectively eliminating some species over a longer period of time.

The standard method for determining lethal concentrations of petroleum hydrocarbons is to expose aquatic species to various concentrations of the test substance for a given time period, usually for 96 hours. The minimum concentration that produces mortality in half of the population at the end of the exposure period is considered lethal. This concentration is designated as the 96-hour LC_{50} or TL_m. Neff et al (1976) reported a 96-hour LC_{50} of 0.3 to 0.6 ppm for the aromatic compounds, 1-methylphenanthrene, fluoranthene, and phenanthrene in the polychaete, Neanthes arenaceodentata. The toxicity (96-hour LC_{50}) of crude oil in water to a variety of adult marine fish and invertebrates tested in static exposures ranges from one to 20 ppm. For No. 2 fuel oil, the range is 0.4 to 6 ppm (Anderson, 1979).

Hyland and Schneider (1976) as noted in Laughlin et al (1978) concluded that lethal effects of soluble aromatic hydrocarbon fractions occur in the one to 100 ppm range for adults and in the range 0.1 to 1 ppm for larvae and juvenile forms. Investigations have also indicated that very high concentrations associated with sediments are required to produce mortality. Lack of significant mortality is observed during exposure to concentrations in excess of 1,000 ppm (Anderson, 1979).

The wide variation of measurements and methods used in chemical toxicity studies makes it difficult to extrapolate the results from one study to another or from laboratory populations to natural populations. When assessing the potential impact of exposure to oil, it is crucial to know if some species or life stages are more sensitive than others to oil toxicity (Rice et al, 1977). It should be noted that historically most toxicity studies have been conducted with organisms capable of adapting to laboratory conditions, not the most sensitive species (Tatem, 1977).

Of greater concern in the case of urban runoff are the effects of sublethal concentrations of petroleum hydrocarbons on marine organisms. Sublethal concentrations are generally considered to be two orders of magnitude less than lethal concentrations for a given species, with lower concentrations considered "safe" (Anderson, 1977). Sublethal effects could result in reduction of populations in the field (Tatem, 1977). Linden (1976) and Wells and Sprague (1976) have found larval development and growth to be affected by low levels of petroleum hydrocarbons. Wells and Sprague have stated that the ratio of "safe" to acutely lethal concentrations of petroleum hydrocarbons was 0.03. This means that for many estuarine organisms which have acute LD_{50} values of 1.0 to 2.0 ppm, water concentrations remaining above 30-50 ppb for any length of time could be harmful (Tatem, 1977).

It is difficult to determine what parameters represent a reliable and sensitive method for determining the condition of an organism or the extent of stress on the animal following exposure to hydrocarbons. Respiration, osmotic and ionic regulation, behavior effects, growth and reproduction, morphological and histological effects, and biochemical alternations have all been suggested as indicators. Respiration has been used most frequently to determine the extent of stress (Anderson, 1977). Measurements of respiratory rate during or after exposure to No. 2 fuel oil indicate that a range of 0.1 to 0.85 ppm total naphthalenes produces a response that differs significantly from those of control animals. Tissue analyses show measurable amounts of naphthalene during this time (Anderson, 1977).

Anderson (1977) has summarized some recent studies used to determine the effects of petroleum hydrocarbons on growth and reproduction. These results are shown in Table 3-2. The concentrations of both total hydrocarbons and total aromatics shown to reduce growth and/or survival range from about 0.2 to 10 ppm.

There are few adequate studies on behavioral effects. The fish, Fundulus similus exhibits abnormal behavior at brain concentrations of 200 ppm. Suppression in the locomotor activity of an amphipod and a coelenterate medusa

TABLE 3-2 SUMMARY OF EFFECTS OF PETROLEUM HYDROCARBONS ON THE GROWTH AND REPRODUCTION OF MARINE ANIMALS

Species	Oil	Exposure (days)	Concentration (ppm)[1]			Growth or Reproduction Parameter	Reference
			TH	TN	TA		
FISH							
Fundulus similus	So.La.C[2]	20	16.0	0.2	9.7	4% hatch of eggs	Anderson et al, 1979
Cyprinodon variegatus	No.2 FO[3]	7	2.0	0.6	1.7	0% hatch of eggs	Anderson et al, 1979
Oncorhynchus gorbuscha	Prudhoe Crude	10	0.7			Reduced growth rate of pink salmon fry	Rice et al, 1975
DECAPODS							
Cancer magister	Alaskan Crude	60			0.2	Reduced survival of zocae on long-term exposure	Caldwell et al, 1977
Rithropanopeus harrasii	No. 2 FO	27	1.0	0.3	0.9	Reduced survival and extended development to megalopa	Neff et al, 1976
Palaemonetes pugio	No. 2FO	27	0.9	0.3	0.8	Reduced growth rate larvae	Tatem, 1977
		3	1.4	0.6		Reduced viability of eggs from exposed gravid females	
Paralithodes camtschatica	Cook Inlet Crude	1-4	1.6			Inhibition of molting in larvae	Mecklenburg, 1977
Pandalus hypsinotus	Cook Inlet Crude	1-4	1.2			Inhibition of molting in larvae	
Homarus americanus	Venezuelan Crude	30	0.14			30 day LD_{50} and retarded development of larvae	Wells and Sprague, 1976

(continued)

TABLE 3-2 (continued)

Species	Oil	Exposure (days)	Concentration (ppm)[1]			Growth or Reproduction Parameter	Reference
			TH	TN	TA		
AMPHIPODS							
Gammarus oceanicus	Crude	60	0.3-0.4			Reduced growth rate of larvae	Linden, 1979
POLYCHAETES							
Neanthes arenaceodentata	No.2 FO	22	1.0	0.3	0.9	Reduced growth rate of larvae	Rossi, 1976
	No.2 FO	28	0.3	0.1		Reduced growth of juveniles by 30%	Anderson, 1979
Ctenodrilus serratus	No.2 FO	28	2.2	0.5	1.4	Reduced survival and reproduction	Carr and Reish, 1977
	So.La.C	28	9.9	0.2	7.0		
Ophyrothrocha sp	No.2 FO	28	1.3	0.3	0.9		
	So.La.C	28	9.9	0.2	7.0		

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[1] TH, total hydrocarbons; TN, total naphthalenes: TA, total aromatics

[2] South Louisiana Crude Oil, API reference oil

[3] High aromatic (38%) No.2 Fuel Oil, API reference oil

was observed after exposure to extracts of four oils at 15 ppm or greater (Anderson, 1979). In general, levels of 0.1 to 0.3 total naphthalenes, regardless of the oil, appear to be the lowest concentrations in water which produce abnormal and deleterious responses during long-term exposure to sublethal levels of petroleum hydrocarbons.

Bioaccumulation is an additional concern with oil pollution. Bivalves tend to slowly and constantly accumulate hydrocarbons while fish and shrimp take up hydrocarbons very rapidly, reaching maximum levels within a few hours (Anderson, 1979). Accumulation of aromatic hydrocarbons in tissues of marine animals appears to be dependent on partitioning of the hydrocarbon between the exposure water and the tissue lipids (Neff et al, 1976). When animals are returned to oil-free seawater, they rapidly release accumulated hydrocarbons from their tissues. Release usually takes 2 to 60 days, depending on the species (Neff et al, 1976).

Lee (1977) has reviewed studies on the accumulation and turnover of petroleum hydrocarbons in marine organisms. Zooplankton can take up a variety of aromatic and paraffinic hydrocarbons from either food or water. Most of the aromatics are lost in depuration studies with a half life of 2 to 3 days. Crustaceans (shrimp, crab, lobsters) can also take up hydrocarbons from food or water.

Depuration varies with species. Deposit-feeding worms take up organic pollutants associated with sediments. Bivalves take up and concentrate hydrocarbons from water. A small amount of hydrocarbons are retained for a longer period after the initial, rapid depuration. Table 3-3 summarizes some results of studies on the toxicity of petroleum hydrocarbons to marine animals. The experiments present evidence that sublethal concentrations of petroleum hydrocarbons may have an adverse effect on marine organisms. Most of the

TABLE 3-3 TOXICITY OF SELECTED MARINE ORGANISMS EXPOSED TO PETROLEUM HYDROCARBONS

Compound Tested	Species	Experiment	Observations	References
No. 2 fuel oil So. Louisiana crude, Bunker C.	*Neanthes arenaceodentata* *Capitella capitata* (polychaetes)	Laboratory-reared polychaetes exposed to WSF* of oils	WSF of No.2 fuel oil more toxic than WSF of crude. For No. 2 oil 48-hr TL_m = 3.2 ppm (*Neanthes*) 48-hr TL_m = 3.5 ppm (*Capitella*). Adults more susceptible than juveniles.	Rossi et al, 1976; Rossi and Anderson, 1976
No. 2 fuel oil, So. Louisiana crude	5 polychaetes: *Ophryotrocha* sp. *O. puerilis* *Ctenodrilus serratus* *Capitella capitata* *Cirriformia spirabrancha*	Laboratory-reared polychaetes exposed to WSF of oils 2.2 4.1 >8.7 96-hr TL_m (crude oil) 12.9 ppm 17.2 >19.8 >19.8 >19.8 Suppression of reproduction at lower concentrations.	96-hr TL_m (No. 2 fuel oil) 2.9 ppm >8.7	Carr and Reish, 1977
Crude oil Benz (a) anthracene	*Capitella capitata* *Nereis virens*	Laboratory studies with oil mixed into sediments	Both species have a mixed function oxidase system that metabolizes PAH	Lee et al, 1979
Toluene, naphthalene, Cook Inlet crude, No. 2 fuel oil	*Oncorhynchus gorbuscha* (pink salmon)	Exposure to WSF at 4°C and 12°C	Breathing rates of fry exposed to toluene and naphthalene immediately increased. 24-hr TL_m, 12°C determined: 5.38 ppm toluene 0.92 ppm naphthalene 1.73 ppm aromatic hydrocarbons from crude WSF 0.65 ppm aromatic HC from No. 2 fuel oil WSF	Thomas and Rice, 1979

(continued)

TABLE 3-3 (continued)

Compound Tested	Species	Experiment	Observations	References
Naphthalenes	*Myoxocephalus* (sculpin)	Laboratory studies on physiology and biochemistry upon exposure	Fish take up naphthalene at concentrations as low as 0.025 pm. Tends to concentrate in the liver. Fish exposed to 1 ppm refused to feed, exposure caused lower rate of O_2 consumption, morphological changes in liver cells.	De Vries, 1979
Crude oil (Prudhoe Bay)	*Macoma inquinata* (clam)	Laboratory and field studies, exposure at 1,000 ug oil/g sediment	Behavior indicated stress; reduced survival; decrease in free amino acid levels in muscle and mantle; deterioration in physiological state as indicated by "condition index".	Roseijadi and Anderson 1979
No. 2 fuel oil	*Fundulus heteroclitus* (estuarine killifish)	Embryos and larvae exposed to WSF in laboratory	Hatching success decreased as WSF increased. Embryos exposed to 25% WSF take up naphthalenes in tissues depressed heart beat rate and O_2 consumption. Nine day biomagnification for naphthalenes was approximately 137.	Sharp et al, 1979
No. 2 fuel oil	*Rhithropanopeus harrissi* (mud crabs)	Crabs exposed continuously after after hatching to WSF containing 0.36 ppm total naphthalenes, 1.26 ppm total hydrocarbons	Acutely toxic to zoeal stages. Crabs able to recover from effect of chronic exposure. Sublethal concentrations to larvae were 0.3 to 0.9 ppm total hydrocarbons; 0.1 to 0.3 ppm total naphthalenes.	Laughlin et al, 1978
PAH	*Gillichthys mirabilis* (sand goby) *Oligocottus maculosus* (sculpin) *Citharichthys stigmaeus* (sand dab)	Studies on uptake, metabolism and discharge of naphthalene and 3,4 - benzopyrene	All 3 species took up more naphthalene than benzopyrene. Fish took longer to flush out naphthalene. Gall bladder was a major storage site.	Lee et al, 1972

(continued)

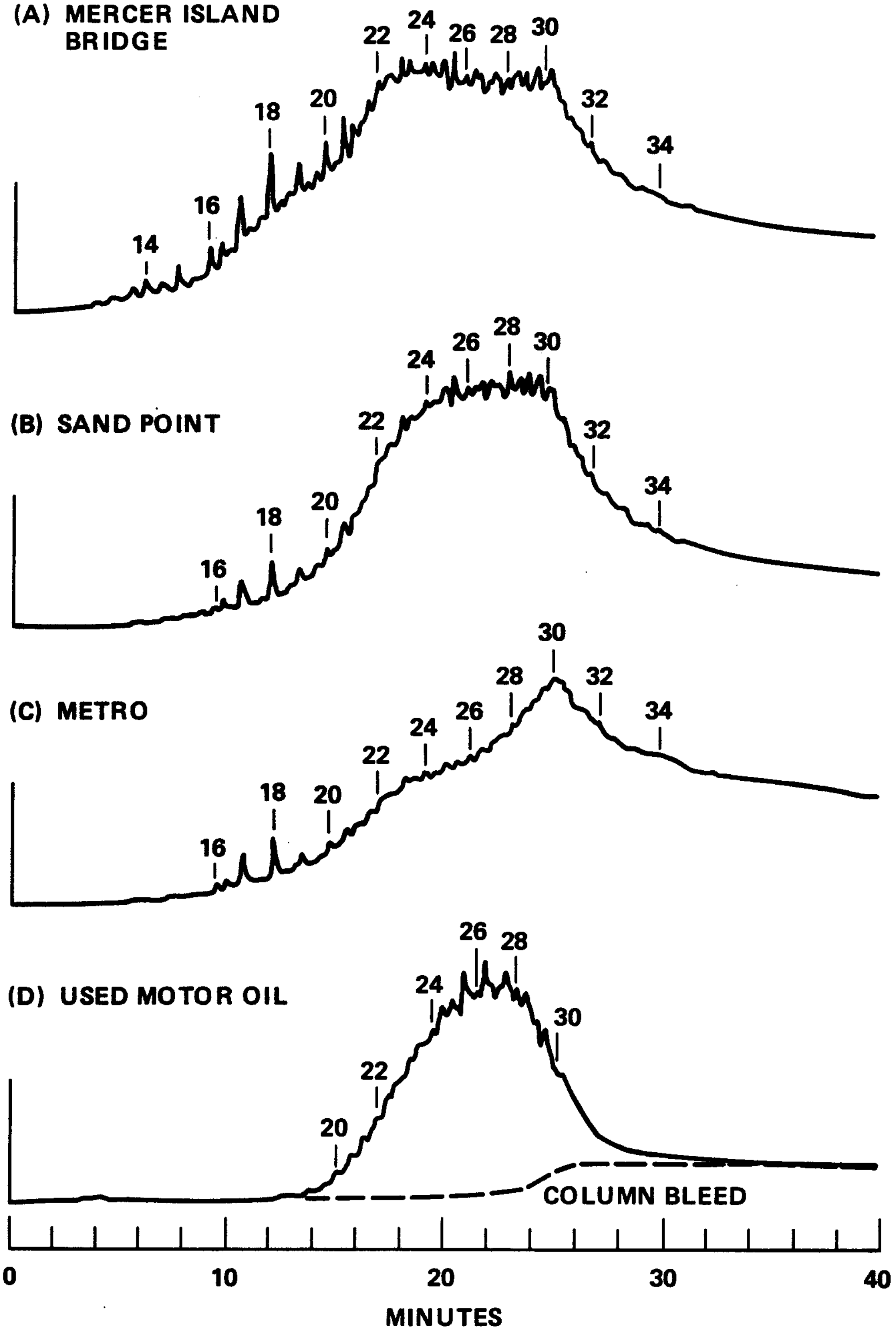

Figure 2-11 Gas Chromatograms on Apiezon L of Aliphatic Hydrocarbons (Wakeham, 1978)

TABLE 3-3 (Continued)

Compound Tested	Species	Experiment	Observation	References
No. 2 fuel oil	*Rangia cuneata* (clam) *Crassostrea virginica* (oyster) *Penaeus aztecus* (shrimp)	Laboratory exposure	Clams exposed for 24 hr to 6.28 ppm total dissolved hydrocarbons accumulated 13.6 ppm total naphthalenes in tissues. Clams accumulated BaP in tissue at 236-fold concentration-BaP slowly released over 30-58 days. Naphthalenes were the aromatic accumulated to the highest concentration by oysters. Shrimp and fish accumulate aromatics rapidly - tissue concentrations often reach maximum level within first hour of exposure. All species released hydrocarbons after exposure.	Neff et al, 1976
Waste oil	*Mytilus edulis* *Mytlus californianus* (mussels)	Field studies	Mussels transferred from clean water stations to polluted stations took up hydrocarbons. When replaced in clean water, hydrocarbon content approached clean water baseline values.	Di Salvo et al, 1975
Petroleum Hydrocarbons	*Mercenaria mercenaria* (clam)	Analysis of hydrocarbons in surface sediments and clams from Narragansett Bay	Sediments and clams contaminated by petroleum hydrocarbons.	Farrington and Quinn, 1973
No. 2 fuel oil	*Palaemonetes pugio* (grass shrimp)	Exposure to 2.6 ppm petroleum hydrocarbons and 0.55 ppm total naphthalenes	After six hours, tissue levels of methylnaphthalenes were 150 times greater than water levels; sublethal effects occurred at concentrations of less than 0.5 to 1.0 ppm.	Tatem, 1977

(continued)

TABLE 3-3 (continued)

Compound Tested	Species	Experiment	Observations	Reference
No. 2 fuel oil	*Crassostrea virginica* (oyster)	Exposure to various concentrations	For concentrations up to 450 ug/l, initial rate of uptake directly related to concentration. Uptake approached equilibrium after 5-6 weeks. After 4 weeks of depuration, concentration remained at levels over 30 times higher than those prior to exposure	Stegeman and Teal, 1973
No. 2 fuel oil	*Fundulus heteroclitus* (estuarine killifish)	Combined effects of salinity, temperature, and chronic exposure of WSF on survival and development of embryos.	0.47 ppm total naphthalenes highly toxic under all conditions. Exposure to oil decreases time interval between fertilization and hatching	Linden et al, 1979
Crude oils, No. 2 fuel oil Bunker C fuel oil	*Cyprinodon variegatus* (sheepshead minnow) *Menidia beryllina* (silverside) *Fundulus similus* (fish) *Penaeus aztecus* post larvae (brown shrimp) *Palaemonetes pugio* (grass shrimp) *Mysidopsis almyra*	WSF toxicity determined	48-hr TL_m at 8.7 ppm total hydrocarbon levels from No. 2 fuel oil as follows: *C. variegatus* 43 ppm *M. beryllina* 40 ppm *F. similus* 23 ppm *P. aztecus* 9.4 ppm *P. pugio* 3.4 ppm *M. almyra* 1.3 ppm	Anderson et al, 1974
Crude, No. 1 light fuel oil No. 4 heavy fuel oil	*Gammarus oceanicus*	Acute and sublethal exposures	Larvae several hundred times more sensitive than adults during acute exposure. Sublethal effects on adults include impaired swimming performance, impaired light reaction, decreased tendency to precopulate, decreased larval production.	Linden, 1976

* WSF = Water Soluble Fraction

experiments were laboratory studies in which the selected species were exposed to the water soluble fractions of No. 2 fuel oil or crude oil, which are not the oil types expected to be present in urban runoff. The toxicity of these oils depends on their water-soluble hydrocarbon concentration (Carr and Reish, 1977). None of the studies on marine organisms tested crankcase oil toxicity and it is not clear that the results of these studies can be extrapolated to different oil types or to a non-laboratory situation. In one study on the effects of various oils on freshwater benthic algal communities, No. 2 fuel oil was the most damaging, used crankcase oil was least toxic and Nigerian crude oil was intermediate in degree of effect on metabolism (Bott et al, 1978).

Ecological Effects

Petroleum hydrocarbons, either in the form of a highly concentrated release as in an oil spill or from chronic inputs can have far reaching effects on aquatic ecosystms. The short term effects of several major oil spills have been well documented. However, few studies addressing the long term ecological implications of spills and chronic input are available and those that are available often lack thorough coverage (Michael, 1977; National Academic of Sciences, 1975). Short term studies will identify only major changes in an ecosystem. Minor alterations may appear to be insignificant but such changes can be cumulative and very significant over the long term.

In the aftermath of a major spill many organisms, especially benthic organisms, will die either from acute oil toxicity or from smothering and fouling (National Academy of Sciences, 1975). Full recovery of the affected area to its original condition may occur very slowly. Recovery is often incomplete and major changes in the community structure may result. Chronic, low-level inputs can ultimately have effects similar to those of a spill. However, the changes in community species structure will occur over a longer period of time. The most sensitive species and those with the least adaptive ability will be the first to be affected and as contamination levels increase there will be a loss of additional species with an overall reduction in species diversity (Wolfe, 1977). As species disappear from an area they may be replaced by more pollution tolerant, opportunistic species as in the case of *Capitella*. Continuous, low level contamination may permanently change the population structure of an area, resulting in a community with a relatively large number of individuals from only a few different species. Such systems are generally considered unstable and more prone to sudden, extreme fluctuations.

CHAPTER 4

OIL AND GREASE MITIGATION TECHNIOUES

Introduction

A comprehensive evaluation of oil and grease in urban stormwater runoff requires an assessment of techniques to mitigate against adverse impacts. In this chapter, we examine control techniques specific to urban runoff and review technologies developed for the petroleum and waste-water industries. Three distinct approaches are distinguished as alternative or conjunctive control strategies, and addressed separately.

First, a "source control" approach is identified as limiting the introduction of oil and grease into stormwater. Carrying out this approach would be difficult since oil and grease in stormwater runoff comes from a multitude of sources of varying intensity not all of which can be characterized. It is widely suggested that the major contributor of oil and grease to urban stormwaters is used automotive oil. An example of direct source control approach would be to provide incentives for proper car maintenance and disposal of waste oil following periodic oil changes in personal vehicles. Another approach to source control would be to regulate the use and development of the land. Allocating generous areas for cultivation and keeping the building of impervious surfaces to a controlled level would help in optimizing the natural biological degradation of oil and grease. A source control that could be used without much alteration in the existing environmental conditions would be a periodic cleaning of areas of high concentration of oil and grease. The cleaning instrumentation may include a vacuum truck in conjunction with a scrubbing machine to avoid the drainage of the dislocated oil and grease into the runoff. This method also would be beneficial in removing oil coated particulates.

Second, a "treatment" approach is identified providing for stormwater processing or management subsequent to oil and grease contamination. A series of treatment methods is briefly reviewed. The most commonly used methods for treatment of urban runoffs appear to be gravity differential systems [the API oil/water separator, the shell parallel plate interception (PPI) and the shell corrugated plate separator (CPI)] and filtration systems using granular materials. These systems are capable of handling large flow rates with minimum operator attention and maintenance.

Unlike wastewaters, storm runoff flows are inconsistent both in time and intensity. Most treatment systems are designed to operate optimally at a certain uniform rate. To adapt stormwaters to these treatment conditions, a system of centralized and decentralized storage of water runoffs is suggested using holding reservoirs, infiltration basins, underground storage reservoirs and catchment basins, or marsh and wetlands. These storage facilities also would give the added advantage of helping in the biological degradation processes.

Third, a "no-control" approach is identified where resources would be spent to gather further information on the effects of oil and grease present at existing concentrations in stormwater or be directed to the removal of pollutants of equal or more importance in urban runoffs.

Problem Characterization

The characteristics of oil and grease in urban stormwater runoff present serious difficulties to successful mitigation. Oil and grease in stormwater is usually diffuse, with levels below 30 mg/l, although concentrations have been found approaching 100 mg/l (Eganhouse and Kaplan, 1981; MacKenzie and Hunter, 1971, Zurcher, et al, 1978; Wakeham, 1977). Urban runoff can occur sporadically, with highly variable flows and frequency. Stormwater may drain from a relatively heterogeneous urban area, with little or no planning for water quality. Responsibility for oil and grease in the runoff generally derives from a multitude of small sources for which liability cannot be practically charged. Control measures must be technologically capable of handling extreme events while economically capable of often being idle or employed at minimal capacity.

Contrasting urban runoff characteristics, waste streams generated from industrial processes usually are much more uniform. Pollutant concentrations and flows generally remain within a defined range, favoring more efficient treatment practices. Oil and grease concentrations are normally higher than in runoff, enabling relatively higher levels of removal at less cost. Liability can usually be directly assessed, promoting accountability for resultant effluents. Costs can often be included as part of the production process, and included as part of the product price. Thus, there is motivation, economic capability and technological efficiency associated with industrial processes promoting oil and grease removal that is not duplicated in considerations of stormflow.

Oil spills present a third set of oil control conditions. Similar to runoff, events are stochastic both temporarily and in magnitude. However, accountability can often be ascertained, providing an economic basis to finance treatment. Spills are characterized by surface slicks with little consideration generally given to dissolved or colloidal fractions. Initially, concentrations are high and favor physical collection mechanisms. Considerations of only the surface fraction allows fairly straightforward and inexpensive treatment techniques for substantial reductions in oil concentration.

Recognizing the basic differences between oil and grease in urban runoff from that in industrial and spill settings presents a challenge to formulating successful mitigating techniques. An approach using or modifying some traditional oil and grease control techniques may prove effective in the urban environment. However, innovative techniques should also be considered to ascertain the most practical means of oil and grease control in urban stormwater.

Source Control

An immediate difficulty in controlling oil and grease in urban runoff is locating and quantifying the relative importance of the major contributory sources. Generally, inputs of oil and grease in urban runoff are thought to be from many diverse sources, although little work has been found delineating these sources.

Automotive Oil Control: A major contributor to oil and grease in urban stormwater is probably automotive oil. Cukor et al (1973) reported that 42% of the automotive oil used in Massachusetts and 67% of the waste oil generated in Oakland probably entered stormwater through either improper disposal techniques or through vehicle loss. The Massachusetts survey estimated that 24% of the automotive oil was improperly dumped while implying that up to 18% may have been lost through leakage and combustion. An obvious source control approach to limit the amount of waste oil dumping would be to provide positive and/or negative incentives for proper oil disposal.

The California Used Oil Recycling Act of 1977 provides a basis for such incentives, although currently with limited effectiveness (California, State of, 1979). Used oil dumping on land is currently prohibited although no effective means exists for monitoring actions or enforcing these restriction on the many individuals who may dump waste oil while changing oil in their personal vehicles. Cukor et al (1973) reported that 81% of the oil changes in the Oakland area were performed at home, thus presenting a large, diverse potential source of illegal dumping. Positive incentives for proper oil disposal was also provided for in the Used Oil Recycling Act. A system of collection stations, haulers, transfer facilities and refiners has been established to reprocess used oil. However, the availability of this disposal method is probably not widely known to the average individual. Disposal using this recycling system would require substantial consumer initiative. Cukor et al (1973) indicated that 60% of consumers preferred low activity disposal methods, such as pouring the oil into a storm drain, rather than high activity disposal methods, such as recycling. Increased public awareness or financial incentives might increase the use of recycling centers, as well as increasing the availability and knowledge of the existence of these centers.

Land Use: Another technique capable of controlling the deposition of oil and grease is to control the use and development of the land. There are numerous methods employed for land use management, most commonly through zoning and tax systems incentives (Andrews, 1972; Burchell and Listokin, 1975; Segan, 1972). Both the density and type of development probably are critical to area oil and grease loading. Different urban land uses are suspected to result in varying oil and grease levels, as we will investigate in this study. Prior work has not been found quantifying area used and/or density with oil and grease deposition.

It is well known that the hydrology of a watershed will change with development (Lindsley et al, 1978). As native surfaces are paved, infiltration will normally decrease. Pollutant deposition may be retained on impervious surfaces affording little opportunity for biological processes to provide significant degradation. Oil has been shown to decompose at a rate of 0.5 $\mathrm{lbs/ft^3}$-month in cultivated soils (Kincannon, 1972), although a much slower rate would be expected without cultivation. Amplifying this loss of natural degradation processes is the expected increase in runoff upon developing an area due to the increase in impervious surfaces. Runoff should commonly occur as sheet flow over impervious areas, with a reduced opportunity for pollutant infiltration into the substrate affording little chance for microbiological degradation. Thus, a mitigation technique retaining some pervious area may provide some control of oil and grease stormwater loading through both source limitation and through encouraging natural decomposition. The retention of some undeveloped areas in conjunction with controlling the amount and types of area development may be important in maintaining limited oil and grease concentrations in urban runoff through the use of non-structural or low structural intensive alternatives.

Oil and Grease Removal

The possibility exists for removing oil and grease subsequent to deposition in the watershed, but prior to deposition into stormwater. There have been mixed reports concerning the effects of intervals between storms on oil and grease concentrations in the runoff. A common assumption incorporated in the EPA's Stormwater Management Model (SWMM) is that pollution loading from a given storm varies with the time from preceding rainfall (Huber et al, 1975). However, Whipple et al (1977) and Hunter et al (1979) report that this interval effect is not valid. Generally, reports negating the effect of storm intervals have been from regions of rather regular, periodic precipitation. However, in the Richmond watershed, the normal precipitation patterns of a prolonged dry period during late spring, summer and early autumn suggest a long period in which oil and grease may accumulate. Seasonal cleaning in areas of heavy concentration prior to anticipated autumn precipitation has the potential of removing the spring and summer accumulation of oil and grease. Regular cleaning throughout the year may also provide for some removal of oil and grease deposits prior to incorporation into stormwater. Unfortunately, little information was found concerning the effectiveness of traditional street cleaning activities in removing oil and grease, although Sartor and Boyd (1972) have related sweeping efficiencies with particle size. Cleaning may hasten the progress of oil and grease into runoff by washing the waste, pollutant rich cleanup water into the storm sewers. Techniques should be evaluated using equipment and materials designed specifically to remove oil and grease, perhaps in a dry process.

A possible method of cleaning oil and grease from areas of heavy concentration would incorporate a scrubbing machine in conjunction with a vacuum truck. An area could be scrubbed with materials such as water and detergents or solvents. A vacuum would follow the scrubbing, removing the waste material prior to incorporation into the storm sewer system. A reverse osmosis procedure might then be employed on the vacuum truck to recover the oil and grease. While no information could be found on a process of this nature currently being employed, the separate components of the system are not unusual. Scrubbers are commonly used for street sweeping and vacuum trucks are used in the petroleum industry to remove spills. This proposed cleaning system could be used either systematically throughout the year or seasonally if heavy accumulation occurred during dry periods.

A less sophisticated method of cleaning oil and grease could use adsorbent material placed over areas of heavy deposition, followed by removal and either disposal or recovery. This technique might simply take the form of straw scattered over parking lots. Unfortunately, literature was not found reporting the efficiency of surface adsorbents in removing oil and grease from concrete and asphalt.

A modification of pavement materials may offer another means of hydrocarbon removal. Porous pavements may allow oil and grease to penetrate into soil layers, becoming available to biodegradation and eliminated from the runoff. Porous pavements are designed to promote a high rate of rainfall infiltration through the omission of fine material during pavement construction (Lynard, 1980; Thelem et al, 1972). Runoff passes through the pavement surface and is stored in the subgrade, or underlying soil. Storage usually occurs in a gravel subgrade, however, any underground void could also perform the function. The sub-base storage occurs prior to infiltration into the underlying soil at infiltration rates which are governed by the existing soil materials (Figure 4-1). Overall storage for porous pavement and their subbases may vary from 65,170 to 207,728 gallons/acre. No work has been found showing whether oil and grease penetrating porous pavements would be degraded similarly to that cultivated in soil, or if an oily crust might be formed prohibiting movement into lower layers and subsequent biodegradation.

Runoff Treatment

Subsequent to oil and grease incorporation into urban runoff, treatment may be undertaken to remove or modify deleterious materials prior to ultimate disposal. The science of oil and grease separation from water encompasses methods from simplicity to high complexity (American Petroleum Institute, 1969; American Petroleum Institute, 1975; American Petroleum Institute 1979;

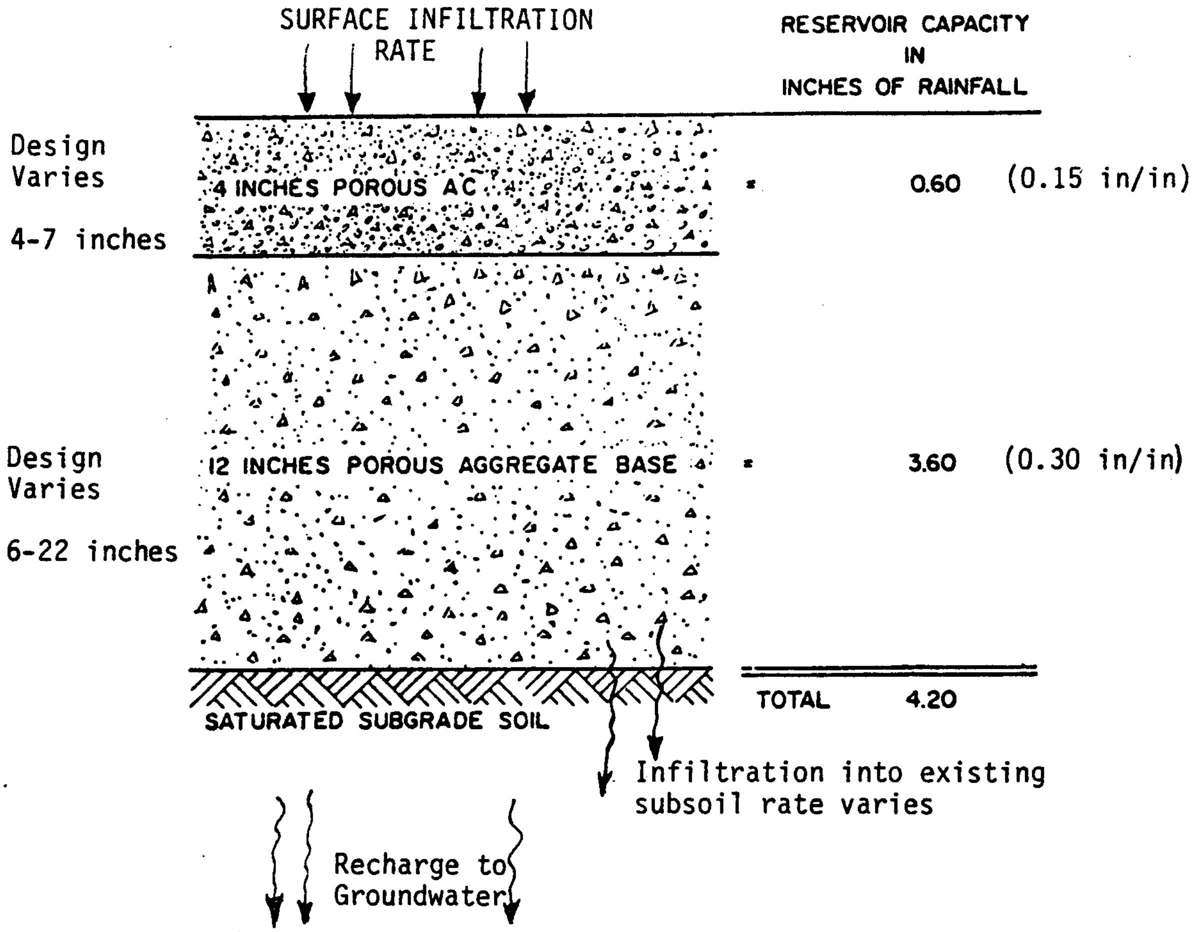

Figure 4-1 Typical Porous Asphalt Concrete Parking Lot Pavement (After Hannon, 1980)

Anonymous, 1980; Canada-Ontario Agreement on Great Lakes Water Quality, 1976; Gnosh et al 1975; Graham, 1973; Hsiung et al, 1974; Hydroscience, 1971; Mann et al; O'Neill et al, 1973; Osamor et al, 1978; Pal, 1974; Roberts, 1977). The potential of various separation techniques is shown in Table 4-1. The application of the technology has varied from control of wastewater discharges to the production of potable water, or high purity processing water. Historically, the implementation of the technology to treat stormwater runoff has relied on simplicity and lowest cost. A brief review of the technological capabilities is presented for informational purposes.

Review of Treatment Methods

The treatment methods presented for review are tabulated below in order of increasing complexity:

a. skimming;
b. gravity differential systems;
c. filtration;
d. dissolved air flotation;
e. coalescence/filtration;
f. absorption and adsorption;
g. electric and magnetic separators;
h. and other more complex and not fully developed methods.

Osamor and Ahlert (1978) have prepared a detailed description of these treatment methods. The most commonly used treatment methods are gravity differential systems (which may also employ skimming and dissolved air flotation) and filtration systems. The gravity differential systems provide the bulk of oil/water separation using various types of systems. These systems include: API oil/water separators; circular separators; plate separators (PPI, CPI, Curved plate separators); and rotational separators (Centrifuges). The filtration systems vary in complexity from slow sand filters with uniform or graded beds to membrane filters utilizing electrodialysis, reverse osmosis, or ultrafiltration. The use of synthetics such as polyurethane is also

TABLE 4-1 SUMMARY OF POTENTIAL TREATMENT TECHNIQUES FOR REMOVAL OF OIL FROM WATER

Technique	Free oil	Oil-coated solids		Unstabilized dispersions		Stabilized dispersion		Solubilized oil	Molecularly dissolved oil
		Settleable	Neutrally buoyant	Primary	Secondary	Chemically	Surface charge		
A. Gravity Differential									
API	XXX*	XX		X					
Hydrogard	XXX	XX		X					
Circular	XXX	XX		X					
PPI	XXX	XX		XX					
CPI	XXX	XX		XX	X				
Fram-Akers	XXX	XXX	XXX	XXX	XX				
Curved-plate finger	XXX	XXX	XX	XX	X				
Gravi-Pak	XXX	XXX		XXX					
Centrifuges	XXX	XXX		XXX					
Hydrocyclones	XX	XXX							
Vortex	XX	XX							
Dispersed air flotation	XXX	XXX	X	XX					
Dissolved air flotation	XXX	XXX	XX	XXX	XX				
Vacuum desorption	XXX	XXX	XX	XXX	XX				
Electrochemical			X	XX	XX		XXX		
B. Filtration									
Granular media		XXX	XXX	XXX	XX	X	X		
Multimedia		XXX	XXX	XXX	XXX	XX	XX		
C. Coalescence/Filtration									
Fibrous media	XXX			XXX	XXX				
Centrifuge	XXX			XXX	XXX				
Bimetallic					XX		XXX		

TABLE 4-1 (continued)

Technique	Free oil	Oil-coated solids		Unstabilized dispersions		Stabilized dispersions		Solubilized oil	Molecularly dissolved oil
		Settle-able	Neutrally buoyant	Primary	Secondary	Chemically	Surface charge		
D. Membrane									
Electrodialysis	XX			XX	XX	XX	XX	X	X
Reverse osmosis	XXX			XXX	XXX	XXX	XXX	XXX	XXX
Ultrafiltration	XXX			XXX	XXX	XXX	XXX	XXX	XX
E. Adsorption									
Carbon synthetics		XXX		XXX	XXX	XXX	XXX	XXX	
F. Electric and Magnetic									
Electrophoretic				X			XX		
Magnetic				XX					
G. Thermal			XX	X					
H. Coanda Effect	X								
I. Viscosity-Actuated	X								
J. Chromatography								XXX	XXX
K. Sonic and Ultrasonic				X	X	X			

* X, poor separation; XX, average separation; XXX, excellent separation.

receiving attention as a suitable filter medium (Canadian Plant and Process Engineering Limited, 1972), although the use of adsorption and absorption systems has been limited to the cleanup of oil spills.

Gravity differential separation is the oldest method for separating oil/water mixtures. In general, oil/water mixtures will separate naturally into two distinct layers of oil and water if allowed to stand undisturbed for a sufficient period of time. The basic principle governing this technique is Stoke's Law, which evaluates the rate of rise of oil globules in water based upon density. Stoke's Law also applies to oil coated solids suspended in water.

The rate of rise of an oil globule is dependent to a large extent on the particle size. For an appreciable separation to occur, within reasonable residence times, the oil droplets and suspended solids must be large. As oil globules rise to the surface, collisions occur, coalescence takes place, and a floating oil film forms at the surface. Subsequent skimming removes the free oil.

The most economical state-of-the-art methods in oil/water separation are of the gravity type. These devices can handle large flow rates, have low power requirements, and need minimum operator attention; but processes are slow, necessitating large equipment. Gravity separation is basic to almost all oil/water separators.

Within the category of gravity separation, the three most common types are: (1) the API oil/water separator; (2) the shell parallel plate interceptor (PPI) and/ (3) the shell corrugated plate separator (CPI), as shown in Figures 4-2 through 4-4. The PPI and CPI use tube settling, or a variation thereof to reduce the size requirements of the overall device. Functionally, all 3 separators perform in a similar manner.

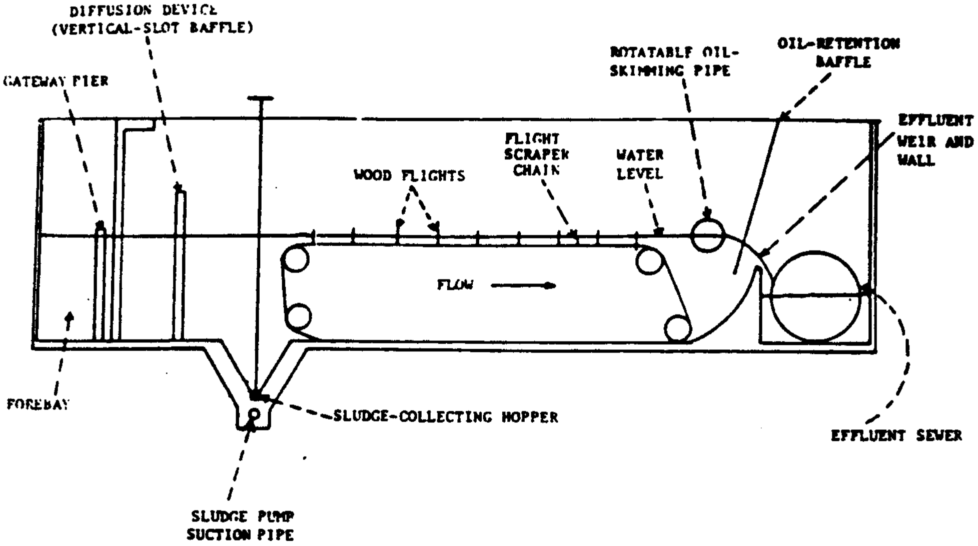

Figure 4-2 API Oil/Water Separator (Osamor and Ahlert, 1978)

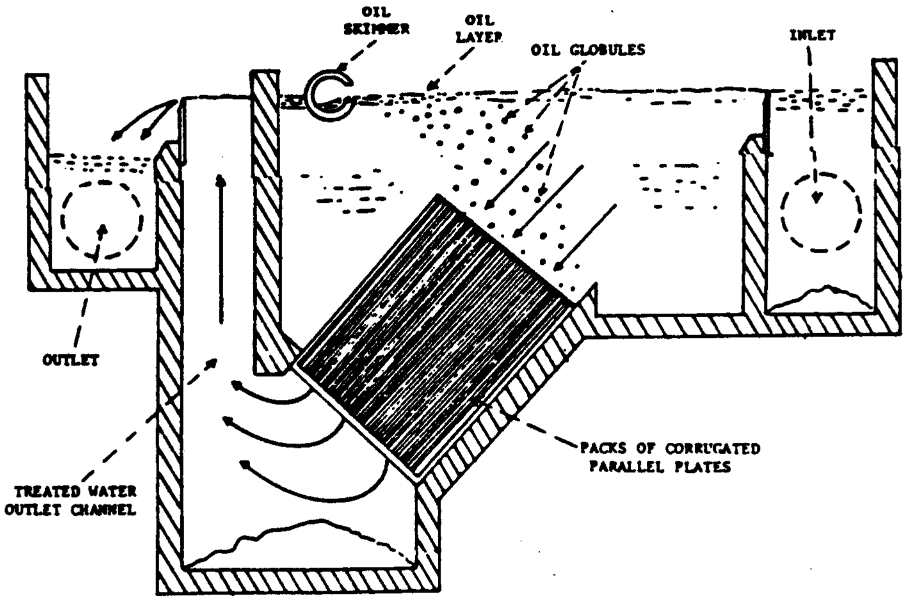

Figure 4-3 Shell Parallel-Plate Interceptor (Osamor and Ahlert, 1978)

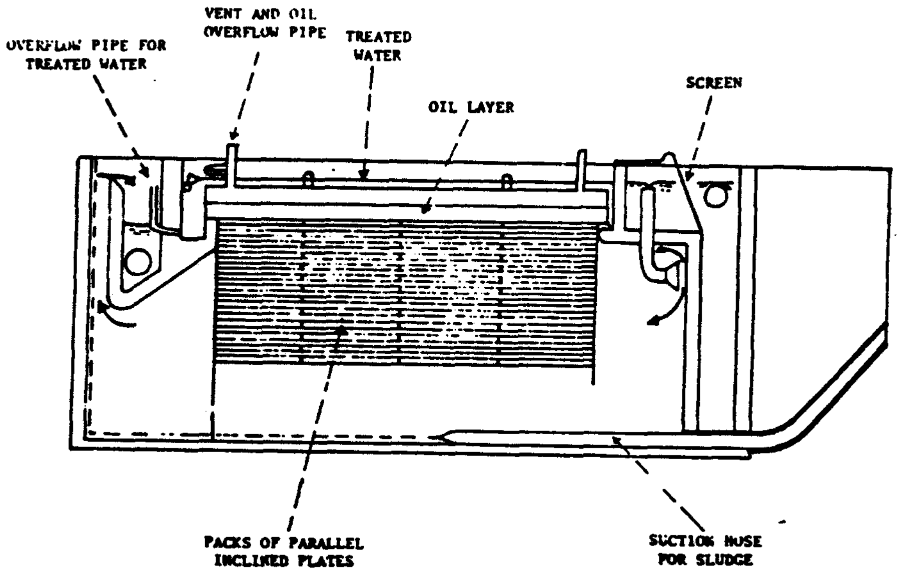

Figure 4-4 Shell Corrugated Plate Interceptor (Osamor and Ahlert, 1978)

The performance of the gravity separators as represented by several investigators (Osamor, et al, 1978) is presented on Tables 4-2 and 4-3. The lowest reported effluent concentrations are about 200 mg/l. These separators are generally used to provide initial or coarse separation, and are almost universally employed as a preliminary unit process for oil removal to lower concentrations.

The concept of gravitational separation between fluids of different densities can be enhanced by the use of centrifuges. Centrifuges can produce faster settling by generating forces of 1,000 to 5,000 times the gravity force. To operate satisfactorily, they require a density difference between the oil and water of at least 5%, and relatively high concentrations of oil (1,000-60,000 mg/l). The latter requirements makes their use unsuitable for the relatively low oil concentrations found in urban runoff. The power, operating, and maintenance requirements would also be unfavorable.

The gas flotation concept of gravity separation has been used for oil/water separation. The flotation variations have employed: (1) dispersed air (2) dissolved air, (3) vacuum desorption, and; (4) electrochemical. The successful operation of the flotation systems is based upon pilot studies, and a fairly steady flow volume and flow characteristics.

Filtration through granular materials is one of the oldest methods for separating oil/water mixtures. This technique is useful for removing suspended matter and associated oil from oily wastewaters. It is best suited for removing oil-coated solids that cause fouling in a coalescing device. Neutrally buoyant oil-coated solids that require infinite settling times can also be removed. Filtration is becoming important in the petroleum industry because of its capacity to reduce the concentration of oily suspended solids

TABLE 4-2 OIL AND SUSPENDED-SOLIDS REMOVAL IN GRAVITY-TYPE SEPARATORS (OSAMOR, 1978)

Oil content (ppm)		Percent Oil Removal	Percent Suspended-Solids Removal	Type
Influent	Effluent			
300	40	87	-	PPI
220	49	78	-	API
108	20	82	-	circular
108	50	54	-	circular
98	44	55	-	API
100	40	60	-	API
42	20	52	-	API
2000	746	63	33	API
1250	170	87	68	API
1400	270	81	35	API

TABLE 4-3 ESTIMATED EFFLUENT QUALITY FROM PRIMARY OIL/WATER SEPARATION PROCESSES (OSAMOR, 1978)

Separators commercially available	Effluent oil concentration (mg/l)
API rectangular	50-75
Circular	50-75
Inland Steel--Hydrogard	50-75
Shell PPI	35-50
Finger-plate separator	35-50
Fram-Akers plate separator	40-100
Keene--Gravi-Pak	20

in production water that are passed to secondary and tertiary recovery operations.

The mechansims involved in filtration are very complex and little understood. With deep granular filters of coarse material, removal is primarily within the filter bed (commonly referred to as depth filtraton). Some solids may be removed by a process of interstitial straining, and oil may be removed by adsorption on the bed material.

Filtration can be accomplished by two general techniques: layer and membrane. The layer technique employs sand and other filtration media in a thickness of 18 to 30 inches. Synthetic substrates such as polyurethane may also prove useful. The membrane techniques are relatively new, and rely upon processes such as reverse osmosis, ultra filtration; and electrodialysis.

The performance of filtration in removing oil and grease is better than that of gravity separation. Effluents with no visible oil and total concentrations of 10-20 mg/1 may typically occur. However, each filter bed has a limited life, and performance drops as filter clogging occurs. Backwashing will renew the filtration capacity. The use of gravity separation prior to filtration may be desirable to decrease backwashing time and filter clogging.

Existing Practices in the Petroleum Industry

A review of the oil and grease control practices in the petroleum industry may provide useful information to possible control in urban runoff. The response of the petroleum industry to emergency spills of oil has been extensively documented (Oil Spill Conference Proceedings, API/EPA/USCG, 1971, 1973, 1975, 1977, 1979). Oil spills do not occur (routinely) at known times and locations. Many occur on the water, and land spills are not discussed. The spill originates from an oil source, and the oil spreads and dissipates away from the site. Rapid deployment to contain the spill is practiced to minimize the area in which oil must be recovered from and to provide collection at the greatest concentration. Stormwater runoff, by comparison, provides a relatively dilute concentration from many disperse sources. The general steps in emergency oil spill response are:

1. Stop oil flow from the source;
2. Contain oil by use of floating booms, or natural wind or tidal action;
3. recovery of contained oil and collect for later disposal; and
4. dispose or reuse oil.

Spill recovery techniques may be adaptable to stormwater oil and grease control. Oil recovery during a spill may be made by use of skimmers, sorbents or centrifugal separates.

Skimmers effectively separate oil and water under smooth water conditions because a surface oil spill (with no mixing) provides conditions that are rarely achieved in the best design of gravity separators. Skimmers may use a floating weir and pump out oil from the surface. They tend to be very effective because oil exists in one form, floating oil, and at a thickness from barely visible up to several inches thick. An appropriate skimming device would be required with any gravity separation system.

Sorbents can be in the form of an endless belt of oleophilic material; rotating disks of oleophilic material; and any floating material to which oil will stick. The first two employ a squeegee or wiper effect to remove the sorbed oil from the belt or disk, prior to readsorption of more oil. The other types of sorbents are usually broadcast or spread over the oil surface, and recoverd by either a mechanical or hand method. The sorbent material and the attached oil is then either disposed or the oil is extracted (usually physically) and the sorbent is reused.

The development of a distributed reusable-sorbent oil recovery system has been accomplished by both the EPA and the Navy (API/EPA/USCG, 1977). The two applications of this technique were for identical conditions; out at sea, with conditions including large waves and currents. Ordinary skimmers and other previously developed techniques were least successful under these conditions.

A critical component integral to the entire collection system in respect to oil recovery or removal is the reusable sorbent. Both the EPA and the Navy used an open cell industrial polyurethane foam. The other components of their systems were a broadcaster, harvester, regenerator and storage units. Although other adsorbents have been investigated, the polyurethane foam was selected as the best choice under the reusable conditions. Some properties of the foam that led to its selection are:

1. high sorptive capacity, up to 80 times its weight;
2. high recyclability (over 100 times) without loss of adsorbency;
3. high (90%) oil recovery by mechanical squeezing; and,
4. low water retention during squeezing (only 3 times original weight).

A limited tabulation of existing practices at Bay Area oil refineries and terminals is presented below. The results are based upon a limited telephone and mail survey.

Number of Locations (Total 15)	Oil/Grease Control Technique
3	API separators with or without flow equalization
2	Holding/oxidation ponds with skimmers
1	Total on-site containment and contract removal by hauling
9	No response at present (either awaiting mail response or no information available)

The separation of oil and water has been studied and practiced by manufacturing companies. The result has been the production of large number of devices which utilize, among others, the treatment methods discussed above. A limited approach was made to collect data on the presently manufactured oil/water separation devices, and to critique, when possible, their operation.

The approach to tabulate manufacturers product literature used a three part approach. The first approach was based upon a (April 1978) state-of-the art survey of oil/water separation equipment (Osamor and Ahlert, 1978). An inquiry letter was sent to each manufacturer listed in the report. The second approach utilized a manufacturer's listing for oil/water separation equipment from a current issue of the Water Pollution Control Federation Journal. The third, and last, approach was simply to follow up on advertisements, reader service cards, information from other people, or any other promising source.

The overall results are adequate for the purposes of applying the results of oil and grease removal in urban runoff. The results are not extremely encouraging for a state-of-the-art review. As an example, from the first approach:

90	letters were mailed out;
42	letters provided no response;
26	letters were returned as undeliverable;
6	letters received response, but no pertinent information;
16	letters received a usable response

The second approach sent letters to 16 current manufacturers (WPCE listing) resulting in:

16	letters were mailed out;
9	letters received usable responses;
2	letters received a non-pertinent response;
5	letters were unanswered

The third approach was used selectively to add information to the overall listing. No specific accounting of the success of this approach is possible.

The tabulation by manufacturer is divided into 3 categories, gravity separation, filtration, and other (miscellaneous), shown in Tables 4-4, 4-5, and 4-6, respectively. The process equipment is tabulated by type, with the least complex appearing first. No distinction was made between manufacturers who provided custom design or standard prebuilt plants.

Centralized Storage

The procedures reviewed above (excepting spill technology) demand water flow at a controlled rate. A major difficulty in treating stormwater is that precipitation occurs stochastically. Runoff events may be extreme, are highly variable and are short and long lived. Technology capable of handling the large range of runoff levels normally expected would have to be extremely versatile, and would probably be very expensive and inefficient. Processes generally maximize efficiencies at selected process rates. Storing runoff during an event to enable treatment systems to proceed at relatively uniform rates may provide a useful approach to maximizing oil and grease control capabilities. Similarly, releasing runoff to the environment at a rate commensurate with biologial assimilatory processes might ameliorate outfall impacts.

There are various methods to accomplish this storage (Hannon, 1980; Lynard et al 1980; Meadows, 1980, Poertner, 1974). The most common method would use water channelization into holding reservoirs or infiltration basins. Large underground storage reservoirs may also be employed, as currently being constructed for the city of Chicago. Some degradation of pollutants would be expected during storage. Infiltration basins would

TABLE 4-4 MANUFACTURERS OF GRAVITY SEPARATION EQUIPMENT

Manufactuer	Equipment Description
Envirex	Clarifiers
Industrial Filter and Pump Co.	Clarifiers
Joy/Denver Equipment	Clarifiers
Pielkenroad	Clarifiers
AFL Industries	SGI Gravity Separator
CE-NATCO	API Clarifier/Separator
Envirex	API Clarifier/Separator
AFL Industries	Plate Clarifiers (PPI, CPI, etc.)
BINAB	Plate Clarifiers (PPI, CPI, etc.)
Chiyoda Chemical Engineering	Plate Clarifiers (PPI, CPI, etc.)
AFL Industries	Vertical Tube Coalescers
CE-NATCO	Coalescence/Clarifier
Facet	Coalescence/Clarifier
Envirex	Flotation Separator
AFL Industries	Dissolved Air Flotation
CE-NATCO	Dissolved Air Flotation
ECO-Research	Dissovled Air Flotation
Envirex	Dissolved Air Flotation
EnviroTech	Dissolved Air Flotation
Industrial Filter and Pump Co.	Dissolved Air Flotation
Joy/Denver Equipment	Dissolved Air Flotation
Permutit	Dissolved Air Flotation
WEMCO	Dissolved Air Flotation
ALFA Laval	Centrifuges

TABLE 4-5 MANUFACTURES OF FILTRATION EQUIPMENT

Manufacturer	Equipment Description
Envirex	Sand Filters
METPRO	Gravity Filters
Neptune Micro-Floc	Multi-Media Filters
BRNAB	Filters (artificial media)
Chiyoda Chemical Engineers	Filters (3 Types)
Industrial Filter and Pump Co.	Filters (many types)
Continental	Pressure Filters
METPRO	Pressure Filters
CE-NATCO	Coalescence/Filters
Continental	Coalescence/Filters
Facet	Coalescence/Filters
ROMICON	Ultra Filtration

TABLE 4-6 MANUFACTURERS OF OTHER OIL/WATER SEPARATION EQUIPMENT

Manufacturer	Equipment Description
Enquip	TSI Water Separation and Oil Recoverer
AFL Industries	Skimmers (3 Types)
Douglas Engineers	Weir Skimmers (2 Sizes)
Metpro Systems	Belt Skimmers
Oil Recovery Systems	Surface Skimmers
Oil Skimmers, Inc.	Oil Skimmer (Tube Type)
Santina and Thompson	Swirl Separators
Calgon	Activated Carbon Systems
Carborundum	Activated Carbon Systems
Chiyoda Chemical Engineers	Activated Carbon Systems

provide for elimination of stormwater at a relatively slow, controlled rate, although offering the potential for pollutant entrapment in ground water. Storage reservoirs could re-release water into the treatment system at a rate suitable to the capabilities of the treatment facility or the biological assimilatory capacity.

Decentralized Storage

Storage could also be accomplished through the construction of numerous catchment basins designed to hold storage from a limited area. Devices may be built in to remove floatables or allow silt sedimentation. These basins could be built uniformally throughout the watershed, or only placed in areas of substantial oil and grease deposition.

The oil and grease traps would be most effective for floating, or easily settled oil and attached solids. Hydraulic detention would be provided to allow the oil/water separation to occur. This concept has been used at several locations, noticeable at the Chicago Metro Bus Terminal (Industrial Waste, 1980) and in King Co., Washington (King County DPW, 1979). The designs employed increased hydraulic detention, and a down-turned outlet located below the water surface to permit separation of floating oils. One design used extensively in Washington State is shown in Figure 4-5.

Although these devices received some use for control of oil, little operating or performance data has been published. The concept is very promising from the viewpoint of simplicity and cost, although a complete analysis is not possible.

A modification of the basic oil/grease trap is available with a separate compartment to separate oil (or other products) for subsequent recovery, as shown in Figure 4-6. Although the initial cost and complexity is greater than

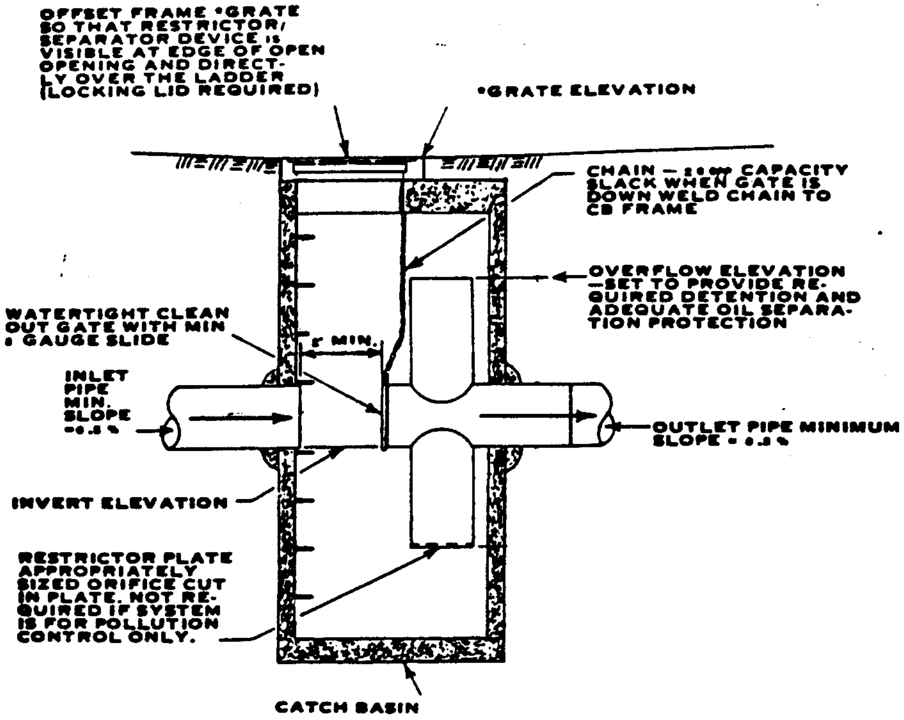

Figure 4-5 Flow Restrictor/Oil Separator Control Device/Catch Basin (After King County, DPN, 1979)

the simple grease traps, the potential exits to provide a revenue return to pay for capital and maintenance costs.

Other devices may hold promise as a method for oil and grease removal, although actual practice has not been demonstrated. A membrane device used to stop rainflow inflow to a sanitary sewer (Hannon, 1980), could be modified with oil absorbent materials to operate as an oil removal device as shown in Figure 4-7. Hydraulic considerations and maintenance requirements would be important design considerations.

Biodegradation

The degradation of oil and grease in cultivated soil has been well documented (Francke and Clark, 1974; Kincannon, 1972), although at hydrocarbon concentrations greater than ordinarily found in urban runoff. Some organisms important to degradation have been identified as Pseudonomas putida and Flavobacterium by McKenna and Heath (1976), Pseudomonas, Micrococcus and Acinetobactor by Ward and Brock (1975) and Pseudomonas, Flavobacterian, Nocardie, Corynebacterium and Arthsobactor by Kincannon (1972). Dominant general responsible for hydrocarbon oxidation in soils have also been reported by Jones and Edington (1968). Techniques utilizing biological degradation processes warrant attention as possible methods of limiting oil and grease loading from runoff.

A major difficulty of assessing the practicality of using soil and water bacteria as a primary component of oil and grease treatment is that little work can be found identifying decomposition rates in systems other than soil cultivation or spills. Important conditions limiting or regulating the rate of microbial decomposition include dissolved oxygen availability (Delaune et al, 1979) nitrogen and phosphorus availability (Atlas and Bartha, 1971;

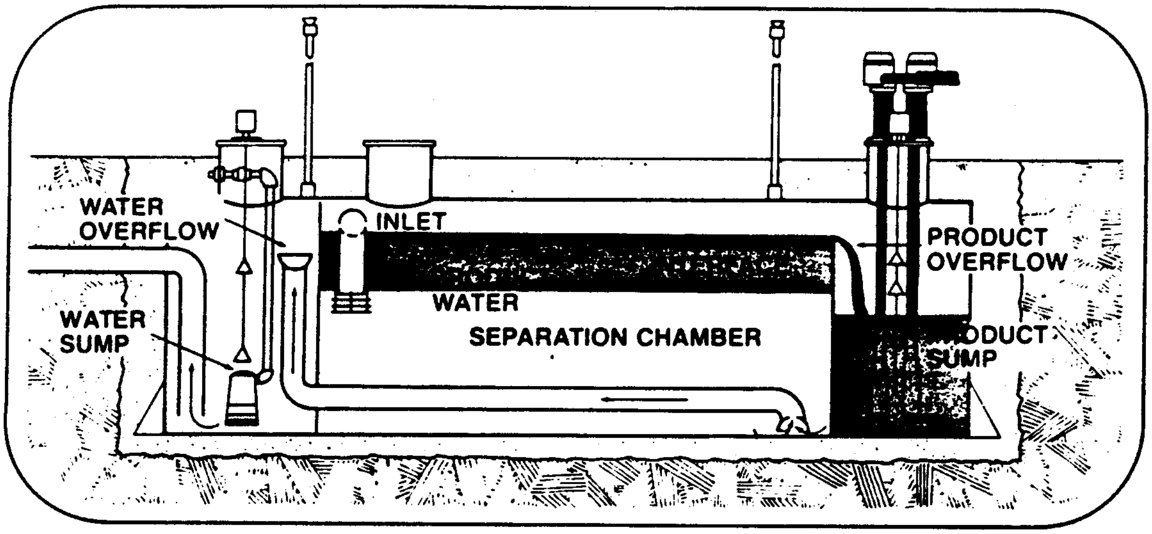

Figure 4-6 TSI Gravity Separator (Patented)

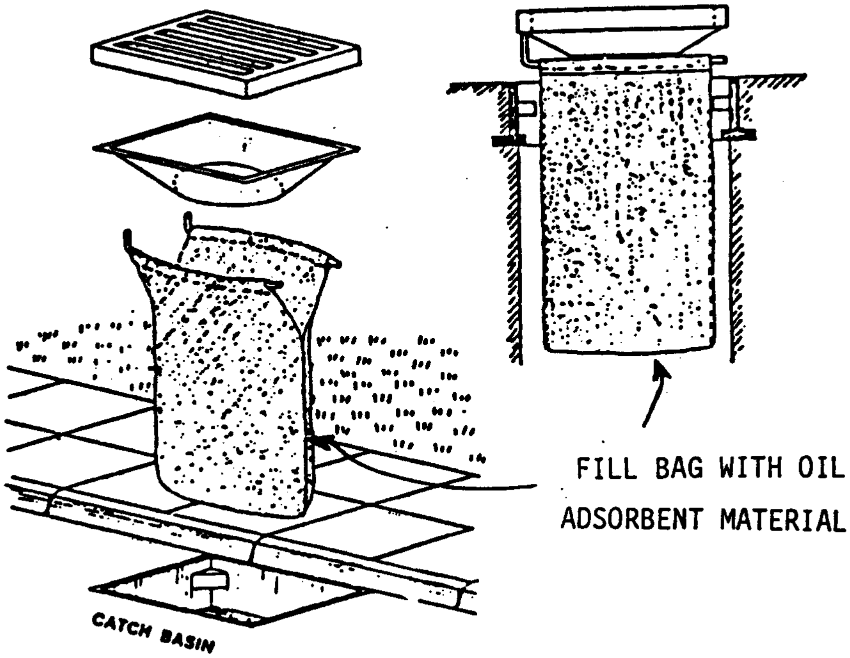

Figure 4-7 Proposed Oil Adsorbent Device for Manhole (Hannon, 1980)

Kincannon, 1972), temperature (Adhearns et al, 1976) salinity (Brown et al, 1970) and substrate acclimation (Brown et al, 1969). It is probable that in an ordinary flood control channel experiencing rapid flows over confined areas, there is little opportunity for degradation. However, if flow were dispersed and retained in a marsh or wetlands, increased degradation might be facilitated by the greater hydraulic retention and soil/water interface.

The use of a marsh/wetland for removal of oil and grease from storm-water runoff has not been undertaken, however, investigations have occurred to measure the effects of oil spills (Baker, 1971; Burk, 1976; Cowell, 1969; Cowell et al, 1969; Delaune et al, 1979; Hunter et al, 1970). In general terms, the biological (plant) reaction to large concentrations of oil has varied from minor damage to death. The immediate species reaction is usually overcome by the next season's growth, although a small number of species is much slower to recover. No recommendations can be made as to a controlled use of a wetland for oil and grease removal. At best, a conservative approach would be warranted, and the availability of an alternative control method would be prudent.

Other possible methods of promoting biological degradation coincide with storage mechanisms discussed above. If stormwater were used in greenbelts or lakes, biological processes would be expected to remove some of the hydrocarbons. However, degradation rates are not known in these situations, and care would be needed to ensure that loading did not overwhelm degradation capacity to result in surface scumming. Similarly, infiltration basins might eliminate some oil and grease, but loading capacity would have to be carefully evaluated.

A system of small, localized greenbelts surrounding areas of heavy oil and grease deposition might offer a further method of promoting biodegradation. An example system would be a greenbelt surrounding a parking lot. Periodic cleaning or washing of hydrocarbon deposits into these green areas might eliminate much of the potential for subsequent pollution. Degradation rates in the greenbelts would have to be determined in order to ensure against overloading the system. However periodic soil cultivation, increasing biological degradation and loading capacity, may be economically feasible in these limited greenbelt areas.

Outfall

The final possibility for runoff treatment prior to ultimate disposal is at the outfall. A possible, if expensive, treatment alternative would use one of the methodologies reviewed in the above discussion of petroleum technologies. A treatment alternative at the outfall would probably rely on some upstream storage to maintain flow at a sustained level to enable efficient treatment.

The location of the outfall probably is important to the effects of oil and grease to the receiving body. A high level of productivity in most bodies of water occurs in the littoral or neritic zones, perhaps presenting the greatest opportunity for detrimental effects to occur from stormwater runoff (Odum, 1971; Wetzel, 1975). Although the threshold levels of oil and grease are not formally established, dilution remains a possible treatment alternative. If outlet structures are located away from sensitive zones, in open water, subsequent dilution and flushing may provide an effective solution to oil and grease pollution in runoff. However, care needs to be taken in siting outlet structures and evaluating pollutant pathways to ensure that any pollution effects are actually lost or reduced to the environment, rather than spatially or temporally altered.

Dispersion of oil and grease could be promoted through the use of synthetic dispersants. Ideally, sufficient dilution of pollutants may maintain hydrocarbons at sub-threshold levels at any particular location while increasing the surface area that bacteria may use to initiate degradation. Doe et al (1978) prepared a bibliography describing some of the oil spill dispersants. However, the use of dispersants also presents possible problems. Dispersing oil and grease may simply alter or increase the area to be affected. Studies indicate that dispersants may be toxic (Lonning and Falk-Persen, 1978; Heldal et al, 1978); effects have been shown in concentrations as low as 1 ppm. Ventallo (1975) reported that detergents, which may be used as dispersants, can reduce oil degradation due to a bacterial preference for detergent degradation. Unfortunately, it is often difficult to obtain the chemical make-up of dispersants from the manufacturers, aggravating the task of determining toxicity and biodegradability. Certainly, the use of dispersants needs a critical evaluation prior to any treatment application.

No Control

A variety of possible mitigation measures to reduce or eliminate oil and grease in stormwater have been presented above. Many of these measures are expensive and require sophisticated technology. Other measures discussed are less demanding technologically, but require investments in land or changes in life style. In evaluating between oil and grease control alternatives, factors suchs as costs, social impact and effectiveness of control should be considered. However, the relative value of oil and grease control in runoff should also be considered in relation to the inputs required for the control.

Little information is available on the effects of oil and grease at the normal concentrations found in stormwater. However, this information is vital if rational decisions are to be made concerning the degree of effort warranted hydrocarbon stormwater runoff control.

Other deleterious materials besides oil and grease such as pesticides, herbicides, nutrients, suspended solids and material with a high biochemical oxygen demand may also be found in stormwaters. Overall runoff quality might improve by diverting resources from oil and grease control into the treatment of other pollutants. Any evaluation of the implementation of oil and grease control techniques should also consider control effects on other pollutants. Additional work needs to be done concerning these other possible pollutants, as well as determining the effects of oil and grease in stormwater, to determine the optimum resource allocation for enhancing environmental quality.

Summary

This section has summarized existing experiences with a variety of types of oil/water separators. Most of the techniques discussed are used primarily for separation of oil/water mixtures produced by manufacturing processes. The optimal treatment method for urban stormwater runoff may be quite different than the optimal technique for oily process wastewater. Further development work is required before the selection of the best technique can be made with assurance.

CHAPTER 5

DATA COLLECTION AND ANALYSIS

Objectives

A field sampling program was conducted during winter 1980-1981 to examine oil and grease concentrations in urban stormwater runoff from a demonstration watershed in Richmond, California. Richmond contains a variety of types of light-to-heavy industry and is located north of Oakland. It is typical of many small towns and cities and is not a "bedroom" suburb of Oakland or San Francisco. Five stormwater sampling stations representative of commercial, industrial, and residential areas were initially selected for evaluation of oil and grease from various land uses. Runoff from a total of seven storm events was sampled.

The sampling program encompassed three major goals:

1. Determination of oil and grease concentrations and load factors corresponding to various land uses.
2. Quantification of the relationships between oil and grease concentration and precipitation/runoff patterns.
3 Chemical characterization of oil and grease runoff from various land uses, with the objective of determining the source of the oil and grease.

Site Description

The study area is a 2.5 square mile area within the city of Richmond. The watershed contains a mixture of commercial, industrial, and urban residential land uses. Single family residential dwellings comprise approximately 70 percent of the total watershed area. Table 5-1 lists and describes the various land uses in the study area. The locations of the selected sampling stations are shown in Figure 5-1.

Eight land use categories were developed for the study area. These were developed from aerial photographs and were based upon similarities to the sampling locations.

1. Undeveloped. Open areas, grass areas, football fields.
2. Industrial property and parking. Total industrial area including parking areas, paved or dirt, and buildings. (Represented by Safeway Distribution Center: Station 2).
3. Large-scale commercial property and parking. Parking lots, paved or dirt, and buildings. Also includes parking lots in non-commercial areas where automobiles are predominant, such as schools. (Represented by Montgomery Wards Lot: Station 3).
4. Small-scale commercial property including the associated parking lots and commercial streets. Street areas including buildings with small scale commercial and industrial businesses dealing with the public, i.e. where small parking lots and automobiles predominate. (Represented by San Pablo Avenue: Station 4).
5. Single-family residential. (Represented by Station 5).
6. Multi-family residential.
7. Freeways, trains and BART tracks.
8. Impervious non-auto. Tennis courts, playgrounds, and other areas which appear to be impervious, not identifiable in other categories.

TABLE 5-1 LAND USE IN THE RICHMOND WATERSHED

Land Uses	% of total area
1. Undeveloped	5.2
2. Industrial parking and property	4.3
3. Large-scale commercial parking and property	6.0
4. Small-scale commercial and industrial parking and property	5.8
5. Single family residential	70.6
6. Multi-family residential	2.1
7. Freeways, trains and BART	3.6
8. Impervious non-auto	2.4

Total Calculated Land Area - 2.541 square miles

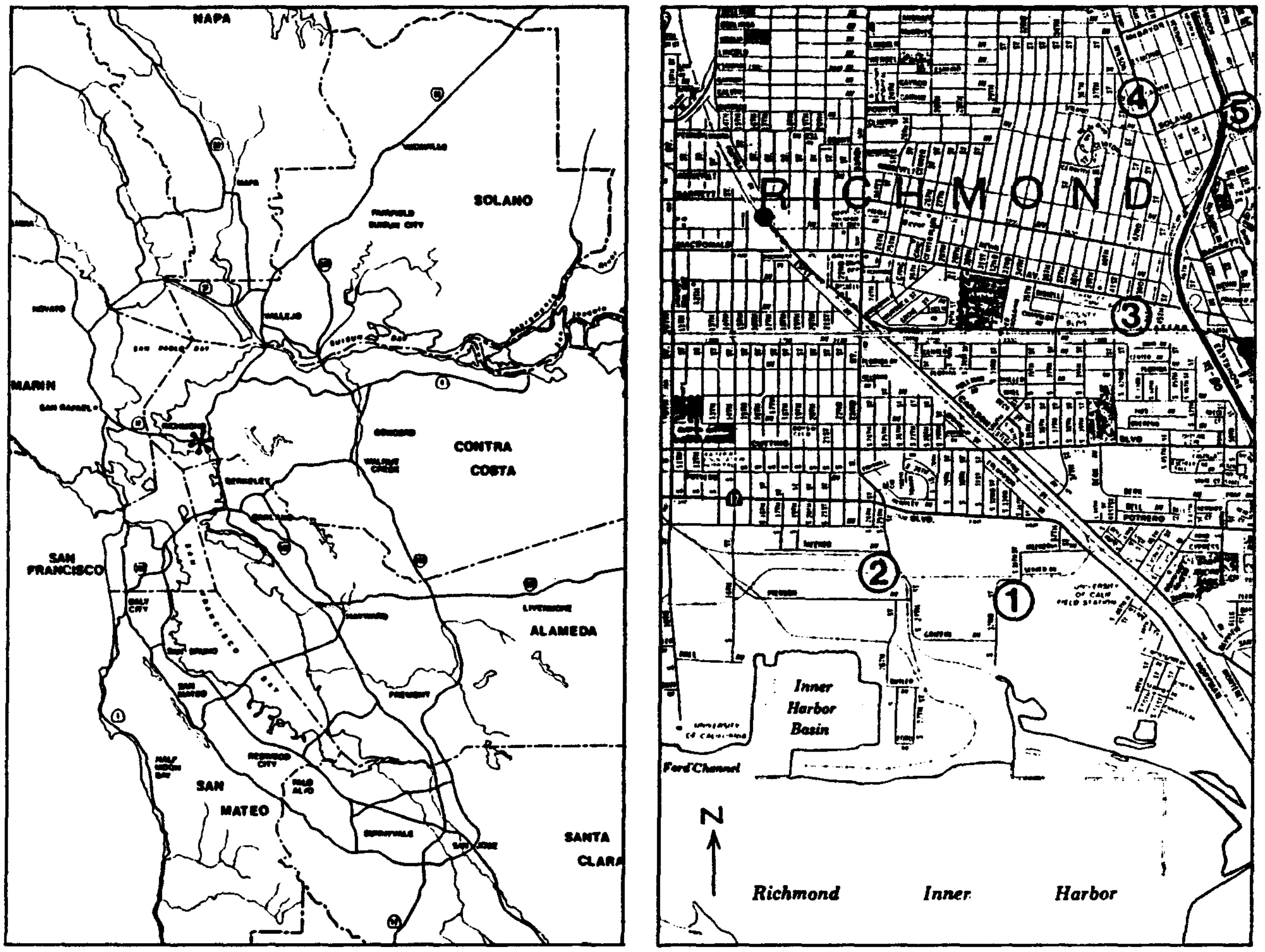

Figure 5-1 Location of Richmond Field Sampling Stations

Sample Station Description

Five sampling stations were selected to represent the following land use categories: mouth of the watershed (station 1); industrial parking and property (station 2 - Safeway Distribution Center); large-scale commercial property and parking (station 3 - Montgomery Wards parking lot); small-scale commercial property and parking (station 4 - service station on Major Street); residential (station 5). Although these stations were generally believed to be representative of a single land use category, often the entire station area represented a composite of two or more land use types. Descriptions of the individual sampling stations and the representative land uses are provided in Table 5-2. Land use and station areas were determined from aerial photographs. Station drainages were determined from Richmond storm flow maps which illustrate water drainage direction and station drainage boundaries. Station 2 (Safeway distribution Center) and Station 3 (parking lot) were assumed to drain only one-half the total measured area; two drains were assumed for each of these large areas. The sampling locations and land uses are described below.

Station 1 - Mouth of the Watershed: Station 1 was located at the mouth of the demonstration watershed, near the intersection of 32nd Street and Griffin Avenue. At this point, the entire study area stormwater runoff flows in a concrete trapezoidal drainage channel to San Francisco Bay. Sampling at this station represents a composite of runoff from all contributing urban land uses in the watershed.

Station 2 - Safeway Distribution Center: Station 2 was located near station 1, but outside of the demonstration watershed. This station was selected because it was thought to represent a large portion of land uses within the watershed, and for its convenience of sampling and monitoring. The

TABLE 5-2. DESCRIPTION OF SAMPLING STATIONS

STATION	SITE DESCRIPTION	AREA LAND USES	DRAINAGE AREA (ft^2)	APPROX. DISTANCE TO MOUTH OF BASIN (ft)#	ELEVATION ABOVE SEA LEVEL (ft)
1	Mouth of Watershed uses in the watershed	Composite of all	7.08×10^7	0	12
2	Safeway Distribution Center 23% impervious non-auto	77% industrial property and parking;	1.17×10^6	2,000	10
3	Parking Lot commercial property and parking	100% large-scale	2.92×10^4	6,250	60
4	Service Station 30% small-scale commercial property and parking	70% residential	8.71×10^5	9,800	103
5	Upstream Residential Area	95% residential 5% undeveloped	5.7×10^6	10,500	98

\# measured as distance to station 1

station was at the collection point for surface runoff from the Safeway Distribution Center, which is located adjacent to the primary watershed. The established sampling point was at the outfall of a 30" concrete culvert which crosses east to west beneath S. 27th Street, north of the intersection with Pierson Avenue. Sampling at this location is representative of an industrial site with heavy truck traffic. (77% industrial parking; 23% impervious non-auto, i.e. roof).

Station 3 - Montgomery Wards Parking Lot: Station 3 was the drainage outlet for the Montgomery Wards front parking lot near the corner of McDonald Avenue and 44th Street. In this area, runoff from the asphalt parking surface is directed to the east side of the lot where it is funneled through a tapered, sloping concrete apron leading to a drop inlet into the underground storm sewer. The sampling was at the tapered apron section. This sampling site was representative of off-street automobile traffic and parking in the commercial district (100% large-scale commercial parking and property).

Station 4 - San Pablo Avenue: Station 4 was located at a curb and gutter section in front of the Regal Service Station on the east side of San Pablo Avenue approximately 100 feet south of the intersection with Garvin Avenue. Runoff in this area is from primarily commercial land use with some contribution from single family residences and apartments. Drainage includes runoff from three service stations and is carried solely in street gutters. No underground sewers exist in this section. Sampling at this station represents heavy automobile traffic, curb-side and off-street parking and service station contributions along a major commercial artery. (70% residential; 30% small-scale commercial).

Station 5 - Upstream Residential Area: Station 5 was located in the residential upper portion of the watershed near the intersection of Solano

Avenue and Amador Street. The sampling site was an open, unlined drainage channel on the upstream (southeast) side of Amador Street. Sampling at this point represents contributions from a well-established urban residential area in moderate to steeply sloping terrain. (95% residential; 5% undeveloped).

Storm Characterization

Runoff from a total of seven storm events was sampled during the 1980-81 winter season. The initial program objective was to sample six storms having rainfall intensities of at least 0.2" within the first six hours of the storm; the rationale was to focus on storms having sufficient "washoff" potential. An additional stipulation was that at least five of the six storms be preceded by a minimum of three consecutive days without rainfall in order to allow an interval for street surface accumulation of contaminants between samplings. Because of an abnormally dry winter season, it was not possible to adhere strictly to these target sampling guidelines. Table 5-3 provides a summary of date of the storm, days since previous storm, storm duration, and total rainfall for each of the seven storms. The storm events varied widely in their characteristics.

Experimental Design

Sample Collection

One liter grab samples were collected at each station with an intended frequency the following time intervals after the beginning of the storm until the end of the storm: 0.5 hour, 1 hour, 1.5 hours, 2 hours, 3 hours, 4 hours, 6 hours, 9 hours, 13 hours, 18 hours. This schedule was intended to provide intensive sampling during the initial runoff period for each storm decreasing the sampling frequency as the storm continued and eventually dissipated. Some modification was occasionally made up this schedule due to field conditions

TABLE 5-3 SUMMARY OF RAINFALL DATA FOR EACH STORM EVENT

STORM	DATE	DAYS SINCE PREVIOUS STORM	STORM DURATION (hours)	TOTAL RAINFALL (in.)
1	12/3/80	11	15.5	2.01
2	12/21/80	18	4.5	0.33
3	1/17/81	1	4.5	0.07
4	1/20/81	1	1	0.4
5	2/13/81	5	3.5	0.35
6	3/4/81	4	6	0.24
7	3/18/81	3	7	0.53

and availability of personnel. All samples were collected directly in one liter glass containers which were pre-washed with freon and capped in accordance with standard methods for oil and grease analysis. Sampling locations were carefully selected and prepared to allow for collection at a point of turbulent flow or free discharge. This procedure was necessary to assure that samples were representative of a fully mixed water column. Specific procedures followed at each sampling station were as follows:

- Station 1 - Samples were obtained in a highly turbulent zone at the double-culvert entrance to the trapezoidal open channel at the mouth of the watershed. Samples were obtained directly by securing the glass sample bottles to a holder attached to the end of an extendable aluminum pole and submerging the bottle, throat upstream, into the most turbulent section of flow. This procedure proved effective under all flow conditions.
- Station 2 - Samples were collected from runoff passing over a sharp-crested V-notch weir fixed at the end of the 30" discharge culvert. Integrated samples were obtained directly in the glass sample container by passing the bottles laterally and vertically through the discharge. This procedure proved to be effective for all flow conditions.
- Station 3 - Samples were obtained by channeling runoff from the parking lot over a sharp-crested V-notch (low flow) and 30" rectangular (high flow) weir at the point of entry to the storm sewer. A complete cross-section of the runof flow was readily obtained by capturing the weir overflow directly in the glass sample containers.

- Station 4 - Samples at this station were taken directly from the gutter flow and, in most cases, necessitated the use of two sample bottles to obtain one full liter of runoff water. This was accomplished by filling two containers halfway or, in instances of low flow, collecting the small volumes in one container and transferring repeatedly to a second bottle. In all cases, both sample bottles were submitted to the laboratory for extraction and analysis as a single sample. The collection point was located in a rutted asphalt section at the end of a smooth, uniform section of concrete gutter and apron. The transition from a smooth to a rough bottom surface created turbulent mixing conditions needed for sampling. This site posed difficulties for sample collection only during extremely low flow conditions, usually toward the end of a storm. Obtaining samples during these times required the use of a sandbag to detain the flow. On two occasions, samples had to be obtained 50 feet "downgutter" where the flow passed through a pothole.
- Station 5 - Samples of stormwater runoff were obtained at this site directly from the flow passing over a sharp-crested 50" rectangular weir installed in the open drainage channel. The glass sample bottles were secured to a holder at the end of an extendable aluminum rod and passed across the weir discharge to obtain an integrated runoff sample. This procedure proved to be effective under all flow conditions.

Duplicates of each routine sample were taken at all stations for all sampling times during storm 3. All procedures for sample collection, preservation, labelling and handling were identical to those for the routine samples. Each one liter sample was preserved in the field immediately following its collection with five milliliters of concentrated hydrochloric acid solution (diluted 1:1 with distilled water).

Collected samples were retained in the field at each sampling station or in vehicles used by the field crew until the conclusion of the storm. Samples were then stored at RAMLIT Associates offices until delivery to the analytical laboratory. In all cases, samples were delivered to the laboratory within 24-30 hours following their collection in the field.

Measurement of Oil and Grease Concentration

The level of oil and grease in the stormwater samples was measured using the Infrared Spectrophotometric Method (Method 413.2) described in the EPA report, "Methods for Chemical Analysis of Water and Wastes" (EPA, 1979). It is virtually identical to the Partition-Infrared method described in Standard Methods (1975). According to this method, the sample is acidified to a low pH (<2) and extracted with fluorocarbon-113 (1,1,2-trichlor-1, 2,2-trifluorethane, or Freon). The oil and grease level is then determined by comparison of the infrared absorbance of the sample extract with standards. All of the organic material extracted from aqueous solution or suspension by the Freon is termed "oil and grease". The material dissolved into the Freon generally includes relatively non-volatile hydrocarbons, vegetable oils, animal fats, soaps, waxes, esters, and fatty acids (Sawyer and McCarty, 1978; Standard Methods, 1975; EPA, 1979). Additional compounds which may be extracted include elemental sulfur and certain organic dyes (Standard Methods, 1975).

Two other methods of measuring oil and grease are described in Standard Methods and are commonly applied to water and wastewater. The two methods, "Partition-Gravimetric Method" and "Soxhlet Extraction Method", involve solvent extraction, heating to evaporate the solvent, and weighing of the residue to determine the oil and grease content of the sample. The first method calls for heating the solvent-extracted sample to 70°C, and the second method calls for heating it to 103°C. This solvent removal step would also tend to volatize any short-chain hydrocarbons and simple aromatics present in the sample. As a result, petroleum fuels from gasoline through No. 2 fuel oils would be completely or partially lost (EPA, 1979). The infrared procedure used in this study does not call for a heating step. Thus, it can measure most of the light petroleum fuels which may be present in the samples. Nonetheless, loss of about half of any gasoline present during the extraction manipulation can be expected (EPA, 1979).

In this study, the primary advantage of the Infrared Method is its superior performance in measuring low levels of oil and grease. Standard Methods recommends its use when measuring oil and grease levels less than 10 mg/l because gravimetric methods do not provide the needed precision for accurate work. The EPA indicates that the Infrared Method is applicable to samples with from 0.2 to 1000 mg/l of extractable material, whereas the gravimetric measurement (combined with the separatory funnel extraction) is applicable to samples with a higher beginning-point range, 5 to 1000 mg/l. In addition, infrared measurements of oil and grease are not susceptible to interferences such as sulfur (EPA, 1979).

Rainfall Measurements

Rainfall data were collected for the duration of the sampling program at an established weather station located within the watershed at the Richmond City Hall. The rain gauge, operated and serviced by city of Richmond engineering personnel, was an automatic tipping bucket gauge with recorder.

In addition, non-recording rain gauges were installed at stations 1 and 4 for observation by field personnel during the course of sampling each storm event. These gauges, while much less precise than the recording gauge at the City Hall, provided immediate information regarding the intensities and total amounts of rainfall which characterized each storm. It was initially anticipated that such immediate information might be needed for field decisions concerning termination of sampling for individual storm events. However, other field observations of rainfall and runoff conditions proved to be more effective indicators.

Flow Measurements

At the time each sample was collected, runoff flow rate was also estimated. Methods were established individually for each station and included the use of sharp-crested weirs, area-velocity measurements, and application of Manning's formula for open channel flow. Details of the procedure followed at each sampling station are described below.

Station 1 Measurement of stream flow at station 1 was made under the assumption of steady, uniform flow in the trapezoidal channel. Figure 5-2 illustrates the channel cross-section at station 1. Dimensions of the channel were obtained from "as-built" plans provided by the City of Richmond Public Works Department. A staff gauge was installed on the 1-1 slope of the east side of the channel at a point approximately 500 feet downstream of the double-culvert entrance to the open channel. This point was judged to be free of excessive turbulence and conveniently located adjacent to an access gate and a street lamp. No apparent inflow, other than direct rainfall, enters the channel between the sampling point and the flow measurement point.

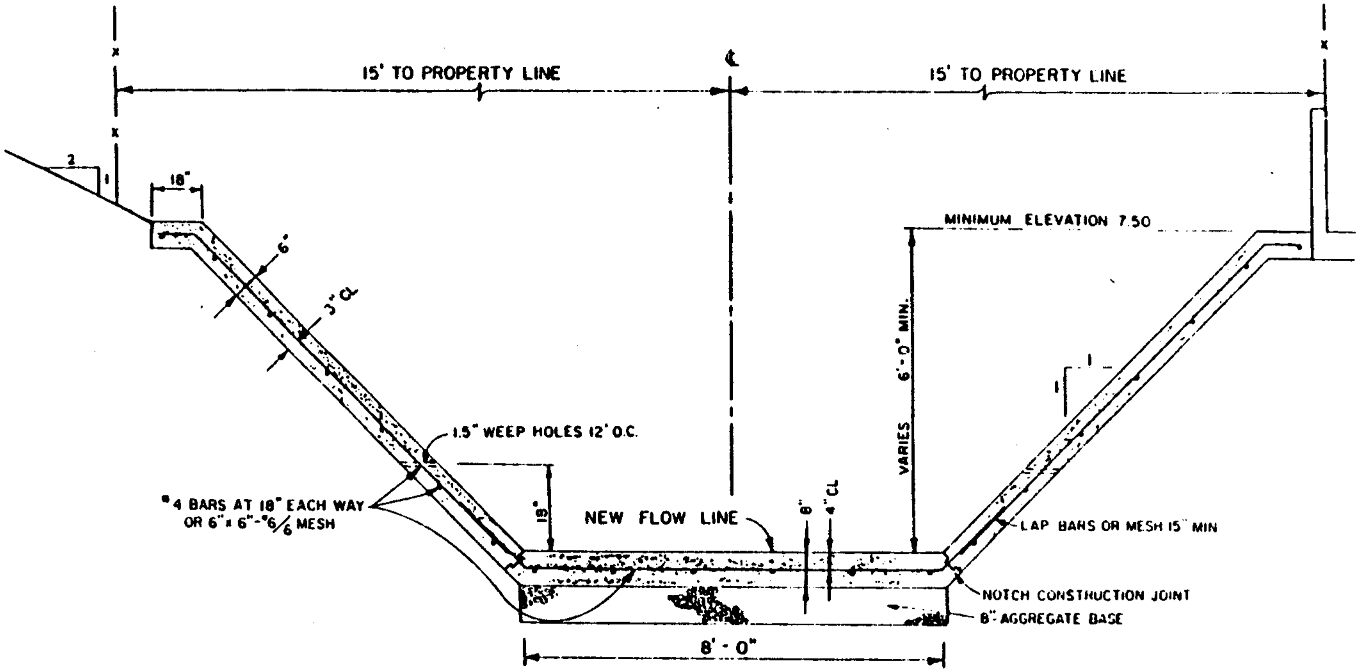

Figure 5-2 Channel Cross-Section at Station 1

The staff gauge installed was a Leopold-Stevens Style "C". It was porcelain-enamel, white with black markings 2 ½" wide, 1/8" thick, with divisions to .01 feet. Initially it was placed on a vertical standard installed mid-channel. Experience during the first storm showed that this positioning led to excessive turbulence and debris accumulation, thus

obstructing stage readings. The gauge was moved to the slope position following the first storm and remained there for the remaining six storm events.

Volumetric flow rates were estimated by application of Manning's formula for open channel flow. Calculations were made as shown by the example below.

$$Q = \frac{K'b^{8/3}\ S^{1/2}}{N} \qquad \text{Manning's Formula*(5.1)}$$

Where: Q = flow

K' = function of channel dimensions and stage height (D)**
b = channel width = 0.00386
n = Manning's n = .014***

As an example, flow for a 2.0" is calculated as follows:

Stage height

$$\frac{D}{b} = \frac{2.0}{8.0} = .25 \qquad (5.2)$$

$$K' = .15(5.3)$$

$$Q = \frac{(.15)\ (8.0)^{8/3}\ (.00386)^{1/2}}{.014}\ (5.4)$$

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* King and Brater Handbook of Hydraulics, 5th Edition, McGraw-Hill, 1963, p. 7-14.

** Ibid., pp. 7-14, 7-38.

*** Ibid, p. 7-17.

$$Q = \underline{\underline{170\ \text{CFS}}}\ (5.5)$$

Station 2 Flow measurement at station 2 was facilitated by the fabrication and installation of a sharp-crested 90° V-notch weir at the outfall of the 30" culvert which drains the Safeway trucking area. The weir proved to be particularly effective in allowing accurate measurement of low flow conditions and in minimizing backwater interference from the tidal slough into which the culvert discharges. The discharge over the weir was in a free discharge condition over 80% of the time. The combination of rainfall intensity and tidal conditions at this station created partially submerged discharge conditions during eight flow readings at storms #1 and #7. Accurate flow measurements were not possible in all of these instances. During one measurement of storm #1, the backwater and high flow conditions totally submerged the weir resulting in a less accurate flow estimation.

Under conditions of partial submergence, upstream and downstream stage measurements were utilized. The submerged flow (Q) was computed as a fraction of the corresponding free discharge (Q_1) for the same upstream stage height (H_u).* This was done with the use of empirical curves of $\frac{Q}{Q_1}$ vs $\frac{Hu}{H_d}$ where H_u equals upstream stage and H_d equals downstream stage height.

Field measurements of the stage height upstream of the V-notch weir were made by a reading staff gauge, consisting of an engineer's rule, permanently positioned within the culvert. During periods of submergence, measurements of backwater conditions were also made from a fixed reference point. Flow rates

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* King and Brater, p. 5-16

were calculated according to the following empirical formula for sharp-crested, 90° V-notch weirs:

$$Q = (2.5)\ (H^{2.5})* \quad * \qquad (5.6)$$

Where: H = upstream stage height

Station 3 Runoff flow at station 3 was measured using two portable sharp-crested weirs installed at the time of sampling. The weirs were fabricated to fit snugly within the tapered apron at the prescribed sampling location but were positioned so that they could be readily secured in place at the beginning of a storm event and removed at its conclusion to minimize changes of vandalism or interference with runoff and activities within the parking lot.

A 90° V-notch weir was used to obtain accurate readings of low flow conditions. A 30" rectangular weir was substituted during periods of intense rainfall and runoff. For each weir, a staff gauge, consisting of an engineer's rule, was fixed in place with each weir installation. The gauge was positioned to allow consistent measurement of water level height at a point upstream and away from the influence of the weir overflow crest.

Flow calculations were made using standard weir formulas and coefficients. The 90° V-notch weir is shown in Figure 5-3, and flow calculations were made as follows:

$$Q = (2.5)(H)^{2.5}** \qquad (5.7)$$

Where: Q = flow

C_e = discharge coefficient - a function of L, b, H, P

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* King and Brater, p. 5-16

** King and Brater, p. 5-14

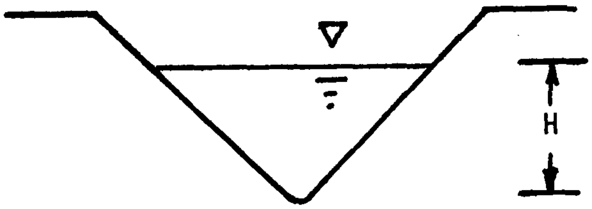


Figure 5-3 Typical 90° V-Notch Weir

L_e = Weir length (30") + correction for contraction (L/b)

H_e = Upstream head (h) + correction factor of .003' for viscosity and surface tension

Station 4 Runoff flow at station #4 was estimated by measuring cross-sectional area (A) and surface flow velocity (V) for the range of conditions encountered during the sampling program. Repeated velocity measurements were taken for a variety of conditions along an established 20' section of uniform concrete gutter and apron at the sampling site. A small bark chip was used as a float to obtain surface velocity. The cross sectional area for various flow depths (curb height) was determined from a cardboard template scribed for the gutter at the sampling point. The flow depth, measured against the curb, was determined at the time each sample was obtained. From these measurements, flow (Q) was computed as follows:

$$Q = 0.85 * V * A \tag{5.8}$$

The values of flow for all field measurements of velocity (and computed area) were plotted against curb height values in Figure 5-4. This forms the stage-discharge rating curve from which flows were estimated for all field measurements of curb height.

Station 5 Measurement of stream flow at station 5 was accomplished using a sharp-crested 50" rectangular weir permanently installed in the unlined open channel. The weir and supporting structure was constructed of rough-sawn redwood, and spanned the channel at the upstream edge of an existing concrete culvert and apron into which the open channel streamflow discharges. A 4" strip of 1/16" flat steel was fastened to the upstream side of the weir to form a sharp-crest.

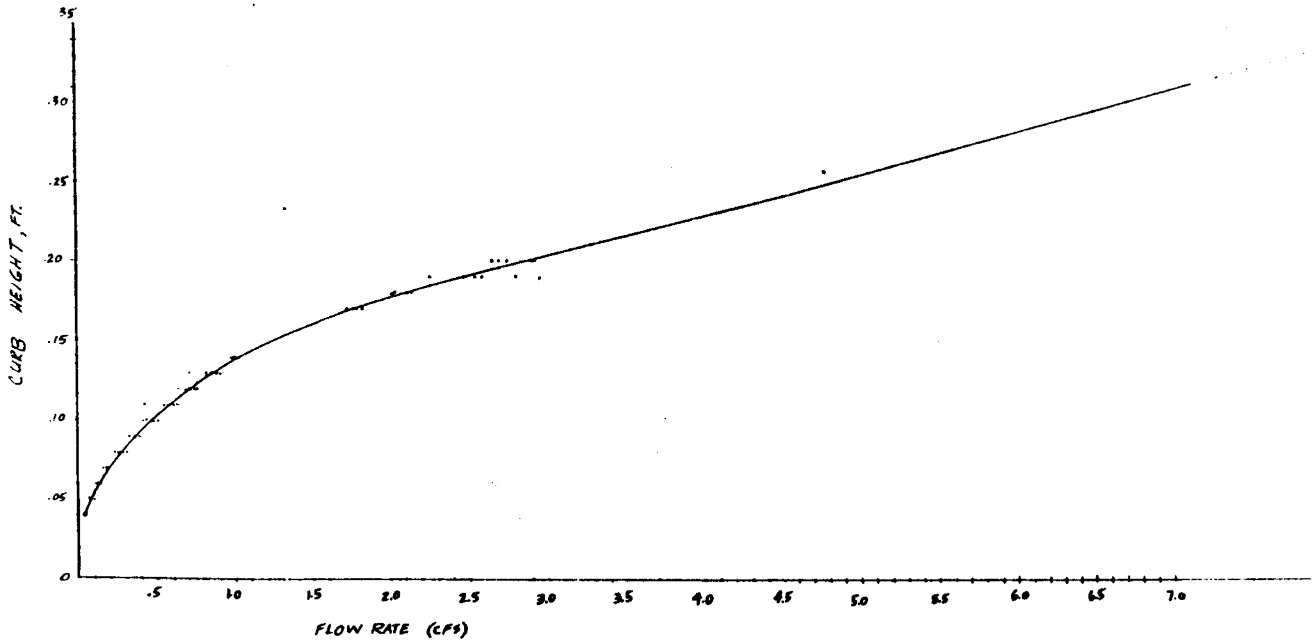


Figure 5-4 Rating Curve for Station 5

Approximately 10 feet upstream of the weir installation, a Leopold-Stevens stule staff gauge, identical to that used at station 1, was mounted on a stationary vertical 2" x 4". This provided measurement of upstream stage height in a quiescent section of the channel. Stage height readings were made and recorded, flow rates were subsequently computed according to the empirical formula for rectangular weirs as previously described for station 3 and according to the dimensions shown in Figure 5-5.

Settlability of Oil and Grease

Two settling column tests were performed to assess the feasibility of gravity separation as a runoff treatment technique. Samples from station 1 (mouth of the watershed) and station 3 (Montgomery Wards Parking Lot) were taken during the fifth storm included in the study (February 13, 1981). Approximately 45 liters of water were allowed to settle in a glass column with an internal diameter of approximately 15 cm and a height of about 1.8 m. Three hundred fifty ml samples were withdrawn from each of three ports at 1, 2, 5, 10 and 30 minutes after mixing with a plunger mechanism. Sampling ports were located at approximately the mid-depth of the column, at about 30 cm below the water surface and at about 30 cm above the bottom of the column. After the 30 minute sample was taken approximately 1 liter was withdrawn from the surface for analysis. The remainder of the sample was then siphoned, with the bottom liter subsequently analyzed for oil and grease. Sample delivery containers, plunger and column were rinsed with freon to collect organics absorbed to surfaces. All samples were analyzed for oil and grease following the Infrared Spectrophotometric Method described above.

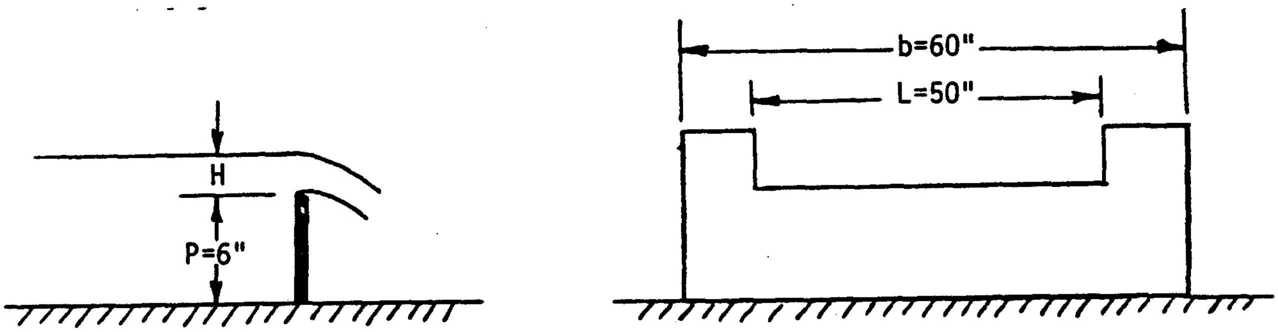


Figure 5-5 Typical Rectangular Weir

Characterization of Oil and Grease in Richmond Watershed Runoff

As was described earlier in this chapter, oil and grease were removed from the water samples by fresh extraction. Selected extracts were stripped of the fresh solvent by heating on a steam bath and a nitrogen stream. Nitrogen was used instead of air owing to the purity of nitrogen available. The residue was redissolved in 100-200 microliters of pesticide quality dichloremethane ($C_{H2}Cl_2$). After mixing, 1 microliter aliquots of the prepared samples were analyzed by gas chromatography.

A Tractor Model 760 gas chromatograph with a flame ionization detector (FID) was used for this study. Instrumental parameters and column conditions were as follows:

Injector: 300°C
Oven: 50°C initial for 2 min., then rising 8°C/min
to 350°C
Column: 6' glass x 1/4" O.D.
10% SP-2100 on 100/120 Supelcoport

As reference standards, n-decane, n-hexadecane, anthracene, C_{24}, and C_{32} were used (Fitch, 1981).

Data Analysis

Data collected from the field sampling program were analyzed using a statistical analysis program, Statistical Analysis System (SAS, 1979). Intermediate variables were calculated and manipulated with FORTRAN. A variety of types of statistical analysis were used, including analysis of variance. The following set of variables were used to describe the storm and runoff characteristics.

1) Oil and grease concentration (OGl, mg/l)
2) Total oil and grease mass runoff per storm (TMASS, lb)
3) Instantaneous runoff flow (FLOW)
4) Total runoff flow per storm (TFLOW, 10^6 gal)

5) Rainfall rate (RRAIN, 10^{-2} in/hr)

6) Total storm rainfall (TRAIN, in.)

7) Mass flow rate of oil and grease (RMASS, lb/day)

8) Days between storms (DBS, days)

9) Time since storm beginning (TSSB, hours)

10) Station number (STANO)

11) Storm number (STONO)

12) Sample number (SAMNO)

Each of the parameters was determined directly, with the exception of total mass and total runoff flow volume, flows, which are defined as follows:

$$\text{TFLOW} = \int_0^{te} \text{FLOW}\, dt \qquad (5.9)$$

$$\text{TMASS} = \int_0^{te} \text{RMASS}\, dt \qquad (5.10)$$

where: te = time of storm flow ending.

To approximate the integration, modified-Euler (often call trapezoidal) integration method was used, as follows:

$$\text{TFLOW} = \sum_{i=o}^{n} (\text{FLOW}_{i+1} + \text{FLOW}_i) * (to+1 - ti)/2 \quad (5.11)$$

$$\text{TMASS} = \sum_{i=o}^{n} (\text{FLOW}_{i+1} * \text{OG1}_{in} + \text{FLOW}_{i+1} * \text{OG1}_{i+1}) * (ti+1 - ti)/2 \quad (5.12)$$

where n = number of sample points

i = sample point number.

The zeroth sample was always treated as the flow rate and oil and grease concentration at the instant of storm beginning, which was always zero. In the case of storm 1, the first sample was not taken until approximately six hours into the storm, which could result in considerable error.

Raw Data and Simple Statistics

The raw data for the entire series of storms and sites is tabulated in Appendix A. There are approximately 290 observations of each variable. Consequently, the raw data are too lengthy to include in the text; however, the simple statistics (mean, standard deviation, standard error, and number of observations) are listed in Tables 5-4 to 5-20.

Runoff Flow

Mean values of instantaneous runoff flow measured at each station for each storm are listed in Table 5-4. These results reflect the average of observations at regular intervals during the storm. Total runoff flow volume for each storm as monitored at each station is presented in Table 5-5. Runoff at each station is related to the area of the drainage basin which feeds the sampling point.

Runoff for each storm can roughly be related to rainfall. Contrary to expectations, however, the runoff-rainfall ratio or runoff coefficient (K value), varied considerably between storms. Storms 1 and 7 had quite high K values. In spite of the fact that a larger storm is expected to have a somewhat higher runoff-rainfall ratio, the K value for storm 1 at station 3 appears unreasonable at first glance. Perhaps this unusual value is caused by inadequate drainage to handle the 2.01 inches of rainfall from storm 1 or by inaccurate measurements due to weir submergence. Accuracy of the K value is limited by potential errors in measurement of runoff flows and estimation of station drainage areas.

TABLE 5-4 MEAN RUNOFF FLOW AT EACH STATION ASSOCIATED WITH EACH STORM EVENT

	Runoff Flow (cfs)				
STATION	STORM	n*	Mean	Std. Dev.	Std. error
1	1	8	100.70	132.05	46.69
	2	8	17.61	18.90	6.68
	3	11	22.71	27.96	8.43
	4	7	2.41	1.10	0.42
	5	6	19.95	10.59	4.32
	6	7	18.10	7.32	2.77
	7	8	70.53	53.03	18.75
2	1	10	2.07	3.60	1.14
	2	8	0.64	0.58	0.21
	3	11	0.28	0.21	0.06
	4	7	0.14	0.09	0.03
	5	6	1.09	0.84	0.34
	6	7	1.01	0.41	0.15
	7	8	1.89	0.07	0.03
3	1	10	0.19	0.27	0.08
	2	8	0.02	0.02	0.01
	3	13	0.01	0.01	0.00
	4	7	0.01	0.00	0.00
	5	6	0.03	0.02	0.01
	6	7	0.03	0.02	0.01
	7	8	0.09	0.07	0.03
4	1	10	2.02	2.99	0.95
	2	8	0.27	0.28	0.10
	3	13	0.17	0.22	0.06
	4	7	0.05	0.05	0.02
	5	6	0.51	0.41	0.17
	6	7	0.44	0.25	0.09
	7	8	1.63	1.26	0.44
5	1	10	3.11	4.53	1.43
	2	8	0.56	0.59	0.21
	3	13	0.38	0.47	0.13
	4	7	0.12	0.09	0.03
	5	6	0.93	1.15	0.47
	6	7	1.57	0.50	0.19
	7	8	2.15	1.57	0.56

*n = number of observations.

TABLE 5-5 TOTAL RUNOFF VOLUME (10^6GAL) FOR EACH STORM AT EACH SAMPLING STATION

		Total Runoff Volume (10^6gal)						
				Station				
		1	2	3	4	5	Storm Mean	Std. Dev
	1	67.019	1.698	0.552	1.541	2.495	14.67	29.27
S	2	3.123	0.125	0.003	0.058	0.134	0.69	1.36
T	3	2.596	0.034	0.001	0.013	0.035	0.57	1.14
O	4	0.381	0.019	0.001	0.006	0.014	0.08	0.17
R	5	2.262	0.129	0.003	0.061	0.111	0.51	9.98
M	6	2.913	0.150	0.005	0.069	0.227	0.67	1.26
	7	16.070	0.388	0.013	0.261	0.429	3.43	7.07
Station Mean		13.48	0.36	0.083	0.29	0.49		
Std. Dev.		24.18	0.60	0.21	0.57	0.89		

The ratio of runoff to rainfall, or runoff coefficient (K value), for each station and each storm, as well as storm and station mean values, are found in Table 5-6. The K value were calculated according to the following formula:

K = total storm runoff/total storm rainfall * station area

The K value, which is characteristic of location, is inversely related to the permeability of the area. In general, paved areas are expected to have a higher K value than undeveloped areas. The field sampling results are consistent with these expectations. Station 3 (parking lot) had the highest runoff-rainfall ratio (0.94), and station 5 (upstream residential area) the lowest (0.18).

Oil and Grease Concentration and Total Mass Load in Runoff

Mean values of oil and grease concentration measured at each station for each storm are found in Table 5-7. These results reflect the average of observations at regular intervals during the storm. There is considerable variability between stations and between storms. Interestingly, at station 1 (mouth of the watershed) the lowest oil and grease concentration was observed for storm 1, but at station 5 (upstream residential area) an extremely high oil and grease concentration was observed during storm 1 compared to later storms.

In order to examine the significance of sampling location and storm number as determinants of oil and grease concentration, mean oil and grease concentration for each sampling station and for each storm were calculated. Mean oil and grease concentration for each station are presented in Table 5-8, and mean concentrations for each storm are represented in Table 5-9. The highest oil and grease concentration (15.25 mg/l) was observed at station 3

TABLE 5-6 RATIO OF RUNOFF TO RAINFALL: K VALUES FOR EACH STATION AND STORM

		K Value						
		Station						
		1	2	3	4	5	Storm Mean	Std. Dev.
	1	.75	1.15	15.03	1.45	.35	3.75	6.32
S	2	.21	.52	.50	.32	.11	.33	.18
T	3	.83	.66	.77	.34	.14	.55	.30
O	4	.22	.66	1.39	.28	.10	.53	.52
R	5	.15	.50	.47	.32	.09	.31	.18
M	6	.27	.85	1.14	.53	.27	.61	.38
	7	.68	1.00	1.34	.90	.23	.83	.41
Station Mean		.44	.76	.94*	.45*	.18		
Std. Dev.		.29	.25	.41	.24	.10		

* For stations 3 and 4, K values for storm 1 have been deleted in the calculation of station mean because of inconsistently high values.

TABLE 5-7 MEAN OIL AND GREASE CONCENTRATION AT EACH STATION ASSOCIATED WITH EACH STORM EVENT

		Oil and Grease Concentration (mg/l)			
Station	Storm	n*	Mean	Std. Dev.	Std. Error
1	1	9	3.56	3.35	1.12
	2	8	3.53	0.57	0.20
	3	11	5.28	3.25	0.98
	4	7	5.76	2.46	0.93
	5	6	9.10	6.14	2.51
	6	7	12.14	7.53	2.84
	7	8	15.71	28.13	9.95
2	1	10	5.32	3.30	1.04
	2	8	3.01	1.52	0.54
	3	12	7.93	6.29	1.82
	4	7	6.90	3.48	1.31
	5	6	8.83	6.59	2.69
	6	7	9.37	4.00	1.51
	7	8	9.51	6.03	2.13
3	1	10	11.99	3.69	1.17
	2	8	19.14	7.99	2.82
	3	13	11.77	5.93	1.64
	4	7	7.94	3.74	1.41
	5	6	31.33	28.88	11.79
	6	7	15.77	9.15	3.46
	7	8	15.00	6.78	2.40
4	1	10	14.05	7.00	2.21
	2	8	8.30	6.32	2.23
	3	13	9.45	7.38	2.05
	4	7	14.14	3.08	1.16
	5	6	11.37	2.91	1.19
	6	7	9.76	6.61	2.50
	7	8	9.03	2.98	1.05
5	1	10	13.47	5.54	1.75
	2	8	1.65	1.08	0.38
	3	13	1.68	0.85	0.23
	4	7	0.80	0.23	0.08
	5	6	2.53	1.89	0.77
	6	7	5.67	3.95	1.49
	7	8	1.65	2.07	0.73

* n = number of observations

TABLE 5-8 MEAN OIL AND GREASE CONCENTRATION (mg/l) OBSERVED AT EACH SAMPLING STATION

		Oil and Grease Concentration (mg/l)				
Station	n*	Mean	Std. Dev.	Std. error of the mean	90% confidence interval of mean	
1	56	7.57	11.56	1.54	5.00	10.14
2	58	7.16	5.07	0.67	6.04	8.27
3	59	15.25	12.02	1.56	12.64	17.86
4	59	10.80	6.00	0.78	9.50	12.10
5	59	4.13	5.24	0.68	2.99	5.26

* n = the number of observations.

Station by Station Comparison of Oil and Grease Concentration Using 90% Confidence Interval

		Station Number				
		1	2	3	4	5
Station Number	1		-	+	-	-
	2			+	+	+
	3				+	+
	4					+
	5					

\+ confidence interval does not overlap
\- confidence interval overlaps

TABLE 5-9 FLOW-WEIGHTED AVERAGE CONCENTRATIONS OF OIL AND GREASE (mg/l)

				Station		
		1	2	3	4	5
	1	5.13	6.70	6.38	12.51	11.40
S	2	3.11	2.71	19.01	8.61	1.84
T	3	4.75	7.02	6.71	6.73	1.13
O	4	4.65	5.90	5.75	11.50	1.86
R	5	6.42	11.01	20.77	10.66	3.14
M	6	10.42	9.45	17.57	10.32	5.85
	7	5.26	6.90	13.49	9.00	2.06
Station mean		5.68	7.10	12.81	9.90	3.90
Std. Dev.		2.31	2.64	6.50	1.94	3.65

(parking lot), and the lowest oil and grease concentration (4.13 mg/l) was measured at station 5. These results appear to reflect differences in oil and grease runoff according to land use. Flow-weighted oil and grease concentrations have also been calculated and are shown in Table 5-9.

The total mass load of oil and grease discharged during a single storm is another very common parameter used to study environmental impact and control alternatives of non-point source pollution. The mass of oil and grease discharged at any time is the product of the oil and grease concentration and the runoff flow at that time. Thus, the total mass load for a storm can be calculated as the integral of this product with respect to time. (See section on data analysis). Table 5-10 presents the total mass load of oil and grease for each storm as measured at each sampling station. Since runoff flow varies with time and location to a greater extent than oil and grease concentration, the total mass load generally fluctuates according to the same pattern as runoff flow.

Hydrocarbon Load Factor

An index of comparison of the potential oil and grease contribution from each land use category under uniform conditions of rainfall would serve as a convenient way of categorizing the load of different land use types. In this study, the hydrocarbon load factor was defined as the mass load of oil and grease per unit area per unit rainfall (lb/sq. mi.-in. rainfall). Rainfall rate was not considered in the calculation of hydrocarbon load factor. Table 5-11 presents calculated values of the hydrocarbon load factor associated with each station for each storm as well as a mean value for each station and each storm.

TABLE 5-10 TOTAL MASS LOAD OF OIL AND GREASE (LB.) FOR EACH STORM AT EACH SAMPLING STATION

		Total Mass Load (lb.)						
		Station						
		1	2	3	4	5	Storm Mean	Std. Dev.
	1	2870.33	94.91	29.37	165.05	237.38	679.41	1227.22
	2	81.07	2.83	0.48	4.17	2.06	18.12	35.21
STORM	3	102.81	1.99	0.06	0.73	0.33	21.18	45.64
	4	14.80	0.94	0.05	0.58	0.22	4.14	7.12
	5	121.21	11.85	0.52	5.43	2.91	28.38	52.06
	6	253.20	11.82	0.73	5.95	11.09	56.56	10.02
	7	704.62	22.34	1.46	19.60	7.36	151.08	309.56
Station Mean		592.53	20.95	4.67	28.79	37.34		
Std. Dev.		1030.52	33.48	10.90	60.43	88.30		

TABLE 5-11 HYDROCARBON LOAD FACTOR DEFINED AS POUNDS OIL AND GREASE PER SQUARE MILE DRAINAGE AREA PER INCH RAINFALL (LB./SQ.MI. - IN. RAINFALL)

		Hydrocarbon Load Factor (lb/sq.mi. - in. rainfall)						
		Station						
		1	2	3	4	5	Storm Mean	StdStd. Dev.
STORM	1	562.21	1124.05	13914.29	2631.73	578.92	3762.24	5737.51
	2	96.72	204.29	1380.95	405.13	30.59	423.54	553.68
	3	578.23	676.90	819.05	334.29	23.09	486.31	313.52
	4	145.67	559.52	1190.48	464.74	26.96	477.47	455.06
	5	136.34	806.19	1419.05	497.11	40.74	579.89	558.94
	6	415.35	1172.62	2895.24	794.55	226.52	1100.86	1066.91
	7	523.41	1003.57	2619.05	1185.26	68.09	1079.88	964.28
Station Mean		351.13	792.45	3462.59	901.83	142.13		
Std. Dev.		217.18	344.67	4671.39	817.32	205.57		

(3463 lb./sq. mi.-in. rainfall), and station 5 (upstream residential area) had the lowest value (142 lb./sq. mi. -in. rainfall).

The hydrocarbon load factor values generally follow the same trends with respect to station as oil and grease concentration. Yet the hydrocarbon load factor is also dependent upon the runoff-rainfall ratio (K value). The higher the K value, the greater the total runoff flow volume from that area and, consequently, the greater the total mass load. For example, the large difference in hydrocarbon load factor values between station 3 and station 4 (service station on major street: 70% residential area; 30% small-scale commercial area), both of which had high oil and grease concentration, can be attributed to the high K value for station 3 and low value for station 4.

The very high hydrocarbon load factor for station 3 may be a result of inaccurate flow measurement during storm 1 at this site, as reflected by an inordinately high K value.

Because of potential errors in measurement of runoff flows and estimation of station drainage areas, K values, from which hydrocarbon load factors are calculated, are subject to considerable inaccuracy. This may result in the fact that the hydrocarbon load factor varies greatly between storms. Consequently, the hydrocarbon load factor may be most accurately viewed as an initial approximation.

Summary of Raw Data and Simple Statistics

The five stations considered in this study, each representative of different land uses, contribute different quantities and concentrations of oil and grease to urban runoff. Characteristics of storm events (hydrologic factors) also were important factors. Table 5-12 summarizes the relationship of oil and grease runoff to each sampling station. The relationship of each storm event to oil and grease runoff is presented in Table 5-13.

TABLE 5-12 SUMMARY OF MEAN OIL AND GREASE CONCENTRATION, MEAN TOTAL MASS LOAD, AND MEAN HYDROCARBON LOAD FACTOR FOR EACH SAMPLING STATION

Station	Description	Drainage Area (ft^2)	Mean oil and grease Concentration (mg/l)	Mean total mass load (lb.)	Mean hydrocarbon load factor (lb/mi^2-in. rainfall)
1	Mouth of the Watershed	7.08×10^7	7.57	592.53	351.13
2	Safeway Distribution Center	1.17×10^6	7.16	20.95	792.45
3	Parking Lot	2.92×10^4	15.25	4.67	3462.59
4	Service Station on major street	8.71×10^5	10.80	28.79	901.83
5.	Upstream Residential area	5.70×10^6	4.13	37.34	142.13

TABLE 5-13 SUMMARY OF THE RELATIONSHIP OF PRECIPITATION/RUNOFF TO OIL AND GREASE CONCENTRATION AND HYDROCARBON MASS LOAD FOR EACH STORM EVENT

Storm	Days since previous storm	Total rainfall (in.)	Mean total runoff flow (10^6 gal.)	K value*	Mean oil and grease concentration (mg/l)	Mean total mass load (lb.)	Mean hydrocarbon load factor (lb/mi^2-in. rainfall)
1	11	2.01	14.67	3.75	9.80	679.41	3762.24
2	18	0.33	0.69	.33	7.13	18.12	423.54
3	1	0.07	0.57	.55	7.27	21.15	486.31
4	1	0.04	0.08	.53	7.11	4.14	477.47
5	5	0.35	0.51	.31	12.63	28.38	579.89
6	4	0.24	0.67	.61	10.54	56.56	1100.85
7	3	0.53	3.43	.83	10.18	151.08	1079.88

* K value is the ratio of runoff to rainfall calculated as runoff/total rainfall for the storm drainage area of the station

of oil and grease runoff to each sampling station. The relationship of each storm event to oil and grease runoff is presented in Table 5-13.

Station 3 (parking lot) had the greatest mean hydrocarbon load factor (3462.59 lb./sq. mi.-in. rainfall) and mean oil and grease concentration (15.25 mg/l). Station 4 (service station on major street: 70% residential area; 30% small-scale commercial area) also was associated with high values for these parameters: mean hydrocarbon load factor, 901.83 lb./sq. mi.-in. rainfall; mean oil and grease concentration, 10.80 mg/l). On the other hand, because of a small drainage area, station 3 contributed the lowest total mass load (4.67 lb). As discussed earlier in this chapter, the hydrocarbon load factor calculated for station 3 may be inordinately large due to inaccurate flow measurements during Storm 1.

Station 5 (upstream residential area) contributed the lowest quantity of oil and grease per unit area and unit rainfall (142 lb./sq. mi.-in. rainfall) and was associated with the lowest oil and grease concentration (4.13 mg/l). However, the total mass load from the large drainage area associated with station 5 was substantial (37.34 lb).

At the mouth of the watershed (station 1), the mean oil and grease concentration was 7.57 mg/l with a mean contribution of 351.13 pounds oil and grease per square mile of the Richmond watershed per inch rainfall.

There was little apparent relationship of precipitation factors such as days between storms or total rainfall to oil and grease concentration. As expected, rainfall was found to be correlated with total runoff which was, in turn, related to total mass load of oil and grease. It was of interest to note that storms associated with high oil and grease concentrations were not necessarily associated with a high hydrocarbon load factor because the K value (ratio of runoff to rainfall) for the storm was low. This was the case, for example, for Storm 5.

Correlation Coefficients

Correlations between all variables considered in this study were analyzed and are presented in Table 5-14. (Storm number and station number were excluded because the numerical values of these parameters would not be expected to be linearly related to any other variables).

Simple correlation coefficients show no significant relationships of oil and grease concentration to any of the other variables examined: runoff flow rate, total storm runoff, days between storms, time since storm beginning, total storm rainfall, and instantaneous rate of rainfall. The Pearson correlation coefficient between oil and grease concentration and each of the above variables was found to be less than 0.1.

The mass loading rate of oil and grease at any time was found to be strongly correlated with runoff flow at that time ($r = 0.85$). Perhaps coincidentally, the total rainfall for a particular storm was observed to show a moderate correlation with days since previous storm ($r = 0.45$).

Linear Regressions

Multivariate linear regressions were performed between oil and grease concentration and six dependent variables: 1) days since previous storm; 2) instantaneous flow rate; 3) instantaneous rate of rainfall; 4) total storm runoff; 5) total storm rainfall; and 6) time since storm beginning. None of these variables appear to be linearly related to oil and grease concentration when all data points were treated as an aggregate; all r^2 values are less than 0.1. Thus, less than 10% of the variability in oil and grease concentration can be explained by one to six of these variables. Regressions were also performed with data from each station analyzed separately. With the exception of results from station 5, these data also show little apparent relationship

TABLE 5-14 CORRELATION COEFFICIENTS BETWEEN OIL AND GREASE LOAD PARAMETERS AND STORM PARAMETERS

	OG1	RMASS	TMASS	DBS	TSSB	FLOW	RRAIN	TRAIN	TFLOW
OG1	1	0.15	-0.07	-0.02	-0.05	-0.06	0.03	0.06	-0.08
RMASS		1	0.53	0.02	0.05	0.85	0.30	0.16	0.52
TMASS			1	0.15	0.25	0.59	0.25	0.44	1
DBS				1	0.34	0.05	0.23	0.45	0.15
TSSB					1	0.08	0.27	0.62	0.24
FLOW						1	0.37	0.180	0.59
RRAIN							1	0.51	0.23
TRAIN								1	0.41
TFLOW									1

between oil and grease concentration and the variables considered. Moreover, no single variable or combination of up to three variables consistently accounts for the most variablity in oil and grease concentration among the five stations. The higher r^2 values observed for station 5 are difficult to explain. Table 5-15 indicates, for each station number, the variables which show the strongest relationships to oil and grease concentration for regressions performed using one to three variables.

Linear regressions were also performed between total mass load and two dependent variables: days since previous storm; and total storm rainfall. A linear relationship was observed between total mass load and total storm rainfall when all data were treated as an aggregate and when data from each station were analyzed separately. For aggregate regressions between total mass and total storm rainfall, an r^2 value of 0.1960 was found. When data from each station were analyzed individually, a much greater degree of variability was explained by total storm rainfall ($r^2 > 0.90$ for each station).

Analysis of Variance

One-way analysis of variance (ANOVA) tests utilizing a randomized block design were performed to test the hypothesis that oil and grease concentration is a function of seven independent variables and the hypotheses that total mass load and total runoff volume are each functions of two independent variables. In each of the ANOVA tests, station number was treated as a block, or class, in order to isolate the effect of the other independent variables. Tables 5-16, 5-17, and 5-18 present ANOVA tests for oil and grease, total mass load, and total runoff volume, respectively.

The analysis of variance for oil and grease concentration was performed using three different models with station number as a block: single variables

TABLE 5-15 MULTIVARIATE REGRESSION ANALYSIS: SUMMARY OF STRONGEST RELATIONSHIPS TO OIL AND GREASE CONCENTRATION

STATION	Number of variables in analysis	Strongest relationship to oil and grease concentration	r^2
1	1	TSSB	0.073
	2	TSSB & TRAIN	0.098
	3	TSSB & TRAIN DBS	0.109
2	1	DBS	0.159
	2	TSSB & FLOW	0.231
	3	TSSB & FLOW & DBS	0.314
3	1	DBS	0.021
	2	TRAIN & FLOW	0.101
	3	TRAIN & DBS & TFLOW	0.111
4	1	TFLOW	0.053
	2	TRAIN & TFLOW	0.0725
	3	FLOW & RRAIN & TFLOW	0.089
5	1	TFLOW	0.662
	2	TSSB & TFLOW	0.775
	3	TSSB & RRAIN & TFLOW	0.781

TABLE 5-16 ANALYSIS OF VARIANCE (RANDOMIZED BLOCK DESIGN) TEST OF THE HYPOTHESIS THAT OIL AND GREASE CONCENTRATION (OG1) IS A FUNCTION OF THE INDEPENDENT VARIABLES; STATION NUMBER IS TREATED AS A BLOCK

Dependent Variable: Oil and Grease Concentration (OG1)

Independent Variables	r^2	F Statistic	Probability >F
MODEL	0.168	14.42	0.0001
1 Independent Variable			
STONO	0.177	2.91	0.0892
TFLOW	0.170	2.16	0.1428
TRAIN	0.171	1.36	0.2447
FLOW	0.167	1.24	0.2663
TSSB	0.173	0.92	0.3375
DBS	0.167	0.08	0.7772
RRAIN	0.168	0.28	0.5942
2 Independent Variables			
TSSB		4.76	0.0300
TRAIN		1.39	0.2395
OVERALL	0.192	11.24	0.0001
6 Independent Variables			
TSSB		6.44	0.1117
TFLOW		2.40	0.1227
TRAIN		2.07	0.1516
RRAIN		0.38	0.5357
DBS		0.05	0.8284
FLOW		0.02	0.8998
OVERALL	0.200	6.93	0.0001

TABLE 5-17 ANALYSIS OF VARIANCE (RANDOMIZED BLOCK DESIGN) TEST OF THE HYPOTHESIS THAT OIL AND GREASE MASS LOAD (TMASS) IS A FUNCTION OF THE INDEPENDENT VARIABLES; STATION NUMBER IS TREATED AS A BLOCK

Dependent Variable: Hydrocarbon Mass Load (TMASS)

Independent Variables	r^2	F Statistic	Probability
TRAIN	0.431	97.89	0.0001
DBS	0.255	8.98	0.003

TABLE 5-18 ANALYSIS OF VARIANCE (RANDOMIZED BLOCK DESIGN) TEST OF THE HYPOTHESIS THAT TOTAL RUNOFF VOLUME (TFLOW) IS A FUNCTION OF THE INDEPENDENT VARIABLES; STATION NUMBER IS TREATED AS A BLOCK

Dependent variable: Total runoff volume (TFLOW)

Independent variables	r^2	F statistic	Probability >F
TRAIN	0.401	78.76	0.0001
DBS	0.253	8.33	0.0042

considered one at a time; two variables in combination; and six variables in combination. Storm number was excluded from two-variable and six-variable analyses because storm number itself is a composite of the other hydrologic parameters, such as rate of rainfall, days between storms, and total storm rainfall.

One-variable analysis indicates that storm number is the single variable which, when considered with station number, is most strongly related to oil and grease concentration. The hypothesis that oil and grease concentration is a function of storm number is significant at the 9 percent level ($\alpha = 0.09$). The r^2 value of 0.177 associated with this test indicates that storm number (and station number as a block) account for approximately 18 percent of the variability in oil and grease concentration.

Time since storm beginning and total storm rainfall were found to be the two variables which, when considered with station number as a block, were found to be most strongly related to oil and grease concentration. The time since storm beginning was found to be related to oil and grease concentration at the 3 percent level of significance ($\alpha = 0.03$). The overall model which considered these two parameters (and station number as a block) was found to account for approximately 19 percent of the variability in oil and grease concentration ($r^2 = 0.192$).

When all six variables in this study were considered in combination (and station number as a block), time since storm beginning was found to be most strongly related to oil and grease concentration ($\alpha = 0.11$). This model accounted for approximately 20 percent of the variability in oil and grease concentration ($r^2 = 0.200$).

Analysis of variance tests performed with total oil and grease mass load and as a dependent variable indicated that this parameter is related to total rainfall and to days between storms at the 1 percent level of significance ($\alpha = 0.01$) Total rainfall was the most important factor. Total runoff flow volume was also found to be related to these two parameteres at the 1 percent level of significance.

Summary of Analysis of Variance and Regressions

The relationship of the variables considered to oil and grease concentration in runoff is not straightforward. Multivariate linear regressions and correlation coefficients show no significant relationships of oil and grease concentration to any of the parameters in the analysis. Grouping the data points by station increased the variability explained by these parameters. The analysis of variance (ANOVA) tests revealed two important conclusions. When station number was treated as a block, storm number was the single variable which accounted for the greatest amount of variability in oil and grease concentration. When all of the six variables considered were included in the analysis and also when two variables were considered (and station number was treated as a block), time since storm beginning was the most important determinant of variability. The relationship of time since storm beginning to oil and grease concentration indicates a potential "first flush effect."

The lack of significant relationship of oil and grease concentration to rate of rainfall or days between storms is surprising. It would be logical to expect a higher oil and grease concentration with a longer period of time for oil and grease to accumulate before washoff by the storm.

Total mass of oil and grease in runoff from a single storm was, as expected, found to be strongly related to the total rainfall during the storm. This conclusion is based upon the straightforward relationship between rainfall and runoff and the fact that total oil and grease mass was calculated directly from flow values. Days between storms was also found to be a significant determinant of total mass of oil and grease. However, since total storm rainfall and days between storms were also found to be significantly related and since days between storms did not correlate directly with oil and grease concentration, the relationship between total mass of oil and grease and days between storms may not be causative.

Scatter Diagrams: Examination of First Flush Effect

As discussed in Chapter 2 a first flush effect -- an initial high pollutant concentration during the early part of a storm which decreases with time and, more generally, a high pollutant concentration during the first storm of the season compared to later storms -- has been documented by some investigators (Hunter et al, 1979) but has not been observed by others (Soderlund and Lehtinen, 1972). In this study, the existence of a first flush effect was examined in two ways: linear regressions of oil and concentration as a function of time; and scatter diagrams showing the relationship of oil and grease concentration, mass loading rate of oil and grease, and instantaneous flow rate as a function of time. This phenomenon was also considered somewhat in analyses of variance and regressions which included time since storm beginning as a variable. Examination of a first flush effect was limited by the fact that storm 1, the largest and first major storm of the 1980-1981 winter season, was not sampled until six hours after the storm began.

Linear regression of oil and grease concentration as a function of time for each storm and station indicated that a moderate "first flush effect" was observed in the Richmond watershed. An inverse relationship of oil and grease concentration to time since storm beginning was shown by a negative slope of the regression line for 24 of 30 storm/station combinations (80%). The decrease of oil and grease concentration as a function of time was found to be significant at the 0.1 level ($\alpha = 0.1$) for 7 of 30 storm/station combinations (23%). These findings are shown in Table 5-19.

Demonstration of a first flush effect by the scatter diagrams was equivocal. A first flush effect was apparent for some storms and some stations, but not for others. Figures 5-6 and 5-7 illustrate a decrease in oil and grease concentration as a function of time for several storms at station 1 (mouth of the watershed) and at station 2 (Safeway Distribution Center; 77% industrial property and parking; 23% impervious non-auto) respectively. Similarly, Figure 5-8 shows for storm 5 a decrease in oil and grease concentration at several stations.

Although a first flush effect may be logically expected, this effect may be obscured by many conflicting trends operating simultaneously. Oil and grease solubilize at a rate proportional to concentration, which would be higher during the early part of the storm as a result of accumulation prior to the storm. Consequently, a first flush effect is reasonable to anticipate. Another factor which would be expected to contribute to a first flush effect is the fact that particulate matter, onto which oil and grease hydrocarbons may be adsorbed, will run off early in the storm event.

A decline in mass loading rate as a function of time since storm beginning, another important phenomenon related to first flush effect was observed for most storms during the sampling period. Thus, most of the oil and grease mass load was discharged early during a storm. Scatter diagrams of mass loading rate versus time were used to examine this relationship. Table 5-20 shows the storms and stations for which mass loading rate decreased as a

TABLE 5-19 LINEAR REGRESSION: OIL AND GREASE CONCENTRATION AS A FUNCTION OF TIME

	STATION				
STORM	1	2	3	4	5
1	0	0	0	0	0
2	-	-	-	+	-
3	-*	-*	-*	-	-
4	-	-	-	-	-
5	-*	+	-	-*	-
6	+	+	+*	+*	-
7	-	-*	-*	-	-

Total decrease: 24/30 (80%)
Total significant decrease: 7/30 (23%)

Symbols

0 : insufficient information
- : decrease observed
+ : increase observed
* : significant at the 0.1 significance level ($\alpha = 0.1$)

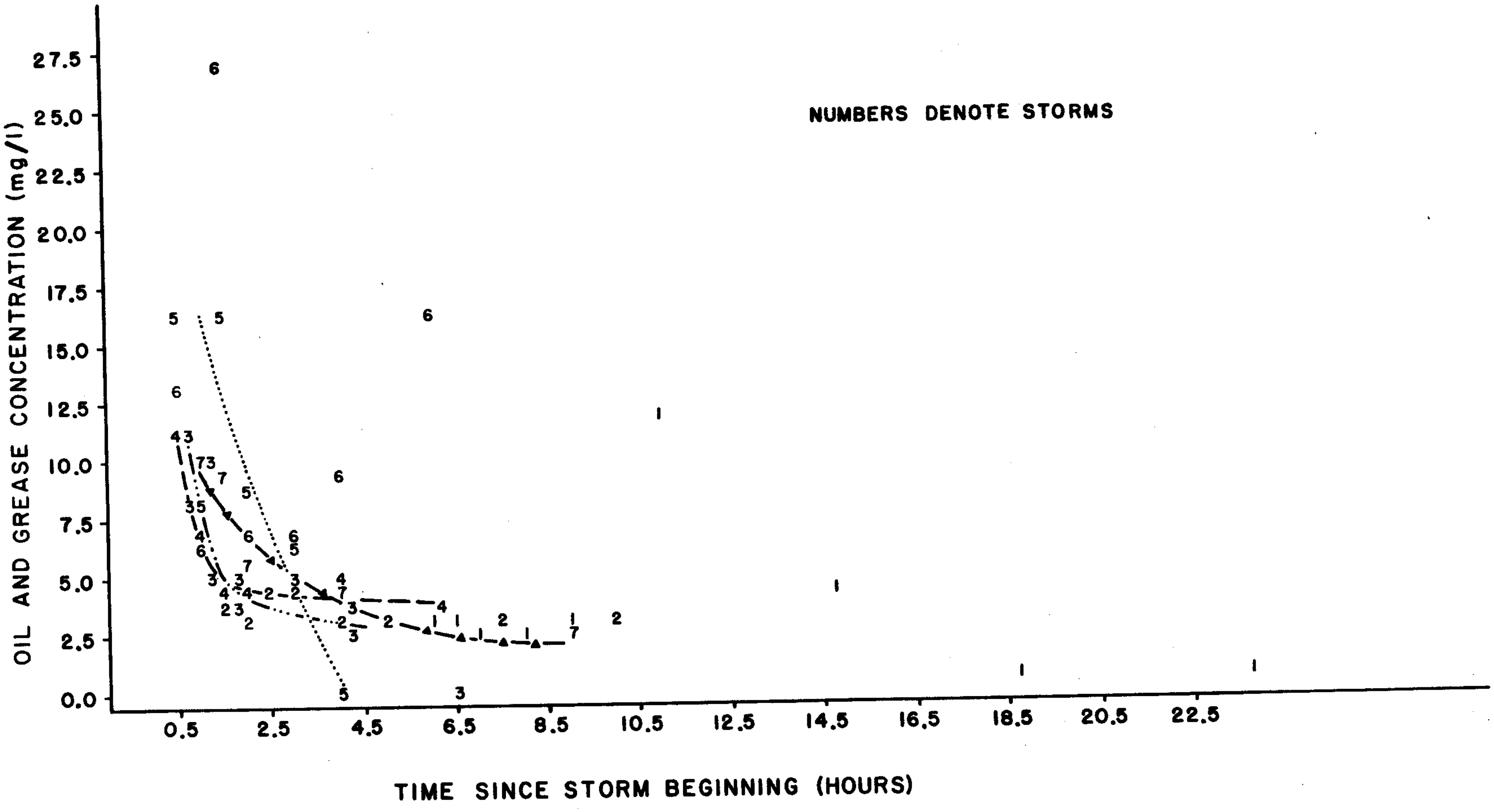


Figure 5-6 Oil and Grease Concentrations as a Function of Time for Station 1

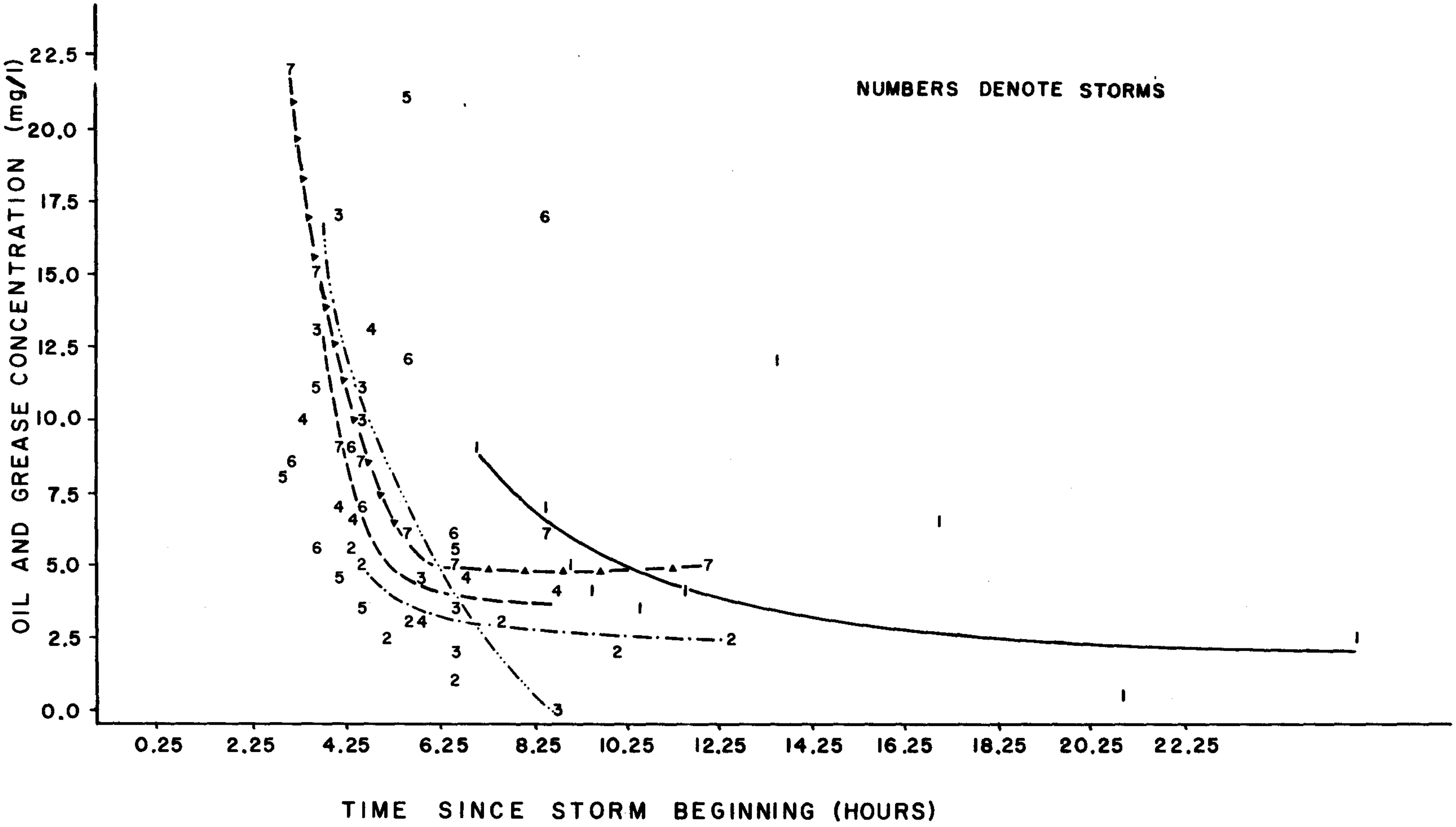


Figure 5-7 Oil and Grease Concentrations as a Function of Time for Station 2

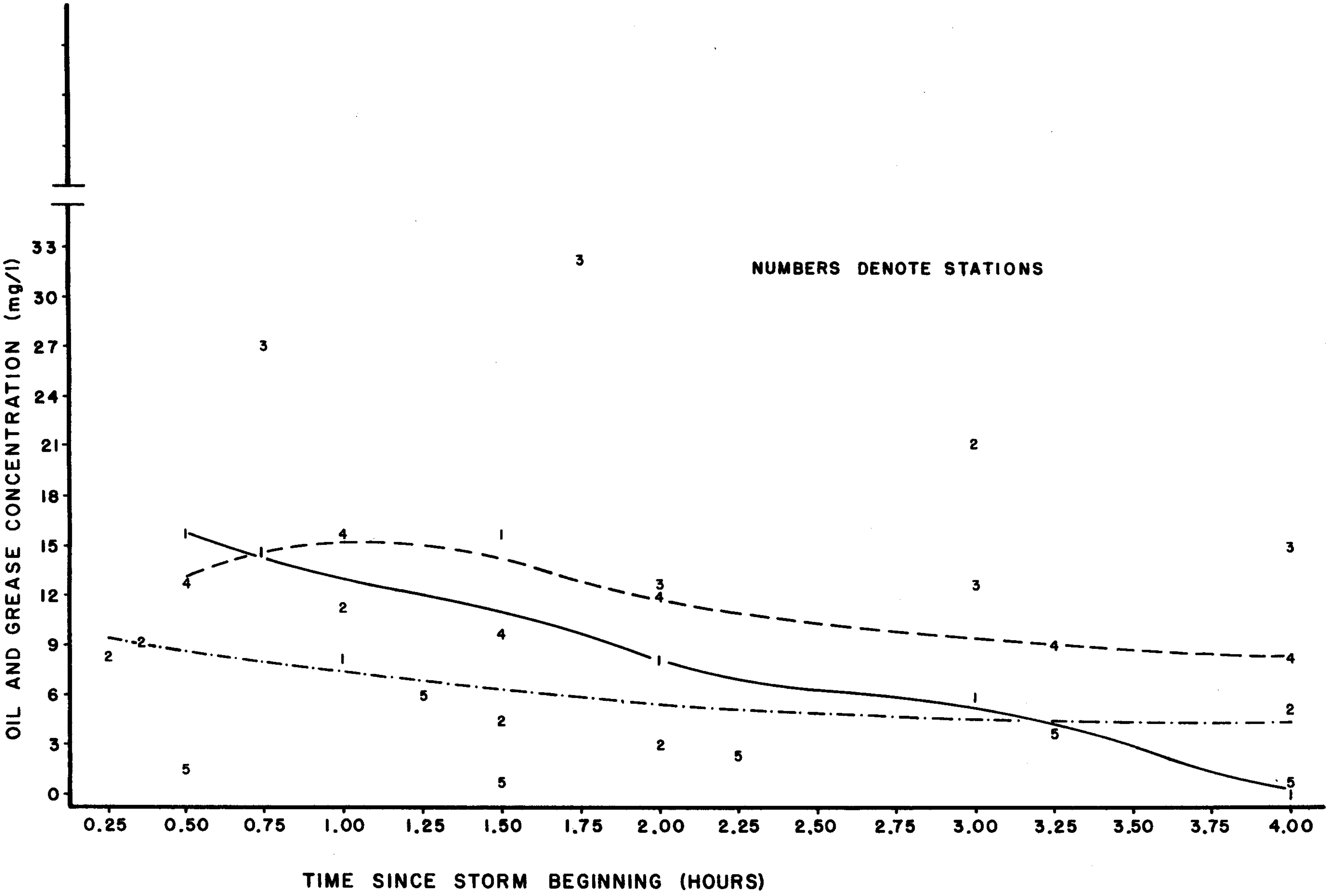


Figure 5-8 Oil and Grese Concentrations as a Function of Time for Storm 5

TABLE 5-20 SCATTER DIAGRAMS MASS LOADING RATE AS A FUNCTION OF TIME

	STATION				
STORM	1	2	3	4	5
1	0	0	0	0	0
2	-	-	-	-	+
3	-	-	-	-	-
4	-	-	-	-	-
5	+	+	+	+	+
6	+	+	+	+	+
7	-	-	-	-	-

Symbols

0 : insufficient information
- : decrease observed
+ : increase observed

function of time. (Because Storm 1 was not sampled until six hours after the storm began there was insufficient information to evaluate this storm.)

A decline in mass loading rate as a function of time may result from a decrease either in oil and grease concentration or in flow rate over time. Very often, a decline in mass loading rate results from a decrease in flow with time.

In order to illustrate the time relationships of runoff flow rate and mass flow rate of oil and grease on a uniform scale, normalized variables were calculated as follows:

Normalized oil and grease mass = RMASS/TMASS

Normalized flow rate = FLOW/TFLOW

These ratios indicate the fraction of total mass or total flow discharged at a particular time. Figures 5-9 and 5-10 illustrate a decrease in normalized oil and grease mass loading rate with time for storm 3 and storm 4, respectively, at various stations. Figures 5-11 and 5-12 illustrate a decrease in normalized flow rate with time for the same two storms.

A "transportation lag" at station 1 may be observed in these figures, indicating the time required for oil and grease and rainfall to travel from all points in the watershed to the mouth of the estuary. Peaks in normalized oil and grease mass and normalized flow rate for station 1 follow in time those for other stations.

Comparison of Results to Previous Studies

This section shall briefly compare the results of the Richmond watershed study to previous work by various authors. This literature is discussed in greater detail in Chapter 2 (Sources of Oil and Grease).

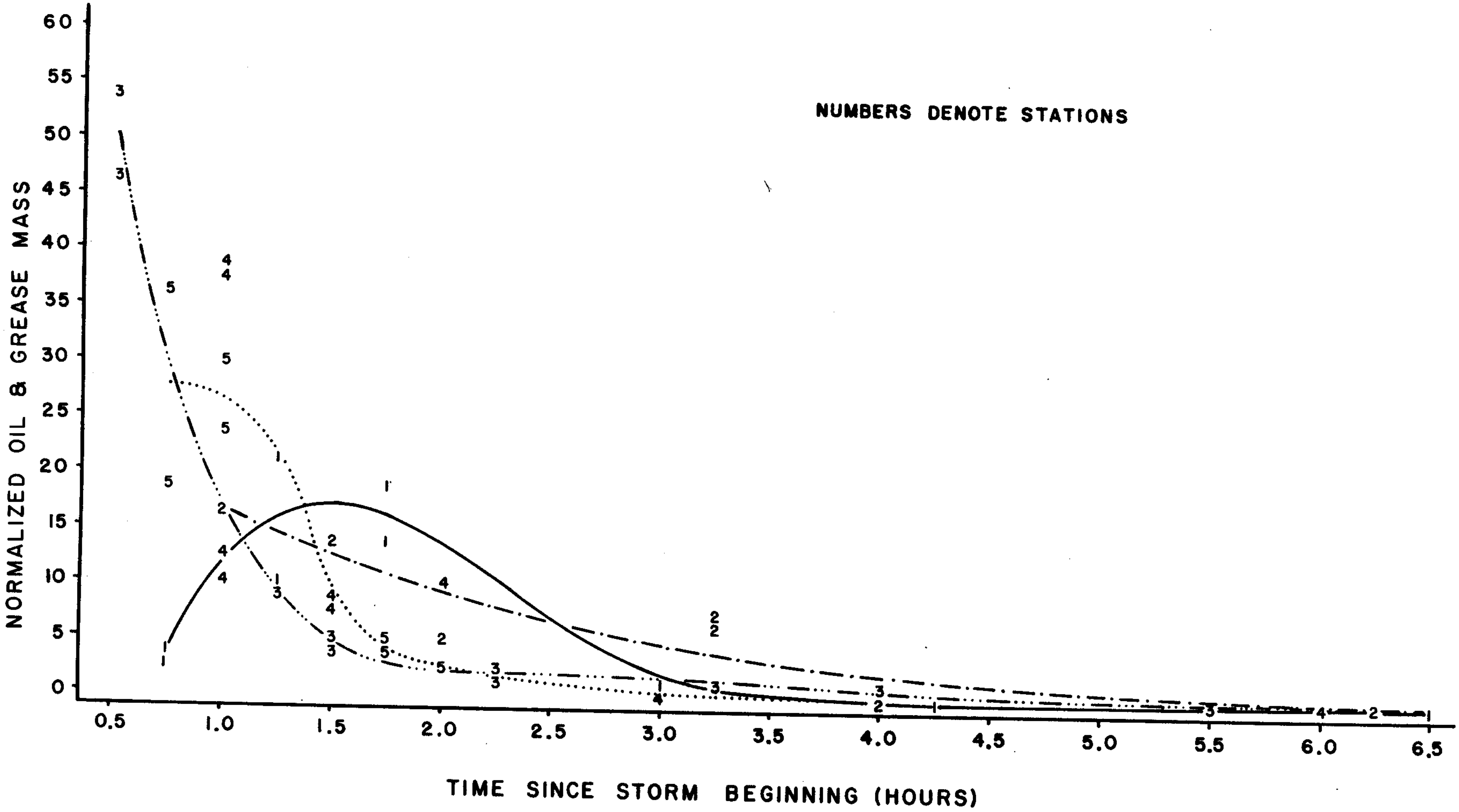


Figure 5-9 Normalized Oil and Grease Mass Loading Rates for Storm 3

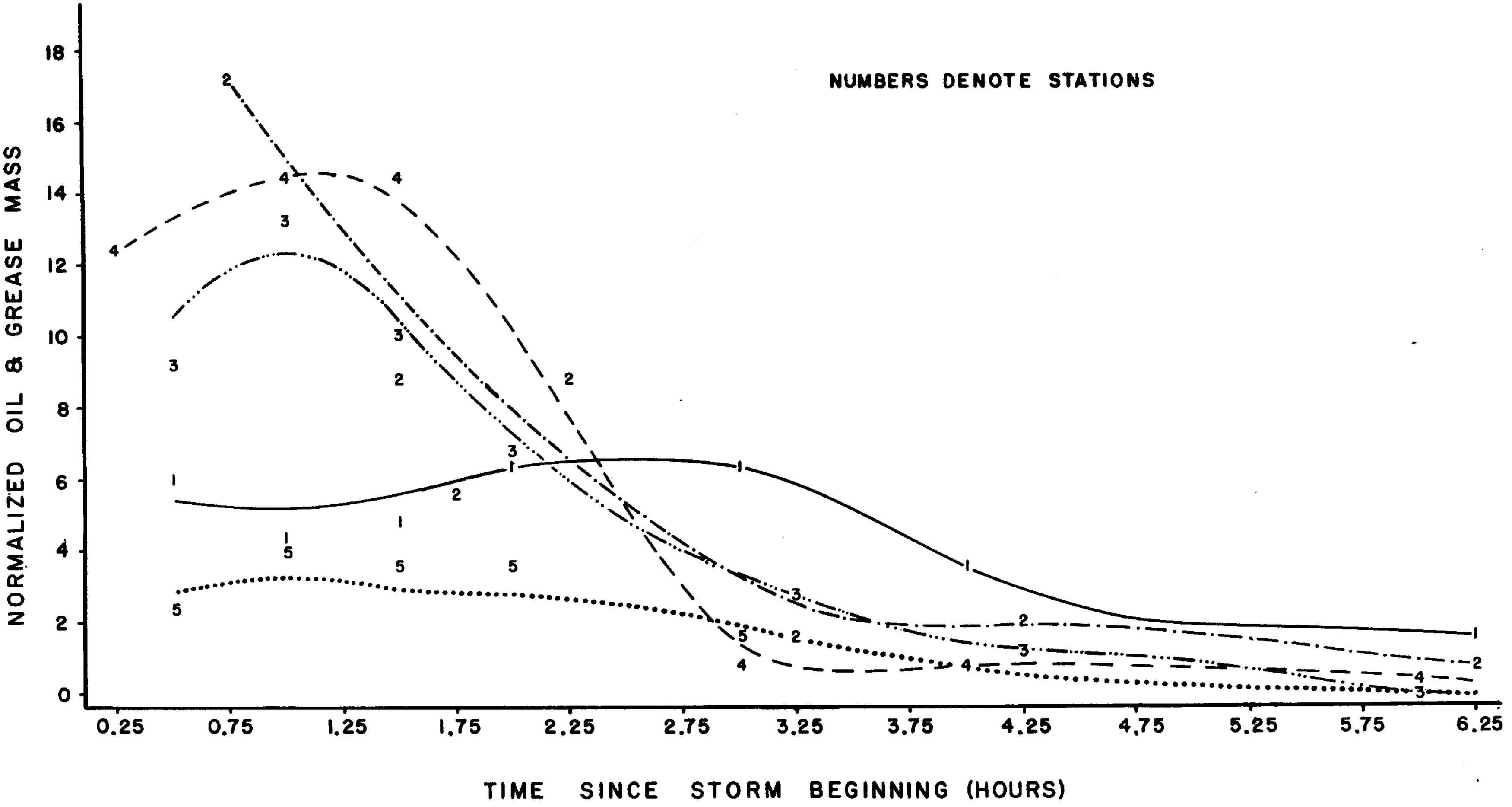


Figure 5-10 Normalized Oil and Grease Mass Loading Rates for Storm 4

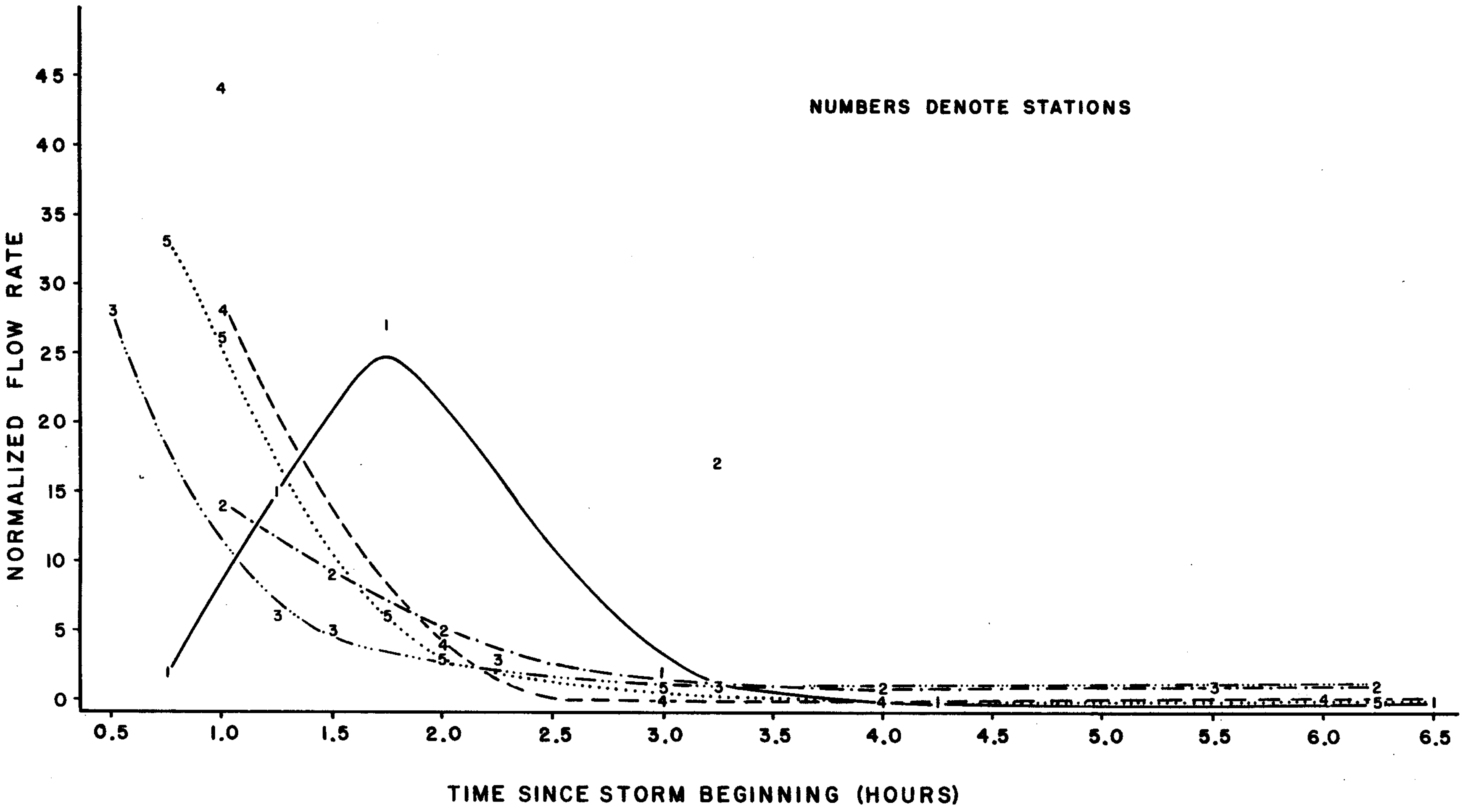


Figure 5-11 Normalized Flow Rates for Storm 3

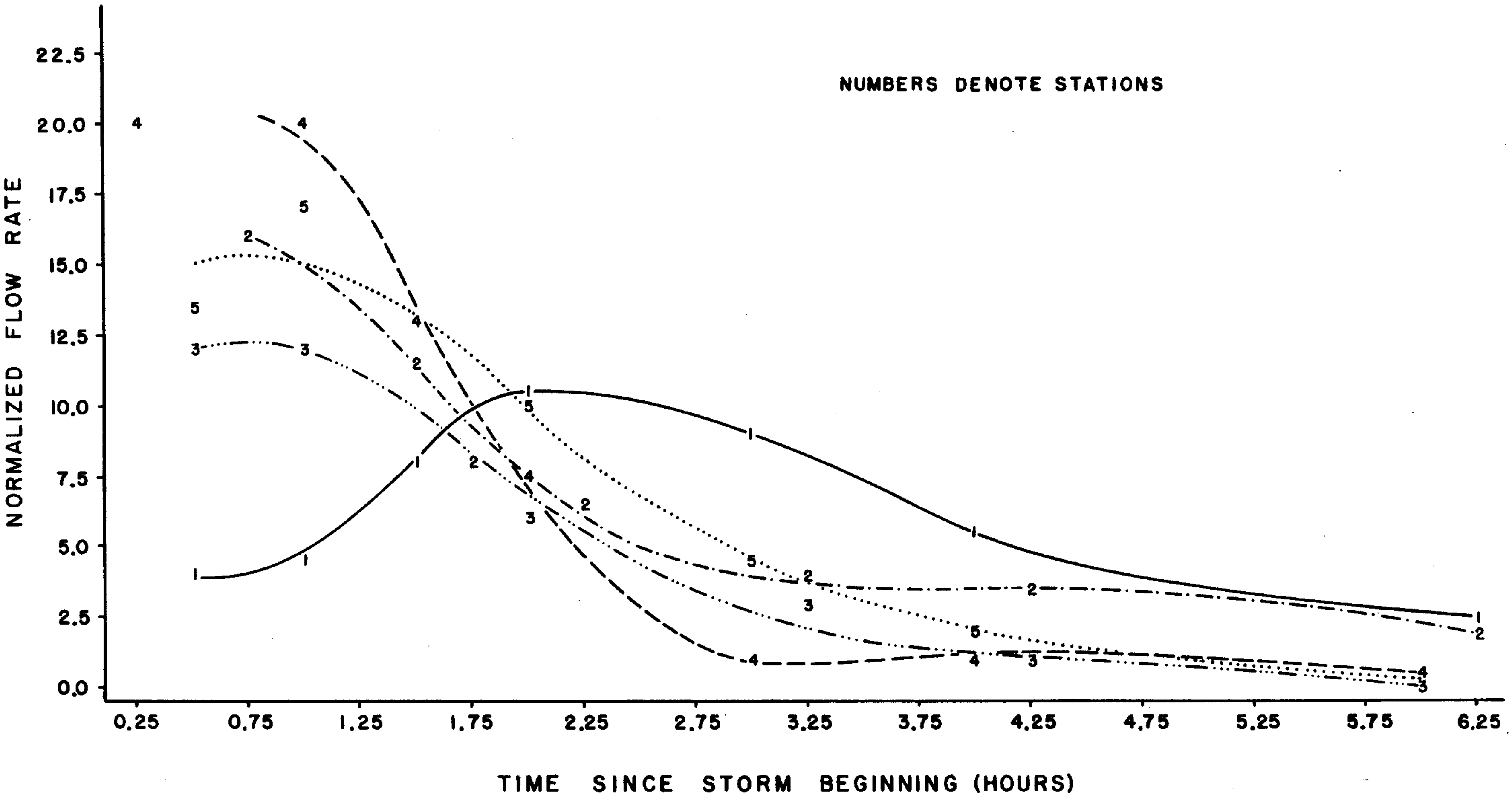


Figure 5-12 Normalized Flow Rates for Storm 4

The concentrations of oil and grease in urban runoff observed in this study were comparable to those observed by other investigators in the United States.

The existence of a "first flush" effect and the importance of the time interval since the last previous storm in determining concentrations of oil and grease in urban stormwater runoff have been addressed by previous works. Days between storms, or the time interval since the last previous storm, was not observed to be a significant determinant of oil and grease concentration in the Richmond watershed. Perhaps, as suggested in Chapter 2, the removal of particulates, onto which oil and grease may be adsorbed, from roads and parking lots by winds and by traffic action when these surfaces have attained a "saturation level" may account for the lack of observed relationship. The existence of a "first flush" effect was generally confirmed by this study; oil and grease concentration declined with time for some storms at some stations. Hunter et al, 1979 discussed these relationships in detail. Similarly to these authors, approximately 16% of the variability in oil and grease concentration was accounted for by time since storm beginning.

The linear relationship of oil and grease concentration to rate of rainfall and to runoff flow observed by Soderlund and Lehtinen (1972), was not confirmed by this study.

The exponential relationship between oil and grease mass load and total storm rainfall observed by Hunter et al, 1979 could not be investigated thoroughly in this study because there was inadequate data for storm 1, the only large storm of the season (2.01 in.).

Summary of Quantitative Data

Sampling station, representative of land use, was found to be a very important determinant of oil and grease contribution to storm water runoff. Parking lot (station 3) was found to contribute the greatest oil and grease load per unit area and to be associated with the highest oil and grease concentration in runoff. An upstream residential area (station 5) was associated with the lowest oil and grease concentration and mass load per unit area.

A moderate "first flush" effect was observed in this study. Other precipitation and runoff characteristics showed poor relationship to oil and grease concentration. Storm characteristics accounted for approximately 20% of the variability in oil and grease concentration when station number was treated as a block in an analysis of variance.

Total mass of oil and grease in runoff from a single storm was, as expected, found to be strongly related to the total rainfall during the storm. This conclusion is, however, based upon a direct relationship between rainfall and runoff and the fact that total mass of oil grease discharged during a storm was calculated directly from flow values.

Interpretation of the data obtained from the field sampling program is limited by the fact that storm 1, the first storm of the winter season and the only large storm of the sampling period, was not sampled until six hours after the storm began. In addition, oil and grease determination during storm 2 was subject to some potential error.

Identification of Oil and Grease by Sedimentation

The results of the settling test indicated very little tendency for oil and grease to separate from the sampled stormwater (Tables 5-21 and 5-22). No

TABLE 5-21 RESULTS OF SETTLING COLUMNS TESTS, STATION 1

Location	OIL AND GREASE; mg/L						
	Time, in minutes						
	0.0	1.0	2.0	5.0	10.0	30.0	Final
Top	8.4	5.7	6.0	6.3	5.9	4.9	6.3
Middle	8.3	7.9	10	9.2	6.7	6.8	-
Bottom	8.7	6.1	8.0	6.6	7.1	7	29

Final Freon rinse: 125 mg/l in 405 ml

TABLE 5-22 RESULTS OF SETTLING COLUMN TESTS, STATION 3

Location	OIL AND GREASE (mg/L)						
	Time, in minutes						
	0.0	1.0	2.0	5.0	10.0	30	Final
Top	9.5	9.1	8.7	8.9	8.3	12	11
Middle	14	14	12	15	14	9.9	-
Bottom	10	10	11	10	10	9.8	20

Final Freon rinse: 610 mg/l in 730 ml

discernable trend could generally be seen either for oil and grease settling to the bottom or floating to the surface. The turbidity and solids did increase in the bottom portion of the column as the sample settled, although with no apparent increase in the oil and grease content. However, when the bottom liter was sampled, oil and grease concentration appeared to be significantly elevated. A similar phenomenon was not evident upon sampling the surface layer.

Oil and grease in the stormwater samples did not appear to alter dramatically through gravity separation. However, some association may be apparent between particulates and oil and grease, as evidenced by the elevated oil and grease concentration in the very bottom layer of the water column. Unfortunately, the results of these tests are complicated by the relatively large retention of oil and grease on the glassware, as evidenced by the relatively high oil and grease on the glassware, as evidenced by the relatively high oil and grease concentration in the freon used for the final rinse. One might conclude that perhaps one half of the oil is free or adsorbed to particulates.

Settling tests were conducted to determine the nature of the oil present in the stormwater samples. The nature of the oil (free, colloidal, or adsorbed to particulates) is extremely important when selecting treatment methods. Conventional gravity separation techniques are only useful for removing free oil and oil adsorbed to large particulates. To remove colloidal or soluble oil coagulation or other emulsion breaking technique is needed.

Identification of Oil and Grease Compounds in Stormwater Samples

General features of the chromatograms are shown in Table 5-23. The standards used and their retention times are listed along the top of the

TABLE 5-23 DISTRIBUTION OF OIL AND GREASE COMPOUNDS IN STORMWATER SAMPLES AS DETERMINED BY GAS CHROMATOGRAPH

X = present in sample. Number in parenthesis is retention time in minutes

SAMPLE NO.	<n-C_{10}	C_{10} (4.75)	n-C_{10} to n-C_{16}	n-C_{16} (10.14)	n-C_{16} to Anthracene	Anthracene (21.68)	Anthracene to n-C_{24}	C_{24} (32.30)	C_{24} to C_{32}	C_{32} (40.22)	C_{32}+	Oil and Grease Concentration (mg/l)
1-1-2					X	X(21.72)	X	X(32.37)	X		X	3.0
1-1-6							X		X		X	12.0
1-1-8					X	X(21.61)	X		X		X	0.8
1-6-1					X		X		X	X(40.16)	X	13.0
1-6-3					X	X(21.56)	X		X	X(40.25)		27.0
1-6-5					X	(32.76)	X		X	X(40.18)	X	6.8
1-6-7					X	X(21.61)	X		X	X(40.20)		16.0
2-1-0					X	X(21.62)	X	X(32.36)	X		X	8.8
2-1-2					X		X	X(32.35)	X		X	4.9
2-1-6	X	X(4.76)	X		X	X(21.71)	X	X(32.23)	X	X(40.17)	X	12.0
2-1-8							X		X		X	0.7
2-6-1						(21.63)	X	X(32.39)	X	X(40.16)	X	8.6
2-6-3	X		X		X	X(21.73)	X	X(32.37	X		X	9.2
2-6-5			X		X		X	X(32.28)	X	X(40.21)	X	12.0
2-6-7					X	X(21.55)	X		X		X	17.0
3-1-0					X		X	X(3229)	X		X	10.5
3-1-2					X		X	X(32.34)	X	X(40.28)	X	11.0
3-1-6					X		X	X(32.25)	X		X	9.5
(3-1-8					X	X(21.64)	X	X(32.20)	X	X(40.23)	X	8.9
3-5-2			X				X	X(32.27)	X		X	88.0
3-6-1	X				X	X(21.71)	X	X(32.40)	X		X	9.4
3-6-3	X		X		X			X(32.28)	X	X(40.17)	X	20.0
3-6-5			X		X	X(21.77)	X		X	X(40.24)	X	12.0
3-6-7					X		X	X(32.23)	X		X	35.0

TABLE 5-23 (continued)

SAMPLE NO.	<n-C_{10}	C_{10} (4.75)	n-C_{10} to n-C_{16}	n-C_{16} (10.14)	n-C_{16} to Anthracene	Anthracene (21.68)	Anthracene to n-C_{24}	C_{24} (32.30)	C_{24} to C_{32}	C_{32} (40.22)	C_{32}+	Oil and Grease Concentration
4-1-0					X	X(21.74)	X	X(32.24)	X	X(40.27)	X	13.5
4-1-2		X			X		X	X(32.27)	X	X(40.23)	X	11.0
4-1-6	X X(4.87)	X			X		X	X(32.24)	X	X(40.16)	X	19.0
4-1-9							X	X(32.24)	X	X(40.16)	X	19.0
4-6-1					X	X21.71)		X			X(40.19)	X16.0
4-6-3			X		X	X(21.66)	X	X(32.25)		X(40.10)	X	9.8
4-6-5					X	X(27.72)	X		X	X(40.25)	X	8.0
4-6-7	X		X		X	X(21.59)	X	X(32.29)	X		X	21.0
5-1-0					X	(21.69)	X	X(32.23)	X	X(40.17)	X	16.0
5-1-2					X		X	X(32.27)	X	X(40.21)	X	17.0
5-1-6						X(21.70)		X(32.22)	X		X	16.0
5-1-8						X(21.77)			X	X(40.27)	X	5.5
5-6-1					X	X(21.60)	X	X(32.21)	X	X(40.15)	X	6.4
5-6-3					X		X		X			6.3
5-6-5	X		X		X		X	X(32.35)	X		X	13.0
5-6-7					X		X		X	X(40.32)	X	1.7
6-6-1					X	X(21.76)	X	X(32.23)	X	X(40.21)	X	
6-6-3					X	X(21.64)	X		X		X	
6-6-5					X	X(21.65)	X	X(32.25	X	X(40.23)	X	
6-6-7					X	X(21.66)	X	X(32.40)	X	X(40.21)	X	

table. The presence of peaks in the chromatograms of the samples with retention times very close to the retention times of the standards are indicated in the body of the table. Also indicated is the presence of compounds in the regions between the retention times of the standards. The chromatograms are generally characterized by an unresolved envelope with a retention-time range from about 17-18 minutes to about 40+ minutes and the presence of relatively few clearly resolved peaks. In relation to retention times of the standards, the unresolved envelope ranged from a retention time less than that of anthracene (21.68 min) to just above that of n-C_{32} (40.22 min).

Three of the chromatograms shown in Figures 5-13, 5-14 and 5-15 illustrated the general pattern just described. These three unusual chromatograms each contain a very short series of highly resolved peaks and only appeared in samples taken from the mouth of the drainage channel (sample station 1). They also were apparently present only during part of the first and sixth storms. For example, unusual peaks in the the first storm were present in the sample taken at 2140 hours but not in the samples taken at 0930 or 1400. Chromatograms of samples from the sixth storm showed unusual peaks in the samples collected at 0415 and 0515 but not in samples collected later at 0645 and 0945.

Identification of the substances causing these highly resolved peaks is not possible on the basis of their retention times on the gas chromatograph. The fact that the peak patterns in the first and third samples during the sixth storm at station one are virtually identical does, however, suggest that the same substance is responsible for the unusual peaks in these two samples. One possible category of substances, refined petroleum products, can fairly safely be eliminated as the cause of the unusual peaks based on the

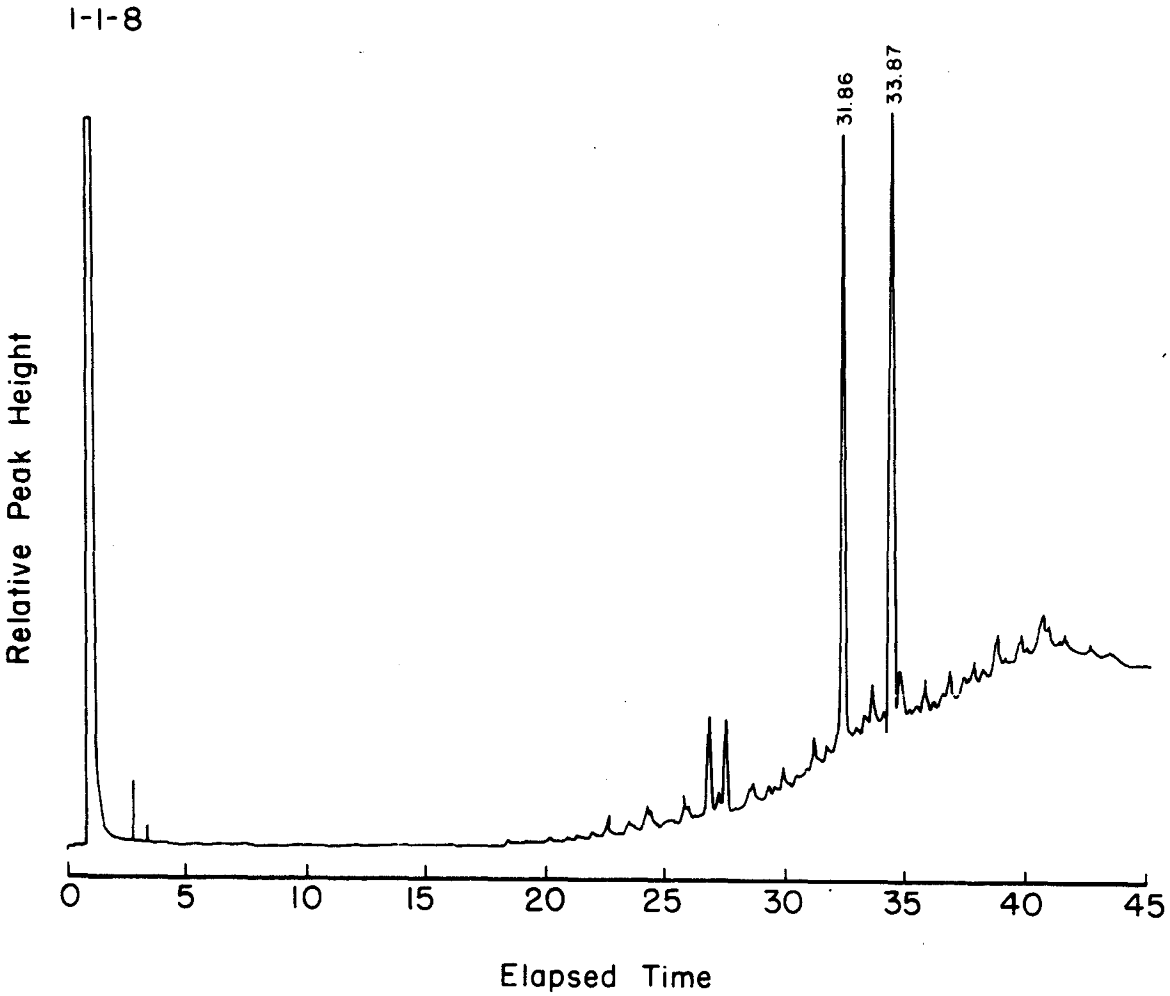


Figure 5-13 Gas Chromatogram for Storm 1, Station 1, Sample 8

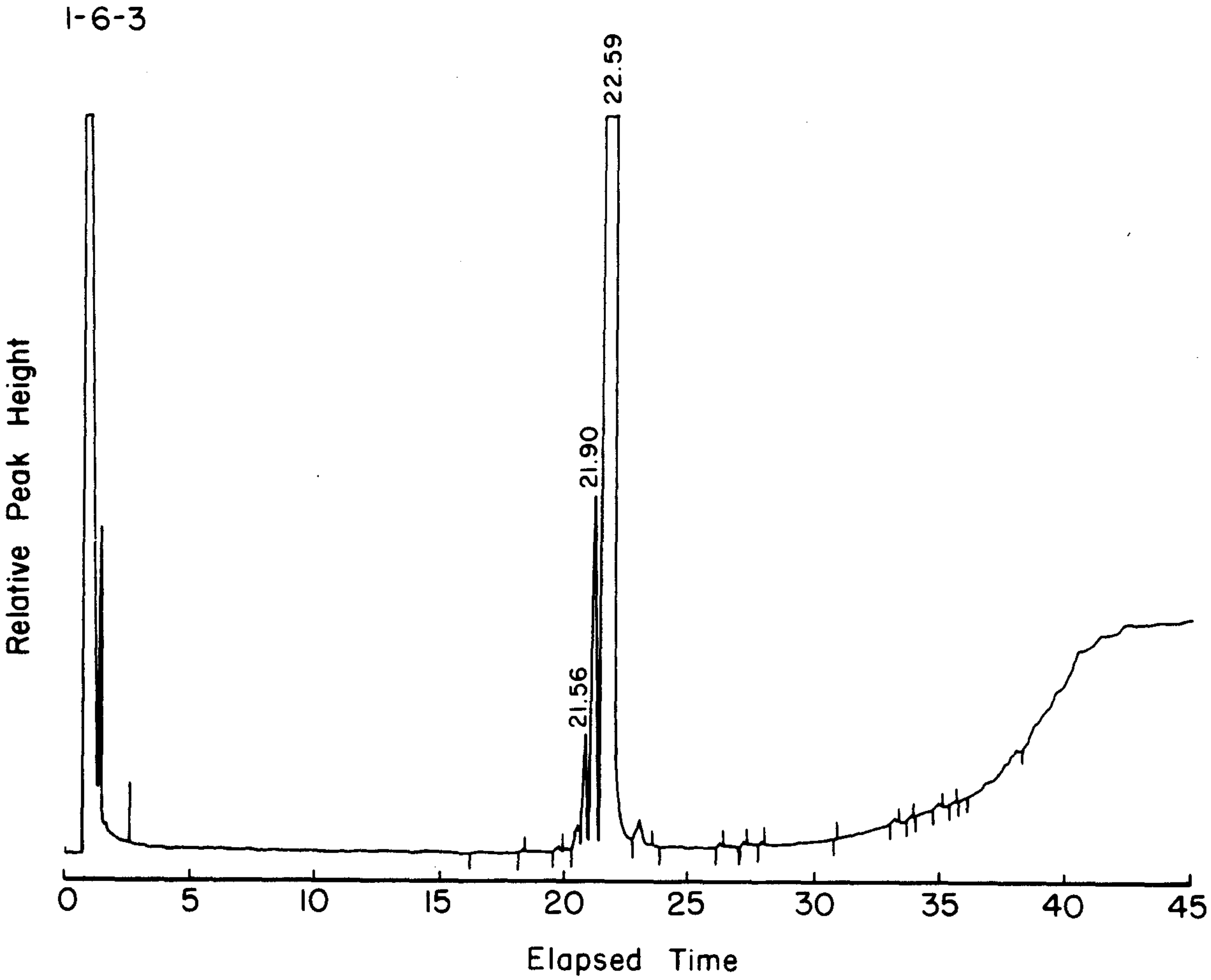


Figure 5-14 Gas Chromatoram for Storm 6, Station 1, Sample 8

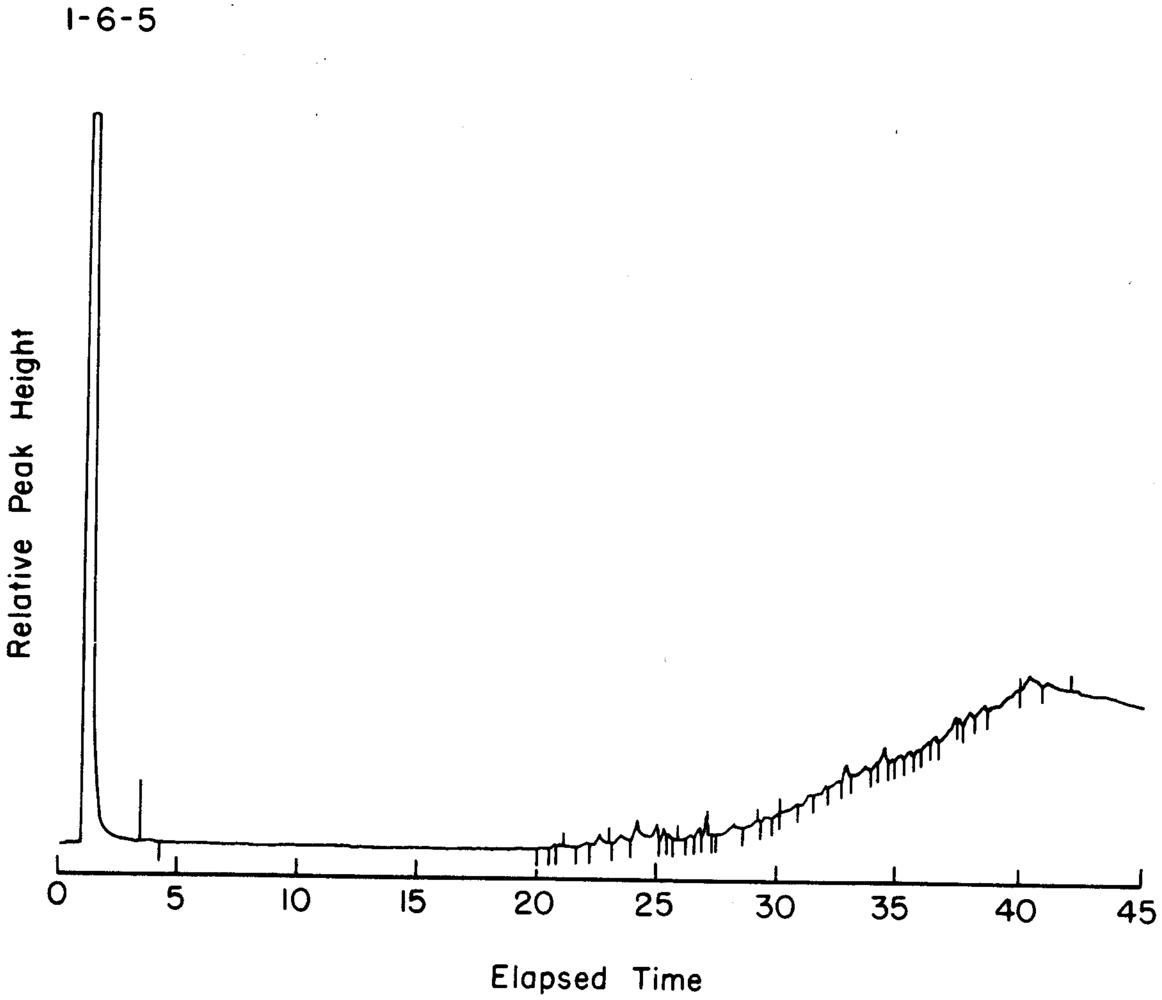


Figure 5-15 Gas Chromatogram for Storm 6, Station 1, Sample 5

chromatogram pattern. This is because the chromatogram pattern for refined petroleum products are characterized by a series of resolved peaks extending over a much wider retention time range than those in the three samples described here. Figure 5-16 shows typical chromatogram patterns for a few refined petroleum products.

Comparison to Previous Work - GC Results

As was discussed in Chapter 2, most previous studies have compared gas chromatogram patterns from the hydrocarbons in urban runoff to gas chromatogram patterns of potential hydrocarbon sources and, on this basis, made tentative hydrocarbon-source identifications. This study did not run samples of possible source substances through the gas chromatograph, consequently, no gas chromatograms of possible sources run at identical conditions as the runoff samples are available for comparison. Comparisons between the chromatograms obtained in this study and the chromatograms in the studies just cited must be made with caution. The extraction procedures and solvents used in each of the cited studies were different than those used in this study. In addition, four of the five studies just cited fractionated the extracted material prior to analysis by gas chromatography. Thus, some of the gas chromatograms from likely sources are strictly for the aliphatic or aromatic fractions (see Figures 2-7, 2-9, 2-10, and 2-11). In addition, equipment and operating conditions for the gas chromatographs differed.

The studies which analyzed used crankcase oil all found it to be characterized by an unresolved envelope of high molecular weight material, not unlike the gas chromatogram pattern obtained in this study for the oil and grease in stormwater runoff. One study also found that the gas chromatogram pattern obtained from the extracts of automobile exhaust particulates was very

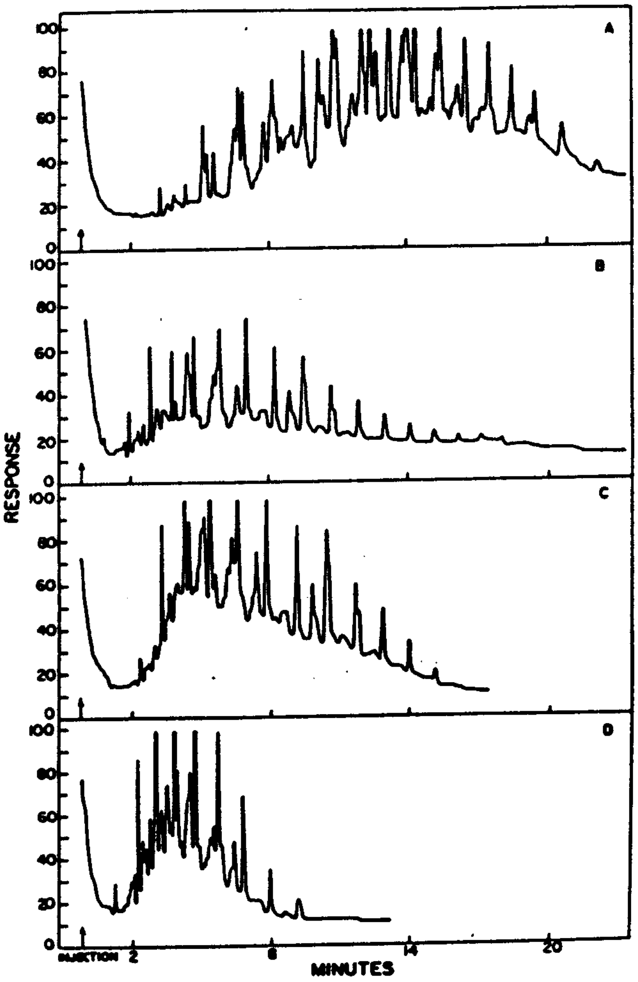


Figure 5-16 Typical Gas Chromatograms for Refined Products A, No. 6; B, No. 4; C, No. 2; and D, kerosene (Dell'Acqua, 1975)

similar, being characterized by an unresolved envelope which ranges from n-C_{22} to n-C_{34}+ and which maximizes at n-C_{29} (Boyer and Laitinen, 1975). Thus, the oil and grease found in the Richmond watershed runoff could largely originate in either or both of these sources.

CHAPTER 6

APPLICATION OF THE ABMAC MODEL TO THE RICHMOND WATERSHED

Introduction

Computer models can be used to simulate the actions of a physical system by means of equations relating the components of the system. In the study of urban runoff waters, models can be used to predict the runoff produced by a given storm and the quality of the runoff water, or to simulate changes in runoff quantity and quality caused by changes in land use or by application of mitigation measures. In doing computer modeling it is most important to choose a model suited to the study. The choice of model for this project is shown later.

Once a model is chosen it must be calibrated. To do this model parameters are chosen, based on experimental data if possible, to reproduce chosen storms as closely as possible. After calibration, the model should be verified by further experimentation. Predictions of water quantity and quality for new storms are obtained from the calibrated model and are compared to independent values actually measured for the storms. If the predicted values match the measured values, then the model is verified. If the values do not match, the model must be recalibrated, or perhaps the theory underlining the model will require modification to produce a closer approximation of reality.

Model Selection

Huber et al (1975) list three types of models used in urban runoff studies, each having a different objective. Planning models are used for overall assessment of the runoff problem of an area, and of the cost and effectiveness of abatement procedures. These models have minimal data requirements, low mathematical complexity, large computational time steps and long simulation times. Examples of planning models are the Army Corps of Engineers (1975) Storage, Treatment, Overflow, and Runoff Model (STORM) and the San Francisco Association of Bay Area Governments Macroscopic Planning Model (ABMAC) (Litwin et al, 1980).

Design models are intended to produce detailed, accurate simulation of a single storm, such as perhaps the 25 year storm for an area. These models are sophisticated and mathematically complex, using time steps on the order of minutes, and short simulation times. Input data requirements tend to be extensive. An example of this type of model is the EPA Storm Water Management Model (SWMM) (Huber et al, 1975).

Operational models are used to produce actual control decisions during a storm event. These models are sophisticated and highly site specific. Such a model would obviously be inappropriate for this study.

It was decided to use a planning model in this project since several years of storms were to be modeled. Flow and oil and grease concentration data were not available on the fine, minute by minute scale demanded by a design model such as SWMM. The SWMM model also required detailed watershed data such as the length, diameter, and slope of all storm sewers, as well as the infiltration rates into these sewers. This degree of accuracy is totally incompatible with the accuracy available for the experimental measurements.

Of the two planning models most readily available, ABMAC was chosen for use and is described in the following section. The STORM model required that pollutant concentration be characterized as a number of pounds of pollutant per hundred pounds of dust and dirt, in conjunction with a daily rate of accumulation of dust and dirt, and length of antecedent dry period. As is explained in Chapter 2, Shaheen (1975) and other authors cast doubt on the importance of the antecedent dry period as a determinant of pollutant concentration in storm water runoff. Also the weight of oil and grease per unit weight of dust and dirt is not known for the Richmond watershed, and it is not clear at this time whether this value is indeed a constant. The finding by Eganhouse and Kaplan (1981a) that total oil and grease concentration is not highly correlated with total particulates in runoff waters argues against a constant oil and grease fraction of dust and dirt. For these reasons the STORM model was not chosen.

Finally the ABMAC model was found to be simple and easily applied. It required as input parameters values easily calculated from actual experimental measurements in the Richmond watershed. The computational time step of one day used by ABMAC as compared with the STORM one hour time step made ABMAC a faster and less expensive tool. Little if any loss of accuracy was incurred by the use of ABMAC rather than any other model since the ABMAC model utilized the greatest degree of accuracy possible from the experimental measurements.

ABMAC Model

ABMAC is the Association of Bay Area Governments (ABAG) Macroscopic Planning Model (MAC). A brief description of the model is presented here. A more detailed account may be found in the model documentation and user's guide (Litwin et al, 1980).

ABMAC is a continuous simulation model based on simple concepts of hydrology and water quality. For this reason its data input requirements are minimal. It requires rainfall data, and runoff coefficients, areas, and pollutant concentrations for all land use types. Any watershed can be divided into as many as 99 subareas, each of which can be characterized by up to six land uses. Up to six water pollutants can be studied. Storage, treatment and overflow can all be simulated. Calculations are made using a daily time step.

Runoff is calculated using the rational method:

$$R = kAr \qquad (6\text{-}1)$$

where R = runoff

k = runoff coefficient

A = area

r = rainfall.

Water quality is represented by a pollutant concentration C:

$$M_p = CR = CkAr \qquad (6\text{-}2)$$

where M_p is the pollutant load, the total mass of pollutant produced. Both the runoff coefficient k and the pollutant concentration C are considered to be constants in this model. A diagram of the model operation is provided in Figure 6-1.

There are several places where simplifications in the model can lead to inaccuracy. The runoff coefficient is not really constant. Dry land will absorb more water than saturated land. The runoff coefficient can thus vary during a storm, and from season to season. For this reason ABMAC is really intended as a yearly model. If used to compare different years of data, the errors introduced by using an average runoff coefficient will tend to average out. The constant k can lead to errors in considering the flow from any one particular storm, however. This can make calibration difficult. The assumption of a constant pollutant concentration discounts first flush effects or any other variation of concentration with time or flow. Again, since an average value is used, the total result over the course of a year may be quite reliable. No time lag, percolation rate, or other hydrologic complication is included.

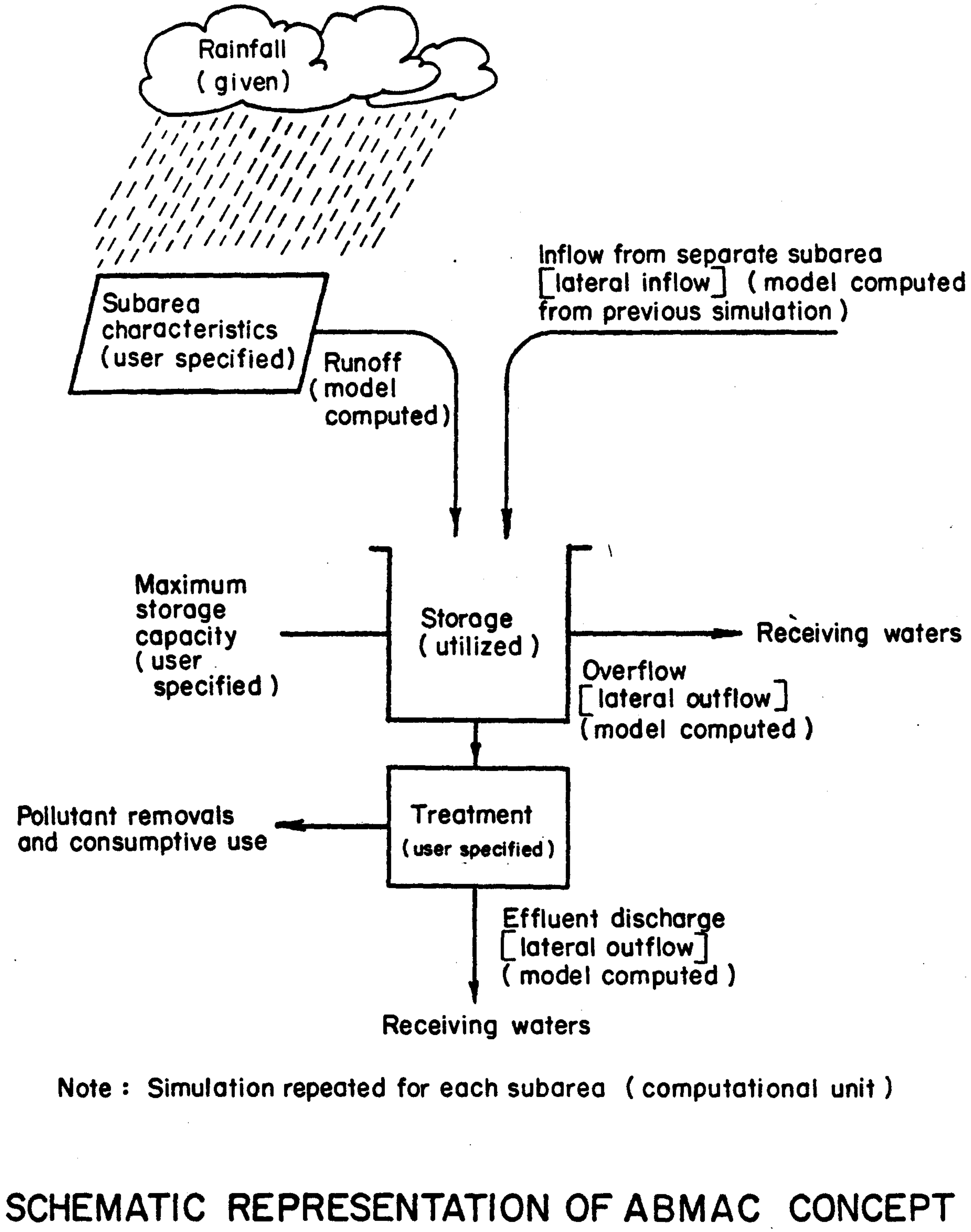


Figure 6-1 Schematic Diagram of the ABMAC Model (Metcalf and Eddy,1980)

It must be noted that the simplifications will not necessarily lead to less exact results than would a more complex model. In assuming a constant value of k one avoids errors in analysis of the variations of k. A complex model can only yield better results if one has the data to properly calibrate and run the model. The ABMAC model provides a good flexible, easily applied tool for the study of water quality in watersheds where hydrology and water quality have not be extensively documented.

Calibration of the ABMAC Model for the Richmond Watershed

Calibration of a computer model is done by choosing values for parameters to be used by the model in its calculations so that model results accurately reflect actual conditions. The calibration in this case was based on flow and water quality data collected during seven storms in the Richmond watershed. The ABMAC model is capable of simulating as many as 99 subareas in a watershed. The entire Richmond watershed was considered as a single subarea for several reasons. The watershed is small, totaling only about 2.2 square miles, and sufficient data were not available to differentiate between similar land uses in different parts of the basin. It was deemed pointless to separate the watershed into different subareas, treat each subarea identically, and then recombine the solutions when the same results could be obtained by considering the watershed as a single unit. No treatment or storage of the runoff was simulated.

The four input parameters required by the ABMAC model are: 1) rainfall data, 2) acreages, 3) runoff coefficients, and 4) pollutant concentrations. Rainfall data were obtained from the civic center rain gauge in downtown Richmond. Rainfall was considered to be even across the watershed since no way of accurately estimating rainfall variations was available.

The other three parameters are functions of land use in the watershed. The six land uses used in the modeling are:

1) Open Land - Parks, undeveloped land
2) Residential - Mostly single family dwellings, including some multifamily buildings
3) Industrial Property - Large industries, factories
4) Commercial Property - Small scale shops and stores
5) Parking Lots
6) Freeways and Railroads - Freeways, BART tracks, railroads and right of ways

Land use areas were determined by means of large detailed aerial maps of the watershed on a scale of 100 feet to the inch. The entire watershed was delineated on these maps, land uses were determined and area measurements were made. The drainage areas for each of the five experimental measurement stations were also determined, and the land use areas within these sites measured. These values are presented in Table 6-1. From these data the area within the watershed devoted to each of the six land uses was calculated and is shown in Table 6-2.

The runoff coefficients and the oil and grease pollutant concentrations for each station were determined from analysis of the measured flows and pollutant concentrations. To determine runoff coefficients k for each station, the measured volume flowing off the area was divided by the total volume of rain falling on the same area for each storm.

$$k_{ij} = \frac{TFLOW_{ij}}{r_j \times A_i} \qquad (6\text{-}3)$$

TABLE 6-1 STATION PARAMETERS

				Fractional Land Use					
STATION	AREA acres	k_i	C_i mg/l	O	R	I	C	P	F
1	1,630.0	.44	5.68	.052	.751	.043	.058	.06	.036
2	26.9	.76	7.10			1.00			
3	.67	.94	12.81					1.00	
4	20.0	.45	9.90		.70		.30		
5	131.0	.18	3.90	.05	.95				

Land Uses

O = Open Land
R = Residential
I = Industrial Property
C = Commercial Property
P = Parking Lots
F = Freeway and Railroads

TABLE 6-2 LAND USE PARAMETERS

Land Use (acres)	AREA	k_u ~~mg/l~~	C_u mg/l
Open Land	85.	.02	0.0
Residential	1221.	.19	3.89
Industrial Property	70.	.76	7.10
Commercial Property	98.	1.00	13.13
Parking Lots	94.	.94	12.81
Freeways & Railroads	59.	.90	7.04

where k_{ij} = runoff coefficient for station i, storm j

A_i = Area of station i

$TFLOW_{ij}$ = runoff volume for station i, storm j

r_j = rainfall for storm j.

The results are presented in Table 5-6. The characteristic runoff coefficient for each station was taken to be the average of these values over all storms.

$$k_i = \frac{1}{n} \sum_{j=1}^{n} \frac{TFLOW_{ij}}{r_j \times A_i} \qquad (6\text{-}4)$$

where k_i = runoff coefficient characteristic of station i

n = number of storms.

Please note that the k values obtained for storm 1 for stations 3 and 4 are unrealistically high and were not included in the average. For those two stations, averages over the last six storms were used to calculate the runoff coefficients. Runoff coefficients for each of the five stations are presented in Table 6-1.

The oil and grease pollutant concentrations for each storm for each station were taken to be the flow weighted average concentrations.

$$C_{ij} = \frac{TMASS_{ij}}{TFLOW_{ij}} \qquad (6\text{-}5)$$

where C_{ij} = pollutant concentration for station i, storm j

$TMASS_{ij}$ = total mass of oil and grease washed off station i by storm j.

Results are presented in Table 5-9. The characteristic oil and grease pollutant concentration for each station was taken to be the average of these values over the seven storms.

$$C_i = \frac{1}{n} \sum_{j=1}^{n} \frac{TMASS_{ij}}{TFLOW_{ij}} \quad (6\text{-}6)$$

where C_i = pollutant concentration characteristic of station i. The oil and grease pollutant concentration characteristic of each of the five stations are presented in Table 6-1.

For use in the ABMAC model the runoff coefficients and pollutant concentrations of the various land uses must be determined based on the above values experimentally determined for each measuring station. For some land uses this determination is straightforward. Station 3 for example is entirely composed of parking lot. In general however, the k and C values for each land use must be calculated by the solution of simultaneous equations. For the runoff coefficient,

$$k_i A_i = \sum_{u=1}^{m} k_u A_{ui} \quad (6\text{-}7)$$

where m = total number of land uses (6)

k_u = runoff coefficient characteristic of land use u

A_{ui} = area of station i devoted to land use u

Or,

$$k_i = \sum_{u=1}^{m} f_{ui} k_u \quad (6\text{-}8)$$

where $f_{uj} = A_{ui}/A_i$ = fraction of station i devoted to land use u. Values for k_i and f_{ui} are given in Table 6-1. Equation 6-8 yields five equations, one for each measurement station i. Now since there are five equations and six unknowns, the system cannot be solved unless a value is assumed for one variable. The value for the runoff coefficient for open land is taken to be .02 based on a value determined by the Los Angeles County Flood Control

District. A sample calculation is presented below. Results for the runoff coefficients for all land uses are presented in Table 6-2 The value calculated for commercial property was slightly higher than 1.00 and was set equal to 1.00. Calculations yielded a value much greater than 1.00 for k for freeways and railroads. Since this was the last k calculated, it contained all the errors. The k value for freeways and railroads was estimated to be about .90, and this value was used in all further calculations.

From Table 6-1, station 5 is 5% open land and 95% residential. A sample calculation using these values and based on equation 7-8 follows:

$$
\begin{aligned}
k_5 &= .05\ k_o + .95\ k_R \\
.18 &= .05 \times .02 + .95\ k_R \\
.179 &= .95\ k_R \\
.19 &= k_R
\end{aligned}
$$

Oil and grease concentrations characteristic of each land use can be calculated in a similar manner. Consider the mass balance for a given storm.

$$M_i = C_i\ k_i\ A_i\ r = \sum_{u=1}^{m} M_{ui} \qquad (6\text{-}9)$$

where M_i = total mass of oil and grease washed off station i by storm

M_{ui} = mass of oil and grease washed off land devoted to land use u within station i.

Therefore,

$$C_i\ k_i\ A_i\ r = \sum_{u=1}^{m} C_u\ k_u\ A_{ui}\ r \qquad (6\text{-}10)$$

where C_u = pollutant concentration characteristic of land use u.

Or

$$C_i\ k_i = \sum_{u=1}^{m} f_{uj}\ C_u\ k_u \qquad (6\text{-}11)$$

Again there are five equations and six unknowns. The value for the oil and grease concentration for open land is assumed to be zero. The actual concentration is probably a function of the plants found in the area, and may vary seasonally. No good general value was found in the literature, but it is generally agreed that the concentration of oil and grease in runoff from open land is small.

With this assumption, the other values for oil and grease concentrations characteristic of the remaining 5 land uses were calculated. The results are shown in Table 6-2. A sample calculation follows.

Applying equation 6-11 to station 5:

$$C_5\ k_5 = .95\ C_R\ k_R + .05\ C_0\ k_0$$

$$3.90 \times .18 = .95 \times .19 \times C_R + .05 \times 0.0 \times .02$$

$$.70 = .18\ C_R$$

$$3.89 = C_R$$

The values presented in Table 6-2 are those that were used in the application of ABMAC. It is recognized that these values are not certain. They are calculated from experimental measurements and reflect any experimental errors. These values could be manipulated. For example, Table 5-9 shows that the pollutant concentration at station 5 is far greater for storm 1 than for the other storms. It can be argued that a more accurate measure of oil and grease concentration characteristic of station 5 would be the average of the other six storms, excluding storm 1. Also, the use of runoff coefficients and oil and grease concentrations measured at station 5 to characterize downtown residential property at station 4 is open to challenge. Perhaps total vehicular traffic should be more important in the modeling, so that high traffic residential and low traffic residential could be considered two different land uses. These suggestions could be experimentally tested and perhaps implemented in later modeling efforts.

Actual runoff and measured oil and grease pollution concentrations are compared with the values generated by the ABMAC model in Table 6-3. For small and middle sized storms the agreement is good. It should be noted that the largest residuals are measured for the largest storms. This effect may be due to limitations in the model. For large storms the ground will become saturated causing k to increase almost to unity for all land uses. In this case, the assumption of constant k made by the model will not hold. It is also interesting to note that Hunter et al (1979) found the total hydrocarbon load to increase exponentially with the total rainfall during a storm. Perhaps in the limit of large storms the linear calculation used in ABMAC is no longer applicable.

Model Simulations

The ABMAC model, calibrated as outlined in the previous section, was used to simulate various mitigation and growth scenarios. Six years of rain data, from 1975 to 1980, were input for each scenario. Pollutant load was calculated for each year, and the average load over the six years was computed. Results are presented in Tables 6-4, 6-5 and 6-6.

First the model calculation of actual pollutant discharge over those years was performed. Next various mitigation measures were assumed to be implemented which reduced the characteristic oil and grease concentration for each land use by 60%. This reduced the contribution per acre of each land use to 40% of its initial value. Simultaneous treatment of the two land uses that yield the largest oil and grease concentrations, commercial property and parking lots, was also simulated. Results of these 60% reductions are presented in Table 6-4. More effective mitigation practices producing a reduction of the measured oil and grease concentrations by 90% were also

TABLE 6-3 MODEL RESIDUALS

Pollutant Load

STORM	(in)	RAIN LOAD (10^3 lb)	MEASURED LOAD (10^3 lb)	MODEL (10^3 lb)	DIFFERENCE
1	2.01	2.870	1.856	1.014	
2	.33	.081	.305	- .224	
3	.07	.103	.065	.038	
4	.04	.015	.037	- .022	
5	.35	.121	.323	- .202	
6	.24	.253	.222	.031	
7	.53	.705	.489	.216	
				.851	

Flow

STORM	RAIN	MEASURED FLOW (in)	MODEL FLOW (10^6 gal)	DIFFERENCE (10^6 gal)	(10^6 gal)
1	2.01	67.02	28.7	38.32	
2	.33	3.12	4.7	- 1.58	
3	.07	2.60	1.0	1.60	
4	.04	.38	.6	- .22	
5	.35	2.26	5.0	- 2.74	
6	.24	2.91	3.4	- .49	
7	.53	16.07	7.6	8.47	
				43.36	

TABLE 6-4. ABMAC MITIGATION SIMULATION - 60% REDUCTION
(Pollutant Load in 10^3 Pounds)

YEAR	1975	1976	1977	1978	1979	1980	Average	% Reduction	% Reduction / % Area
RAIN (in)	20.10	9.91	16.08	25.48	27.86	18.01	19.57		
POLLUTANT LOAD FROM ACTUAL CONCENTRATIONS	18.55	9.15	14.84	23.52	25.71	16.62	18.06		
POLLUTANT LOAD AFTER 60% REDUCTION IN:									
RESIDENTIAL	16.09	7.93	12.87	20.39	22.30	14.42	15.67	13.2	.18
INDUSTRIAL	17.52	8.64	14.01	22.21	24.28	15.70	17.06	5.5	1.28
COMMERCIAL	15.03	7.41	12.03	19.06	20.84	13.47	14.64	19.0	3.17
PARKING LOTS	15.46	7.62	12.36	19.59	21.42	13.85	15.05	16.7	2.88
FREEWAY & TRACKS	17.53	8.64	14.02	22.22	24.30	15.71	17.07	5.5	1.53
COMMERCIAL & PARKING LOTS	11.94	5.89	9.55	15.13	16.55	10.70	11.63	35.6	3.04

TABLE 6-5. ABMAC MITIGATION SIMULATION - 90% REDUCTION (Pollutant Load in 10^3 Pounds)

YEAR	1975	1976	1977	1978	1979	1980	Average	% Reduction	% Reduction / % Area
RAIN (in)	20.10	9.91	16.08	25.48	27.86	18.01	19.57		
POLLUTANT LOAD FROM ACTUAL CONCENTRATIONS	18.55	9.15	14.84	23.52	25.71	16.62	18.06		
POLLUTANT LOAD AFTER 90% REDUCTION IN:									
RESIDENTIAL	14.85	7.32	11.88	18183	20.59	13.31	14.46	19.9	.27
INDUSTRIAL	17.00	8.38	13.60	21.55	23.57	15.23	16.56	8.3	1.93
COMMERCIAL	13.27	6.54	10.62	16.83	18.40	11.89	12.93	28.4	4.73
PARKING LOTS	13.91	6.86	11.13	17.63	19.28	12.46	13.55	25.0	4.31
FREEWAY & TRACKS	17.02	8.39	13.61	21.57	23.59	15.25	16.57	8.3	2.31
COMMERCIAL & PARKING LOTS	8.63	4.26	6.91	10.94	11.97	7.74	8.41	53.4	4.53

TABLE 6-6. ABMAC GROWTH SIMULATION (Pollutant Load in 10^3 Pounds)

YEAR	1975	1976	1977	1978	1979	1980	Average	% Increase
RAIN (IN)	20.10	9.91	16.08	25.48	27.86	18.01	19.57	
POLLUTANT LOAD FROM ACTUAL CONCENTRATIONS	18.55	9.15	14.84	23.52	25.71	16.62	18.06	
ALL OPEN LAND BECOMES COMMERCIAL	23.63	11.65	18.91	29.96	32.76	21.18	23.07	27.7
20% RESIDENTIAL BECOMES COMMERCIAL	32.32	15.94	25.86	40.97	44.80	28.96	31.98	74.3

simulated. This 90% reduction was also calculated for each land use in turn and finally for both commercial property and parking lots simultaneously . These results are presented in Table 6-5.

The percent reductions in yearly pollutant load for these attempted mitigation measures are presented in Tables 6-4 and 6-5. For cost effective pollution control, the area that must be treated to effect the indicated reduction is important. For this reason, the fractional reduction in pollutant load divided by the fraction of the area of the watershed that was treated is presented in the last column in Tables 6-4 and 6-5. It can thus be seen that a 90% reduction in the pollution from residential property causes an overall reduction in pollutant load comparable to that caused by a 90% reduction in pollution from parking lots. However, control of parking lot emission is probably much less expensive than controlling emissions from residential property since the total area to be treated is much less.

Two growth simulations were performed and the results are given in Table 6-6. In the first case it was assumed that all the undeveloped land in the basin, 5% of the total land area, was converted to commercial property. In the second case it was hypothesized that 20% of the residential land, amounting to 15% of the entire basin, was converted to commercial property. This was done as a rough attempt to simulate replacement of low density single family houses by large multifamily dwelling due to an increase in the population, with a concurrent increase in the amount of commerical property to serve the expanded population. The results of these growth simulations are striking. Even the small scale change, affecting only 5% of the basin directly, yields a 28% increase in overall pollutant load. If growth is to be permitted, mitigation measures must be implemented simply to maintain the status quo with respect to oil and grease pollution. It should be noted that changes in land use are not the only possible source of increases in the total pollutant load. An increase in auto use in residential areas, for example, could increase the oil and grease concentration characteristic of these areas, yielding an increase in the total pollutant load.

Summary

The ABMAC model has been applied to show how the estimated oil and grease concentration and estimated flow from various land uses can be quantified. The ABMAC model is probably the simplest runoff model available to perform this function. It is a linear model, and as such shows the typical errors associated with linear models such as overestimating flows from small storms and underestimating the large storms. Also the routing problems are ignored.

The use of ABMAC to simulate mitigation results is a useful method of determining the potential benefit of mitigation techniques. The model is too simple, and the data base collected in this study is too limited to allow direct simulation of specific mitigation techniques. A more sophisticated model would be required to perform direct simulation of specific mitigation techniques, and a new data base would also be required.

The results of the ABMAC simulations should be used to assess the potential benefits of control of particular land use types, making it possible to concentrate mitigation efforts on projects likely to be most effective in reducing total pollution for the basin.

CHAPTER 7

SELECTED MITIGATION TECHNIQUES

The techniques reviewed in Chapter 4 can be classified in three categories: favorable, marginal and unfavorable, according to their technical and economical applicability. Each technique can be further classified as a structural or nonstructural technique. The basis of selection and recommendation has been made on the technical merits of each technique as well as the suitability of each technique to the site-specific features of land-use types. For example it was shown earlier that residential property contributes about the same amount of oil and grease mass as parking lots; however, the residential area is many times greater in area than parking lots for the Richmond watershed. Consequently, application of structural control techniques for parking areas should be much more economical than for residential property. The application of the proposed mitigation techniques will vary greatly depending upon the nature of the land use (e.g. new or old, economic resources, acceptance of owners, etc.). The favorable or marginally favorable techniques for the Richmond watershed may not be favorable for other watershed.

Favorable Non-Structural Control Techniques

Non-structural control measures comprise techniques utilizing existing technology and physical facilities to reduce the detrimental effects of oil and grease released into the environment. These measures can include mechanisms for limiting oil and grease discharge at its sources, cleaning oil and grease deposits prior to incorporation into stormwater and modifying areas of deposition to minimize harm. Non-structural control measures often can be implemented quickly, without the long lead-time usually required for construction of structural control equipment. Non-structural control measures often take the form of economic incentives or penalties, government regulations, persuasion, and direct intervention. The major difficulties inherent in selecting appropriate non-structural control measures are determining the effectiveness and associated costs of any proposed measure, and determining how to select measures that are equitable among the affected parties.

This study indicates areas where oil and grease introduction into the watershed may be most effectively controlled. A parking lot and a site collecting runoff from a gas station and commercial streets were found to have the highest hydrocarbon load factor (3400 and 900 lb oil/sq. mi. of rainfall, respectively) of these land-uses examined. Since areas of high vehicle activity were implicated as the major areas of oil and grease loading into the watershed, limiting the emissions from motor vehicles is an attractive method of pollutant control.

Three non-structural control measures were selected as most favorable to the control of oil and grease in the Richmond watershed. The promotion of oil and grease recycling and the development of a vehicle inspection and maintenance program were two techniques selected to control the introduction of pollutants into the area. The establishment of stricter controls on point source dischargers and perhaps on non-point sources were selected as the third non-structural mitigation measure. The actual physical technique to accomplish the reduction in discharge is left to the discretion of the discharger, or to the government entity responsible for pollution control.

Control measures employing various land use strategies were not considered as non-structural alternatives. The Richmond watershed is a highly

not to be included

developed area having less than 5% undeveloped property, and the development of land-use controls would require considerable physical modifications in the existing stormwater system. Such modification would most likely be economically and politically unfeasible. Similarly, techniques using a modification of existing facilities to control oil and grease were considered as structural alternatives if a substantial economic investment would be required. For undeveloped areas land-use control might be very favorable.

Oil and Grease Recycling An attractive mechanism for reducing automotive oil input into a watershed is to encourage the recycling of used crankcase oil, in lieu of dumping. The National Recycling Coalition (1981) reports that 1.2 billion gallons of lubrication oil are used annually in the United States. Approximately 35% of this lubricating oil is lost or consumed due to leaks and combustion, resulting in over 750 million gallons of used automotive oil potentially available for recycling. Another 0.65 billion gallons annually of waste oil is potentially available from industrial sources. Since the re-refining capacity of the United States is only about 150 million gallons of oil per year (National Recycling Coalition, 1981), it is apparent that greater capacity is needed to recycle the bulk of the waste material. The large difference between waste oil quantities and recycling capacity indicates that there is a significant quantity of waste oil which probably enters the environment through stormwater and other discharges.

In California, the Used Oil Recycling Act of 1977 (SB 68) was adopted in recognition of the potential for waste oil recovery. Moskat (1980) of the California Solid Waste Management Board estimates that in 1980 over 96 million gallons of used oil were available for recovery in the state, consisting of about 58 million gallons of used automotive type and 38 million gallons of used industrial oil. Approximately 36 million gallons of oil were re-cycled in California during 1980, a much greater reuse percentage than for the nation as a whole. However, there remains a large quantity of waste oil that is probably being illegally dumped.

The economic incentive to the individual motorist for waste oil recycling is low, even though value of waste oil has dramatically increased over the past decade. To illustrate the lack of incentive, it is helpful to consider a simple example. Most automobiles use four to six quarts of crankcase oil, and even if the oil were worth $0.80/gallon (the approximate value of crude oil), the financial incentive for individuals to recycle is only about $0.80 to $1.20 per oil change. This lack of economic incentive for oil recycling and other aspects of oil recycling are further discussed by Weinberger (1974), who concludes that institutional methods need to be developed before a high percentage of individuals will recycle used oil.

Novel institutional incentives may be needed, such as the construction of recycling centers, which provide facilities for the individual motorist to change crankcase oil. The convenience of using the facility (crawling under one's automobile to reach an oil pan is an unpleasant task to most motorists) may significantly increase recycling. The cost of the center could be partially recovered by the value of the reclaimed oil, or through franchises to oil venders who could be given space at the center.

The data collected in this study do not identify the route of oil introduction into the Richmond watershed; it is insufficient to accurately separate the contribution of oil and grease in the runoff resulting from illegal dumping from the contribution resulting from legal vehicle operation.

However from the National Recycling Coalition's (1981) estimate for current recycling, and their estimates that 35% of automotive lubricating oil is lost to leaks and combustion, it appears that 60 million gallons of waste oil is unaccounted for, with an unknown portion being illegally dumped.

Vehicle Inspection and Maintenance Programs. These programs may also prove effective in reducing watershed oil and grease loading resulting from automotive combustion emissions and crankcase drippings. Recognizing that 35% of crankcase oil may be released to the watershed during normal vehicle operations, a significant decrease in watershed oil and grease will probably result from improved vehicle performance and maintenance. The potential decrease can be projected from Moskat's estimate of 140 million gallons of new oil solid in California in 1980. Therefore, approximately 35% or 49 million gallons of crankcase oil are lost annually through motor vehicle operation.

The data from this study conclusively indicates that locations with the highest motor vehicle activity produce the highest oil and grease mass emission. This supports the hypothesis that improved motor vehicle condition will be an effective mechanism to reduce oil and grease emissions. It has been shown that the existing California inspection program required in the sale of a motor vehicle results in a mean reduction in hydrocarbon emissions of 11% (Department of Consumer Affairs and California Air Resource Board, 1981). A proposed, improved inspection procedure is projected to result in a 15 to 20% reduction in hydrocarbon emissions. This reduction further supports the value of vehicle inspection programs to reduce oil and grease emissions in urban stormwater.

Establishing a program to improve the condition of motor vehicles is potentially difficult and expensive. However, a vehicle inspection program may become practical if associated with vehicle inspection for air quality control. Section 172 of the Federal Clean Air Act mandated that individual states, in areas of non-attainment of air quality objectives, "establish a specific schedule for implementation of a vehicle emission control inspection program, it may be possible to expand the objectives to include some regulations concerning oil emissions and leakage.

Satisfying automobile air quality objectives through an inspection and maintenence program would result directly in a decrease in oil associated with particulate emissions deposition. Limiting oil leakage through a vehicle inspection and maintenance program appears more difficult. There are many potential sites for oil leakage in an automobile engine, many of which are quite expensive to repair. Any program requiring the mandatory repair of all oil leaks would probably be impractical. However, an inspection program locating some areas of oil leakage may provide incentive for some individuals to repair their automobiles.

The data from this study do not separate the relative contributions to the watershed of oil and grease exhaust deposits from oil and grease drippings. However, since vehicle activity is associated with areas of high oil and grease levels in stormwater runoff, an inspection and maintenance program of even limited effectiveness and may prove beneficial in significantly reducing total watershed oil and grease loading.

Identification of Critical Components of Oil and Grease - In Chapter 3 of this report reviewing the effects of oil and grease on the environment, it was recognized that toxicity varies substantially with the type of hydrocarbon constituents of the oil and grease. Currently, the only control of petroleum hydrocarbon discharge is through oil and grease NPDES permits and other regulations on point source dischargers. In many instances the NPDES permits or other regulations do not specifically control the toxic constituents in oil and grease, but only regulate the maximum concentration or total mass discharged. Therefore specific hydrocarbons in concentrations which might be toxic or harmful can be legally discharged from industries and municipal waste treatment facilities. Furthermore, the concentration of oil and grease in the stormwater runoff in the Richmond watershed was sufficiently high to potentially cause environmental harm to the Bay if the monitored oil and grease contained significant fractions of specific toxic hydrocarbons.

Some additional legislative control of oil and grease appears warranted, specifically with regard to toxic hydrocarbon components. The Regional Water Quality Control Board, which establishes discharge limits based on provisions of the Federal Clean Water Act, appears the most appropriate agency to provide the needed control measures. Furthermore, the hydrocarbon loading from stormwater runoff needs to be examined further to determine the need for adopting non-point source control to futher limit hydrocarbon loading into San Francisco Bay.

The costs of imposing additional legislative control are hard to ascertain. The technological requirements to determine levels of specific hydrocarbons or hydrocarbon groups are expensive, requiring sophisticated equipment and substantial expertise. Estimates of costs for effluent clean-up cannot be made without first identifying and quantifying the current hydrocarbon constituents of stormwaters. However, the potential for environmental harm to the Bay from hydrocarbon pollution, and indications of existing harm from current pollution levels, appear sufficiently grave to warrant further investigation and possible regulatory control.

Favorable Structural Control Techniques

The structural control measures considered for recommendation comprise techniques requiring additional equipment and/or materials, or use existing resources in a new manner requiring capital investment to reduce the effects of oil and grease loading in the watershed. Structural measures to control oil and grease usually are employed after the material is deposited within the watershed, rather than reducing the input into the watershed. Due to the expense of most structural control measures, rigorous value assessments need to be made before a measure can be adopted.

The rigorous value assessment needed prior to construction is beyond the scope of this investigation because many of the proposed techniques are new and unproven. Furthermore, detailed cost estimates cannot be made without the services of an Engineering/Architectural firm to evaluate each site.

Several structural techniques appear favorable to control oil and grease in the Richmond watershed. Improved street and parking surface cleaning, using porous payments in parking lots, channeling stormwater into vegetated areas, and using adsorbants in sewer inlets all appear viable mechanisms to remove oil and grease prior to its introduction in the stormwater system. The use of dispersion devices at the end of storm drains also warrants attention as a mechanism to reduce the effects of oil and grease pollution. In this way oil and grease and other harmful materials can be isolated from sensitive shoreline areas. Any recommended dispersion techniques would have to be critically evaluated to ensure that the resulting dilution of pollutants would be sufficient to eliminate the possibility of imposing harmful effects over a more widespread area.

Cleaning of Surface Material - Land use areas characterized by substantial vehicle densities had the highest concentration of oil and grease in the surface water runoff. On a unit area basis, runoff from parking lots and commercial streets constituted the largest contributors of oil and grease to the watershed. The modeling results indicate that a 90% reduction in oil and grease from commercial streets and parking lots, consisting of only 11.8% of the total land area, would result in over 50% reduction in total oil and grease loading to the watershed. Thus, it appears economical to selectively reduce oil and grease from parking lots and commercial streets in recognition of the advantages of controlling a relatively small area to affect the largest proportion of pollutant control.

Sweeping is the usual method to reduce pollutants from streets and parking lots. Field et al (1977) report that the costs of removing particulates by street sweeping are less than 50% of the removal costs at wastewater treatment plants. However, conventional sweeping practices are of unknown efficiency in reducing oil and grease pollution. Determinations of the proportion of hydrocarbons found on particulates are consistently over 80% (Shaheen, 1975, Hunter et al, 1979, and Eganhouse and Kaplan, 1981) with most pollutants associated with very fine particulates (Sartor et al, 1974). However, Sartor et al (1974) also report that traditional sweepers leave behind most of this fine material (85% of material finer than 43 um and 52% of material finer than 246 um.). Thus, the particles most likely to be left behind by traditional sweeping techniques are those containing the most significant quantities of oil and grease.

A practical method of oil and grease control may result from the utilization of sophisticated cleaning techniques to remove fine particulates. Advanced cleaning methods would probably also improve aesthetics and reduce other contaminant loading to the watershed. The use of efficient cleaning techniques appear to offer a cost-efficient approach to remove oil and grease pollution prior to incorporation into stormwater runoff.

A difficulty inherent in a program to effectively clean areas of high vehicle activity is the lack of information concerning techniques capable of effective sweeping and their associated expense. Considerable modification of existing equipment may be required, which would probably result in initial high costs. However, if standard systems were designed and employed over large areas, economies of scale may result in a cost-effective approach to pollutant limitation.

A method of street cleaning which appears promising is wet-sweeping technique, using specially designed street sweepers. The street sweeper would first spray a small area with water containing biodegradable soaps or detergents, which serve to solubilize the oil and grease deposited on pavement surfaces. The sweeper next removes the water with a combination of sweeping and vacuum action. A sophisticated version of sweeping truck could contain a filtration system which would treat the recovered water to reduce the volume of oil and grease solution. This proposed sweeping machine is a hybrid of existing technologies and has never before been tested. A series of prototype machines should be developed and evaluated prior to any widespread adoption. As the effects of wet-sweeping on pavements longevity should be evaluated.

<u>Porous Pavement</u> - Another practical method of controlling oil and grease in runoff may consist of modifying pavement material in parking areas. Road surface characteristics have been reported to significantly influence the degree of contaminant loading at a given location (Sartor et al., 1974 and Russell and Blois, 1980). Furthermore, the results of the modeling activity suggest that controlling oil and grease from parking areas would institute an effective mechanism for regulating the total area oil and grease pollution. Although parking lots constitute only 6% of the land area in the study watershed, a 90% reduction in the oil and grease content of stormwater emitted from parking lots would result in about a 25% reduction in the total oil and grease load to the entire watershed stormwater.

The use of porous asphalt pavement may provide a practical means of modifying surface pavement parking material to provide a reduction in pollutant loading. Porous pavements provide a high rate of rainfall infiltration by omitting fine particles during pavement construction. Water is retained in the base and pavement materials, providing an opportunity for pollutant adsorption and degradation. Porous pavement also reduce the magnitude of total peak runoff, providing flood control benefits.

The major difficulty in evaluating the anticipated performance of porous pavements is the lack of data base from which to determine effectiveness and applicability to various situations. Little is known about the maximum safe rate of pollutant loading into porous pavement, before a result in a breakdown of assimilatory capacity occurs. While the inital costs of porous pavements are estimated to be about 50% greater than for conventional pavement (Dinitz, 1980), much of this expense may be attributed to unfamiliarity with construction requirements; porous pavement construction materials and techniques do not appear inherently more expensive than conventional methods. The anticipated reduction in the need for runoff control devices such as sewers, catchment basins and gutters may provide offsetting economic benefits.

Another important unknown quality of porous pavement is its durability. Without an existing long-term record, it is difficult to assess how long this pavement material can be used without restoration, a vital economic consideration. Also the characteristics of oil and grease on porous payment are unknown; the oil may "plug" the pavement, reducing its porosity.

Other types of porous pavement besides porous asphalt may also be practical as parking area surface material, including concrete block type materials allowing vegetative growth directly in the parking area and gravel infiltration areas. These systems offer many of the same advantages and disadvantages of asphalt porous pavement, and suffer the same lack of proven history as effective pavement material. Research is progressing using these materials, with preliminary results indicating that they will at minimum be effective for selected applications.

Oil Sorption Systems - These systems also appear favorable. Oil sorption systems have been developed using a variety of types of materials in order to clean-up oil spills on open waters. These materials, which include naturally occuring material such as straw, hay, shredded urban solid waste, and synthetic materials such as polymethane foam. The development of these techniques was performed in the early 1970's when oil spills were more prevalent. Lengthy evaluations have been reported by Cochran, et al (1973), Miller et al (1973), and Gamtz and Meloy (1973). These reports all address spills, where very high concentrations of oil are present. This contrasts to urban stormwater, where very low concentrations occur. Therefore an experimental program is needed before widespread use can be anticipated.

The experimental programs required to develop the sorption system should not be costly or lengthy. The previously cited studies show that the sorptive capacity of polymethane foams is very large; consequently the problem of sorbing oil and grease from stormwater will become one of designing an appropriate hydraulic structure to provide intimate contact between foam and stormwater, without causing flooding. The previous figures of hypothetical systems (Chapter 4) appear to be acceptable, and contains sufficient mass of sorbent to sorb very large quantities of oil and grease. The hydraulics of the proposed system have not thoroughly been investigated, and will need experimental verification.

The cost of the proposed system will be quite small. It is probable that structural modification of existing sewer will not be required. Maintenance will be required routinely, but will be simple and composed primarily of replacing sorbent and cleaning debris from the sorption system. Sorbent costs vary widely and prices have been found ranging from $2.00 to 10.00 per cubic foot.

Greenbelts - One innovative mitigation measure that is uniquely suited to small areas where the stormwater runoff has a high hydrocarbon concentration, such as parking lots, is the construction of greenbelts. The purpose of these grassy areas is to catch runoff from a large paved area and allow it to percolate through soil, thus filtering and adsorbing hydrocarbons, allowing them to be metabolized by naturally occurring soil bacteria. The use of greenbelts for oil and grease control is a new concept; consequently the design must be based largely upon analogies to land and overland treatment.

Most of the literature on treatment of water by land application concerns wastewater treatment (Reynolds et al, 1980). The greenbelt combines aspects of several of the standard application methods (Rich, 1980). The diagram in Figure 7-1 shows a hypothetical application to a parking lot. The lot is graded so that all runoff waters are channeled into one or more greenbelts. At the entrance to the belt is a concrete spreading apron to facilitate equal distribution of the waters over the belt, and lessen the chances of erosion. The greenbelt may consist of a layer of topsoil supporting plant life, underlain by a layer of sand, which rests on a thick bed of gravel. Runoff waters percolate down through the top layers which decrease hydrocarbon concentration through adsorption and filtration. According to Rich (1980), such percolation removes essentially all suspended solids which should also reduce hydrocarbon concentration.

The gravel layer acts both as a drain, keeping the upper layers from saturation, and as a reservoir where stormwater is stored while it percolates into the surrounding soils at depth. Since the soil underlying the parking

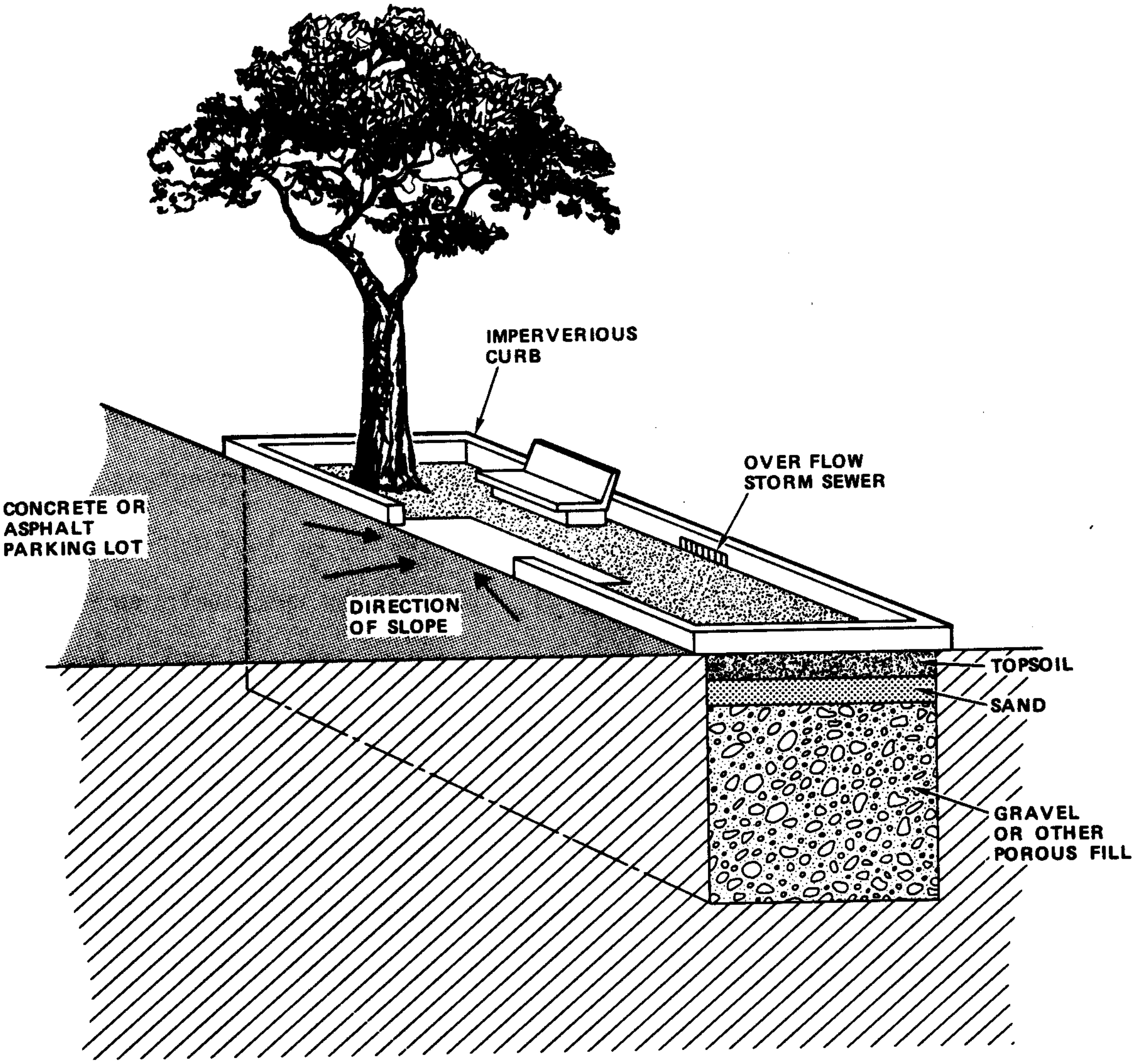


Figure 7-1 Hypothetical Green Belt for Treatment of Stormwaters

lot will be isolated from surface infiltration, percolation out of the gravel bed should be quite rapid. For large or very intense storms beyond the design capacity of the greenbelt, a storm drain inlet is constructed on the far side of the belt. In this manner the waters in excess of the greenbelt's treatment capacity are removed, preventing erosion or damage to the plant cover. Note that the greenbelt will absorb the first-flush waters of all storms. It was noted previously that the oil and grease concentration declines with time for the Richmond watershed, and that this phenomena has been noted by others.

The major cost involved in using greenbelts is the land requirement. The price of the land and the proportion of land needed to control runoff will be highly variable, dependent upon local land values, soil conditions and rainfall pattern and quantity. Construction costs should be relatively low for greenbelts in developing areas, requiring mainly gravel, sand, topsoil and concrete. Building greenbelts in existing parking lots would be more expensive, requiring modification of existing facililties including drainage gradients and storm sewers. Maintenance of the greenbelts also may be a significant cost, requiring trash collection, gardening serivce, and perhaps dry season watering. However, aesthetic benefits resulting from the greenbelts may help defray many of these costs.

Wetlands - Wetlands offer a mecahnism for treating stormwater runoff after contamination with oil and grease but prior to its discharge. The general application of this technique is quite limited and site-specific because of the availability of suitable land. However, the Bay Area offers many sites where marshes have been dredged, filled and/or channelled that retain a practical potential for wetland development.

The use of wetlands for stormwater treatment is generally considered a very attractive alternative. Besides meeting water quality objectives, wetlands offer improved aesthetics, wildlife habitats and recreation areas. However, wetlands also are suspected of being expensive, and little is known about their pollutant removal capabilities.

No information was found describing the effectiveness of wetlands in removing oil and grease from stormwater runoff. Since the majority of oil and grease in runoff is normally found associated with particulates, it would be reasonable to assume that a wetlands would act primarily as a sedimentation trap. Pollutant removal from the water column would occur as the particulates settled, with subsequent degradation responsible for their ultimate elimination. The removal of other pollutants besides oil and grease would also be anticipated. Wetlands have been found to have varying effectiveness in removing certain metals and nutrients from wastewater treatment facility effluents. However, an accurate assessment of oil and grease removal potential cannot be made until pilot studies have been conducted.

The costs of wetlands appear relatively high. Wetlands require a substantial quantity of land. Construction costs for the first wetland areas will undoubtedly be higher than the construction costs of wetlands build after the technology is fully developed. This results because of the increased safety factors needed when designing under uncertainty. However, even the high initial construction costs will be less than the cost of conventional wastewater treatment plants.

Wetlands appear to offer both very attractive and unattractive features. However, the potential value of a wetlands, should it be able to provide substantial water treatment as well as aesthetic, wildlife and recreational values, appears sufficient to warrant further investigation as a favorable control technique.

Dispersion Devices - Diffusers are also a favorable control measure. Dispersion devices have been successfully used for many years to reduce the effects of sanitary and industrial effluents on rivers and oceans. The cities of Los Angeles and San Diego, and the counties of Orange and Los Angeles all use diffusers to mitigate the effects of wastewater treatment plant effluents on coast waters.

A diffuser does not reduce the amount of pollution discharged to the receiving body but dilutes the concentration of the pollutants. For this reason many environmentalists are opposed to diffusers and prefer treatment methods. In the case of urban stormwater, treatment systems are very expensive and are used intermittently, which results in poor performance and reliability. Diffusers however can work well on an intermittent basis and can be fully automated, which reduces operating costs. Furthermore, for small and medium rains the diffuser may be able to discharge all storm water without pumping. The need for pumping will depend on the tidal cycle and topography.

The major cost of using dispersion devices are the construction costs and operating costs, should pumping be required. To obtain specific cost estimates it would be necessary to select a site, since runoff quantity and pipe length would be highly site specific. However, the capital requirements of a diffuser facility would be expected to be approximately several hundred thousand dollars by cost from an equivalent sized rain water pumping facility (Hansen et al, 1979) and $25/ft of diffuser pipeline. Additionally, some routine maintenance would be required to keep debris from clogging the system and to keep pumps in good working order. Figures 7-2 and 7-3 show a typical system.

Unknown costs would be those imposed on the environment due to the spreading of pollution. Since the dispersion device is intended to remove

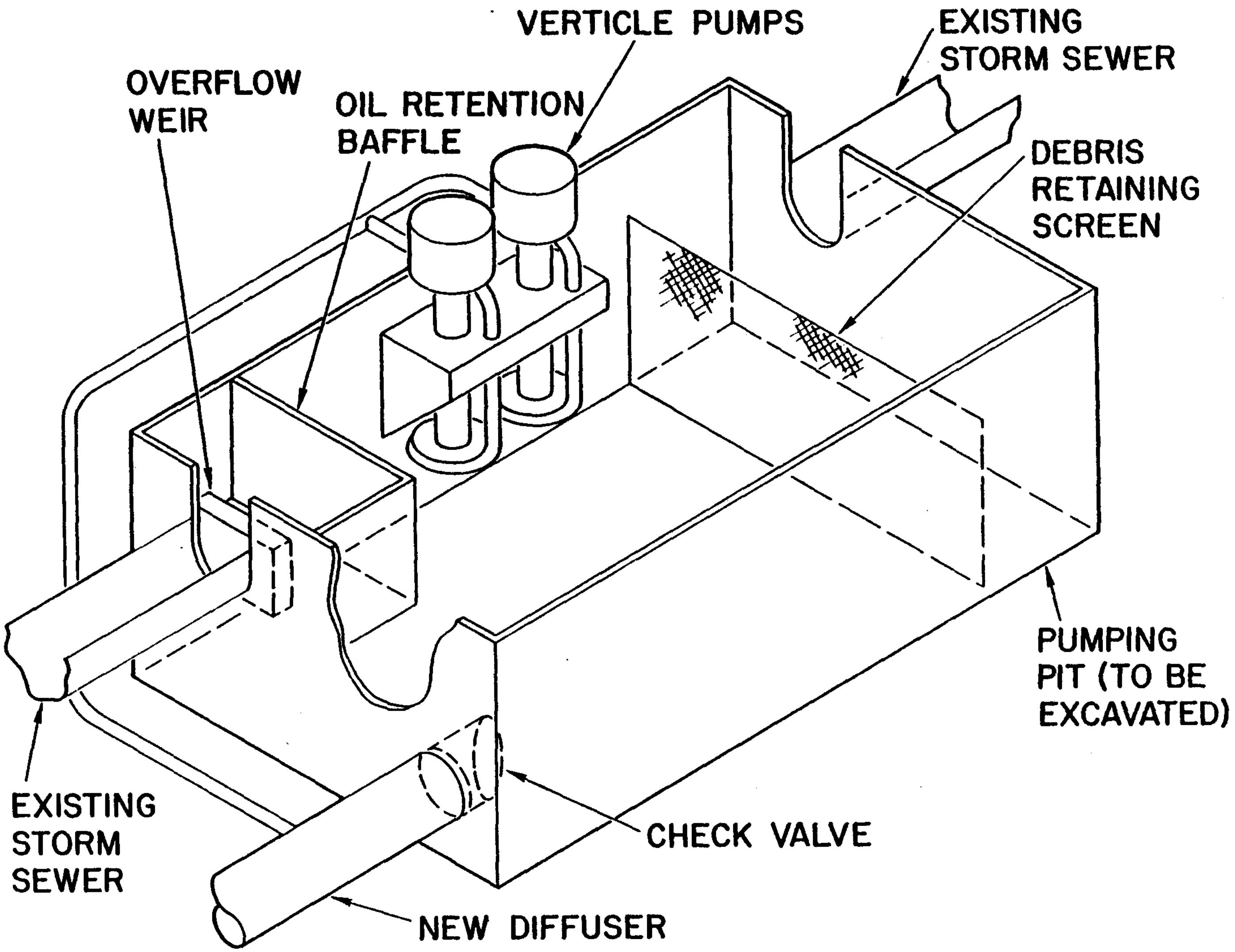
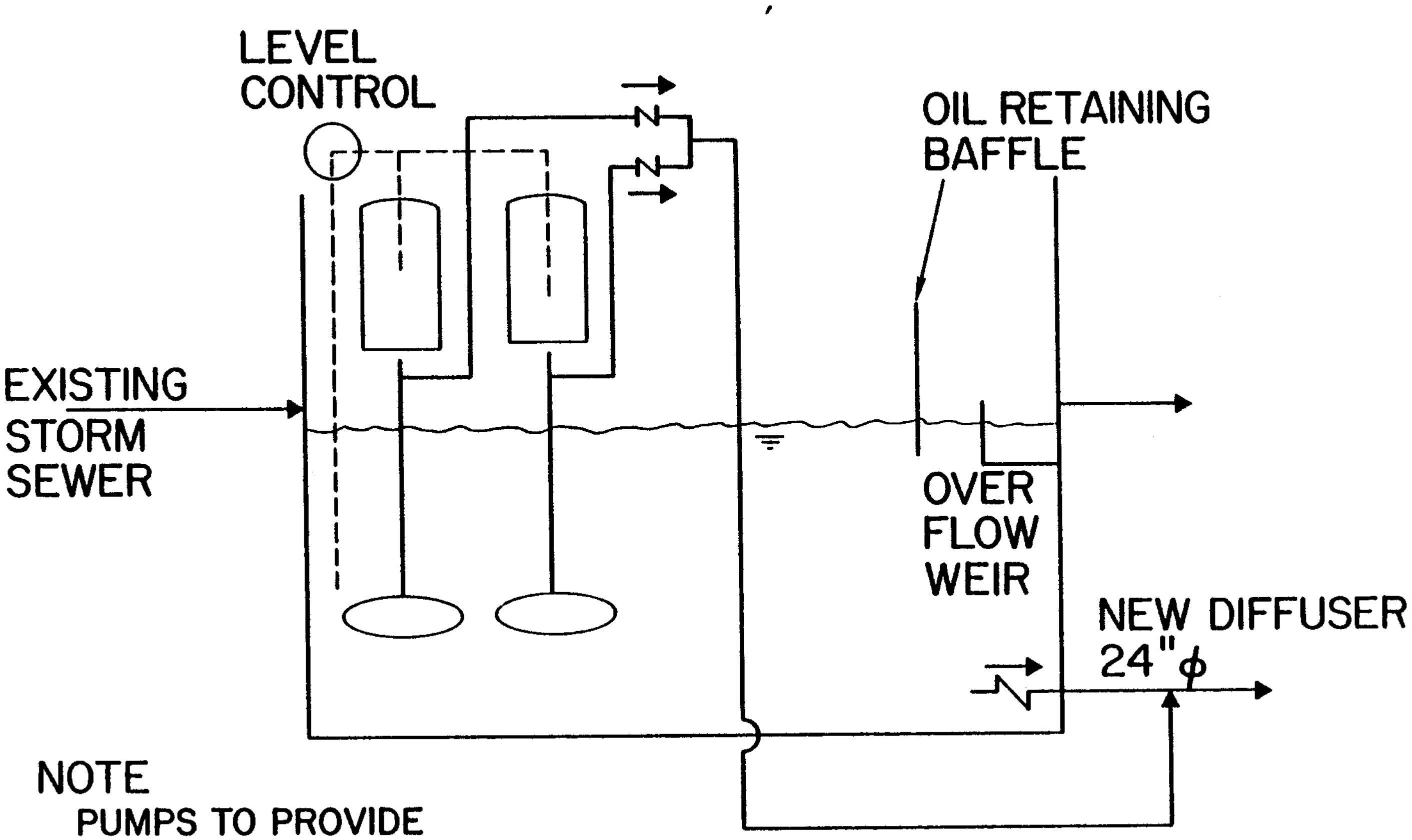


Figure 7-2 Hypothetical Diffuser Pumping Facility Schematic Diagram



NOTE
PUMPS TO PROVIDE
7000 GPM@30' TDH
WITH ONE OPERATING
AND 10,500 GPM@60'
TDH WITH TWO OPERATING

Figure 7-3 Hypothetical Diffuser Pumping Facility Process Flow Diagram pollutants away from critical near-shore areas with subsequent dilution in off-shore areas, environmental costs imposed by the diffuser must be significantly lower than the existing environment damage imposed by runoff to justify the system. The potential for a significant environmental impact from oil and grease has been substantiated in this study, such that diluting runoff pollutant concentrations and removing runoff from sensitive areas appears a favorable mitigation measure, and should be studied further.

Marginally Favorable Control Techniques

The marginally favorable control techniques include the recently developed, efficient wastewater treatment in conjunction with a stormwater storage system. Included among these treatment techniques are dissolved air flotation, corrugated or parallel plate separators, and high rate filtration, using either mixed or multimedia. Also considered marginally favorable are oil and grease trap systems.

The stochastic nature of storms makes the treatment of stormwater solely through treatment plant inefficient and uneconomical. In order to treat 90% of the existing storms, for the Richmond Area, one would need to build a 5 MGD plant (approximately) which should cost approximately 2.5 million dollars (EPA, (1979). This investment would be prohibitively large for almost all communities.

Corrugated or parallel plate separates, such as the Shell designs presented in Chapter 4, are an effective means of treating free oil and grease, particularly when the concentrations of free oil and grease are high. In the case of urban storm water the concentrations are low and a large portion of the oil and grease is collodial or dissolved. Therefore, the highest obtainable efficiency for this type of treatment is only as high as the free oil and grease portion, which is approximately 40-60% for this study and in the range of 50-60% for storm water analyzed by Eganhouse et al (1981b). Also these types of treatment systems would require frequent cleaning, due to the built-up of silt and grit. Oil/water separators of this type would have to be specially designed to allow removal of silt and grit, which is not normally found in oily process water.

Dissolved air flotation and high rate filtration are slightly more attractive than oil/water separators, since their efficiency can be higher, and the surface area requirements would be lower. The reduced area requirements result because of the high loading rates (5 GPM/ft^2) which are possible in a filter or dissolved air flotation unit. The cost of filtration or flotation equipment will be higher than the cost of simple oil/water separators. To obtain maximum efficiency it will be necessary to use a coagulant. Unfortunately this increases the operational expertise required, and may present a special problem due to the highly variable nature of storm water.

A combined treatment/storage system may be slightly more effective since hydraulic equalization can be provided, optimizing the efficiency of treatment while reducing the required size. Storage facilities also provide added retention time to enhance the breakdown of oil and grease. They present the advantage of being simple in structural design and operation and their construction can be done in stages. They improve reliability of the treatment system and help it adapt to stochastic flow and variable water quality.

The disadvantage of the combined storage-treatment are: the physical size of the storage facilities (to accommodate the 98% of the stormwater flows observed in this study) the storage facility would have to be in the order of 70 million gallons); the need of periodic cleaning of the facilities of sediments and the high costs of building and operating the system.

The best combination of the marginally favorable treatment systems might be constructed in conjunction with a diffuser. This might be the best choice to control oil and grease if a valuable natural resource were in extreme danger. It would not be possible to justify the high cost of those control measures for most other circumstances.

Oil and grease traps are considered marginally favorable because they would be less efficient than the oil sorption systems discussed previously, and would be virtually the same cost. Scattering adsorbent material over large areas would not be effective unless used in combination with sweeping machines, which was discussed previously, and is a better alternative.

Unfavorable Control Techniques are conventional oily waste treatment systems, such as API-type oil/water separators, conventional secondary treatment, and combining storm water with sanitary wastes.

Conventional API-type oil/water separators are best suited for higher concentrations of oil and grease which would clog or disrupt other types of separators. They are best suited for oily process waters and would be more expensive than other treatment alternatives for this application. Conventional secondary treatment usually removes free oil and grease, and a portion of the colloidial or dissolved oil and grease, depending upon the type of compounds present. Eganhouse et al (1981b) found that hydrocarbons comprise the largest portion of oil and grease in urban storm water, and that hydrocarbons are poorly removed in secondary treatment. Furthermore, the cost of secondary treatment will be higher than the marginally-favorable treatment techniques.

Combining storm waste with sanitary wastes is the poorest of all alternatives, and probably would result in additional pollution of the Bay. This would result due to overflows of the combined water during heavy storms.

Increasing the size of secondary facilities to accommodate storm water would be more expensive than the marginally-favorable treatment techniques.

Summary

The most favorable structural mitigation techniques are porous pavement, green belts, sorption systems, wetlands, dispersion devices, and improved cleaning methods. Most conventional treatment systems will be marginally favorable or poor. Application will be highly site-specific. Table 7.1 summarizes the advantage and disadvantages of the favorable techniques. Legislative controls to require cleaner automobiles and encouragement of oil recycling are probably the most cost effective solutions.

Table 7.1
Summary of Control Techniques

Recommended Mitigation Technique	Projected Oil and Grease Land-Use Area	Removal Potential*	Direct Costs Developing Watershed**	Direct Costs Richmond Watershed**	Associated Benefits	Associated Costs
1) Oil and Grease Recycling	Entire Watershed available in California	Unknown: Upper limit of 60 million gallons	Negligible	Negligible of associated toxic material	Energy conservation, aesthetics, reduction used oil to recycling center	Small individual cost of transported
2) Vehicle Inspection and Maintenance Program	Entire Watershed	Unknown: Upper limit of 49 million gallons available in California $28, $24 and $18, respectively (1978)	Air Emission programs in Arizona, Oregon and New Jersey have average fee + repair cost of $28, $24 and $18, respectively (1978)	Air Emission programs in Arizona, Oregon and New Jersey have average fee + repair cost of	Provides added incentive for air emission inspection program labor and administration costs	Individual effort to submit vehicle for inspection. State capital,
3) Specific Hydrocarbon Group Discharge and Non-point Source Controls	Entire Watershed	Unknown: Intended to reduce the toxicity rather than the quantity of discharge	Unknown, do not know if any changes required. Additional monitoring costs incurred.	Unknown, do not know if any changes required. Additional monitoring costs incurred.	Encourage research on specific toxic materials. Determine scope of pollution problem	If non-compliance, other control must be used.
4) Surface Cleaning and commercial streets	Parking areas efficiency, maximum reduction of 35% or about 6 x 10^3 lbs.	Assuming 90% process	Industrial broom sweeper costs about $30/hr for 100,000 - 200,000 ft^2 coverage	Industrial broom sweeper costs about $30/hr for 100,000 - 200,000 ft^2 coverage	Aesthetics Reduction of other pollutants	Administrative cost to ensure compliance.
5) Porous Pavements	Parking areas efficiency, maximum reduction of 17% or about 3 x 10^3 lbs.	Assuming 90% process	Similar to costs of conventional pavement undeveloped land.	Extremely high, requiring destruction of existing facilities. Practical only on volume	Aesthetics Reduction of other pollutants. Reduction of runoff	Minimal performance recorded, uncertain durability
6) Wetlands	Entire watershed entire discharge watershed, about 18 x 10^3 lbs.	Unknown: Upper limit from requirements - highly variable	Low construction costs. Major expense is land to change flow at existing marsh at outfall.	Relatively low, requiring dredging and fill pollutants. Recreation Wildlife	Aesthetics Reduction of other mance. Erosion	Maintenance Uncertain perfor-

Table 7.1 (continued)

Recommended Mitigation Technique	Projected Oil and Grease Land-Use Area	Removal Potential*	Direct Costs Developing Watershed**	Direct Costs Richmond Watershed**	Associated Benefits	Associated Costs
7) Green Belts	Parking areas	Assuming 60% process efficiency, maximum reduction of 17% or about 3000 lbs.	Low construction costs. Major expense is land requirement - high variability	Extremely high, requiring destruction of existing facilities. Practical only on undeveloped land.	Aesthetics Reduction of other pollutants Reduction of runoff flow	Uncertain performance Maintenance Periodic dredging
8) Adsorbents in Sewer Inlets	Parking areas and commercial streets	Assuming 60% process efficiency, maximum reduction of 36% or about 6000 lbs.	Installation cost will be very low. Capital cost may be zero	Negligible	Labor rather than material intensive. Can be applied selectively.	Routine maintenance replacement adsorbent at $6-20 per sewer inlet. Subject to vandalism
9) Dispersion Devices	Entire watershed	No removal sand dollars, depending upon diffuser size.	Capital costs will be several hundred thou- acres of land will be needed.	If associated storage is required, 1 to 3 tional pollutants, particularly coliforms, near the coast line.	The diffuser will also reduce conven- maintenance.	Operating cost of $2000/year. Routine

* Assuming full application in the recommended land use area.

** Direct costs to the Richmond watershed needs to take into account the existing land use components of the watershed, most of which is already developed. Direct costs to a developing watershed, account for the costs that would occur in an undeveloped watershed that was being developed in a similar fashion to the Richmond watershed.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

The objective of this project was to determine the environmental effects of oil and grease contained in urban storm water on marine environments and to recommend suitable control measures. To accomplish the first objective a literature review was conducted to ascertain known effects of chronic, low level discharge of oil and grease into marine waters. The results of this review indicate that there are significant effects of low level oil and grease pollution, and that continuous low level pollution of the type found in urban storm water can change the ecology of a marine environment. The diversity of species has been observed to decrease and in some cases new, pollutant resistant species have emerged. The effects of toxic materials have not been fully investigated, but in some cases bio-accumulation has been observed in humna food fish and shellfish in the San Francisco Bay. It must be emphasized that there are many potential effects which have not been thoroughly investigated.

To accomplish the second objective an experimental program was developed to determine oil and grease pollution by land-use type. Five sampling stations were selected in a stormwater basin in Richmond, California, to characterize various land uses commonly found in an urban area. The mouth of the watershed was selected as a sample site, along with four other sites at a commercial parking lot, commercial street, residential area, and light industrial facility. Samples from stormwaters were collected at controlled intervals during severe storm events in the Winter and Spring of 1981.

The experimental results conclusively show that the land use strongly affects the oil and grease contained in stormwater. The mean concentration of oil and grease at each station were all significantly different from one another at the 90% level of confidence. The concentration at the mouth of the watershed was not different from other stations, which was expected.

The major contributing factor to oil and grease in stormwater appears to be motor vehicles. Land uses with the greatest motor vehicles activity had the highest concentration of oil and grease in stormwater and the highest hydrocarbon load factor (lbs hydrocarbon/sq. mi.-inch of rainfall). Parking lots and commercial streets had the highest concentration and hydrocarbon load factor, 15.25 and 10.80 mg/l, and 3460 and 900 lb/sq. mi. inch rainfall, respectively. Residential area had the lowest concentration and hydrocarbon load factor having a concentration of only 4.13 mg/l and 140 lb/sq. mi. in rainfall, respectively.

The effects of storm characteristics on oil and grease concentration were also investigated. Very few correlations between storm characteristics and oil and grease concentration were noted. Time between storms, rainfall intensity and duration, and total rainfall had no significant effect on oil and grease concentration. The only significant relationship was a strong correlation between total rainfall (or total runoff volume) and total mass of oil and grease pollution. A moderate "first flush" effect was noted, indicating that the stormwater just after the initiation of rainfall is more contaminated than stormwater at later points in the storm.

Chemical characterization of the oil and grease using gas chromatography was attempted. These result were of limited value, with emissions from crankcase drippings being the most strongly implicated source. Virtually no hydrocarbons derived from gasoline were found. Several spills of specific compounds were also found. Column settling tests indicate that at least 50% of the oil and grease in stormwater is either free oil and grease or adsorbed to particulates.

Oil and grease control techniques were reviewed. It was found that most existing techniques were developed for processing industries, such as oil refineries, or for clean-up of oil spills, where high oil and grease concentrations exist. Most of the existing techniques are not suitable for mitigating the effects of oil and grease in stormwater. Of the techniques reviewed three non-structural techniques and six structural techniques appeared promising and warrant further development.

The non-structural techniques include encouragement of recycling of used crank case oil, reduced emissions from automobiles through better inspections, and improved standards through recognition of the toxic and non-toxic components in oil and grease. It was found that there exist a large disparity between the quantity of used crankcase oil available for recycle, and processing capacity of re-refining facilitites. This indicates that a large portion of the used crankcase oil is potentially discharged in environmentally unsound ways. Findings of the Air Resources Board indicate that vehicle exhaust hydrocabon emissions can be reduced by 10 to 20 percent with yearly inspections. It is hypothesized that such vehicle inspections would also reduce the hydrocabon emissions leaks, due to increased operator awareness of oil leaks and associated problems. Improved standards which recognize the toxic constituent of oil and grease, while deemphasizing the non-toxic constituents, are needed.

The six structural control techniques which merit further work are improved cleaning of parking lots and streets, adsorbing oil and grease from runoff at sewer inlets prior to its introduction into the stormsewer system, porous pavement to allow infiltration of storm water, green belts around parking lots to allow infiltration of runoff and removal through adsorption onto grasses and plants, diffusers at the mouth of the watershed, and wet lands or marshes at the mouth of the watershed which will trap oil and grease from stormwater and allow it to be naturally treated. These techniques all have site specific characteristics and advantages and weakness for each application. Also the techniques are largely unproven for this application.

It is recommended that the nine proposed mitigation techniques be further developed. Controlled pilot scale studies need to be performed before they can be commercialized. A pilot study of an expanded recycling program could be accomplished through the efforts of a regional agency or other interested groups. Recommendations have already been sent to the California State Regional Water Quality Control Board to differentiate among the specific constituents of oil and grease in establishing water quality standards. The Board has agreed to pursue this recommendation through their Shellfish Program and Aquatic Habitat Program. Similarly, the water quality benefits of a vehicle inspection and maintenance program should be brought to the attention of those concerns evaluating the air quality program in the State.

Pilot programs for most of the structural control measures could be accomplished without major equipment requirements. In the Bay Area, locations exist where, with some minor modifications, monitoring could be accomplished to evaluate the effectiveness of porous pavements and green belts. These evaluations could also be done in new developments. Adsorbants could be evaluated using modifications of existing structures, with some additional effort in the laboratory to determine adsorbant capabilities. An evaluation of sweeping techniques could proceed with preliminary examination of current equipment used in various manners over different surfaces. Further design would proceed using data obtained from this preliminary work. Diffuser use at the mouth of watersheds would be the most difficult and capital of intensive technique to evaluate, being highly site specific, raising serious ecological questions and being subject to great political concern. Wetlands could be examined through the use of such resources as the marsh in Fremont currently being designed and constructed by the Association of Bay Area Govenments as a research facility to determine marsh capabilities and desirable specifications to treat stormwater runoff.

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Appendix 1

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                                    S T A T I S T I C A L   A N A L Y S I S   S Y S T E M                                   1
                                                                                         17:23 TUESDAY, SEPTEMBER 8, 1981

 OBS    STANO    STONO    SAMNO    TIME     TSSD     OG1     FLOW        TRAIN    DBS    RRAIN    TPLOW      TMASS      RMASS

   1      1        1        1       900     6.00     2.9    104.000    / 2.01     11     61.0    67.019    2870.33     1625.7
   2      1        1        2       930     6.50     3.0     52.500      2.01     11      1.0    67.019    2870.33      849.0
   3      1        1        3      1000     7.00     2.4     40.000      2.01     11      1.0    67.019    2870.33      517.5
   4      1        1        4      1100     8.00     2.7     18.700      2.01     11      0.0    67.019    2870.33      272.2
   5      1        1        5      1200     9.00     3.2     18.700      2.01     11      2.0    67.019    2870.33      322.6
   6      1        1        6      1400    11.00    12.0    170.000      2.01     11     32.0    67.019    2870.33    10996.2
   7      1        1        7      1740    14.75     4.2    398.000      2.01     11     85.0    67.019    2870.33     9010.4
   8      1        1        8      2140    18.75     0.8      3.700      2.01     11     16.0    67.019    2870.33       16.0
   9      1        1        9      2645    23.75     0.8       .         2.01     11      3.0    67.019    2870.33         .
  10      2        1        0       730     4.50     8.8      0.640      2.01     11     53.0     1.698      94.91       30.4
  11      2        1        1       900     6.00     6.8      1.260      2.01     11      8.0     1.698      94.91       46.2
  12      2        1        2       930     6.50     4.9      0.540      2.01     11      1.0     1.698      94.91       14.3
  13      2        1        3      1000     7.00     3.8      0.400      2.01     11      1.0     1.698      94.91        8.2
  14      2        1        4      1100     8.00     3.5      0.180      2.01     11      0.0     1.698      94.91        3.4
  15      2        1        5      1200     9.00     3.9      0.510      2.01     11      2.0     1.698      94.91       10.7
  16      2        1        6      1402    11.00    12.0      6.000      2.01     11     32.0     1.698      94.91      389.1
  17      2        1        7      1730    14.50     6.4     11.000      2.01     11     80.5     1.698      94.91      379.5
  18      2        1        8      2120    18.50     0.7      0.090      2.01     11     20.5     1.698      94.91        0.3
  19      2        1        9      2635    23.50     2.4      0.080      2.01     11      3.0     1.698      94.91        1.0
  20      3        1        0       820     5.25    10.5      0.570      2.01     11     58.0     0.552      29.37       32.3
  21      3        1        1       915    62.50    18.0      0.570      2.01     11      3.5     0.552      29.37       55.3
  22      3        1        2       945     6.75    11.0      0.009      2.01     11      1.0     0.552      29.37        0.5
  23      3        1        3      1010     7.25    14.0      0.008      2.01     11      0.5     0.552      29.37        0.6
  24      3        1        4      1100     8.00    18.0      0.002      2.01     11      0.0     0.552      29.37        0.2
  25      3        1        5      1200     9.00    13.0      0.070      2.01     11      2.0     0.552      29.37        5.5
  26      3        1        6      1400    11.00     9.5      0.098      2.01     11     32.0     0.552      29.37        5.0
  27      3        1        7      1715    14.25     9.4      0.590      2.01     11     74.0     0.552      29.37       29.9
  28      3        1        8      2110    18.25     8.9      0.000      2.01     11     27.0     0.552      29.37        0.0
  29      3        1        9      2625    23.50     7.6      0.000      2.01     11      3.0     0.552      29.37        0.0
  30      4        1        0       800     5.00    13.5      3.600      2.01     11     57.0     1.581     165.05      262.0
  31      4        1        1       855     6.00    10.0      0.850      2.01     11      4.0     1.581     165.05       45.8
  32      4        1        2       930     6.50    11.0      1.000      2.01     11      1.0     1.581     165.05       59.3
  33      4        1        3      1005     7.00    14.0      0.080      2.01     11      1.0     1.581     165.05        6.0
  34      4        1        4      1055     8.00    13.0      0.046      2.01     11      0.0     1.581     165.05        3.2
  35      4        1        5      1150     9.00    27.0      0.270      2.01     11      2.0     1.581     165.05       39.3
  36      4        1        6      1400    11.00    19.0      5.700      2.01     11     32.0     1.581     165.05      583.8
  37      4        1        7      1715    14.25    14.0      8.600      2.01     11     74.0     1.581     165.05      649.0
  38      4        1        8      2115    19.25     0.0      0.020      2.01     11     27.0     1.581     165.05        0.0
  39      4        1        9      2600    23.00    19.0      0.020      2.01     11      3.0     1.581     165.05        2.0
  40      5        1        0       755     5.00    16.0      4.300      2.01     11     57.0     2.495     237.38      370.9
  41      5        1        1       905     6.00    20.0      1.100      2.01     11      4.0     2.495     237.38      118.6
  42      5        1        2       940     6.75    17.0      0.740      2.01     11      1.0     2.495     237.38       67.8
  43      5        1        3      1015     7.25    10.0      0.270      2.01     11      1.0     2.495     237.38       27.7
  44      5        1        4      1100     8.00    10.0      0.080      2.01     11      0.0     2.495     237.38        4.3
  45      5        1        5      1200     9.00    17.0      1.550      2.01     11      2.0     2.495     237.38      142.0
  46      5        1        6      1400    11.00    16.0     10.800      2.01     11     32.0     2.495     237.38      931.4
  47      5        1        7      1730    14.50     9.2     11.900      2.01     11     80.5     2.495     237.38      593.1
  48      5        1        8      2130    18.50     5.5      0.320      2.01     11     20.5     2.495     237.38        9.5
  49      5        1        9      2615    23.25     5.0      0.010      2.01     11      3.0     2.495     237.38        0.3
  50      1        2        1      1500     1.50     3.8     51.800      0.33     18     26.0     3.123      81.07     1061.0
  51      1        2        2      1530     2.00     3.1     40.000      0.33     18      0.5     3.123      81.07      668.4
  52      1        2        3      1600     2.50     4.5     22.400      0.33     18      0.5     3.123      81.07      543.3
  53      1        2        4      1630     3.00     4.2      9.600      0.33     18      1.0     3.123      81.07      217.3
  54      1        2        5      1730     4.00     3.1      7.100      0.33     18      2.0     3.123      81.07      118.6
  55      1        2        6      1830     5.00     3.0      7.100      0.33     18      1.5     3.123      81.07      114.8
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                                       S T A T I S T I C A L   A N A L Y S I S   S Y S T E M                                    2
                                                                                                 17:23 TUESDAY, SEPTEMBER 8, 1981

 OBS   STANO   STONO   SAMNO   TIME    TSSB    OG1     FLOW    TRAIN   DDS   RRAIN   TFLOW     TMASS      RMASS

  56     1       2       7     2105    7.50    3.3     2.100   0.33    18     0.5    3.123    81.074      37.35
  57     1       2       8     2323   10.00    3.2     0.800   0.33    18     1.0    3.123    81.074      13.80
  58     2       2       1     1510    1.75    5.6     1.820   0.33    18    26.0    0.125     2.831      54.94
  59     2       2       2     1535    2.00    4.9     1.140   0.33    18     0.5    0.125     2.831      30.11
  60     2       2       3     1600    2.50    2.5     0.610   0.33    18     0.5    0.125     2.831       8.22
  61     2       2       4     1630    3.00    2.8     0.440   0.33    18     1.0    0.125     2.831       6.64
  62     2       2       5     1730    4.00    1.0     0.400   0.33    18     2.0    0.125     2.831       2.16
  63     2       2       6     1835    5.00    3.0     0.590   0.33    18     1.5    0.125     2.831       9.54
  64     2       2       7     2100    7.50    1.9     0.110   0.33    18     0.5    0.125     2.831       1.13
  65     2       2       8     2330   10.00    2.4     0.040   0.33    18     1.0    0.125     2.831       0.52
  66     3       2       1     1500    1.50   21.0     0.048   0.33    18    26.0    0.003     0.476       5.43
  67     3       2       2     1530    2.00   22.0     0.019   0.33    18     0.5    0.003     0.476       2.25
  68     3       2       3     1600    2.50    8.1     0.001   0.33    18     0.5    0.003     0.476       0.04
  69     3       2       4     1630    3.00   13.0     0.038   0.33    18     1.0    0.003     0.476       2.66
  70     3       2       5     1730    4.00   33.0     0.001   0.33    18     2.0    0.003     0.476       0.18
  71     3       2       6     1830    5.00   26.0     0.018   0.33    18     1.5    0.003     0.476       2.52
  72     3       2       7     2045    7.25   14.0     0.005   0.33    18     0.5    0.003     0.476       0.38
  73     3       2       8     2345   10.25   16.0     0.000   0.33    18     1.0    0.003     0.476       0.00
  74     4       2       1     1505    1.50    6.3     0.840   0.33    18    26.0    0.058     4.169      28.53
  75     4       2       2     1530    2.00    3.0     0.420   0.33    18     0.5    0.058     4.169       6.79
  76     4       2       3     1600    2.50    5.8     0.210   0.33    18     0.5    0.058     4.169       6.57
  77     4       2       4     1630    3.00   14.0     0.070   0.33    18     1.0    0.058     4.169       5.28
  78     4       2       5     1730    4.00    7.5     0.142   0.33    18     2.0    0.058     4.169       5.74
  79     4       2       6     1830    5.00    9.8     0.420   0.33    18     1.5    0.058     4.169      22.19
  80     4       2       7     2040    7.25   20.0     0.050   0.33    18     0.5    0.058     4.169       5.39
  81     4       2       8     2350   10.25    0.0     0.000   0.33    18     1.0    0.058     4.169       0.00
  82     5       2       1     1510    1.75    1.2     1.200   0.33    18    26.0    0.134     2.059       7.76
  83     5       2       2     1530    2.00    0.8     0.660   0.33    18     0.5    0.134     2.059       2.85
  84     5       2       3     1605    2.50    1.4     0.380   0.33    18     0.5    0.134     2.059       2.87
  85     5       2       4     1630    3.00    2.0     0.160   0.33    18     1.0    0.134     2.059       1.72
  86     5       2       5     1730    4.00    3.2     0.380   0.33    18     2.0    0.134     2.059       6.55
  87     5       2       6     1830    5.00    3.3     1.660   0.33    18     1.5    0.134     2.059      29.53
  88     5       2       7     2040    7.25    0.7     0.050   0.33    18     0.5    0.134     2.059       0.19
  89     5       2       8     2400   10.50    0.6     0.010   0.33    18     1.0    0.134     2.059       0.03
  90     1       3       1      620    0.75    8.3     6.400   0.07     1     5.0    2.596   102.813     286.33
  91     1       3       1      620    0.75   11.0     6.400   0.07     1     5.0    2.596   102.813     379.48
  92     1       3       2      645    1.25    4.8    40.000   0.07     1     0.0    2.596   102.813    1034.93
  93     1       3       2      645    1.25    9.9    40.000   0.07     1     0.0    2.596   102.813    2134.55
  94     1       3       3      715    1.75    4.9    71.200   0.07     1     0.0    2.596   102.813    1880.56
  95     1       3       3      715    1.75    3.6    71.200   0.07     1     0.0    2.596   102.813    1381.64
  96     1       3       4      830    3.00    4.9     6.020   0.07     1     0.0    2.596   102.813     158.47
  97     1       3       4      830    3.00    4.7     6.000   0.07     1     0.0    2.596   102.813     152.01
  98     1       3       5      940    4.25    2.4     0.780   0.07     1     1.5    2.596   102.813      10.09
  99     1       3       5      940    4.25    3.6     0.780   0.07     1     1.5    2.596   102.813      15.14
 100     1       3       7     1200    6.50    0.0     1.100   0.07     1     0.5    2.596   102.813       0.00
 101     2       3       1      630    1.00   13.0     0.460   0.07     1     5.0    0.034     1.991      32.23
 102     2       3       1      630    1.00   13.0     0.460   0.07     1     5.0    0.034     1.991      32.23
 103     2       3       2      655    1.50   17.0     0.300   0.07     1     0.0    0.034     1.991      27.49
 104     2       3       2      655    1.50   17.0     0.300   0.07     1     0.0    0.034     1.991      27.49
 105     2       3       3      735    2.00   11.0     0.170   0.07     1     0.0    0.034     1.991      10.08
 106     2       3       3      735    2.00    9.8     0.170   0.07     1     0.0    0.034     1.991       8.98
 107     2       3       4      840    3.25    4.6     0.570   0.07     1     0.0    0.034     1.991      14.13
 108     2       3       4      840    3.25    4.3     0.570   0.07     1     0.0    0.034     1.991      13.21
 109     2       3       5      930    4.00    3.5     0.040   0.07     1     1.0    0.034     1.991       0.75
 110     2       3       5      930    4.00    1.9     0.040   0.07     1     1.0    0.034     1.991       0.41
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                                    S T A T I S T I C A L   A N A L Y S I S   S Y S T E M                                         3
                                                                                          17:23 TUESDAY, SEPTEMBER 8, 1981
 OBS    STANO    STONO    SANNO    TIME    TSSD     OG1     FLOW     TRAIN    DBS    RRAIN    TFLOW    TMASS     RMASS

 111      2        3        6        .       .      0.0      .         .       .       .      0.034    1.991       .
 112      2        3        7      1150    6.25     0.0    0.040     0.07      1      1.0     0.034    1.991     0.0000
 113      3        3        1       600    0.50    20.0    0.028     0.07      1      5.0     0.001    0.056     3.0186
 114      3        3        1       600    0.50    17.0    0.028     0.07      1      5.0     0.001    0.056     2.5658
 115      3        3        2       645    1.25    16.0    0.006     0.07      1      0.0     0.001    0.056     0.5175
 116      3        3        2       645    1.25    18.0    0.006     0.07      1      0.0     0.001    0.056     0.5822
 117      3        3        3       700    1.50     8.0    0.005     0.07      1      0.0     0.001    0.056     0.2372
 118      3        3        3       700    1.50    11.0    0.005     0.07      1      0.0     0.001    0.056     0.2965
 119      3        3        4       740    2.25     3.6    0.003     0.07      1      0.0     0.001    0.056     0.0582
 120      3        3        4       740    2.25     8.7    0.003     0.07      1      0.0     0.001    0.056     0.1407
 121      3        3        5       840    3.25     9.9    0.001     0.07      1      0.0     0.001    0.056     0.0534
 122      3        3        5       840    3.25    10.0    0.001     0.07      1      0.0     0.001    0.056     0.0539
 123      3        3        6       930    4.00    18.0    0.001     0.07      1      1.0     0.001    0.056     0.0970
 124      3        3        6       930    4.00    12.0    0.001     0.07      1      1.0     0.001    0.056     0.0647
 125      3        3        7      1100    5.50     0.0    0.001     0.07      1      1.0     0.001    0.056     0.0000
 126      4        3        1       625    1.00     8.9    0.570     0.07      1      5.0     0.013    0.730    27.3449
 127      4        3        1       625    1.00     9.3    0.570     0.07      1      5.0     0.013    0.730    28.5739
 128      4        3        2       635    1.00     4.7    0.360     0.07      1      0.0     0.013    0.730     9.1204
 129      4        3        2       635    1.00     3.8    0.360     0.07      1      0.0     0.013    0.730     7.3739
 130      4        3        3       705    1.50     8.7    0.120     0.07      1      0.0     0.013    0.730     5.6275
 131      4        3        3       705    1.50    10.0    0.120     0.07      1      0.0     0.013    0.730     6.4683
 132      4        3        4       725    2.00    15.0    0.046     0.07      1      0.0     0.013    0.730     3.7193
 133      4        3        4       725    2.00    31.0    0.046     0.07      1      0.0     0.013    0.730     7.6865
 134      4        3        5       825    3.00     7.4    0.005     0.07      1      0.0     0.013    0.730     0.1994
 135      4        3        5       825    3.00     8.9    0.005     0.07      1      0.0     0.013    0.730     0.2399
 136      4        3        6       925    4.00     6.5    0.003     0.07      1      1.0     0.013    0.730     0.1051
 137      4        3        6       925    4.00     8.6    0.003     0.07      1      1.0     0.013    0.730     0.1391
 138      4        3        7      1130    6.00     0.0    0.003     0.07      1      1.0     0.013    0.730     0.0000
 139      5        3        1       620    0.75     1.9    1.170     0.07      1      5.0     0.035    0.329    11.9826
 140      5        3        1       620    0.75     1.0    1.170     0.07      1      5.0     0.035    0.329     6.3066
 141      5        3        2       630    1.00     1.6    0.910     0.07      1      0.0     0.035    0.329     7.8483
 142      5        3        2       630    1.00     2.0    0.910     0.07      1      0.0     0.035    0.329     9.8103
 143      5        3        3       710    1.75     1.3    0.210     0.07      1      0.0     0.035    0.329     1.4715
 144      5        3        3       710    1.75     1.0    0.210     0.07      1      0.0     0.035    0.329     1.1320
 145      5        3        4       735    2.00     1.0    0.120     0.07      1      0.0     0.035    0.329     0.6468
 146      5        3        4       735    2.00     2.8    0.120     0.07      1      0.0     0.035    0.329     1.0111
 147      5        3        5       835    3.00     2.8    0.030     0.07      1      0.0     0.035    0.329     0.4529
 148      5        3        5       835    3.00     1.5    0.030     0.07      1      0.0     0.035    0.329     0.2426
 149      5        3        6       930    4.00     2.8    0.030     0.07      1      1.0     0.035    0.329     0.4528
 150      5        3        6       930    4.00     2.2    0.030     0.07      1      1.0     0.035    0.329     0.3558
 151      5        3        7      1140    6.25     0.0    0.010     0.07      1      1.0     0.035    0.329     0.0000
 152      1        4        1      1535    0.50    11.0    1.500     0.04      1      3.0     0.381   14.795    88.9397
 153      1        4        2      1605    1.00     6.6    1.900     0.04      1      1.0     0.381   14.795    64.0366
 154      1        4        3      1635    1.50     4.4    3.100     0.04      1      0.0     0.381   14.795    73.5235
 155      1        4        4      1700    2.00     4.4    4.000     0.04      1      0.0     0.381   14.795    94.8690
 156      1        4        5      1800    3.00     5.2    3.400     0.04      1      0.0     0.381   14.795    95.3002
 157      1        4        6      1900    4.00     4.7    2.100     0.04      1      0.0     0.381   14.795    53.2021
 158      1        4        7      2115    6.25     4.0    1.000     0.04      1      0.0     0.381   14.795    21.5611
 159      2        4        1      1550    0.75     9.9    0.300     0.04      1      3.5     0.019    0.936    16.0091
 160      2        4        2      1625    1.50     6.0    0.220     0.04      1      0.5     0.019    0.936     8.0639
 161      2        4        3      1645    1.75     6.6    0.150     0.04      1      0.0     0.019    0.936     5.3364
 162      2        4        4      1715    2.25    13.0    0.120     0.04      1      0.0     0.019    0.936     8.4088
 163      2        4        5      1820    3.25     3.2    0.080     0.04      1      0.0     0.019    0.936     1.3799
 164      2        4        6      1915    4.25     4.6    0.070     0.04      1      0.0     0.019    0.936     1.7357
 165      2        4        7      2120    6.25     4.2    0.040     0.04      1      0.0     0.019    0.936     0.9056
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                                    S T A T I S T I C A L   A N A L Y S I S   S Y S T E M                                   4
                                                                                            17:23 TUESDAY, SEPTEMBER 8, 1981

 OBS   STANO   STONO   SAMNO   TIME   TSSD    OG1     FLOW    TRAIN   DBS   RRAIN   TFLOW     TMASS     BMASS

 166     3       4       1     1535   0.50    6.9    0.012    0.04     1    3.00    0.001     0.048      0.45
 167     3       4       2     1605   1.00    9.7    0.012    0.04     1    1.00    0.001     0.048      0.63
 168     3       4       3     1635   1.50   11.0    0.008    0.04     1    0.00    0.001     0.048      0.47
 169     3       4       4     1705   2.00    9.9    0.006    0.04     1    0.00    0.001     0.048      0.32
 170     3       4       5     1810   3.25    8.3    0.003    0.04     1    0.00    0.001     0.048      0.13
 171     3       4       6     1910   4.25    9.8    0.001    0.04     1    0.00    0.001     0.048      0.05
 172     3       4       7     2100   6.00    0.0    0.000    0.04     1    0.00    0.001     0.048      0.00
 173     4       4       1     1525   0.25   11.0    0.120    0.04     1    3.00    0.006     0.576      7.12
 174     4       4       2     1555   1.00   13.0    0.120    0.04     1    1.00    0.006     0.576      8.41
 175     4       4       3     1625   1.50   20.0    0.077    0.04     1    0.00    0.006     0.576      8.30
 176     4       4       4     1655   2.00   15.0    0.046    0.04     1    0.00    0.006     0.576      3.72
 177     4       4       5     1755   3.00   14.0    0.005    0.04     1    0.00    0.006     0.576      0.38
 178     4       4       6     1855   4.00   15.0    0.005    0.04     1    0.00    0.006     0.576      0.40
 179     4       4       7     2100   6.00   11.0    0.003    0.04     1    0.00    0.006     0.576      0.18
 180     5       4       1     1530   0.50    0.5    0.190    0.04     1    3.00    0.014     0.217      0.51
 181     5       4       2     1558   1.00    0.7    0.240    0.04     1    1.00    0.014     0.217      0.91
 182     5       4       3     1630   1.50    0.9    0.160    0.04     1    0.00    0.014     0.217      0.78
 183     5       4       4     1700   2.00    1.0    0.140    0.04     1    0.00    0.014     0.217      0.75
 184     5       4       5     1805   3.00    1.0    0.060    0.04     1    0.00    0.014     0.217      0.32
 185     5       4       6     1905   4.00    1.0    0.030    0.04     1    0.00    0.014     0.217      0.16
 186     5       4       7     2055   6.00    0.5    0.010    0.04     1    0.00    0.014     0.217      0.03
 187     1       5       1      750   0.50   16.0   13.900    0.35     5   11.00    2.262   121.214   1198.80
 188     1       5       2      825   1.00    8.0   12.400    0.35     5    1.00    2.262   121.214    534.72
 189     1       5       3      900   1.50   16.0   17.100    0.35     5    1.00    2.262   121.214   1474.78
 190     1       5       4      930   2.00    8.5   15.000    0.35     5    3.00    2.262   121.214    687.26
 191     1       5       5     1030   3.00    6.1   40.800    0.35     5    6.00    2.262   121.214   1341.53
 192     1       5       6     1130   4.00    0.0   20.500    0.35     5    3.00    2.262   121.214      0.00
 193     2       5       1      745   0.25    8.1    0.400    0.35     5   11.00    0.129    11.851     17.46
 194     2       5       2      820   1.00   11.0    1.020    0.35     5    1.00    0.129    11.851     60.48
 195     2       5       3      900   1.50    4.3    0.400    0.35     5    1.00    0.129    11.851      9.27
 196     2       5       4      930   2.00    3.1    0.560    0.35     5    3.00    0.129    11.851      9.96
 197     2       5       5     1030   3.00   21.0    2.500    0.35     5    6.00    0.129    11.851    282.99
 198     2       5       6     1130   4.00    5.3    1.670    0.35     5    3.00    0.129    11.851     47.71
 199     3       5       1      810   0.75   27.0    0.030    0.35     5   11.50    0.003     0.520      4.37
 200     3       5       2      845   1.25   88.0    0.012    0.35     5    1.00    0.003     0.520      5.69
 201     3       5       3      910   1.75   32.0    0.018    0.35     5    2.00    0.003     0.520      3.10
 202     3       5       4      930   2.00   13.0    0.018    0.35     5    1.50    0.003     0.520      1.26
 203     3       5       5     1030   3.00   13.0    0.072    0.35     5    6.00    0.003     0.520      5.05
 204     3       5       6     1130   4.00   15.0    0.005    0.35     5    3.00    0.003     0.520      0.40
 205     4       5       1      800   0.50   13.0    0.270    0.35     5   11.00    0.061     5.427     18.92
 206     4       5       2      835   1.00   16.0    0.570    0.35     5    1.00    0.061     5.427     49.16
 207     4       5       3      900   1.50   10.0    0.270    0.35     5    1.00    0.061     5.427     14.55
 208     4       5       4      935   2.00   12.0    0.360    0.35     5    3.00    0.061     5.427     23.29
 209     4       5       5     1040   3.25    9.1    1.300    0.35     5    7.50    0.061     5.427     63.77
 210     4       5       6     1125   4.00    8.1    0.270    0.35     5    1.50    0.061     5.427     11.79
 211     5       5       1      805   0.50    1.5    0.240    0.35     5   11.00    0.111     2.912      1.94
 212     5       5       2      840   1.25    5.7    0.990    0.35     5    1.50    0.111     2.912     30.42
 213     5       5       3      905   1.50    1.0    0.450    0.35     5    0.50    0.111     2.912      2.43
 214     5       5       4      940   2.25    2.1    0.380    0.35     5    4.50    0.111     2.912      4.30
 215     5       5       5     1045   3.25    3.9    3.220    0.35     5    6.00    0.111     2.912     67.69
 216     5       5       6     1125   4.00    1.0    0.320    0.35     5    1.50    0.111     2.912      1.72
 217     1       6       1      415   0.50   13.0    9.000    0.24     4    5.25    2.913   253.201    636.97
 218     1       6       2      445   1.00    6.0   14.400    0.24     4    2.50    2.913   253.201    465.72
 219     1       6       3      515   1.50   27.0   21.600    0.24     4    2.00    2.913   253.201   3143.61
 220     1       6       4      545   2.00    6.6   24.900    0.24     4    1.50    2.913   253.201    885.84
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                                    STATISTICAL ANALYSIS SYSTEM                                              5
                                                                                  17:23 TUESDAY, SEPTEMBER 8, 1981

OBS    STANO    STONO    SAMNO    TIME    TSSB     OG1       FLOW     TRAIN    DBS    RRAIN    TFLOW     TMASS      RMASS

221      1        6        5       645    3.00     6.8     27.100     0.24     4     3.00     2.913    253.201     993.32
222      1        6        6       745    4.00     9.6     20.500     0.24     4     1.50     2.913    253.201    1060.81
223      1        6        7       945    6.00    16.0      9.100     0.24     4     2.50     2.913    253.201     784.83
224      2        6        1       418    0.50     8.6      0.560     0.24     4     5.25     0.150     11.823      25.96
225      2        6        2       449    1.00     5.5      0.700     0.24     4     2.50     0.150     11.823      20.75
226      2        6        3       528    1.75     9.2      1.620     0.24     4     2.75     0.150     11.823      80.34
227      2        6        4       549    2.00     7.1      1.180     0.24     4     0.75     0.150     11.823      45.16
228      2        6        5       649    3.00    12.0      1.260     0.24     4     3.00     0.150     11.823      81.50
229      2        6        6       749    4.00     6.2      0.560     0.24     4     1.50     0.150     11.823      18.72
230      2        6        7       945    6.00    17.0      1.220     0.24     4     2.50     0.150     11.823     111.79
231      3        6        1       420    0.50     9.4      0.015     0.24     4     5.25     0.005      0.733       0.76
232      3        6        2       450    1.00    12.0      0.022     0.24     4     2.50     0.005      0.733       1.42
233      3        6        3       520    1.50    20.0      0.063     0.24     4     2.00     0.005      0.733       6.79
234      3        6        4       550    2.00    11.0      0.030     0.24     4     1.50     0.005      0.733       1.78
235      3        6        5       650    3.00    12.0      0.039     0.24     4     3.00     0.005      0.733       2.52
236      3        6        6       750    4.00    11.0      0.012     0.24     4     1.50     0.005      0.733       0.71
237      3        6        7       955    6.00    35.0      0.063     0.24     4     2.50     0.005      0.733      11.89
238      4        6        1       415    0.50    16.0      0.180     0.24     4     5.25     0.069      5.947      15.52
239      4        6        2       445    1.00     3.0      0.460     0.24     4     2.50     0.069      5.947       7.44
240      4        6        3       515    1.50     9.8      0.360     0.24     4     2.00     0.069      5.947      19.02
241      4        6        4       545    2.00     4.2      0.710     0.24     4     1.50     0.069      5.947      16.07
242      4        6        5       645    3.00     9.0      0.270     0.24     4     3.00     0.069      5.947      13.10
243      4        6        6       745    4.00     5.3      0.270     0.24     4     1.50     0.069      5.947       7.71
244      4        6        7       945    6.00    21.0      0.850     0.24     4     2.50     0.069      5.947      96.22
245      5        6        1       410    0.50     6.4      1.770     0.24     4     5.25     0.227     11.088      61.06
246      5        6        2       440    1.00     4.3      1.870     0.24     4     2.50     0.227     11.088      43.34
247      5        6        3       510    1.50     6.3      1.360     0.24     4     2.00     0.227     11.088      46.18
248      5        6        4       540    2.00     6.8      2.220     0.24     4     1.50     0.227     11.088      81.37
249      5        6        5       640    3.00    13.0      0.900     0.24     4     3.00     0.227     11.088      63.07
250      5        6        6       740    4.00     1.2      0.990     0.24     4     1.50     0.227     11.088       6.40
251      5        6        7       940    6.00     1.7      1.870     0.24     4     2.50     0.227     11.088      17.14
252      1        7        1      1045    0.50    85.0     12.500     0.53     3     8.00    16.070    704.624    5727.18
253      1        7        2      1115    1.00    10.0     24.900     0.53     3     4.00    16.070    704.624    1342.18
254      1        7        3      1145    1.50     9.3    126.000     0.53     3     4.00    16.070    704.624    6316.33
255      1        7        4      1215    2.00     5.4     93.600     0.53     3     5.50    16.070    704.624    2724.47
256      1        7        5      1315    3.00     6.3    148.000     0.53     3    12.50    16.070    704.624    5025.90
257      1        7        6      1415    4.00     4.4     93.600     0.53     3     7.50    16.070    704.624    2219.93
258      1        7        7      1615    6.00     3.1     57.900     0.53     3     9.00    16.070    704.624     967.50
259      1        7        8      1915    9.00     2.2      7.800     0.53     3     2.50    16.070    704.624      92.50
260      2        7        1      1050    0.50    22.0      1.620     0.53     3     8.00     0.388     22.342     192.11
261      2        7        2      1120    1.00    15.0      3.400     0.53     3     4.00     0.388     22.342     274.90
262      2        7        3      1150    1.50     8.8      1.730     0.53     3     4.00     0.388     22.342      82.06
263      2        7        4      1220    2.00     8.5      1.000     0.53     3     5.50     0.388     22.342      45.82
264      2        7        5      1320    3.00     5.8      3.930     0.53     3    12.50     0.388     22.342     122.87
265      2        7        6      1420    4.00     5.1      2.300     0.53     3     7.50     0.388     22.342      63.23
266      2        7        7      1620    6.00     5.9      0.950     0.53     3     9.00     0.388     22.342      30.21
267      2        7        8      1925    9.50     5.0      0.160     0.53     3     2.50     0.388     22.342       4.31
268      3        7        1      1050    0.50    17.0      0.160     0.53     3     8.00     0.013      1.463      14.66
269      3        7        2      1120    1.00    11.0      0.230     0.53     3     4.00     0.013      1.463      13.64
270      3        7        3      1140    1.50    22.0      0.070     0.53     3     4.00     0.013      1.463       8.30
271      3        7        4      1220    2.00    17.0      0.110     0.53     3     5.50     0.013      1.463      10.09
272      3        7        5      1320    3.00    17.0      0.084     0.53     3    12.50     0.013      1.463       7.70
273      3        7        6      1420    4.00    17.0      0.050     0.53     3     7.50     0.013      1.463       4.58
274      3        7        7      1915    9.00     0.0      0.000     0.53     3     2.50     0.013      1.463       0.00
275      3        7        7      1620    6.00    19.0      0.040     0.53     3     9.00     0.013      1.463       4.10
```

```
                                   S T A T I S T I C A L   A N A L Y S I S   S Y S T E M                                   6
                                                                                       17:23 TUESDAY, SEPTEMBER 8, 1981

OBS    STANO    STONO    SAMNO    TIME    TSSB    OGI .   FLOW    TRAIN    DBS    RRAIN    TFLOW    TMASS     RMASS

276      4        7        1      1045    0.50    13.0    3.00    0.53      3       8.0    0.261    19.601    210.221
277      4        7        2      1115    1.00    11.0    3.30    0.53      3       4.0    0.261    19.601    195.667
278      4        7        3      1145    1.50    13.0    2.10    0.53      3       4.0    0.261    19.601    147.155
279      4        7        4      1215    2.00     6.4    0.71    0.53      3       5.5    0.261    19.601     24.493
280      4        7        5      1315    3.00     6.0    2.50    0.53      3      12.5    0.261    19.601     80.854
281      4        7        6      1415    4.00     6.1    1.00    0.53      3       7.5    0.261    19.601     32.881
282      4        7        7      1615    6.00     9.1    0.36    0.53      3       9.0    0.261    19.601     17.659
283      4        7        8      1910    9.00     7.6    0.03    0.53      3       2.5    0.261    19.601      1.229
284      5        7        1      1040    0.50     1.1    0.08    0.53      3       8.0    0.429     7.359      0.474
285      5        7        2      1110    1.00     2.6    2.83    0.53      3       4.0    0.429     7.359     39.662
286      5        7        3      1140    1.50     2.3    3.91    0.53      3       4.0    0.429     7.359     48.475
287      5        7        4      1210    2.00     1.1    2.34    0.53      3       5.5    0.429     7.359     13.875
288      5        7        5      1310    3.00     6.1    4.30    0.53      3      12.5    0.429     7.359    141.387
289      5        7        6      1410    4.00     0.0    2.46    0.53      3       7.5    0.429     7.359      0.000
290      5        7        7      1610    6.00     0.0    0.99    0.53      3       9.0    0.429     7.359      0.000
291      5        7        8      1905    8.75     0.0    0.32    0.53      3       2.5    0.429     7.359      0.000
```

APPENDIX 2

NOMENCLATURE

A	Area
C	Pollutant concentration
DBS	Days between storms (days)
FLOW	Instantaneous runoff flow
k	Runoff coefficient
m	Total number of land uses
M_p	Total mass of pollutant
n	Total number of storms
OG1	Oil and grease concentration (mg/l)
R	Runoff volume
r	Rainfall
RMASS	Mass flow rate of oil and grease (lb/day)
RRAIN	Rainfall rate (10^{-2}in/hr)
SAMNO	Sample number
STANO	Station number
STONO	Storm number
TFLOW	Total runoff volume (10^6 gal)
TMASS	Total oil and grease mass runoff per storm (lb)
TRAIN	Total storm rainfall (in)
TSSB	Time since storm beginning (hours)

SUBSCRIPTS

i	Station number
j	Storm number
u	Land use

APPENDIX 3

CHANGES TO ABMAC COMPUTER CODE

In the course of this study several changes were made in the ABMAC computer program. These changes are documented below. All code line numbers refer to the ABMAC listing in Appendix B of the ABMAC manual (Litman, 1980). The program consists of two parts: a main program called MAIN which performs initializations and sets up the options desired by the user, and a single subroutine called DAILY which does the actual calculations of runoff and water quality on a day by day basis. All but one of the coding changes were made in subroutine DAILY. DATACHK, the data checking program designed for use with ABMAC, was not used in this study and hence no changes were made in the DATACHK code.

1) In line DAILY 399 the variable ARAIN(L) was changed to IDDDATA(L). this code thus becomes a check for a zero mnoth or day on an input card. In put cards with zero rainfall on a given day are routinely handled by the program at line DAILY 284.
2) DAILY 417 is intended as a check to properly update the year to be for which data is input. In our study January was chosen as the first month of the water year. In this case the update in DAILY 417 is unnecessary and will introduce errors. This line of code was cancelled by inserting a C in column one, thus making it an inactive comment card. When the program is used for water years beginning in any other month but January this line of code is needed, and the C must be removed from column one.

3) In DAILY 79 the order of the variables in the write statement was changed to correspond to the format statement and produce the correct date in the error message. The line now reads:

```
5 WRITE (WRITNO,61) MDATA,DDATA,YDATA
```

4) A check for zero month or date on the first rain data card was inserted after DAILY 124. Line DAILY 125 was deleted. The check inserted is analogous to that in lines DAILY 398 through 403, with changes as noted below in note 7. The added lines of code are:

```
   DO 51 L-1,9
51 IF (IMDATA(L).EQ.0.OR.IDDATA(L).EQ.0) GO TO 52
   NGAP = 9
   GO TO 53
   52 NGAP = L-1
   IGAP = 1
```

The final line is line DAILY 126 with the number 53 added.

5) The formats of all pollutant concentration output headings were changed to read "O&G", for oil and grease, instead of "OTHERS" in the final column. The liens changed were MAIN 371 and DAILY 148, 167, 203, 242, and 551.

6) The format used to print the pollutant concentrations were changed to increase the number of decimal places printed. This was necessary to provide accurate information on concentrations as low as those needed for oil and grease modeling. The formats of all the pollutant concentrations were changed for the sake of consistency. The lines changed are:

LINE NUMBER	OUTPUT	CHANGED FROM	TO
DAILY 382	Daily	6F8.0	6F8.4
DAILY 454	Monthly	6F8.0	6F8.2
DAILY 458	Monthly	6F8.0	6F8.2
DAILY 470	Yearly	6F8.0	6F8.2
DAILY 477	Yearly	6F8.0	6F8.2
DAILY 498	Subarea total	6F8.0	6F8.2
DAILY 517	Subarea year avg.	6F8.0	6F8.2
DAILY 556	End of run	6F8.0	6F8.2

7) The program was changed to allw the rainfall data to be input as nine rain days per card with a blank space between the entries instead of ten rain days per card without any blanks. The new format is easier to read and allows for faster more accurate checking of extensive rainfall input data. The READ statements in DAILY 71 and 397 were changed so that the index L now runs from 1 to 9 instead of from 1 to 10. The FORMAT statement line DAILY 72 now reads:

```
50 FORMAT (212,F4.2,8(13,12,F4.2))
```

This change in the input format also necessitated changes in several other lines of code. These changes are reflected in the code that was added in note 4 above. The maximum number of entries per card was changed from 10 to 9. DAILY 401 now reads:

```
NGAP = 9
```

The DO loop in DAILY 398 was changed to check 9 entries instead of 10. The code is now

```
DO 381 L = 1,9
```

8) Comments on lines DAILY 69 and 396 were changed to reflect the actual units in which rainfall data is to be input. The correct unit is inches, and not 10^{-2} inches/hour as stated in the comments.

These changes are flagged in the source code by comment cards bearing the characters *ALZ*.