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Full-scale comparative evaluation of two slow sand filter cleaning methods

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FULL-SCALE COMPARATIVE EVALUATION OF TWO SLOW SAND FILTER CLEANING METHODS

BY

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I cannot suffiently express my appreciation to my wife and family for their patience and support during this period. I also appreciate the many friends and clients who encouraged and supported me in my effort.

TABLE OF CONTENTS

CHAPTER

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AFDC	acriflavin direct count
BDOC	biodegradable organic carbon
cms	cubic meters per second
COD	chemical oxygen demand
CFU	colony forming units
DO	dissolved oxygen
EBCT	empty bed contact time
FRM	Folin reactive material
gal	gallons, U.S.
gpm	gallons per minute
h	hectare
lb	pounds
m	meter
mg	milligram
m/hr	meters per hour
m/s	meters per second
M	molar
MG	million gallons
MGD	million gallons per day
mL	milliliter
ML	million liters
NOM	natural organic matter
NTU	nephelometric turbidity units
POC	particulate organic carbon
RO	reverse osmosis
sf	square feet
SSF	slow sand filter
SUVA	specific UV absorbance
sy	square yards
THMFP	trihalomethane formation potential
TOC	total organic carbon
ug	microgram
UNH	University of New Hampshire
USEPA	US Environmental Protection Agency
UVA	Ultraviolet absorbance@ 254 nm, cm^{-1}

ABSTRACT

FULL-SCALE COMPARATIVE EVALUATION OF TWO SLOW SAND FILTER CLEANING METHODS

by

Jan A. Kem

University of New Hampshire, December, 1996

Slow sand filters are an established treatment method for water with low turbidity. They usually are effective for the removal of turbidity, microorganisms (including cysts of Giardia and Cryptosporidium), and particles, but they require significant periods of time for cleaning. In the 1950's, West Hartford, CT developed a harrowing process to reduce the time and labor required for cleaning at that plant. A 1988 study observed those filters had higher removal rates for non-particulate dissolved organic carbon and UV absorbing materials, surrogates for trihalomethane formation, than did filters at two other plants cleaned by the conventional scraping method.

This study was planned to compare the effectiveness of the two cleaning methods and their effects on performance of full-scale filters on a side-by-side basis using a new plant at Gorham, NH. Headlosses through those filters developed very slowly, and the study was transferred to a similar plant at Newport, NH where operations were studied through the initial ripening phase and one cycle of cleaning by each cleaning method. This information was supplemented with data collected from separate plants which had been using the two methods since the 1950's and from pilot scale filters. The effects of filter application rates, source water, and filter media characteristics were studied with laboratory scale columns. Removal performance of the full scale filters were compared for temperature, turbidity, particles, nonpurgeable dissolved organic carbon, and UV absorbing materials. The upper 30 cm of filter media at each of the plants was sampled over the study. Concentrations of volatile solids, protein, carbohydrates, bacteria, iron, manganese, calcium, and aluminum were compared and related to performance. The differences between filter cleaning methods were compared in relation to labor and time required, wastes generated, and resultant media characteristics.

Overall performance of the slow sand filters was influenced by water temperature, sand media age, filter biomass content, source water quality, filtration rate, and empty bed contact time. Some removal trends suggested filter harrowing resulted in higher removals of organic carbon and UV absorbing materials but the conclusion must be qualified because the trend was not consistent and was dependent on other confounding factors, e.g. water source, temperature, and sand age.

CHAPTER 1

INTRODUCTION

There are three recognized problems smaller water supply systems must overcome in the production of safe drinking water (AWWA, 1982; Lippy, 1984). The first problem is that small community water systems generally experience much higher unit water costs than larger systems. The second problem is that few treatment technologies for common water supply contaminants have been successfully scaled-down to be operationally and economically applicable to small water supply systems. The third problem is that few communities are able to afford skilled operators devoted solely to operating complex treatment processes. In short, low cost, treatment performance reliability, and simplicity of operation and maintenance are all critical elements of treatment technology in small water supply systems.

Passage of the 1986 Amendments to the Safe Drinking Water Act required the USEPA to specify where filtration of surface water sources is mandatory. Common filtration methods applicable for small water systems include the following options (Hansen, 1987) :

- package conventional or direct filtration treatment plants,
- ultrafiltration (membrane or cartridge),
- diatomaceous earth (precoat) filtration, and
- slow sand filtration.

Under appropriate circumstances, slow sand filtration may be the simplest and the most efficient method of water treatment. According to the World Health Organization (Huisman and Wood, 1974), slow sand filtration is simple, inexpensive, reliable, and is still the chosen method of purifying water supplies for some of the major cities of the world. For example, the Thames Water Authority in London uses slow sand filters to provide drinking water to over 8 million people.

Although more widely used in European countries, a survey of twenty-seven slow sand filtration plants in the United States (Slezak and Sims, 1984) indicated that most are currently serving small communities (<10,000 persons), are more than 50 years old, and are effective and inexpensive to operate. In a more recent study comparing the combined costs of construction and operation of package water filtration plants and slow sand filters in New Hampshire, the slow sand filter plants were found to provide finished water at a lower cost (Mann, 1995). A comparative study between slow sand filtration and direct filtration (Cleasby et al. et al., 1984) concluded that slow sand filters were superior especially where simple operation is important.

The characteristic features of the slow sand filter, besides its slow rate of filtration, are the lack of chemical pretreatment and the cleaning of filter beds by surface scraping and sand removal. Other distinguishing characteristics include uniformly sized sand at all bed depths, small effective size of the sand media, accumulation of source water bacteria and other materials in a schmutzdecke ("dirty layer") at and near the surface of the bed, no filter media backwashing, and relative long filter run times between cleaning. A filter ripening period at the start-up of each filter run is required for optimum treatment performance. A filtered water outlet control structure is desired to maintain submergence of the media under all conditions to minimize potential air binding problems.

A significant drawback of slow sand filters is the relative long filter downtime required during conventional cleaning and the necessity to decide when a filter has "ripened" sufficiently to be placed back on line following a filter-to-waste period. Use of pristine, cold water supply sources can lengthen the ripening time. Since filter cleaning, sand handling, and subsequent filter downtime may represent a significant portion of operating costs (Letterman and Cullen, 1985), more efficient filter cleaning techniques may need to be developed before slow sand filters can become more attractive to many small communities.

1.1 SLOW SAND FILTER CLEANING METHODS

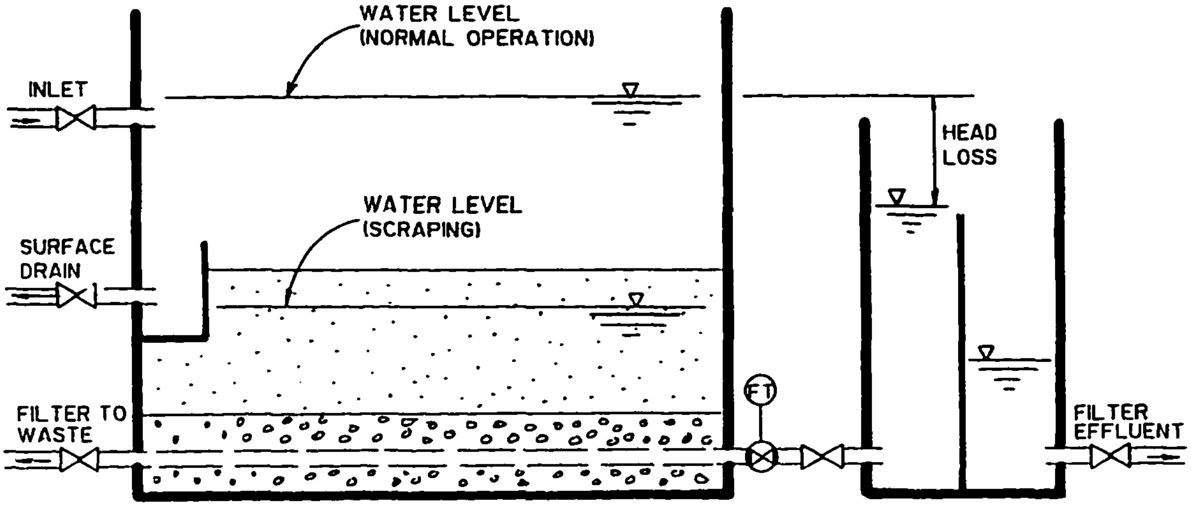
Conventional Surface Scraping- Terminal headloss in a slow sand filter is reached when the cake formed at the surface, i.e. schmutzdecke, and upper sand layers impedes water passage. The filter is typically restored to design flows by manually or mechanically scraping away the top layers of the media, usually 1-2 cm (0.5-1.0-in.), after draining the filter supernatant water below the media surface. Scrapings continue until a minimum sand layer is reached, usually 30 cm to 50 cm (9-15-in.) when the remaining sand is removed, cleaned together with the stored sand, and placed back in the filter to the original bed depth. Huisman and Wood (1974) recommend resanding by a method known as trenching or throwing-over of remaining sand on top of cleaned sand. Trenching may help to avoid deposit accumulation in the lower parts of the filter bed and is thought to help "seed" the replacement sand with microorganisms to minimize the biological ripening period.

The classical scraping cleaning technique is considered labor intensive and frequently requires a ripening period after cleaning. Letterman and Cullen (1985) concluded from a study of six plants in central New York that filter scraping requires approximately 5 labor hours per 93 square meters (5 lh/1000 sf) of filter surface while the resanding operation requires approximately 50 labor hours per 93 square meters (50 lh/1000 sf). They defined ripening as "the interval of time immediately after a scraped and/or resanded filter was put back on line in which the turbidity or particle count results for the scraped/resanded filter are significantly greater than the corresponding values for a control filter." Ripening periods were evident in slow sand filters with lengths varying from 6 hours to 2 weeks.

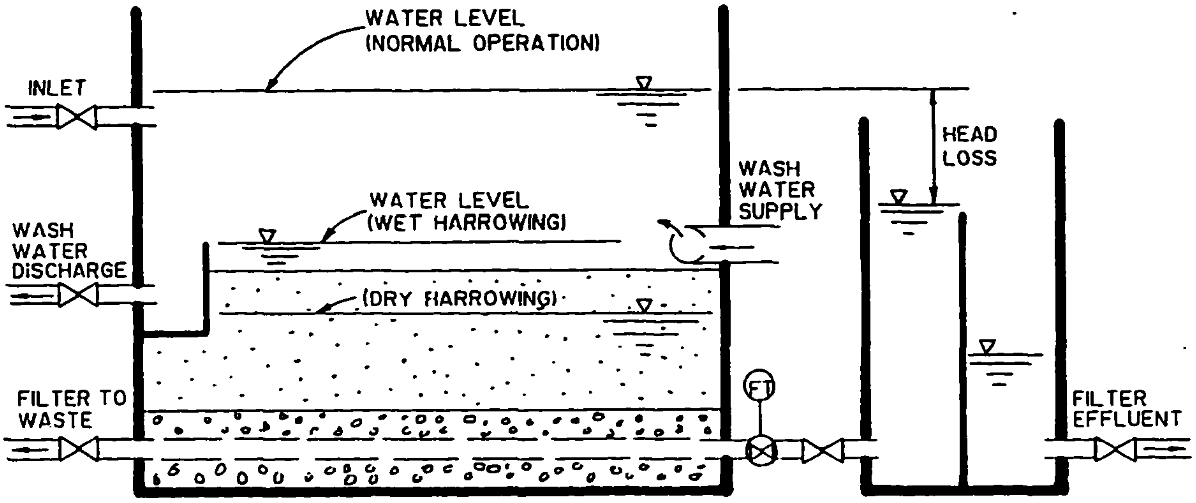
Filter/Schmutzdecke Harrowing- Operators at West Hartford, Connecticut, developed a unique method of cleaning slow sand filters (Minkus, 1954; Collins et al, 1988; Collins et al, 1989; Allen, 1991). When filter headloss approaches the maximum allowable headloss of 1.8 m (5.9-ft), the supernatant water is drained to a height approximately 30 cm (1-ft) above the sand media. A rubber-tired tractor equipped with a comb-tooth harrow is placed on the filter to rake the sand media. Simultaneously, the filter surface sumps are kept open causing a steady discharge of overlaying water. As the harrow is dragged over the sand, colloidal debris in the top 30 cm (1-ft) of sand media is loosened and caught by the moving water stream and is eventually discharged at the filter surface and not down through the filter bed. When the filter supernatant water drops below 8 cm(3-in), harrowing is suspended until the filter has refilled by reverse flow to a depth of 30 cm (1-ft) when harrowing is resumed. The process is repeated until the entire filter surface has been wet harrowed. The filter is then drained overnight and, on the following day, the filter is dry harrowed to loosen the sand and level the surface. The filters are then refilled from below with filtered water from adjacent filters to a depth of about 30-cm (1-ft) and then to overflow level with raw water before being returned to service. Filter run lengths generally last 4-8 weeks. The entire filter sand bed is removed and thoroughly cleaned once every 8-10 years.

Only fine clay colloids and other small particulate debris are removed by filter harrowing and very little sand is lost. Other major treatment advantages also seem apparent. The harrowing method typically requires significantly less time and labor to complete than the usual scraping method. One driver can usually harrow a 0.13 to 0.2 ha (1/3-1/2 acre) filter surface in less than 2 hours. Moreover, harrowed filters are put back on line within hours, instead of days or weeks. The method apparently causes a majority of the debris of the surface deposit to be washed away while a portion of the bacterial population attached to the sand media is raked into the depths of the filter sand bed. The ability to maintain a high bacterial population after cleaning is believed (Fenstermacher, 1989; Collins et al., 1988, 1989) enables the harrowed filters to be quickly placed back on line without a deterioration in treatment performance. The process piping requirements for each of the two filter cleaning methods are shown schematically in Figure 1.

Analyses of cores taken from three mature full-scale slow sand filters revealed a significant relationship between trihalomethane formation potential mass removal rates ($mg/m^2 \cdot hr$) and filter media biomass as shown in Table 1 (Collins et al., 1988,1989). Filter biomass was



SCRAPING



HARROWING

Figure 1: Typical sections of slow sand filters for scraping and harrowing.

TABLE 1: RELATIONSHIP BETWEEN FILTER BACTERIAL BIOMASS AS QUANTIFIED BY ACRIFLAVINE DIRECT COUNT (AFDC) AND FOLIN REACTIVE MATERIAL (FRM) IN THE TOP 30 CM OF THREE MUNICIPAL SLOW SAND FILTERS AND ORGANIC PRECURSOR MASS REMOVAL RATES
(AFTER APHA, 1989)

Season and Filter Location	AFDC Log Concentration Factor[a]	FRM Log Concentration Factor[b]	NPDOC[c] Mass Removal Rate[e]	THMFP[d] Mass Removal Rate[e]
Winter				
Springfield, MA	9.13	3.94	13.5	0.6
West Hartford, CT	10.25	4.47	78.6	6.2
New Haven, CT	-	-	3.2	0.2
Fall				
Springfield, MA	9.62	4.13	17.1	0.6
West Hartford, CT	9.85	4.14	187.5	4.2
New Haven, CT	9.82	4.01	42.6	1.0

[a] log $\sum$ ($AFDC_i$ x $Depth_i$), in AFDC/g dry weight and smpling depth in inches.
[b] log $\sum$ (FRM_i x $Depth_i$), in ug/g dry weight and sampling depth in inches.
[c] non-purgeable dissolved organic carbon
[d] trihalomethane formation potential
[e] mg/m^2 • hr = ($C_{influent}$ - $C_{effluent}$) x hydraulic loading rate

quantified indirectly by acriflavine direct cell counts (AFDC) and directly by Folin reactive material (FRM) over filter bed depth. Mass removal rate was determined by multiplying the filter hydraulic loading rate by the difference between influent and effluent concentrations. Two of the full scale filters, i.e. Springfield, Massachusetts, and New Haven, Connecticut, utilized the surface scraping method while the third sampled filter, i.e. West Hartford, Connecticut, used filter/schmutzdecke harrowing. As shown in Table 1, higher THM organic precursor mass removal rates were observed for slow sand filters having higher filter media bacterial biomass, i.e. the West Hartford filters. Although other factors such as the lability of the natural organic matter (NOM) and the respiratory activity of the bacterial population must be considered, there appears to be a strong relationship between the filter/schmutzdecke harrow cleaning technique and superior treatment performance in removal of NPDOC and trihalomethane formation potential.

Filter/schmutzdecke harrowing of slow sand filters may also be advantageously utilized to quickly mature slow sand filters after cleaning when the water source is of exceptional quality. Biological maturation of pilot slow sand filters in Gorham (New Hampshire) was determined to be a very slow process typically requiring several months to establish a surface deposit over the entire filter surface. For example, a pilot slow sand filter with an effective sand size of 0.34 mm and uniformity coefficient of 2.0 operating at a hydraulic flow rate of 0.25 m/hr (0.1 gpm/sf) developed less than 10 cm (4-in) headloss after 189 days of continuous operation. The raw water turbidity, dissolved organic carbon, UV absorbance, total coliform, and temperature levels during the pilot study (May-November 1989) averaged below 0.20 NTU, 2.0 mg/L, 0.06 cm^{-1}, 12 CFU/100 mL, and 10°C, respectively. A filter cleaning method that will minimize removal of biomass and bacterial population in the mature schmutzdecke and top filter sand layers was desirable at Gorham to reduce slow sand filter maturation requirements.

1.2 PROJECT GOALS, OBJECTIVES, AND EXPECTED BENEFITS

This research study proposed to evaluate the performance of two slow sand filter cleaning methods, surface scraping, and filter harrowing, under controlled full-scale conditions at a recently constructed slow sand filtration facility in Gorham, New Hampshire. The facility went on-line in February 1991 and appeared to offer a unique opportunity to quantify cleaning effectiveness, maintenance costs, filter downtime, headloss development rates, and filter-to-waste requirements for each cleaning method in full-scale filter comparisons. The project goal was to document any financial savings and treatment effectiveness that a small community could reap by utilizing one filter cleaning method over another.

The Gorham, NH plant was in operation for over two years before cleaning was necessary and so the plans to use that facility for comparative operations were suspended. Data on comparative cleaning operations were obtained at Newport, NH. Data on comparative filter characteristics was developed from full-scale filters at Gorham and Newport, NH, Newark, NY, West Hartford, CT, and pilot plants at Portsmouth, NH. Data on filter performance was developed from each of the previously mentioned facilities and laboratory scale studies at the UNH environmental engineering laboratories.

The following parameters were used for comparison between the two cleaning methods:

- Filter performance
- Effectiveness of cleaning operations
- Filter-to-waste requirements to achieve an acceptable treatment performance
- Headloss development rate after each filter cleaning
- Filter downtime required for each cleaning episode
- Variation in cleaning frequency rate, and
- Yearly maintenance costs associated with operation and cleaning of each filter.

CHAPTER 2

LITERATURE REVIEW

2.1 HISTORY

2.1.1 Slow Sand Filtration

Sand filters have been used to treat water since the early nineteenth century (Huisman and Wood, 1974; Slezak and Sims, 1984; Ellis, 1985). Untreated water was filtered through a bed of sand and the resulting water was used for drinking, washing, and industrial purposes. The earliest known design of these filters has become known as a "slow sand filter." This type of treatment is still used. Seventy-one slow sand filter plants were identified in the United States in 1988 (Logsdon, 1991). That study found that forty-five percent of the plants served populations of less than 1,000 and seventy-six percent served populations of less than 10,000 persons. A few larger plants also use slow sand filtration, most notably West Hartford, CT in the US, but also including Amsterdam, Antwerp, London, Paris, and Zurich in Europe (Huisman and Wood, 1974; Weber-Shirk, 1992). After 1900, "mechanical filters" (generally of the rapid-sand filter type) gained in popularity and they have become the prevalent type of filtration. Rapid sand filters are generally used after chemical coagulation and settling and are able to treat raw water containing concentrations of turbidity, clays, algae, and other matter that could not be treated or treatted economically by slow sand filters.

Slow sand filters attracted renewed attention after 1970 for their low costs for operation and their reliable removal of coliform bacteria and Giardia cysts (Logsdon, 1991). At least 225 slow sand plants had been identified by 1994 in the United States (Brink and Parks, 1996). The need to remove dissolved organic precursor material also has led to renewed research.

The essential features of a slow sand filter include a tank to maintain a relatively constant supply of water and pressure over a layer of fine to medium filter sand, a layer of support gravel and underdrain system to collect the filtered water, and a system of valves and piping to control the rates of flow, depth of water over the filter sand, and back pressure on the underdrain system (Huisman and Wood, 1974). Slow sand filters operate at very low filtration rates, from 0.1 to 0.2 m/hr (60-120 gpd/sf), and usually without pretreatment. Generally accepted design criteria are presented in Table 2. The mean depth of sand found in the 1988 survey was 0.92 m (3.0 ft.), most with sand having an effective size between 0.2 and 0.5 mm and a uniformity coefficient less than or equal to 3.0. The cost of treatment was from 0.3 to 2.6 cents per cubic meter (one to ten

TABLE 2: RECOMMENDED DESIGN CRITERIA FOR SLOW SAND FILTRATION.

Design criteria	Recommended Standards For Water Works (1992)	Huisman and Wood (1974)	Visscher et al. (1988)
Period of operation	Not stated	24 hr/day	24/hr/day
Filtration rate, m/hr (gpd/sf)	0.08-0.3 (45-150)	0.1-0.4 (60-240)	0.1-0.2 (60-120)
Depth of sand, m (in.)			
Initial	0.8 (30)	1.2 (40)	0.8-0.9 (31-35)
Minimum	Not stated	0.7 (28)	0.5-0.6 (20-24)
Sand, Effective size, mm	0.30-0.45	0.15-0.35	0.15-0.30
Uniformity coefficient	<2.5	<3, prefer <2	<5, prefer <3
Depth of supporting media, including underdrains, m (in.)	0.25-0.5 (10-21)	Not stated	0.3-0.5 (12-24)
Depth of supernatant water, m (ft.)	>0.9 (>3)	1-1.5 (3.2-4.8)	1 (3.2)
Freeboard, m (ft.) Note: Total headroom over sand to permit normal movement for scraping and sand removal operations.	Not stated	0.2-0.3 (.6-1.0)	Not stated
Prior studies required for specific raw water supply?	Yes	Recommended	Not stated

(Table modified from Pyper and Logsdon, 1991) cents per 1,000 gallons)(Logsdon, 1991). Source water criteria for using slow sand filtration are summarized in Table 3.

TABLE 3: SOURCE WATER CRITERIA FOR SLOW SAND FILTRATION.

Parameter	Guideline (a)	Guideline (b)
Turbidity	<5 NTU	5-10 NTU
Algae	No heavy seasonal blooms experienced. Chlorophyll-a < 5 mg/m^3	200,000/L and depending on species present. Assumes covered filters.
True color	5-10 Platinum-cobalt color units	15-25 Platinum-cobalt color units
THMs	-	60 ug/L
NPDOC	-	2.5 mg/L
UV Absorbance, cm^{-1}	-	0.080 AU
Dissolved oxygen	-	>6.0 mg/L
Phosphorus, as PO4	-	30 mg/L
Ammonia	-	3 mg/L
Iron	<0.3 mg/L	<1 mg/L
Manganese	<0.05 mg/L	-

(a) After Logsdon, 1991; Hendricks, 1991; Bellamy et al., 1985a.
(b) Spencer and Collins, 1991.

Early filters were thought to improve the clarity and esthetics of the water by straining silt and clay from the flow, but they were later found also to remove bacteria, color, organic materials, and THM precursors. Turbidity, coliform, virus, and both Giardia cyst and Crytosporidium oocyst removal are required by the Safe Drinking Water Act. Color is removed for aesthetic reasons. The removal of NPDOC and UV absorbing materials is important as these substances are surrogate parameters for predicting the presence of thrihalomethane formation potential (THMFP) (Amy, et al., 1986). Typical removal rates that have been reported are summarized in Table 4.

TABLE 4: TYPICAL REMOVALS REPORTED FOR SLOW SAND FILTERS.

Parameter	Removals reported	References
Turbidity, NTU	97.8% Raw water ≤10, >90% Raw water <1, 70-80% 55%	Cleasby et al., 1984 Logsdon, 1991 Fogel, 1993
Particles	2 log at 2.4-4 um to 4 log at 40-50 um 96.8% or better for 7-12 um	Slezak and Sims, 1984 Cleasby et al., 1984
Coliformbacteria, total	99.4% Mature filters, >99% Mature filters, 0-5°C, >90% Immature filter, <60% 1-2 log 2-3 log	Cleasby et al., 1984 Logsdon, 1991 Fogel, 1993 Bellamy et al., 1985(a)
Giardia cysts	New or mature filters, filter rate = 0.12 m/h, >99.9% >99.98% 93% >99.99% after ripening	Logsdon, 1991 Bellamy, 1985(a) Fogel, 1993 Ghosh et al., 1989
Cryptosporidium oocycts	48% >99.99% after ripening	Fogel, 1993 Ghosh et al., 1989
Viruses	Filter rate ≤0.2 m/h, 99.9% Similar to rates for total coliform.	Logsdon, 1991 Ellis, 1985
Color, true	20-25% <25%	Steel, 1947 Cleasby et al., 1984
NPDOC	12-33%	Collins and Eighmy, 1989
UV absorbing material	17-40%	Collins and Eighmy, 1989
THMFP	9-27%	Collins and Eighmy, 1989

2.2 OPERATIONS

2.2.1 Ripening on Initial Commission

A filter will not achieve the performance levels required for use when it is first placed in operation, "because the vital living organisms on which treatment depends are not yet present and building them up is a slow process calling for careful supervision." (Huisman and Wood, 1974). Huisman and Wood were among the earliest to report on performance and operation when interest in slow sand filtration was renewed. Many subsequent investigators have used their work and, to preserve a common information base, much of the general descriptive material on operation will be taken from their writing before also presenting conclusions by others.

"When filters are to be first started, they should be filled from below to expel air bubbles from the interstices of the sand, and then from above to the normal working depth. The outlet valve should then be opened and the effluent run to waste at about one quarter of the normal rate, without interruption, for a period of at least several weeks in tropical climates and longer where temperatures are low. The time also depends on the nature of the raw water. The flow is gradually increased until it reaches the designed rate. Formation of a schmutzdecke and an increase in the head loss are signs that ripening is proceeding satisfactorily, but comparative chemical and bacteriological analyses of raw and effluent are needed to demonstrate that the filter is in full working condition and that the water may be diverted to the public supply. Any interruption longer than the period required to fill the clear well may necessitate another period of ripening to maintain effluent quality" (Huisman and Wood, 1974). Although there is no consistent definition of "ripening," filter is said to be ripened when the effluent quality is better than its influent though the effluent quality must be able to meet regulatory requirements before it may be used. The length of the time for ripening varies widely, ranging from one week to several months (Hendricks, 1991).

It is essential for the sand to have been washed thoroughly before it is placed in a filter so that effluent turbidity levels will fall to acceptable levels within a few days or weeks (Logsdon, 1991; Ghosh et al., 1989). One objective of pilot testing is to determine the length of ripening time needed (Hendricks, 1991).

2.2.2 Cleaning

As water continues to be filtered, impurities are deposited on the surface of the sand media and in the interstices of the media. This interstitial material includes microorganisms, allochthonous and autochthonous biodegradable and non-biodegradable oranic materials, and inorganic matter. These deposits increase resistance to the flow of water and the difference in pressure, or "headloss", between the surface of the water over the filter and the water leaving the underdrains increases. Eventually the headloss will approach the available difference between the elevation of the overlying water surface and the bottom of the filter. If the filter were allowed to continue operating, the headloss would exceed the available difference and negative pressures would result just below the schmutzdecke layer. This could cause release of dissolved gases, resulting in local "air binding" of the spaces between sand grains. Filter air binding could reduce removal efficiencies by increasing localized hydraulic loading on the remaining filter bed. Filters are cleaned before the headlosses accumulate to the maximum level to avoid this condition.

2.3 CLEANING METHODS

Cleaning is the chief operating expense at slow sand filter plants and much effort has been made to simplify this operation and to introduce mechanical processes where possible. Surface scraping has been used almost universally, but several other processes have been tried. Dry raking has been used to lengthen the period of service and save time, using 2 or 3 rakings between scrapings. When the bed is then scraped, a much greater depth of sand must be removed than otherwise (Turneaure and Russell, 1924; Letterman and Cullen, 1985). Deep spading and loosening also have been used, but this process was of doubtful value as it disturbed the action of the filter much more than surface raking (Turneaure and Russell, 1924). In a more recent pilot operation, it was demonstrated that mixing the upper 10 cm (4 in.) of sand after it had been cleaned by scraping reduces removals as compared with operation following normal cleaning (Bellamy et al. 1985a).

In-place cleaning by agitation and washing within a travelling box has been used in Wilmington, Del. (Turneaure and Russell, 1924); Paris and Ashford Common Works of London (Renton et al., 1991); Antwerp (Huisman and Wood, 1974; Renton et al., 1991); and Hartford, CT (Minkus, 1954). Hydraulic movement of the sand to portable cleaning equipment and replacement has been used in drained filters (Turneaure and Russell, 1924; Letterman and Cullen, 1985) and in operating filters (Renton et al., 1991). Removable synthetic geotextile material placed on the media surface has also been considered (Mbwette and Graham, 1988; Vochten et al., 1988).

Scraping remains the predominating method in use, however.

2.3.1 Scraping

The scraping method of cleaning has been widely described (Huisman and Wood, 1974; Letterman and Cullen, 1985; Hendricks, 1991; and many others). Scraping involves draining the filter, removing the upper 1 to 2 cm (0.5 to 1 inch) from the filter to expose a cleaner sand surface, and returning the filter to service. Because a portion of the sand media has been removed, a period of re-ripening may be necessary before the filtered water may be used. The depth of the sand bed is progressively depleted by the amount of sand removed each time it is scraped. Eventually the remaining sand will have become too shallow to effectively treat the incoming water. The filter will then need to be "resanded" by adding a layer of new sand over the remaining sand or by replacing all the sand in the filter, and the new sand ripened as required for a new filter. Letterman and Cullen (1985) also described the scraping practices at a number of plants in upstate New York and presented information on the variations practiced within an area under the same regulatory body. The use of mechanical equipment for scraping has also been described (Huisman and Wood, 1974; Renton et al., 1991).

2.3.2 Harrowing

Wet raking while maintaining a cross-flow of water to carry away suspended materials to suitable drains, referred to as the "Brooklyn method", had been attempted but it was regarded as difficult to clean a filter to a sufficient depth and did not come into general use (Turneaure and Russell, 1924). After several other cleaning methods had been tried without satisfaction, a modification of this method was adopted in the early 1950's at the West Hartford, CT plant and is still being used (Minkus, 1954; Allen, 1991). The protocol for harrowing as practiced at West Hartford is as follows:

1. Between 3 and 5 A.M., close the raw water supply.

2. By 8 A.M., lower a small tractor through the narrow entrance shaft to the sand level.

3. The water level in the filter is maintained at about 5 to 30 cm (2 to 12 inches) above the sand while the tractor pulls a small spring toothed harrow over the surface for 4 to 5 hours. This stirs up the top materials and washes them across the sand to an outlet drain. This water, from the raw water supply, is introduced from a channel along one side of the filter and flows to a drain channel along the side of the filter opposite the supply channel. The velocity of the flow across the filter surface is only about 0.1 to 0.25 cm/s (0.05 to 0.1 fps) but the tractor keeps circling the bed and resuspending the material until most of it reaches the drain channel. Filtered water is also introduced up through the filter from the underdrain to prevent debris from further penetrating the filter during wet harrowing. This upflow is at a rate of approximately 0.02 m/hr (0.008 gpm/sf) and far below the rate necessary to fluidize the sand media.

4. After about 4 hours, the underdrain is opened, and the water drained to about 30 cm (12-inches) below the surface of the sand.

5. The next morning, either the same tractor or a larger crawler tractor is used to pull a larger toothed-harrow for a half day to scarify the bed to a greater depth and break the deeper crust.

6. The filter is then filled from below to above the sand surface with filtered water, then raw water is added from above the filter to raise the level to about one meter (3- ft.) above the sand. The filter is then opened to the system but at only about a quarter of its capacity for the first shift.

Collins et al. (1989) found a significant relationship between the mass removal rates of THMFP ($mg/m^2 \cdot hr$) and the filter media biomass as quantified by FRM and AFDC. They found that the filters cleaned by harrowing outperformed those cleaned by scraping. They also reported harrowing required less time and labor than did the surface scraping method and that the effluent quality did not deteriorate due to the cleaning because the bacterial population was maintained.

2.3.3 Ripening after Cleaning

Nearly all investigators report the initial performance of a filter that has just been cleaned must be carefully monitored because it may exhibit a ripening period. Letterman and Cullen (1985) defined a ripening period as "occurring when a filter which had just been put in operation removes particulates at a lower efficiency than removed by an identical filter which had been operating for a significant time." The adverse impacts of ripening are reduced by filtering to waste until the desired performance is again reached (Logsdon, 1991). Not all filters necessarily exhibit ripening (Letterman and Cullen, 1985).

After cleaning and filling, the filter should be started slowly and gradually. If ripening is necessary, the effluent is run to waste until analyses demonstrate that it satisfies the normal quality standards. The process is markedly accelerated as compared to when the bed was initially placed in service (Huisman and Wood, 1974). This period can range from overnight, as at the Newport, NH filters monitored in this investigation, to 24-48 hours (Logsdon, 1991). The development of the schmutzdecke is sometimes considered to be necessary for full efficiency in removing particles, especially if Giardia cysts are of concern (Cleasby et al., 1984). This was particularly important during the first four filter cycles in their pilot plant operation, though not during later operations. Only four of 10 cleaning operation at plants using the scraping method have shown their ability to remove turbidity and coliform was affected after cleaning (Letterman and Cullen, 1985), but no comparable information was reported for removal of DOC or UV absorbing materials. The length of ripening observed in these four plants ranged from 6 hours to two weeks. Neither prechlorination nor water temperature appeared to correlate with ripening period duration.

2.3.5 Reconditioning

"During the long operating period, some of the raw water impurities and some of the products of biodegradation will have been carried into the sand bed to a depth of some 0.3 to 0.5 m, according to the grain size of the sand" (Huisman and Wood, 1974). To prevent cumulative fouling and increased resistance, this depth of sand should be removed before resanding but it does not need to be discarded (Logsdon, 1991). A practice known as "throwing-over" the remaining sand onto cleaned sand laid on the supporting gravel has been described (Huisman and

Wood, 1974; Renton et al., 1991) and would retain the sand without allowing the bed to become stratified.

Renton et al. (1991) noted that if the lower layers of sand were allowed to remain within the filter over a prolonged period, an accumulation of silt and organic debris effectively clogged the bed, thereby reducing subsequent run times and output. Thames Water Utilities Ltd. facilities have used hand trenching. This method involved hand excavation of a trench across the filter, washing the excavated sand, and replacing the washed material into the filter in the course of rebuilding the gravel and sand layers. Sometimes unwashed excavated sand was placed on the surface of the replacement sand adjacent to the trench. This would build the filter up to approximately normal operating depths but leave the older layers with their accumulated debris on top where it could continue to cause head loss. Manual trenching had the advantage that no special tools or skills were required but it was costly in both time and labor. A "deep skimming" process is now used to replace the former hand labor method, cutting down to the support gravel layer. Resanding is required every 12 to 15 filter runs or as necessary when the minimum depth of 0.3 m (1-ft) is reached. That thickness has been established within their jurisdiction to maintain the adequate particle removals as an effective barrier against pathogens. The resanding operations take 2 to 3 weeks to complete followed by a one to 3 week conditioning period for "ripening" before the beds are returned to service. Performance of deep skimmed beds is such that they produce an average of 24 percent more water than when reconditioned sand is placed on an older layer containing debris. Resanding by the trenching method also produced a marked improvement but strict comparisons were not made as to the use of differing sand grades, clean sand criteria, and operating conditions which may also influence behavior of the beds. Initial head losses for a bed which had been scraped was 0.59 mm but only 0.28 mm after reconditioning with deep skimming (Renten et al., 1991).

Various sand washing methods have been reported (Huisman and Wood, 1974: Renton et al., 1991; Allen, 1991; Whitman, 1992). A completely clean sand is difficult to attain. Washing rarely removes the strongly adherent organic coating entirely from grains and, after exposure to air, this material can "become soluble and serve as a substrate for bacterial growth." Under favorable temperatures and moisture conditions, the sand will contain large numbers of bacteria and not all will contribute to the treatment process. Resanding should be done in the winter if washed sand is to be used (Huisman and Wood, 1974). When washed, the sand loses its finer particles and coarser sand may allow deeper penetration of impurities (Huisman and Wood, 1974).

2.4 PERFORMANCE FACTORS AFFECTING REMOVAL OF WATER IMPURITIES

2.4.1 General Factors

Early reports on slow sand filters considered their ability to remove particles due to the straining properties of the sand or schmutzdecke layer. Later studies recognized performance was related to other biological and physical mechanisms present in the filters. Removal mechanisms for slow sand filters have been described in detail elsewhere (Huisman and Wood, 1974; Ellis, 1985; Hendricks, 1991; Haarhoff and Cleasby, 1991; Weber-Shirk, 1992; Weber-Shirk and Dick, 1997).

Weber-Shirk (1992) summarized the development of theories regarding the performance of slow sand filters. Simpson, in 1827 prior to building a full-scale filter, stated "the principle of the action depends upon the strata of filtering material being finest at the top, the interstices being more minute in the fine sand than the strata below; and the silt, as its progress is arrested, (while the water passed from it renders the interstices between the particles of sand still more minute, and the bed generally produces better water when it is pretty well covered with silt than at any other time." This theory has remained prevalent and much of the literature emphasizes the role of the formation of a dirty-skin, the "schmutzdecke," as an effective filtering media (Cleasby, et al., 1984; Letterman and Cullen, 1985). In 1939 Simpson believed the process included something more than straining. Other investigators also began to look at other mechanisms. Piefke (Fuertes,

1901) concluded that straining could not account for the removal of bacteria and proposed biological action on the surface and in the sand was responsible for most of their removal. Meek and Shieh (1984), as well as operating data from numerous plants including those cited by Letterman and Cullen (1985), noted that reripening was not necessarily required after the removal of the schmutzdecke by scraping. Studies by Hendricks (Meek and Shieh, 1984) demonstrated that it was the maturity of the biomass within the filter that was critical to removal of Giardia cysts, regardless of the age of the scmutzdecke and the time since resanding over mature support gravel layers.

Filtration generally has been studied as a clean bed process which traps particles (Camp, 1964; Ives and Sholji, 1965; Yao et al.,1971; O'Melia and Ali, 1978; and numerous others). O'Melia and co-workers have been particularly notable in their application of collector theory based on consideration of efficiency of both particle transport to a collector and subsequent particle capture by the collector. The equation for initial removal efficiency in a clean bed has been given as:

$$\ln(C/Co) = -\frac{3(1-f)\alpha\eta L}{2d} \qquad (1)$$

where C and Co are effluent and influent concentrations,
f = bed porosity
α= single collector attachment efficiency ("stickiness")
η= single collector transport efficiency
L= total bed depth
d= filter media diameter.

The combined term, $\alpha\eta$, is frequently considered as the single collector removal efficiency. Experimental observations further indicate that submicron particles are transported primarily by Brownian motion while sedimentation and interception dominates for larger particles. In practice, however, suspended particles accumulate in the filter and function as additional collectors, resulting in improved removal and additional headloss (Darby et al, 1992).

Other investigators have sought to model the effects of ripening (Darby et al.,1991). These methods have included using mono- and heterodisperse suspensions, with additional terms to account for retained particle attachment efficiency, fraction of particles acting as additional collectors, fraction of particles contributing to headloss, the transport efficiency of retained particles, the removal efficiency of collected particles, and the density of additional particles(Darby et al., 1992). These extensions of the collector theories make the understanding of full-scale filters more realistic but point out the complexity of ripening even under controlled laboratory conditions.

Huisman and Wood (1974) and Hendricks (1991) viewed the biofilm developing on the sand grains as increasing the "stickiness" of the media and its ability to capture and hold particulate matter until it was metabolized. Studies using water from natural sources indicate that accumulation of matter in filter media is also affected by microbial growth, and the biodegradation is affected by the form of the nutrient carbon sources, whether particulate or soluble (Hijnen and Van der Kooij, 1992). The type and amount of carbon present affect the removal potential of a filter as does the mass and extent of acclimation of the biological population. DOC has been identified as a potentially important source of particle volume in floc formed using chemical coagulation, and it has been suggested that 1.6 ppm of particle volume per mg DOC/L should be added when estimating the final volume of particles resulting from treatment (Wiesner and Mazounie, 1989). Subsequent metabolism of assimilable organic material would reduce the volume in a biological filter. Metabolism would also release products to lower portions of the filter and eventually to the filter underdrains (Bouwer and Crowe, 1988).

Hendricks and Bellamy (1991) listed process variables affecting microorganism removal efficiencies by field-scale slow sand filters. These variables are listed in Table 5.
These variables also have been identified in relation to the removal efficiency for turbidity, particles, and organic matter. There has been little discussion of the relationships between these variables and removal of NPDOC and UV absorbing materials.

A 1988 study of relative performances between three filter plants in New England found differences in removals of NPDOC, UV absorbing materials, and THMFP (Fenstermacher, 1989;

TABLE 5: PROCESS VARIABLES AFFECTING REMOVAL EFFICIENCIES IN SLOW SAND FILTERS.

Category	Variable
Design	Hydraulic loading rate Sand size (effective size, and uniformity coefficient) Headloss allowed Sand bed depth (maximum and minimum) Treated water storage (to maintain steady flow)
Operating	Frequency of scraping Length of time filter is out of operation after scraping Minimum bed depth permitted Length of time to "maturity" Flow variation (alleviated by treated water storage) Age and type of schmutzdecke
Ambient	Water temperature Raw water quality (particle size, color, turbidity) Kinds of micro-organisms present Concentrations of micro-organisms Algae kinds and concentrations Turbidity character and magnitude Organic compounds and concentrations Nutrients and concentrations

(After Hendricks and Bellamy, 1991)

Collins and Eighmy, 1988; Collins et al., 1992b). They concluded performance differences were affected by enhanced biomass developed in one of the plants by the cleaning method used at the plant. Correlations between the FRM and bacterial content of the filter media with depth and overall performance were noted (Spanos, 1989) but other factors might also have been related to the differences in performance.

2.4.2 Design parameters

The hydraulic loading rate has been regarded as the principal controllable factor in operation of slow sand filters, affecting the relative cost of facilities and the length of time between cleaning events (Slezak and Sims, 1984). Bellamy et al. (1985a) operated parallel pilot filters over a 16 month period on raw water spiked with settled sewage and Giardia cysts at selected temperatures and loading rates. They reported removals of turbidity, coliform and standard plate counts declined with increases in hydraulic loading. Removals of Giardia cysts were consistently above 99.98 percent at all loadings and differences were not significant. They concluded that loading rates should be considered in design due to the unmistaken influence of hydraulic loading rates on percent removals. This position appears to have continued support in establishing design criteria for slow sand filters.

Hendricks and Bellamy (1991) reviewed literature on this topic ranging from Hazen (1913), "the efficiency of removal almost uniformly decreases rapidly with increasing (flow) rate", to more recent sources. They concluded that the removal of turbidity, coliform bacteria, Giardia cysts, and standard plate count are uniformly high and loading rates should not be a deciding factor in design. Taylor (1974) concluded there was no difference in performance for loadings between 0.12-0.25 m/hr to 0.5-0.6 m/hr (0.05-0.1 to 0.2-0.24 gpd/sf). Collins et al. (1992) found differences in treatment performance which were statistically indistinguishable between the rates of 0.05 m/hr and 0.10 m/hr (0.02-0.04 gpd/sf). It is generally agreed that the loading rate should not be varied rapidly (Huisman and Wood, 1974; Haarhoff and Cleasby, 1991; Hendricks, 1991). Ellis (1985) summarized a number of reports with the conclusion that the appropriate hydraulic loading rate should be related to raw water quality established from pilot scale investigations.

Haarhoff and Cleasby (1991) reviewed removal of organic carbon and reported studies with diverse results ranging from "no removal" to as much as 60 to 75 percent removals. They concluded many of the differences were the results of variations in the composition of organic materials in the raw water as measured by the tests for TOC, COD, THMFP, etc. Haberer et al. (1984) related the removal of DOC and permanganate value to filtration rates. Removals of either DOC or permanganate value declined by approximately 40 percent as the filter rate was increased from 0.1 to 0.4 m/h (0.04 to 0.16 gpd/sf). Studies by Rechenberg(1965) reported the effluent permanganate consumption to be a function of filter rate according to the equation:

$$Ce = (0.8vf\hat{}0.17) \times Ci \qquad (2)$$

where Ce and Ci are the effluent and influent permanganate consumption, and vf is the relative filtration rate (Huisman and Wood, 1974). Collins et al. (1992) did not find the differences in NPDOC removal, when expressed in percentage removal, to be significantly different between rates of 0.05 and 0.10 m/h (0.02 and 0.04 gpd/sf) but the mass of DOC removed was higher at the higher hydraulic loading.

Most plants are designed to use approximately the same depth of sand. Generally, the depth of filter sand is relatively constant over the area of each filter and for all filters at a particular plant after they have been resanded. The depth within a filter varies slowly over time if the filter is cleaned by scraping 1-2 cm (0.5 to 1 in) every one to three months. To the extent that the filter depth approaches one meter (3.2 ft.), the empty bed contact time (EBCT), in hours, will be approximately the reciprocal of the hydraulic loading rate, in meters/hour. The normal range of EBCT for 1.0 m (3.2-ft) deep filters operating within hydraulic loading rates of 0.1-0.2 m/hr (0.04-0.08 gpd/sf) would be 10 to 5 hours. The EBCT is a process parameter which also has been related to filter performance, particularly when relating performance to adsorptive or biological processes. These processes are time-dependent and higher loading rates reduce the contact period.

Billen et al. (1992) studied biological filters and concluded that reductions in rapidly hydrolyzable macromolecular BDOC were essentially completed within 20 to 30 minutes but there was no significant reduction of slowly hydrolyzable materials within "practical contact times." There was no definition given for practical contact times, but that study was relating experience with granular activated carbon (GAC) contactors which would normally have an EBCT of less than one hour. Wang and Summers (1994) concluded EBCT was "the key parameter for design and operation of drinking water biofilters" and DOC removal was independent of filter velocities in the range of 1.5 to 5 m/s (0.6 to 2.0 gpd/sf). Wang and Summers (1993) also concluded that DOC removal was a function of the product of biomass and contact time, thus mass transfer and biokinetics must be considered. Their studies found one-third of the biodegradable natural organic matter (NOM) removed within a 30 minute EBCT was removed within the first 3 minutes.

Attention should also be given to the uniformity of flow across the filter area. Variations in head loss due to the accumulated materials in or on the surface, possible air binding within the media, the uniformity of the sand, and the construction of the underdrain system cannot be prevented, but can be minimized (Huisman and Wood, 1974).

2.4.3 Filter sand

Huisman and Wood (1974) considered the quality of the filter effluent to be dependent primarily on the grain size of the filter sand, and not on hydraulic loading rate so long as the flows remained within generally defined limits. Their reasoning, however, related the performance with available surface area of the sand grains which is related to grain size. They believed the greater the surface area, the more contact between the "constituents of the raw water, thus speeding up chemical reactions (surface catalysis)." The total area of sand grain surface is also related to the depth of the sand media and they equated a depth of 0.6 m (2-ft) of a sand with grains of 0.15 mm to a depth of 1.4 m (4.6-ft) of a sand with a grain size of 0.35 mm. That relation is also consistent with the formula for the removal of particulates given by Montgomery (1985):

$$N/N_0 = \exp\left[\frac{-\psi(1-\varepsilon_0)}{d_m} L\eta\right] \qquad (3)$$

where N/N_0 = ratio of particles removed
ψ = a shape factor
ε_0 = porosity of media
L = total depth of the media
η = collision factor, and
d_m = media size.

Their conclusions concerning the importance of grain size were qualified by the affects of raw water quality, ripening, and cleaning operations.

Most specifications for sand adapt the "Standard for Filtering Material" (AWWA, 1989) by revising the grain sizes from those specified for rapid sand filters (effective size of 0.35 -0.65 mm, and uniformity coefficient $\leq$ 1.7) to those for slow sand filters as shown in Table 2. An additional modification used in some areas is to allow the use of locally available sand with an acid solubility exceeding 5 percent (Letterman and Cullen, 1985). Studies reported in 1894 by the Massachusetts Board of Health concluded the use of sand "containing a considerable amount of lime" would result in increased head losses and increase the hardness of the water from slow sand filters (Turneaure and Russell, 1924). Specifications for rapid sand filter media limit the acid solubility so that acidic water applied to the filter would not dissolve significant quantities of the filter material (AWWA, 1989). The raw water supplies in central New York State (Letterman and Cullen, 1985) have pH, alkalinity, and hardness in ranges compatible with the native sand found in the area and dissolution has not been reported as a concern. Other variances from specifications, including those for uniformity coefficients, are often allowed to permit the use of locally available and/or less expensive supplies (Ellis, 1985; Huisman and Wood, 1974).

The effective size of the sand should be based on at least a simple pilot-plant investigation to ensure satisfactory results for the particular raw water source (Ellis, 1985). A very fine sand should be more effective in removal of the various raw water constituents, but with more rapid development of headloss and more frequent cleaning. Coarse sand reduces the frequency of cleaning, but removals are lower and deep clogging may require scraping to greater than normal depths of 1-2 cm (0.5-1 in.). Bellamy et al. (1985b) reported that although the removals of coliform bacteria declined from 99.4 percent to 96.0 percent and standard plate counts increased from 470 to 1050 colong forming units (CFU)/mL as the effective size was increased from less than 0.3 mm to 0.615 mm, the removals from filters using both sizes were still high and the removals of Giardia cysts were complete over both sizes. They concluded that the argument for using a finer sand was reasonable only on the basis that it would reduce the schmutzdecke penetration into a coarser sand and thus reduce the volume of sand to scraped during each cleaning.

It is essential that the sand of all sizes and sources be thoroughly washed to remove the finest grains, clay, organic matter, and other materials that would "wash out" when the filter is first used, contributing to turbidity, coliform, and otherwise reduce the quality of the filtered water. It is also essential that the sand be the same throughout the filter area so that the filtration rate is the same (Turneaure and Russell, 1924). The porosity of the filter media will remain the same for grains of the same shape, but historical opinions have stated that the smaller openings between finer media will clog more quickly if there is a large variation in particle size as represented by a larger uniformity coefficient and with the development of interstitial biomass(Turneaure and Russell, 1924; also as expressed in most specifications for filter media). DiBernardo and Rivera (1996) concluded, however, that filter runs were longer for sands of the same effective size if the uniformity coefficient were greater, 4.3 vs 2.2. These authors also reported porosity and hydraulic conductivity increased with increasing uniformity coefficient.

2.4.4 Sand bed depth (maximum and minimum)

Ellis (1985) summarized the action of slow sand filters as "principally the result of straining through the developing filter skin and the top few mm of sand, together with biological activity." Others have stressed the biological activity extending from a few centimeters to the entire depth of the bed (Logsdon, 1991; Collins et al., 1992; Weber-Shirk, 1992; Wang, 1995).

The depth of sand to be provided in a filter depends on three factors: First, the thickness of sand in which the population of purifying bacteria is high, about 0.3 to 0.4 m(1-1.3-ft); second, the depth below the first in which the degradation byproducts from the first zone are stabilized, about 0.4 to 0.5 m (1.3-1.6-ft); and third, the allowable thickness of filter that is to be scraped off before the filter depth is to be restored (Huisman and Wood, 1974). Together, they suggested a total depth of 1.2-1.4 m (3.9-4.6-ft) be initially provided to allow for 5 years of operation between resanding operations, with 0.7-0.9 m (2.3-3-ft) minimum thickness when the filter is to be resanded. Rachwal et al. (1988) reported 0.3 m (1-ft) to be the minimum depth permissible for the Thames Water Authority system. Bellamy et al (1985b) found coliform bacteria removal decreased from 97 to 95 percent as bed depth was reduced from 0.97 m (3.2-ft) to 0.48 m (1.6-ft.), and recommended allowing filters to be depleted only to this extent before resanding. Ellis (1985) summarized the available literature and, agreeing with established criteria for the initial filter depth, concluded that the basis for minimum depth varied with the quality of water to be produced. As little as 0.3 m (1-ft) was necessary for turbidity and coliform removal, but 0.6 m (2-ft) was necessary "to ensure the removal of all viruses, and perhaps to complete the oxidation of ammonia." Experiments at the Lawrence Experiment Station by the Massachusetts Board of Health revealed that filters 1.2-1.5 m (4-5 ft.) thick were less affected than filters 0.3-0.6 m (1-2 ft.) thick by variations in flow rate or by scraping, though their performance under uniform conditions was not significantly different (Turneaure and Russell, 1924).

2.4.5 Headloss allowed

Filtration removes particulate and dissolved materials from the incoming water. The coarser materials accumulate on the surface while finer materials are trapped both in the schmutzdecke on the surface and within the filter media. As the materials accumulate within the filter, deposits reduce the pore space leading to increased resistance to flow, measured as head loss. The loss is small after filter cleaning but increases more rapidly near the end of a filter cycle. The length of the filter run will be determined in part by the magnitude of the allowable head loss. The head loss should not be allowed to closely approach the depth of water over the filter which might allow the pressure below the schmutzdecke on the filter surface to fall below atmospheric pressures and result in air-binding. Although the available headloss limits the length of the filter cycle and is related to the operating costs of slow sand filters, the maximum allowable loss has not been related to performance except in relation to the extent to which the filter pores have accumulated materials.

2.4.6 Frequency of cleaning

Slezak and Sims (1984) surveyed 22 slow sand filter plants in the United States and reported the length of filter cycles to range from 40 to 46 days in the spring, summer, and fall to 60 days in the winter, though the percent coefficient of variation was 63 to 73 percent by season. The frequency of cleaning was site specific and related to the available head, grain-size distribution, influent water quality, water temperature, and algae (Letterman and Cullen, 1985; Logsdon, 1991). Ellis' (1985) summary of literature on slow sand filters also cautioned against applying results of one application to another site and recommended pilot-scale investigations to determine the optimum filter rate and whether silt might be carried deeply into the filter requiring greater cleaning than normal. That literature summary also indicated that higher filter rates would shorten filter runs, but increase the total production between cleaning.

Collins et al. (1992) found that increased hydraulic loading, from 0.05 to 0.10 m/hr (0.02-0.04 gpd/sf), significantly increased the frequency that filters needed to be cleaned since the accumulated particulate and dissolved organic materials contributed to head loss development. The productivity of the filter in that study was strongly affected. One of the filters operating at 0.10 m/hr required cleaning three times over a 132 day period while another using the same water at 0.05 m/hr never reached a terminal headloss of 1.3 m. Other studies and reports also have attributed the cause of frequent cleaning to higher hydraulic loading rates on filters. No information was found in comparing cleaning frequency between the scraping and harrowing cleaning methods.

Turneaure and Russell (1924) reported the amount of water filtered in the period between cleaning operations ordinarily ranged from 40 to 80 MG/acre (37-74 cubic meters per square meter, 920-1800 gal/sf). Letterman and Cullen (1985) reported the frequency of cleaning by scraping to be between 1 and 1.5 months. The volume of production per filter cycle was 112-650 cubic meters per square meter (3000-16,000 gal/sf). They did not find a clear relationship between raw water quality, scraping procedures, and cleaning frequency, but found convenience and tradition were more important determinants. The period of service was also reported to depend upon the character of the water, upon the fineness of the sand, upon the maximum allowable loss of head, and for many waters the algal growth season. Renton et al.(1991) found that a filter usually required cleaning when it had trapped between 1 and 300 grams of carbon per square meter. At a flow rate of 5 cubic meters per second per 12 hectares of sand, treating water containing 500 mg of carbon per cubic meter (0.15 m/hr, or 0.06 gpd/sf at 0.5 mg/L), the relative headloss accumulation rate would be 1 to 5% per day (Steel, 1947). Based on these operating conditions, using a filter sand of 0.3 mm effective size with a uniformity coefficient between 1.7 and 2.3 and a maximum headloss of one meter, each bed would be expected to require cleaning three to four times a year. In practice the beds were cleaned before maximum headloss was attained and the number of cleanings per year averaged between six and seven times. Filter productivity was not affected by the flow rate and the filters averaged 190 to 195 cubic meters per square meter of filter between cleaning. Rachwal et al. (1996) reported productivities of from 100 to over 2,000 cubic meters per square meter as typical and from 100 to 200 in studies at the Thames Water's Kempton Part AWTC demonstration plant.

2.4.7 Length of time filter is out of operation after cleaning

"The quicker the cleaning can be completed, the less will be the disturbance to the bacteria and the shorter the period of re-ripening" has been one guide in plant operations. "Provided they have not been completely dried out, the microorganisms enmeshed below the surface will quickly recover and will adjust themselves to their position relative to the new bed level" (Huisman and Wood, 1974). Destabilization of the biological population by dewatering for a prolonged period (Pyper and Logsdon 1991; Hendricks and Bellamy, 1991) and the ambient temperature while the filter is cleaned (Ellis, 1985) has been considered more significant than removal of the schmutzdecke as the cause for a ripening period. The Thames Authority found that scraping of slow sand filters and keeping the filter dry for periods in excess of 72 hours requires the beds to be run to waste to allow ripening (Renton et al., 1991). Visscher (1991), however, recommended Intermittent operation should not be permitted because an unacceptable deterioration of bacteriological quality occurs 4 to 5 hours after filters recommence operation. A pilot filter being cleaned by scraping was tested by intentionally disturbing the media to a depth of 10 cm (4 in). The efficiency of coliform removal following this cleaning decreased by 0.5 - 1 log as compared to a control filter which had been scraped but not disturbed (Bellamy et al., 1985a). Letterman and Cullen (1985), in their study of plants in central New York State, found evidence of ripening in only 4 of 10 cleaning events. The need for ripening appeared to be related to the extent of filter disturbance, depletion of filter depth, and quality of the particulate matter. It did not relate to temperature, use of prechlorination, scraping methodology, or cleaning frequency. Cleasby (1984) reported that the removal of particles in the size of 7-12 um was reduced for two days after cleaning, but still remained over 94 percent in all cases.

2.4.8 Length of time to maturity

New and newly reconditioned filters go through a period of ripening when they are first operated. Ellis (1985) stated that the schmutzdecke would develop within a few days but maturing was concerned with changes in depth. He related the rate of maturation to the slow development of a balance of microorganisms and bacteria taking up to 40 days. During this period, an initial deposit is laid down on the sand grains by physical processes and subsequent formation of an adhesive film of bacterial slime (Logsdon, 1991). Galvín (1992), in a study of changes to media in a rapid sand filtration plant, determined that organic and inorganic coatings developed over a prolonged period, and recommended sand replacement or reconditioning only after 21 years by which time the rate of accumulation of organics had slowed. The ability of a filter to remove particulate and dissolved materials, measured as turbidity, coliform, DOC, or other parameters, develops at various rates. Higher raw water temperatures and nutrient concentrations were reported to reduce the time required to achieve targeted removal rates (Huisman and Wood, 1974; Bellamy et al., 1985b; Ellis, 1985; Hendricks, 1991; Logsdon, 1991). The reported times required to achieve maturity in slow sand filters are listed in Table 6. Collins (1990) reported 30 to 40 days were necessary before pilot filters at Gorham, NH, began removing turbidity from this exceptionally high quality source water and 100 to 120 days for the filters to reach high levels of removal. NPDOC and UV adsorbing materials were not removed within the 190 day pilot study.

TABLE 6: REPORTED MATURATION TIMES FOR SLOW SAND FILTERS (LOGSDON, 1991).

Maturation time, days	Remarks
60	"before viral removal was normal"
35	"before E. Coli was absent in the filtrate"
60	"before filtrate was less turbid than influent"
40	"before total coliform counts were generally ≤ 1/100 mL"
35-50	"before total coliform in filtrate stabilized"
280	"before Giardia removal went from 99% to 100%"
100	"before erratic removal results disappeared"

Wang et al., (1993) reported the biomass at the surface of granular activated carbon columns, operating with pre-coagulated and settled river water, reached a steady-state after five months. Servais et al.(1994) reported three months were required to reach a steady state for granular activated carbon filters.

Bellamy et al. (1985b) stated that pilot-scale filters would mature within days, rather than weeks, if the nutrient levels were supplemented with diluted and sterilized sewage. Ghosh et al. (1989) reported "essentially no microbial growth had occurred in the schmutzdecke of pilot filters in 75 days after a winter start (water temperatures of 4-8°C). Collins et al. (1992) found the age of the filter media correlated with the biomass content as measured by AFDC and FRM. They concluded that it was not possible to overemphasize the importance of filter ripening to performance of slow sand filters.

There is also a time over which silt, clay, and other particles are washed out of the newly placed sand. The time required at one plant in northern Idaho, using a sand with 4 percent clay fines, was over nine months (Tanner, 1990). This process is not a part of filter maturation and its effects on filtrate quality could be confused.

2.4.9 Age and type of schmutzdecks

A substantial amount of the literature is related to the development of the schmutzdecke (Huisman and Wood, 1974; Ellis, 1985; Logsdon, 1991). There is apparently no agreement on the exact point at which the schmutzdecke is considered to end and the intergranular biomass to begin. If the schmutzdecke is considered to be the accumulated material at the sand/water interface (Haarhoff and Cleasby, in Logsdon, 1991), then the age of the schmutzdecke will be limited by the cleaning cycle. If this layer is also to include the top 1 to 2 cm of the sand layer, the age will be similarly limited if the filter is cleaned by scraping. Some of this intergranular material may not be removed by harrowing, however, and could become mixed into the depth penetrated by the harrow.

Haarhoff and Cleasby (1991) attributed particle removal mainly to the schmutzdecke layer and considered removal within the bed to be minor. Cleasby (AWWA, 1990) stated the solids removal occurred as"cake filtration" as the materials entered the face of the granular bed, becoming even more dominant as the filter cycle progressed. Ellis (1985) also concluded that purification resulted from straining through the filter skin and through the top few millimeters of sand and included biological activity as a reason for removals. Bellamy et al., (1985b), however, did not find the straining theory supported by tests comparing removal of coliform bacteria by filter media of different sizes and overlaid with 0.5 cm diatomaceous earth (effective size = 0.013 mm).

2.4.10 Water temperature

Logsdon (1991) summarized several studies showing water temperature to be a critical parameter in removal of particulates. Information was presented demonstrating that the removal of Giardia cysts was reduced from 99.9 to 99.5 percent when the water temperature declined from 9 to 2 °C. Bellamy et al. (1985b) ran two identical pilot-scale filters in parallel, with the temperatures of 17°C and 2 °C, and found coliform bacteria removals were 99.6 and 92 percent, respectively. They concluded slow sand filtration was sensitive to the effects of low temperatures. Huisman and Wood (1974) and Haarhoff and Cleasby (1991) also related performance to temperature and temperature related processes such as the ability of the filter to nitrify ammonia .

Van de Vloed (1956) related the reduction in permanganate consumption to water temperature with the formula:

$$\text{Permanganate consumption, mg/L} = (T+11)/9 \qquad (4)$$

where T is temperature in °C. It also has been noted that nitrification of ammonia practically ceases at 6 °C (Huisman and Wood, 1974). Servais et al. (1992), studying biological GAC filtration with glucose, found the EBCT had to be doubled when the water temperature decreased from 20 °C to 8 °C to maintain the same BDOC removal efficiency, even though the average bacterial biomass was constant. Meek and Shieh (1984) recommended 5 °C as the minimum water temperature at which a slow sand filter can function. Welté and Montriel (Graham and Collins, 1996) concluded that adsorption accounts for the removal of BDOC by slow sand filters at temperatures of less than 8°C. Substantial biodegradation occurred at higher temperatures. The temperature threshold was found to be 12°C for the processes removing DOC. Seger and Rothman (1996) found TOC removal rates directly related to raw water temperatures, ranging from 5 percent at 2°C to 20 percent at 15°C.

Temperature also physically affects the loss of head through the filter media through its impact on viscosity of water. As the temperature changes from 20 °C to 4°C, the absolute viscosity increased from 0.01005 g/cm sec.(2.36 lb/ft.hr) to 0.01567 g/cm sec. (4.23 lb/ft.hr). This will increase the headloss, a function of the absolute viscosity and density of water, by approximately 80 percent.

2.4.11 Raw water quality

Letterman and Cullen (1985) found the nature of particulates in raw water was the most significant factor on filtrate quality as measured by turbidity and particle count. Ghosh et al. (1989) reported poor removals of particles in sizes less that 3 um. The distribution of particle sizes in the raw water also was important, with the presence of larger particles resulting in an increase in removal of smaller particles (Mackie and Bai, 1993).

The nature of NOM in water and treatment has been discussed elsewhere (Aiken et al., 1995; Owen et al. 1995; Klevens, 1995). There have been efforts to identify specific classes of chemical compounds or to relate treatability to a number of parameters, as NPDOC, UV absorbance, humic and non-humic fractions, molecular weights, and biodegradability. Due to the complex composition of humic substances which compose much of the NOM, however, it is not practical to fully analyze such source materials. Most of the organic material is resistant to microbial degradation, however (Larson, 1978; Dahm, 1981; Meyer et al., 1987; Wang, 1995). A small portion (about 15 percent of the BDOC), generally consisting of readily available low molecular weight substances, is rapidly biodegraded within three minutes (Wang, 1995).

NPDOC (and DOC) and UV absorbance at 254 nm have been used to characterize water supplies as they have been accepted as surrogate parameters for TTHMFP (Amy et al., 1986; Edzwald et al., 1985). NPDOC and DOC are used in most studies to identify the total available carbon mass but biodegradable dissolved organic carbon (BDOC, sometimes BOM) and assimilable organic carbon (AOC) are used in others (Servais et al., 1987; Huck, 1990; Mogren et al., 1990; Block et al., 1992; Prevost et al., 1992; Collins and Vaughan, 1993). Differences in water characteristics result from the source of NOM (Aikens and Cotsaris, 1995) and cultural differences in the watershed (Berner and Berner, 1987), season (Klevens, 1995), and analytical methods (Collins and Vaughan, 1993). Klevens (1995) found BDOC of raw Croton Reservoir water to be 19 percent in the fall as opposed to 7 percent in the winter, as well as the concentration in the fall being approximately 25 percent higher.

Edzwald (1993) related the nature of NOM to a parameter he termed as "specific UV absorbance (SUVA)," or the UV absorbance at 254 nm per m divided by the NPDOC concentration in mg/L. The values for NOM, compiled from Reckhow et al. (1992) were:

Hydrophobic	SUVA	Hydrophilic	SUVA
Humic acid	6-6.5	Acids	1
Fulvic acid	4-4.5	Bases	3
Weak	3.5	Neutrals	3.5-4
Bases	<1		
Neutrals	<1		

Edzwald concluded that chemical coagulation should be expected to remove 50 percent or more UV absorbance and THM precursors and 70 percent of NPDOC if the SUVA were 4 to 5. If SUVA were less than 3, the UV absorbance and THM precursor removal should be less than 50 percent and NPDOC removals less than 30 percent. Although developed in relation to coagulation studies, he was proposing a means to differentiate between hydrophobic and hydrophilic, aromatic and aliphatic carbon, and related potential treatability of the water. Collins et al. (1992) considered NOM removal characteristics specifically for slow sand filters, finding lower SUVA values were associated with higher UVA and DOC removal. Klevens (1995) reported a poor correlation between these parameters, however, but noted this may have been due to the low aromaticity of the Croton Reservoir water.

Dissolved oxygen concentrations should be sufficient to maintain oxic conditions through the filter media, or about 3 mg/L, or anaerobiosis would cause production of sulfides and ammonia and the release of iron and manganese (Huisman and Wood, 1974). Time intervals sufficient to produce anoxic conditions during cleaning operations would also be expected to cause these effects.

Prechlorination is used in many plants for algae and zebra mussel control. Logsdon (1991) summarized reports in which some opposed the practice and others noted positive benefits. Letterman and Cullen (1985) found turbidity removal was somewhat higher at slow sand filter plants which prechlorinated at low concentrations, not sufficient to leave a residual in the filter effluent, but did not believe it was significant. Goldgrabe et al., (1993) found prechlorination sufficient to maintain a residual level of 1.0 mg/L in the clearwell following the filters improved removals of particles but shortened slow sand filter run by about 10 percent. Prechlorination had no significant effect on the removal of turbidity. Prechlorination at high concentrations does produce significant changes in filter biomass (Jacobson and Wellington, 1949; Ludwig, 1961, as reported by Logsdon), resulting in a change in the appearance of the schmutzdecke and subsurface sand and reducing volatile solids concentrations in the schmutzdecke layer. Wang et al. (1995) found prechlorination at rates of 2.5-3.0 mg/L virtually eliminated development of biomass in rapid-rate anthracite-sand media filters.

2.4.12 Microorganisms population and concentrations

Slow sand filters are inhabited by a complex population of organisms (Huisman and Wood, 1974; Duncan, 1988; Haarhoff and Cleasby, 1991; Weber-Shirk, 1993). The filter surface becomes coated with a layer of detritus from the supernatant water, particles collected at the surface by straining and biomass growth. This surface mat contains high numbers of organisms and volatile matter which decline with depth into the media. Most of the available organic energy source is in the influent water and is removed as it passes through the surface of the filter. Less readily degraded compounds and degradation products from the upper layers of the filter are transported more deeply into the filter. These numbers also vary with the availability of energy source, seasonal water characteristics, temperature, predation, filter age, flow rate, cleaning practices, and time since the last cleaning operation. The biomass accumulations are low because of the low substrate concentrations and do not entirely cover the sand or carbon grains (Wang and Summers, 1993).

Organisms in slow sand filters have been identified and counted (Duncan, 1988; Harrhoff and Cleasby, in Logsdon, 1991; Weber-Shirk, 1993; Lloyd, 1996; Wolton et al.,1996). Weber-Shirk (1993) and Lloyd (1996) showed positive correlation between bacterial removals and the presence of specific protozoan predators. Vertical profiles for algae, protozoa, invertebrates, bacteria, and viruses have been presented (Haarhoff and Cleasby, 1991). Seger and Rothman (1996) reported the biomass, as represented by ATP and total cell count, varied with water temperature in the top 6 cm of the filter but not at greater depths. Horizontal distributions of organisms have not generally been considered. Harrhoff and Cleasby (1991) reported an investigation of algal variations across the filter surface and considered the changes due to hydraulic and environmental differences. Spanos (1989), using FRM as an indicator of biomass to compare the density of biomass between cores taken from filters, found no significant difference between two cores taken within one filter, or between pairs of cores taken from two filters at the same plant.

The purpose of this investigation was not to determine the classifications and numbers of organisms within the filters but to consider the relative changes to the filter media resulting from the different cleaning methods. The filter biomass is a complex population and it has been variously characterized. The selection of an indicator of filter biomass should consider a substance common to all cells, one not stored but released upon death, easily measured, and widely used (Wang et al., 1995). Eighmy et al. (1988) related the numbers of microbial population in a filter with Folin-reactive material (FRM), acriflavine direct counts (AFDC), nutritionally specific heterotrophs, and with extractable iron and manganese. Spanos (1989) and Eighmy et al. (1992) also compared the concentrations of organisms in filters relative to other parameters, comparing acriflavin direct counts (AFDC), with FRM, iron, manganese, and heterotrophic spread plate counts on R2A agar. Wang et al., (1995) used phospholipid analyses to indicate the presence of active biomass. Liu et al. (1992) also considered carbohydrates as a biomass indicator based on its presence in bacterial capsular material. Klevens (1995) used protein, DAPI direct counts, heterotrophic plate counts, phospholipids, and the incorporation of C-14 L-aminoacetate and C-31 phospholipids. Yordanov et al. (1996) used heterotrophic plate counts, FRM, total biofilm carbohydrates, and chlorophyll-a. Total volatile solids historically have been used in sludge analyses to measure the organic content of heterogenous organic solids. Lazarova and Manem (1995) reviewed analytical methods for characterization of biofilms. They concluded that further studies were needed, but both total protein and lipids content were simple assays to give indications of biofilm activity.

Numbers of organisms and concentrations of materials found present in slow sand filters are summarized in Table 7, and comparisons of mass relative to such concentrations are summarized in Table 8. All reported declining numbers or concentrations with increasing depth. Seger and Rothman (1996) found decreasing concentration of ATP in slow sand filters to a depth of 30 cm, but no further change below that level to the bottom of their sampling at 70 cm. Moll and Summers (1996) found decreasing concentrations of phospholipids throughout the full 70 cm range in their study of rapid sand biofilters but with an increasing percentage of the phospholipids attached to the media surfaces as depth increased, from 60 percent attached at the surface to 90 percent at a depth of 70 cm. Eighmy et al.(1991), Duncan(1988), Collins et al.(1992), and Yardanov et al. (1996) sampled to depths of 15 cm or less in slow sand filters. Their results also indicated bacterial counts and FRM declined significantly with increasing depths. Yardanov et al. (1996) reported carbohydrate concentrations at the schmutzdecke level but not with depth.

The biomass in the filter media has been considered essential to the satisfactory performance of slow sand filters by most recent researchers(Bellamy, 1985b; Spanos, 1989; Collins, 1988, 1989, 1990, 1992; Weber-Shirk, 1992; Wang, 1995) although abiotic removal of particulates has also been shown (Weber-Shirk and Dick, 1997). Higher accumulations of biomass have also been correlated to higher removals of DOC, UV absorbance, and THMFP (Collins et al., 1992). The importance of biomass is also implied by a review of the performance factors listed earlier, most of which can be directly related to the simplified two-film biological

TABLE 7: REPORTED ORGANISM COUNTS AND CONCENTRATIONS OF BIOMASS INDICATORS IN BIOFILTERS.

References	Eighmy et al., 1988	Duncan, 1988	Collins et al., 1992b	Moll and Summers, 1996	Seger and Rothman, 1996	Yardanov et al. , 1996
Type of filter	Slow sand	Slow sand	Slow sand	Rapid sand	Slow sand	Slow sand
Application rate,m/hr		0.4, after 20 days	0.021-0.25		0.13	0.10
Schmutzdecke						
(depth in cm)	(not stated)	(0-1 cm)	(not stated)	(0 cm)	(3 cm)	(0-2.5 cm)
POC	-	2.1 mg/cm^3	-	-	-	-
Bacteria	10^9-10^10 AFDC/gdw	4x10^9 EPI/cm^3	0.3 -4x10^10 AFDC/gdw	-	4x10^7 DAPI/gdw	3-8x10^7 CFU/gdw
Protozoa	-	2x10^3/cm^3	-	-	-	-
Protein	2.1 mgFRM per gdw	-	0.5-3 mgFRM per gdw	-	-	0.5-2.3 g FRM per gdw
Carbohydrate	-	-	-	-	-	100-1500 ug per gdw
Phospholipids	-	-	-	48 nmol/gdw (attached)	-	-
ATP	-	-	-	-	32-60 ug/gdw	-
Upper media (2-15 cm depth)						
POC	-	0.2-1.2mg/cm^3	-	-	-	-
Bacteria	10^8-10^9 AFDC/gdw	1-4x10^9 EPI/cm^3	0.3-2x10^9 AFDC/gdw	-	1.5x10^7 DAPI/gdw	-2x10^7 CFU/gdw
Protozoa	-	1-5x10^3/cm^3	-	-	-	-
Protein	0.5-0.8mg FRM per gdw	-	0.5-3 mgFRM per gdw	-	-	0.2-0.8 gFRM per gdw
ATP	-	-	-	-	32-43 ug/gdw	-

Table 7 continued on next page.

Table 7 continued from preceeding page.

Lower Media (20-70 cm depth)						
POC	-	0.2 mg/cm^3	-	-	-	-
Bacteria	-	1x10^9 EPI/cm^3	6x10^7-2x10^9 AFDC/gdw	-	-	-
Protozoa	-	2-3x10^3/cm^3	-	-	-	-
Protein	-	-	0.2-0.3 mg FRM per gdw	-	-	-
Phospholipids	-	-	-	23-45 nmol/gdw	-	-
ATP	-	-	-	-	22-35 ug/gdw	-

TABLE 8: COMPARISON OF REPORTED ORGANISM COUNTS AND CONCENTRATIONS OF BIOMASS INDICATORS IN SLOW SAND FILTERS.

References	Eighmy et al., 1988	Charackis and Marshall, 1990		White, 1983	Seger and Rothman, 1996
Reference material	FRM	Carbohydrate		Phospholipids	ATP
Conversion	0.8-2.0 x10^-12 g. protein per cell	1.9-2.6 percent of protein (glycerol limiting)	1.8-18.6 percent of protein (ammonia limiting)	1 nmol lipid-P =10^8 bacteria the size of E. coli.	0.2x10^-9 ug ATP per cell, with C.V. of 25%.

models presented in texts on chemical and biological engineering processes. The bacteria in the surface layer and on the sand grains have been deposited and selectively reproduced, using influent organic matter as a source of energy for metabolism and growth and dissimilating wastes to be used by other organisms or carried from the filter in the water. The upper part of the filter contains the most concentrated populations of bacteria due to the supply of food, but the active zone of the filter extends throughout the filter depth (Huisman and Wood, 1974; Spanos, 1989; Wang, 1995). Huisman and Wood (1974) considered the most active zone to be above a depth of 30-40 cm (12-16 in) but noted that depth would depend on the filter rate. Duncan (1988) has reported the most thorough study of the organisms found through the depth of a filter but the relative numbers, depths, and species were dynamic with changes in raw water characteristics and filter conditions. Sudden changes to the filter rate or the removal of the surface layer by cleaning, and time out of operation for cleaning or resanding caused similarly abrupt changes to the biomass.

Other organic materials also accumulate by adsorption, including clays and humic substances which contribute to further removals. Eventually, however, the accumulation of biomass and other substances can lead to a decrease in the effective retention time and, with constant activity, reduce the removal of soluble materials (Nouvion et al., 1987). The relative porosity of discrete particles is estimated as 0.6-0.8 and that of flocculent particles as 0.9-0.95 (Montgomery, 1985).

2.4.13 Algae

Algae are present in almost all water sources, converting dissolved inorganic carbon, nitrogen, phosphorus, and other nutrients into biomass. Most algal growth in fresh water is dependent upon light as an energy source, though some species are also able to use organic carbon sources for energy. Although algae can be beneficial to the treatment process if they are an active part of the schmutzdecke, algae can seriously affect filter operations by shortening the time between cleaning to as little as one sixth of the normal time (Ellis, 1985). Other algal effects on filter operations include: production of tastes and odors in the water; increases in the concentration of soluble and biodegradable organics in the water; development of anoxic conditions in the filters; and increased difficulties with filter cleaning. As most filters are covered and algae cannot build biomass without light energy, the negative effects of algae predominate on filter operations. Species, concentrations, and community dynamics vary widely with water characteristics, temperature, available sunlight, and the nature of the water body (quiescent or moving, shallow or deep, turbidity, etc.). Algal enumeration was considered essential in judging the acceptability of a raw water for treatment with slow sand filters (Cleasby et al., 1984).

The general annual algal cycle begins in the spring and early summer with increasing algal development as lake or stream water warms, reaching one or more peak concentrations during warm weather, and dying in the late summer and fall as the sunlight intensity and water temperatures decline. Sudden changes in the environment, such as temperature, sunlight, or available nutrients, can also result in a sudden die-off of the algal population. The diurnal algal metabolic cycle uses sunlight during part of the day to produce biomass through photosynthesis and oxygen during the entire day and to aerobically metabolize the biomass for energy throughout the 24-hour day. Additional oxygen is necessary to oxidize metabolic wastes and organic materials released when the cells die and lyse. There is usually a slight excess of oxygen production over uptake in natural waters, with the balance of the unoxidized biomass removed from the chain by burial at the bottom of the water body (Berner and Berner, 1987). The oxidation processes of respiration and degradation continue in a covered slow sand filter after photosynthesis ceases due to the lack of sunlight.

The algal load on filters will affect filter operation in several ways, yet the dissolved organic load created by the death and lysis of the cells releases appreciable amounts of materials such as glycolic acid, polypeptides, and carbohydrates that are readily biodegradable (Ellis, 1985). Huisman and Wood (1974) claimed the organic load contributed by algae to be equivalent to the organic uptake during growth, yet the predominant source of nutrients for algae are inorganic and so the load must exceed the original organic mass. The weighted average of the organic load during a death phase of the algal cycle may be more biodegradable than before growth but that would have to be due to the prevalence of readily biodegraded compounds released by the cell. The biodegradability of the NPDOC in the fall of the year is reported to be greater than in the spring (Prevost, 1991; Klevens, 1995).

2.5 COSTS

The cost of treating water by slow sand filtration has been studied (Slezak and Sims, 1984; Logsdon et al, 1990; Berg et al., 1991; and others). In their review of 27 plants, Slezak and Sims (1984) reported filter cleaning to be a major component of the operating costs. The operating costs ranged from $0.003 to 0.026 per cubic meter ($0.01 to 0.10 per 1,000 gallons) for 59 percent of the plants to as much as $0.13 per cubic meter ($0.50 per 1,000 gallons) for 5 percent of the plants in this 1984 study. Cleaning and the handling of sand represented 60-80 percent of the direct operating costs Ashford Commons works of the Thames Water Authority (Rachwal et al., (Graham, 1988) and so reductions in these would have a significant impact on the plant cost. In all cases, labor was the most significant portion of the cleaning cost.

Huisman and Wood (1974) reported costs for cleaning large filter areas, 2,000 sm (21,520 sf). Those costs are summarized in Table 9. The time taken lowering the water level in preparation for the removal of the filter from service had not been taken into account. Additionally, they considered the length of the filter cycle for the filters using different cleaning methods to be equal (Huisman and Wood, 1974). Those costs comparisons were considered "illustrative" and valid only when the personnel were fully occupied on other useful work when not engaged in cleaning filters.

TABLE 9: COMPARISON OF CLEANING METHODS, PER 100 SQ. METERS (1,000 SF) (AFTER HUISMAN AND WOOD, 1974):

Parameter	Manual scraping	Tractor scrapers		Gantry scraper Amsterdam	Hydraulic method
		London	Berlin		
Hours required for:					
Draining	0.1 (0.09)	0.1 (0.09)	0.1 (0.09)	0.1 (0.09)	0.0
Cleaning	0.45 (0.42)	0.2 (0.18)	0.25 (0.18)	0.15 (0.14)	0.3 (0.28)
Refilling	0.25 (0.23)	0.25 (0.23)	0.25 (0.23)	0.25 (0.23)	0.0
Re-ripening	1.2 (1.1)	1.2 (1.1)	1.2 (1.1)	0.2 (0.18)	0.2 (0.18)
Total time out of service, hrs	40	35	36	14	10
Total number of persons employed	8	4	2	2	1
Total labor-hours involved	3.75 (3.5)	1 (0.9)	0.75 (0.7)	0.5 (0.46)	0.5 (0.46)

Renton et al (1991) reported on the efforts of the Thames Water Authority to improve the cleaning of their 3,100 sm (33,400 sf) filters, from mechanical scraping to suction dredging. Their information is summarized in Table 10. Those results are summarized in Table 11. They concluded that the labor and time required were dependent upon the extent to which mechanical equipment could be used and the depth of sand removed. A summary of labor requirements from other references for scraping and for harrowing are presented in Table 12. Letterman and Cullen (1985) also reported on the labor required for resanding 15-30 cm (6-12-in.) to be 54 labor-hours per 100 sm (50 ph/1000 sf).

TABLE 10: COMPARISON OF CLEANING METHODS, PER 100 SQ. METERS (1,000 SF) (AFTER RENTON ET AL, 1991):

Parameter	Dry method (scraping)	Suction dredging method
Hours required for:		
Draining (b)	0.3-0.4 (0.3-0.4)	0
Cleaning	0.13-0.26 (0.12-0.24)	0.3 (0.3)
Refilling	0.3-0.4 (0.3-0.4)	0
Re-ripening	(a)	Not reported
Total time out of service, hrs	24-30	8-9
Total number of persons employed	3	1
Total labor-hours involved	Not reported	0.5
Percent of time out of service	4.2	1.3

(a) No ripening is required if the filter is out of service less than 72 hours.

(b) The overnight lowering of the water level in preparation for cleaning was included.

Letterman and Cullen(1985) studied cleaning practices and ripening in plants in six plants using the scraping method in upstate New York.

TABLE 11: LABOR REQUIREMENTS FOR FILTERS CLEANED BY SCRAPING (LETTERMAN AND CULLEN, 1985)

Location	Ave. volume per filter cycle ML /100 sm (MG/sf)	Cleaning operations per year	Depth of sand removed per operation cm (in.)	Labor hours per operation per 100 sm (1000 sf)	Labor hours per year for cleaning per 100 sm (1000 sf)	Labor hours per year for resanding per 100 sm (1000 sf)
Auburn	2.4x10^6 (6,844)	4.3	1.2 (0.5)	4 (4)	14.6 (13.6)	8.9 (8.3)
Geneva	5.5x10^6 (15,718)	2.0	2.5 (1.0)	4-5 (4-5)	4.2 (3.9(1))	12.5 (11.6)
Hamilton (3)	1.5x10^6 (4,302)	2.0	2.5 (1.0)	9-10 (8-9)	19 (18)	NA
Ilion (3)	5.4x10^6 (15,487)	1.8	8-10 (3-4)	22-45 (21-42)	4.9 (46)	31 (29)
Newark	3.6x10^6 (10,122)	3.3	2.5 (1.0)	2 (2)	7.1 (6.6)	11.2 (10.4)
Ogdensburg	1.0x10^6 (2,978)	12.0	2.5 (1.0)	4-5 (4-5)	52-65 (48-60) 280 (260)(2)	NA
Waverly (3)	1.1x10^6 (3,200)	9.7	2.5 (1.0)	5 (5)	52 (48)	38 (35)

(1) The total labor per year based on labor per 1,000 sf and the number of operations per year is 8-10 hours/1000 sf. The figure shown is the reported total in the report.

(2) This figure is the reported total in the report, including resanding.

(3) Physical limitations restrict the convenience of cleaning operations at this plant.

TABLE 12: SUMMARY OF LABOR REQUIREMENTS FROM MISCELLANEOUS SOURCES.

Cleaning method	Labor hrs/100 sm (hrs/1000 sf)	Reference
Scraping	1.3 (1.2)	Seelaus et al. (1986)
Scraping	4.3 (4)	Tanner (1987)
Scraping	4.3 (4)	Huisman and Wood (1974)
Scraping	6.5 (6)	Slezak and Sims(1984)
Scraping	2.2 (2)	Kors et al. (Graham & Collins, 1996)
Harrowing	1.2 (1.1)	Allen (1991)

Reducing the frequency of cleaning reduces the number of times that a filter must be re-ripened to regain performance efficiency. Shorter cleaning times will also reduce the probability that the cleaned filter will require re-ripening.

2.6 SLOW SAND FILTER LIMITATIONS

The concerns which have limited slow sand filtration as a viable treatment option for many small communities include the limited acceptability of raw waters, the limited ability of the filters to remove organic precursor materials, and the extensive filter downtime associated with cleaning (Collins et al., 1991). The first of these can be addressed by selection of the appropriate treatment processes for the available water sources and/or pretreatment processes for the principal process.

The ability of slow sand filters to remove organic precursors has been studied (Collins et al., 1988; Eighmy et al., 1993). Ozone pretreatment with doses of 2-6 mg/O_3/L can dramatically improve THMFP removal 40-70 % (compared to 10-15% for conventionally operated plants without pretreatment) were observed. Up to 35% NPDOC BDOC removal was observed, vs 10-15% without pretreatment. The harrowing method was also associated with improved removal of THM precursors. More efficient filter operation could be realized by longer filter runs, quicker cleaning, and shorter ripening periods. Long term improvements would also be achieved by extending the periods between resanding.

CHAPTER 3

METHODS AND MATERIALS

3.1 OVERVIEW

Investigations were carried out on three separate scales of filters- full scale, pilot plant, and laboratory scale. Analytical methods and quality control for the various facilities were similar. This section describes the facilities and the methods used during the investigations. The number of facilities studied at each scale, the factors considered at that facility, and the process measurements and parameters analyzed at each facility are summarized in Appendix A.

3.2 FULL SCALE STUDIES

3.2.1 Gorham, New Hampshire

Gorham, New Hampshire (1989 population, 3,173) is located at the intersections of Routes 2 and 16 near the Maine-New Hampshire border 15 kilometers (9 miles) north of Mt. Washington. The city was supplied with unfiltered, chlorinated water from either/or both its Perkins Brook and Icy Gulch surface water supplies. The 1986 Amendments to the Safe Drinking Water Act required filtration of surface water sources and studies were undertaken by the city's consulting engineer, Rist-Frost Associates, P.C. and their subconsultant (Collins, 1990) which recommended the construction of a slow sand filter plant. The completed facility is a 3.8 ML/d (I.0 MGD) plant incorporating three separate filter beds of which only two have been used. The plant began filtering to waste January 21, 1991 and began delivering filtered water to the system February 12, 1991 (Bernier, 1994). Each filter has a design capacity of 1.26 ML/d (0.33 MGD) at a loading of 0.13 m/hr (0.05 GPM/sf).

The individual filters are 20 meters by 23 meters (65 x 75 ft) and contains 0.68 meters

(27-in) of washed sand with an effective size of 0.25 mm and a uniformity coefficient of I.8 (Rist-Frost, 1991). The filters are covered and accessible by concrete ramps within the control building area. The effluent is monitored by a Venturi flow tube for flow and a Hach Model 1720C Low Range turbidimeter (Hach, Loveland, CO). The schematic details of a single filter are shown in Figure 2.

The filters incorporate an arrangement that facilitates harrowing. This arrangement includes an adjustable weir along the entire length of one side of the filter, an inlet header pipe along the entire length of the wall opposite the adjustable weir, and the ability to supply a reverse flow of filtered water from the underdrain system up through the filter media. This reverse flow is below the rate required to suspend the media as in a backwash for a rapid sand filter. Concrete ramps are provided so that a small tractor has convenient access to the filter surface.

The harrowing process is carried out by closing the influent raw water valve to the designated filter, and draining the supernatant water level down to approximately the top of the adjustable weir 30 centimeters above the media surface. This depth of water is sufficiently shallow that a cross flow provides sufficient velocity to carry colloidal and fine suspended particles across the filter surface, provided they are periodically resuspended by the passage of the tractor and harrow. The flushing water supply enters the filter at the water surface level from the header pipe along the far wall. The upflow through the media during this time is not intended to suspend sand media but to prevent downward passage of colloidal solids and material removed from the sand grains during the harrowing operation. The washwater flows to a 0.70 ML (185,000 gal) wastewater equalization pond where it infiltrates into the sandy soil under the conditions of a state underground injection well permit (Bernier, 1994). The additional cost of incorporating these features to facilitate harrow cleaning techniques over the conventional scraping method was estimated to be approximately 7% of the construction cost (Scott, 1991).

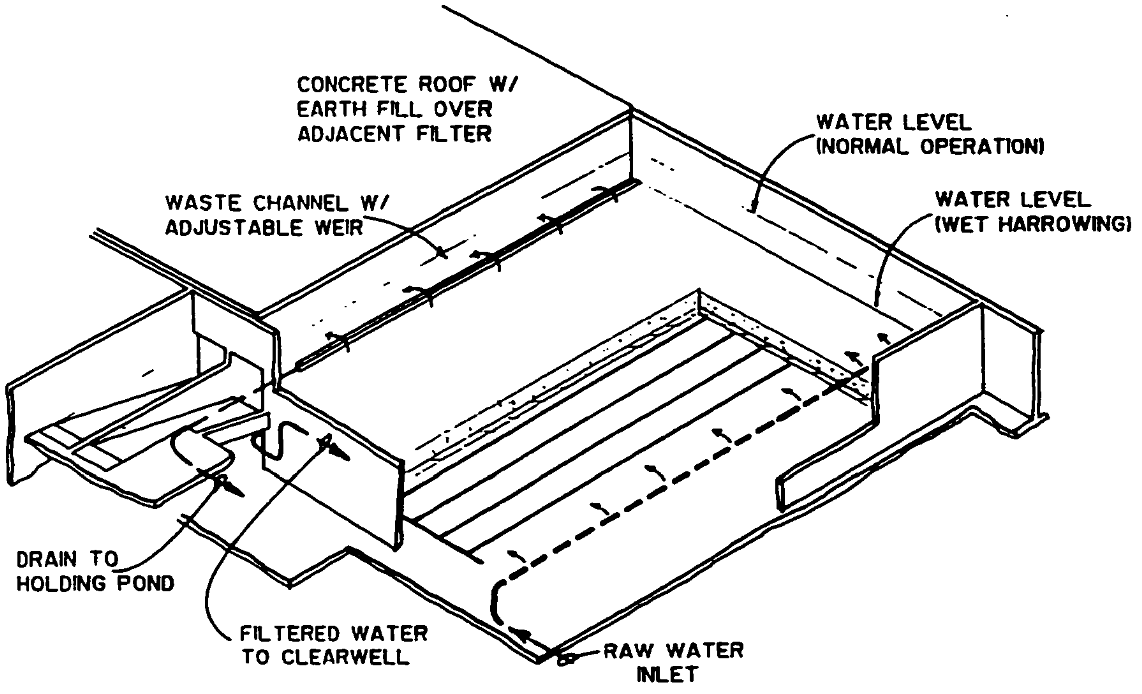


Figure 2: Schematic of Gorham, NH filter.

Samples of raw and filtered water were taken from sampling taps in the pipe gallery. Cores of the filter media were taken at three horizontally spaced locations established by random number selection (Collins, et al., 1992).

This plant was to be used in the investigation to consider the effects of cleaning one filter by harrowing and the adjacent filter by scraping. In this manner, both filters could be operated with identical raw water quality and under the same environmental conditions (Collins, 1991). Cleaning procedures were to be initiated when filters reached a terminal head loss of about 2 m (6-ft) or when effluent turbidities exceeded 1.0 NTU. A study period of 12 to 18 months was anticipated. The facility began operation in February 1991 and data collection was begun in May of 1992. Because no cleaning operation had been necessary through the summer of 1993 and the prospect of repeated cleaning of the same filter was even more remote, plans to use this facility for comparative operations were suspended. The operating plans, the study preparation, and the development of the quality assurance/quality control documents for this facility, however, were utilized in the data collected for this plant and for the other facilities discussed later.

3.2.2 Newport, New Hampshire

Newport, New Hampshire (1990 population, 6,110) is located at the intersection of Routes 11 and 10 on the southwestern side of the state and about 30 km (20 miles) south of Lebanon, New Hampshire. Until October 1992, the city was supplied with unfiltered, chlorinated water from its upland, high quality, supply from Gilman Pond. There is also a ground water supply at Pollards Mills for backup. As they had at Gorham, NH, the city's Consulting Engineer, Rist-Frost Associates, P.C. recommended construction of a slow sand filter plant. The completed facility is a 2.6 ML/d (0.7 MGD) plant incorporating three separate filter beds and all three beds are used. Each filter is designed for a nominal capacity of 0.88 ML/d (0.23 MGD) at a design application rate of 0.13 m/hr (0.05 gpm/per sf) (Rist-Frost-Shumway, 1993). This plant was designed by the same engineer as at Gorham, NH and used the same basis of design and the same sand media specification. This plant is nearly identical to the Gorham facility except for the location of the access ramps to the filters and the smaller design flow. Because the head loss developed at a faster rate in Newport than at Gorham, arrangements were made with the Town of Newport to use filters at their slow-sand filter plant in place of those at Gorham for the study under the USEPA grant.

The facilities are depicted in Figure 3. The individual filters are 21 meters long x 17 meters wide (68 by 55.7 ft) and contain 0.68 meters (27 in) of washed sand with an effective size of 0.25 mm at a uniformity coefficient of 1.8. (Rist-Frost-Shumway, 1993). The filters are covered and accessible by 1.8 meter (6 ft) concrete ramps within the control building.

The filter design is also similar to that described for Gorham, providing an influent pipe along one side of the filter, an adjustable weir along the opposite side, and the ability to supply a reverse flow from the underdrain system up through the filter media. The ceiling height is approximately 3 m (10-ft.) above the level of the sand. The washwater holding pond was sized for the estimated volume of water from cleaning two filters consecutively, or 0.75 ML (200,000 gal) (Scott, 1994). The pond discharges both through the sandy bottom and to a surface stream. Solids settled rapidly and remain on the pond bottom.

Samples of raw and treated water were taken from taps in the pipe gallery. Samples of wash water were taken from the drain outlet to the settling pond or creek or, after dark, from sample taps in the pipe gallery.

3.2.3 Newark, New York

Newark, New York (1990 population, 9,611) is located at the intersection of Routes 31 and 88 in Wayne County, New York, midway between the cities of Syracuse and Rochester, NY. The Village has been supplied with water from Canandaigua Lake since 1951 through its slow sand filtration plant located in the Village of Shortsville, midway between Canandaigua Lake and

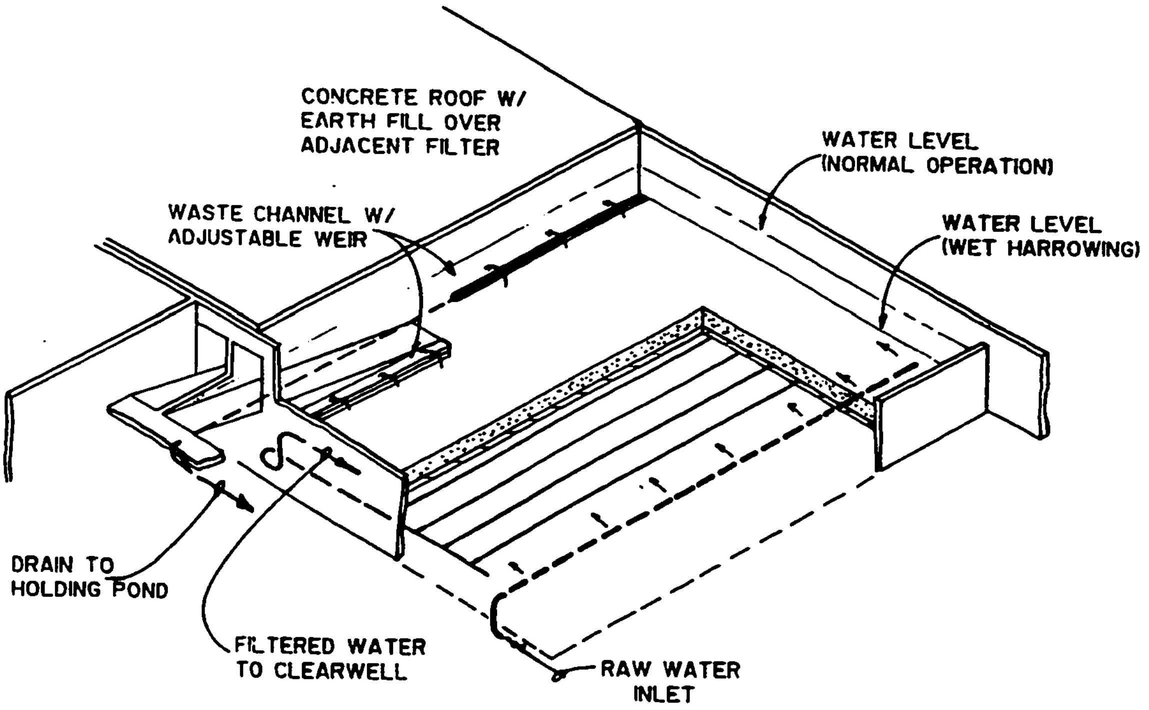


Figure 3: Schematic of Newport, NH filter.

the Village of Newark. In 1969, pressure diatomaceous filters having a capacity of 2.8 ML/d (0.75 MGD) apiece were added to increase the treatment capacity of the plant. The completed facility has a capacity of 13 ML/d (3.5 MGD) using the four original slow sand filters and the two pressure diatomaceous earth filters. Each slow sand filter has a nominal capacity of 1.9 ML/d (0.50 MGD) at loading of 0.16 m/hr (0.064 gpm/sf). The slow sand filters have always been cleaned by scraping.

The individual filters are 42 meters by 12 meters (139-ft. by 39-feet) and contain 0.9 meters (3-ft.) of washed sand with an effective size of 0.39 mm and uniformity coefficient of 2.4. The filters are covered and accessible by 2.8 meter (9.3 ft) wide concrete ramps from outside the control building. Ceiling height in the filter area is 2.4 m (8-ft.). The layout is presented in Figure 4.

When the level of sand reaches a minimum allowable level of approximately 30 cm (12-inches), the remaining sand is removed and new sand was placed over the gravel around the pipes. The sand was purchased locally and washed before placement. The filter was filled from the bottom as after a normal cleaning operation, 40 kg (100 lb) of hypochlorite added, and run to waste until there was satisfactory turbidity and coliform removal. The filters monitored for this study had been rebuilt in January 1992 (Filter No. 3) and May 1990 (Filter No. 4). Although sand had been saved for the last two years and washed using a sand washing device constructed by plant personnel, none had been returned to the filters through January 1994. Before that, filter sand was used for fill. No wastewater was produced during cleaning.

The raw water is from Canandaigua Lake, one of the Finger Lakes of New York State. Unlike the waters of New England, the water is very hard and has a high alkalinity and alkaline pH (Bloomfield, 1978). Samples of raw and filtered water were taken from taps in the pipe galleries.

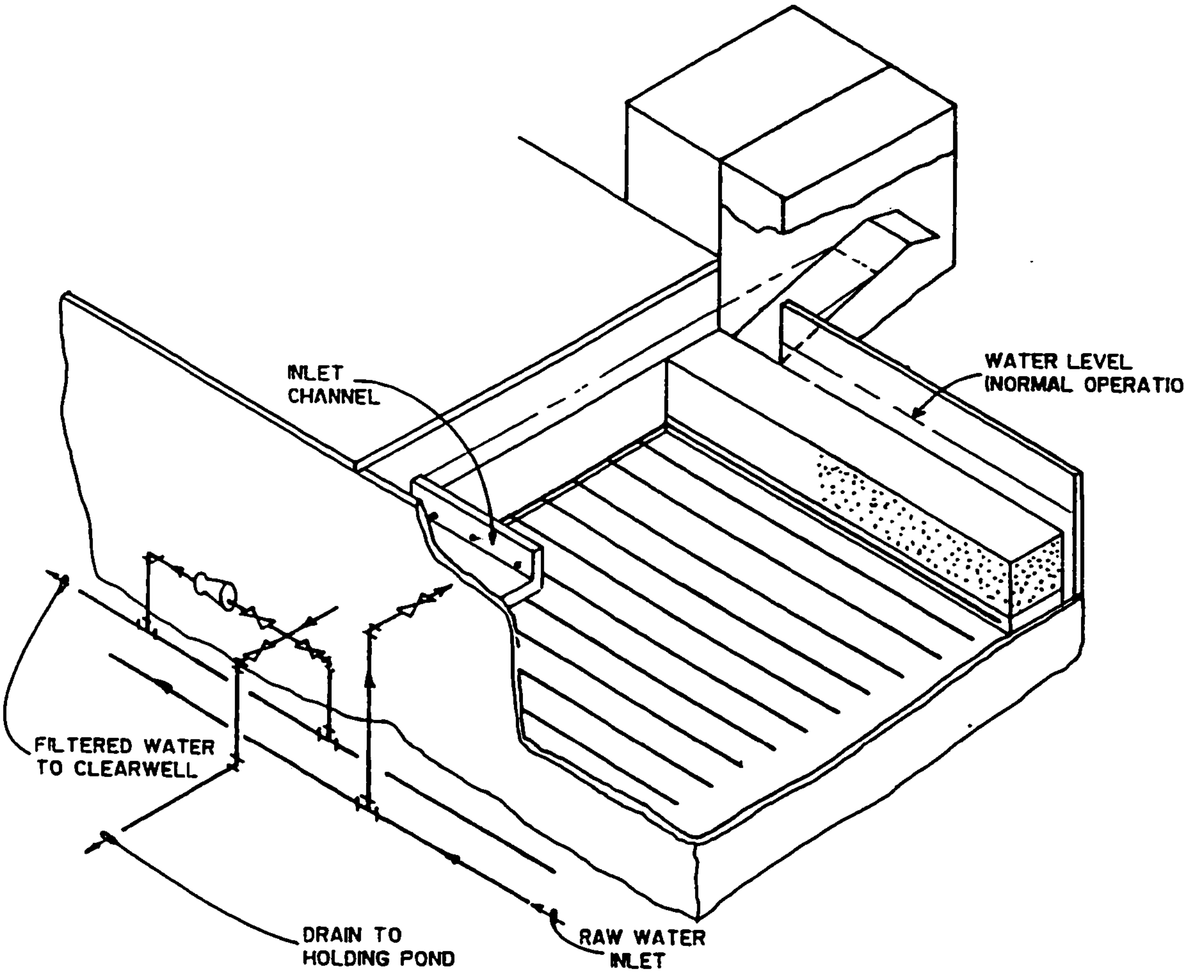


Figure 4: Schematic of Newark, NY filter.

3.2.4 Hartford Metropolitan District Commission, West Hartford, Connecticut

This plant is one of two principal plants serving the Hartford Connecticut metropolitan area and has a current capacity of 189 ML/d (50 MGD) using raw water from upland reservoirs (Allen, 1991). This facility has 22 slow sand filters with a total surface area of 5.1 hectares (12.5 acres) with filters constructed over a period of time as outlined in Table 13. The filter capacity is based on an application rate of 0.16 m/hr (0.064 gpm/sf). The filter sand ranges in depth from 0.6 to 0.7 meters (24 to 27-inches). The effective sizes of the sand used over the years have ranged from 0.25 to as high as 0.35 mm and with uniformity coefficients of from 1.4 to 3, but with the smaller effective size and lower uniformity coefficients required in more recent years (Fenstermacher, 1988). The filters are covered and accessible from buildings located at the point at which sets of four filters have corners coming together. The access is by ladder and by overhead electrically powered hoists on monorails. Manholes provided through the roof structures can be used for ventilation or delivering sand. The filter layout is shown in Figure 5.

TABLE 13: FILTERS AT WEST HARTFORD, CT

Filter Numbers	Year constructed	Surface area hectares (acres)
1-8	1922	0.20 (0.5)
9-10	1927	0.30 (0.75)
11-14	1941	0.20 (0.5)
15-18	1953	0.20 (0.5)
19-22	1960	0.30 (0.75)

The filters were originally constructed to be cleaned using the scraping method but costs and the inconveniences of those operations led to the development of alternative methods (Minkus, 1953). Various alternative methods were used in the years from 1922 to 1950 until the present method of harrowing was developed which has been used continuously since the mid

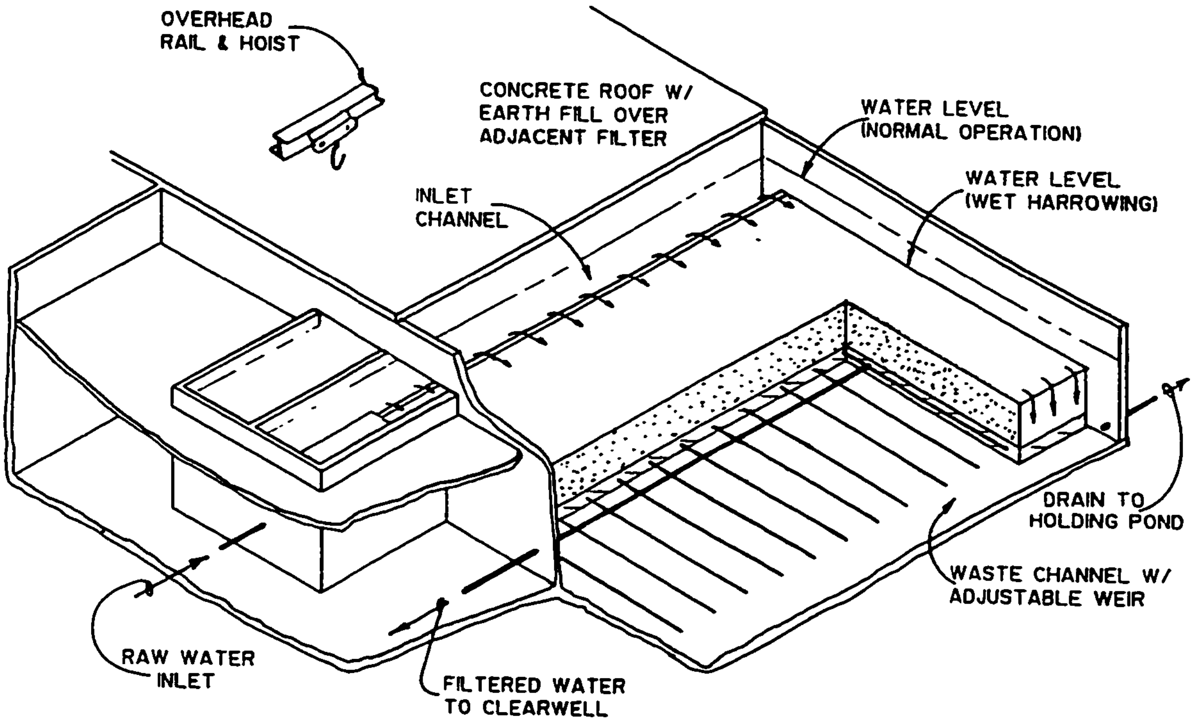


Figure 5: Schematic of West Hartford, CT filter.

1950's. The harrowing method developed at this facility is the one on which the cleaning methods for both Gorham and Newport plants have been based.

The West Hartford filters are much larger and older than those at Gorham and Newport and so additional description of the cleaning method will be necessary. The inlet of the filter to be cleaned is closed at some time between 3 and 5 AM on that day to allow the water surface to fall to near the weir overflow level. The crew performing the wet harrowing operation opens the drain to finish lowering the level and lowers the tractor and harrow into the filter with a monorail hoist. The filter is wet harrowed until the early afternoon when the filter underdrain is opened to the drain to further lower the water surface below the surface of the sand. The first tractor and its spring-toothed harrow is removed and moved to the filter this crew is to wet harrow the following day. The following day, a second crew moves its tractor and scarifying harrow into the filter and dry harrows the sand until early afternoon. The surface is inspected, and the underdrain system partially opened to allow filtered water from the three adjacent filters to begin filling the cleaned filter from below. After the water level rises above the sand, raw water is introduced through the regular inlet to complete the filling and the filter is opened to begin flowing to the clear well at a rate of 1.9 ML/d (0.5 MGD) until the following morning. The flow is then increased in 1.9 ML/d (0.5 MGD) steps until it reaches its full capacity.

The sand in the filters has been removed, washed, and replaced at intervals of from 10 to over 20 years. New sand is purchased only as necessary to replace losses from the cleaning operations (Allen, 1991). The filters used in this study were last reconditioned in 1974 (Filter No.1), 1980 (Filter No. 18), and 1993 (Filter No. 21).

Samples of raw water were taken from sampling taps in the pipe galleries of Filter No.1 for Filters 1-10 and 18-22, and in the pipe gallery of Filter No. 18 for that filter. Filtered water samples were taken from taps in the pipe galleries for each of the filters sampled. Wastewater samples were taken in the pipe galleries of those filters. The results of the analyses are presented in Chapter 4.

Slow sand filters must be reconditioned periodically because filter capacity decreases over time despite regular harrowing. The filters at the West Hartford plant have been reconditioned after varying intervals. The goal had been to recondition filters at intervals as short as 7 or 8 years but filters had gone over 20 years due to budget restrictions in the 1970's and 80's, thus deferring the financial costs (approximately $95,000 per filter for the past two operations, each on 0.3 hectare (3/4-acre) filters) and time out of service. Instead a filter was selected for reconditioning based on its reduced capacity. Reconditioning had been accomplished formerly using plant employees, but the work is done now by outside contractors under public bidding. The contractor supplies the labor and supervision, and the Metropolitan District Commission (MDC) supplies the equipment and water. The work procedure is specified by the MDC and inspected periodically by them. Data on these operations were also collected and analyzed as a part of this report.

Wastewater, from harrowing and reconditioning, was discharged to surface channels on the plant site which flow to a settling pond, then to a off-site river.

3.3 PILOT PLANT STUDIES

Pilot plant studies were carried out from August 19, 1992 to September 19, 1993 at the Portsmouth, NH water treatment plant located in Madbury, NH. Three parallel pilot plants were operated using a common water supply to compare the effects of cleaning methods under intensive conditions and to record rates of head loss development, filter cycles, and the effects of aging on the filter media.

The plant's water supply is from the Bellamy Reservoir which is a shallow surface water supply with high color, relatively high turbidity, and high concentrations of iron, manganese, and organic carbon. The reservoir and water treatment plant were constructed by the U.S. Army Corps of Engineers and put into service in 1961. The Portsmouth plant uses conventional alum coagulation, flocculation, and rapid filtration and has a design capacity of 43 ML/d (5.5 MGD) (Fenstermacher, 1989).

The pilot filters for this study were constructed from 30 centimeter (12-inch) diameter, Schedule 80 pipe. A diagram of the plant is presented in Figure 6.

The filters were flanged 60 centimeters (24 in) from the bottom to facilitate installation, cleaning, and sampling of the filter bed. The flanges were sealed with a rubber gasket and secured with 8 bolts around the perimeter. The influent line was a 1.3 centimeter (1/2 in) PVC line extending to the center of the filter just under the surface of the water. An overflow tube located 91 centimeters (36 in) above the sand surface maintained the height of water on the filter. The 0.6 centimeter (1/4 in) diameter PVC rod was cemented around the perimeter of the interior filter wall 7.5 centimeters (3 in) below the sand media surface to reduce sidewall channeling. The ratio of filter diameter to media effective size was 700 which greatly exceeded the ratio of 50 which should avoid measurable effects on rates of head buildup and variation in turbidity and particle count (Lang et al., 1993). An underdrain was provided by a 0.6 centimeter (1/4 in) NPT X l.5 centimeter (5/8 in) hose-barb adapter threaded into the center of the bottom of the filter base. A piezometer connection was also made about 2 centimeters (1 in) above the base through the side of the filter with a similar connection.

Raw water was supplied from the main plant raw water supply to a constant head tank located above the pilot plant filters. Individual connections from near the bottom of the constant-head tank were connected by Tygon tubing to a multi-head peristaltic pump (Cole-Parmer, Chicago, IL) and by tubing to each of the filters. The pump maintained equal flow to each of the parallel filters at a rate more than sufficient to match the output. The excess flow

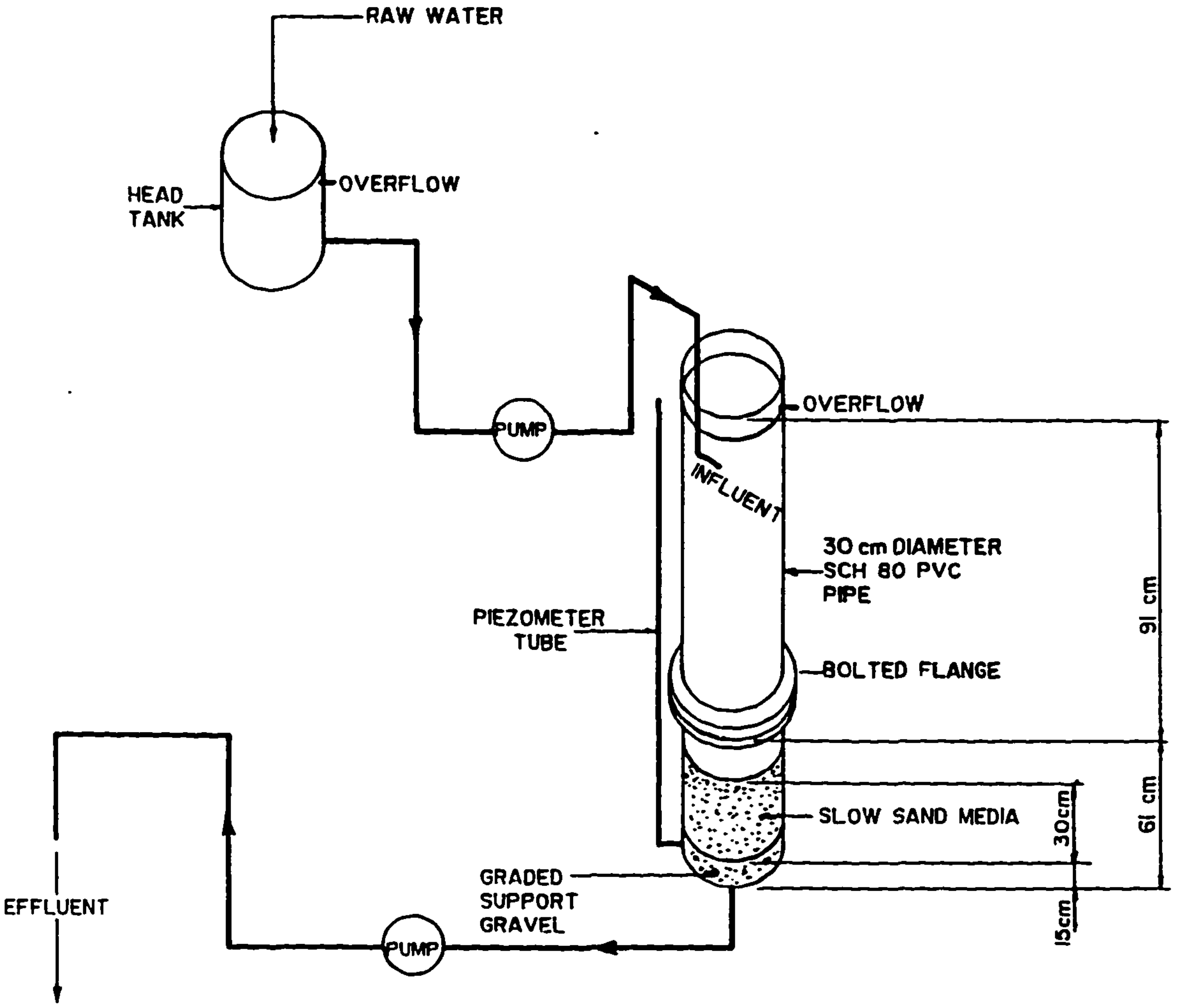


Figure 6: Pilot plant filter.

passed through the overflow connections to the building drainage system. Filtered water from each of the filters flowed through tubing to a second multi-head peristaltic pump and then to the building drainage system. The rate of flow to and from the filters could be measured by stopwatch and graduated cylinder.

The filter beds were constructed in several layers. Supporting layers of gravel at the bottom of the filter provided a means of flow collection from the sand above the gravel and to the central take-off connection. The coarse gravel layer was about 2 cm thick at the bottom of the filter and was overlain by two additional layers of gravel and then sand. Specifications of the supporting gravel and the sand media are summarized in Table 14. For these studies, the layer of sand media was approximately 30 centimeters (12 in) thick and the top 15 centimeters (6 in) was monitored as the active zone. The filters were operated with equal application rates of 0.12 meters/hr (0.63 GPM/sf) throughout the study period.

TABLE 14: PILOT PLANT MEDIA SPECIFICATIONS

Media layer	Thickness cm	Effective size mm	Uniformity Coefficient
Supernatant water	100	-	-
Filter sand	30	0.6	2.0
Supporting gravel No. 1	6.5	2.3	2.0
Supporting gravel No. 2	6.5	3.0	1.8
Supporting gravel No. 3	2	5.0	5.0

All filters were cleaned initially by scraping to allow uniform ripening. After two cycles of cleaning, the filters were drained, sampled, and cleaned utilizing parallel methods of scraping for Filter No. I, harrowing to a depth of 5 centimeters for Filter No. 2, and harrowing to a depth of 15 centimeters for Filter No. 3. Scraping was carried out using a stainless steel spatula to a depth of approximately 0.6 cm (1/4 in) or as required to remove the dark brown schmutzdecke layer.

Harrowing was carried out using a 1.2 cm (1/2-in.) dia. steel rod on which laboratory tape was used to mark 5 and 15 cm (2 and 6-in), respectively, as maximum depth for penetration. All filters were drained for cleaning so that the water surface was below the surface of the sand. After scraping or harrowing, treated water was pumped in reverse through the underdrain zone of each filter and up through the media until the water level rose above the sand. Raw water was then added through a side port located 5 cm (2-in) above the surface of the sand. After the level had reached 30 cm (1-ft) or more above the sand surface, additional water was added from the top using a hose with a baffled outlet so that the sand surface would not be disturbed. After the water level reached the overflow elevation, the system was turned on in the forward direction and the filter cycle started.

The raw water was sampled from the tube discharging to Filter No. I. Filtered water was sampled from the several discharges of the multi-head peristaltic pump drawing from the respective filter underdrain connections. Raw water temperatures were determined using a laboratory thermometer suspended in the constant head tank.

3.4 LABORATORY SCALE STUDIES

Laboratory scale sand filter tests were carried out in the fall and winter of 1993 at the Environmental Engineering Laboratory at University of New Hampshire to compare filter characteristics that could not be measured in the field scale plants.

The laboratory filters consisted of glass columns measuring 2.54 cm diameter x 53 cm long (1-in. x 21-in.), containing approximately 40 cm (16-in.) of a selected sand media. The ratio of column diameter to media effective size was 50 to avoid measurable variations in turbidity and particle counts. The ends of the tubes were capped with a valve and connected with tubing to a laboratory pump (Masterflex, Cole-Parmer, Chicago, IL). The system was arranged so that the pump would draw water from a stoppered one-liter reservoir on a shelf above the filter column and discharge at a controlled rate into the bottom of the filter. The filtered water exited the filter at its upper end and flowed to the reservoir on the shelf above the filter. A schematic view of a single filter column is presented in Figure 7.

Eight columns were mounted in parallel on a wooden support frame. Each column had its own reservoir and pump head, but the pump heads were mounted on common variable speed drive motors to maintain similar flow rates. The entire system was located in a constant temperature room maintained at 20± 0.5°C. The filter columns were operated at various flow rates.

Filter media used in the columns was taken from a variety of sources and stored in a refrigerator. Generally, the sand was screened on the day columns were filled. The sands were wet screened on a No. 45 sieve (0.014 mm opening)under a flow of RO filtered laboratory water until the water ran clear. The sand was placed in a column with a stainless steel laboratory spatula, while maintaining sufficient water depth in the column to cover the settled sand. The column was filled in layers and vibrated for 5-seconds at each layer with a Maxi-Mixer (Thermolyne Corp., Dubuque, Iowa) to remove air. The sand was supported at the bottom of the column by a plastic mesh to prevent its entrance into the valve and tubing below the column. After filling, the columns were placed on the wooden support frame, connected to the pumped circulation system which temporarily had general purpose laboratory water in the reservoir flacks, and the pumps started. Air bubbles were released in part by the upflow of water but more importantly by vibration of the columns. Pump flow rates were calibrated at this time. When ready, the reservoirs were emptied and refilled with the designated "raw water" to be used in the tests.

The general purpose, sources of sand, and sources of water used for the individual laboratory filter column runs are summarized in Table 15. The sand used during Column Run No. 4 received additional preparation. A portion of the sand was screened several days before it was to be placed in a column to allow it to be cleaned of organic matter by burning in a muffle furnace overnight. This was then cooled, and cleaned by repeated acid extraction with 1:1 nitric acid until

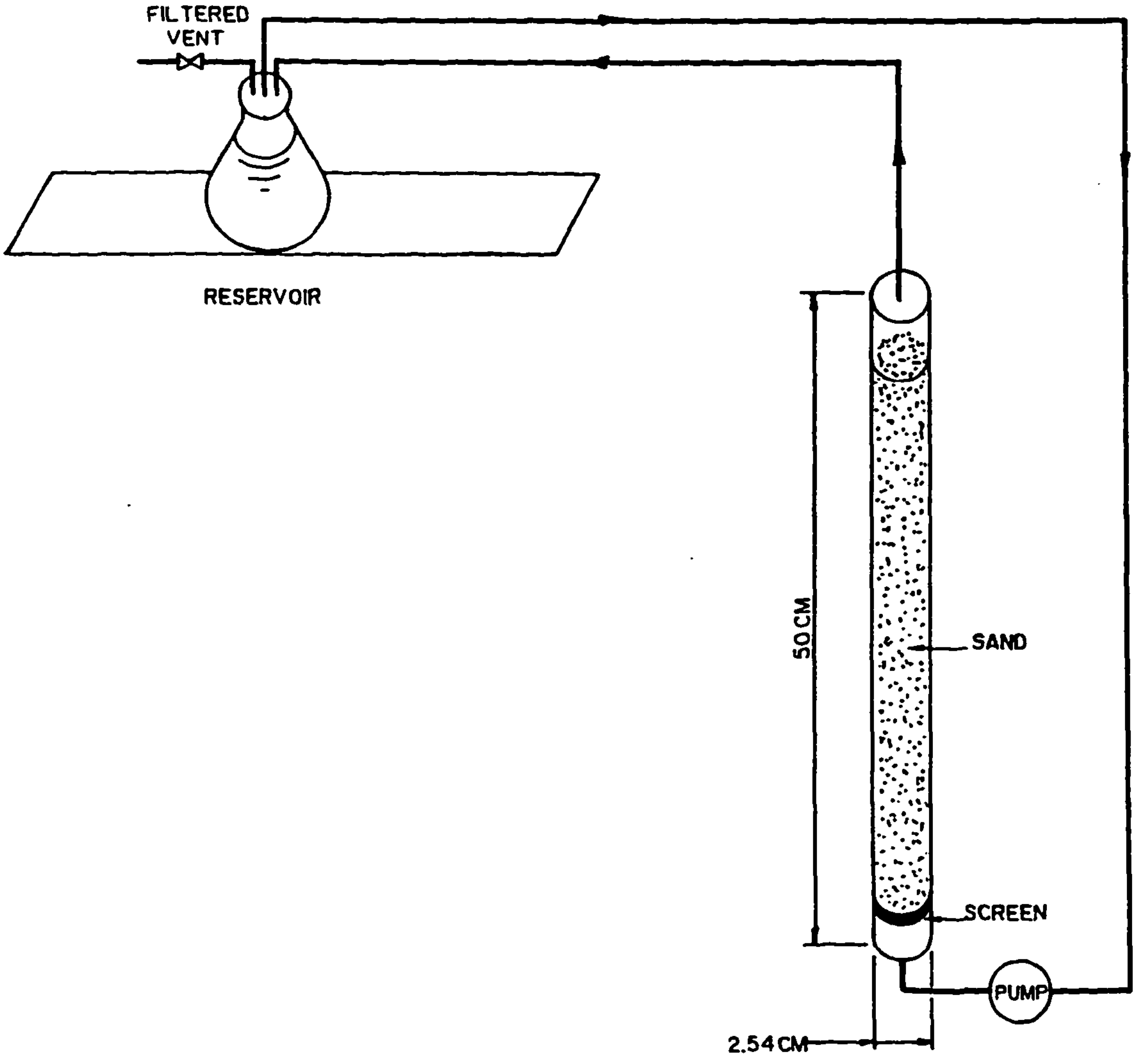


Figure 7: Laboratory filter column.

TABLE 15: SUMMARY OF LABORATORY FILTER COLUMNS RUN, BY SOURCES OF SAND AND WATER.

Column Run Set	Variables compared	Sources of sand	Sources of water
No. 1	Age of sand, depth of sand in filter, and natural vs artificial carbon source.	West Hartford plant Filters 1 and 18, at depths of : top 1.2 cm 25-30 cm.	West Hartford, and glucose/glutamic acid solution.
No. 2	Water source and source of sand media.	West Hartford, CT Filter 1, Newark, NY Filter 4, and Pilot slow sand filter.	West Hartford, Newark, and glucose/glutamic acid solution.
No. 3	Filter rate (m/hr) and water source.	Pilot slow sand filter.	Portsmouth , and glucose/glutamic acid solution.
No. 4	Filter media coating.	Pilot slow sand filter.	Portsmouth, and glucose/glutamic acid solution.
No. 5	Filter rate (m/hr).	Pilot slow sand filter.	Portsmouth plant.

the spent acid was colorless and the sand attained a uniform white color. The sand was extensively rinsed with general purpose laboratory water and stored until the day before it was to be used when it was neutralized to a pH of 7.0±0.1 with 1 N sodium hydroxide. This cleaned sand was then mixed with freshly screened sand in the specified proportion, by weight, in a plastic bag before loading into the columns.

"Raw water" supplies were taken from several field sources, collected in acid-washed and capped 20 L plastic containers, and stored under refrigeration. Solutions of glucose and glutamic acid were prepared as a stock solution containing 0.3 g/L, measured as carbon, each of glucose and glutamic acid and diluted to an NPDOC concentration approximately equal to that of the other water source or sources immediately before use. A covered flask of each raw water was also maintained in the constant temperature room to determine if water characteristics changed independently of the filter action. Samples were taken from the raw water before starting the pumps. Subsequent samples were taken at timed intervals from the filter discharge tubing at the connection to the supply reservoir above the filter. Sampling times and room temperatures were recorded.

3.5 LABORATORY METHODS AND MATERIALS

3.5.1 General

The various analytical methods used have been listed separately below by the form in which the sample existed, whether aqueous or solid. It was necessary to use differing equipment for some aqueous sample methods because the full scale plants were so widely distant fro each other and reference is accordingly made in those sections. Sources of documentary information are also listed in this section.

Several grades of water were used in the course of the experiment. Ordinary supplies used to wash glassware with phosphorus free detergent was from the Durham public water supply. General purpose rinsing water was taken from the RO system installed within the building. That system typically removes 95 to 99% of the polyvalent ions, greater than 99% of large molecular weight organics, and over 99% of large bacteria (Gallagher, 1992). Type II laboratory water was supplied within the laboratory from the reverse osmosis supply by passage through multi-media ion exchange columns and filtered with 0.22 micron filters. This system, with the trade name of "Milli-Q" (Millipore Filter Corporation, Bedford, MA) was used for rinsing acid washed glassware, and for preparation of reagents.

Glassware, porcelain, plasticware, and container caps were washed with tap water and phosphorus-free detergent, rinsed with water from the RO system, and further cleaned as required for special purposes. Chromic acid-cleaned glassware and plasticware were filled or immersed with a chromic acid cleaning solution prepared from a commercial reagent, and allowed to stand for a minimum of one hour. The chromic acid cleaning solution was then returned to a storage container and the cleaned ware rinsed at least three times with Type II laboratory water, air dried, covered with aluminum foil, and stored for subsequent use. Glassware and plasticware given a nitric acid wash was filled or immersed in a 1:1 nitric acid solution for at least one hour. The nitric acid cleaning solution was returned to its storage container and the cleaned ware washed at least three times with Type II laboratory water, air dried, and covered with poly-film or a watch glass before further use.

After March 1993, certain pieces of glass or porcelain ware were cleaned with the muffle furnace. These pieces were to be used for tests where it was essential that all organic material had been removed. Furnace cleaning is a derivation of a method (Weber-Shirk, 1992) for cleaning glass beads to remove residual carbon. This method was also used in a study (Kaplan, et al, 1993) of preparation methods for bioassay vessels and other glassware. In that study glassware cleaning with potassium dichromate-sulfuric acid was compared with heating in a muffle furnace for six hours. It was concluded that high temperature eliminated organic carbon contaminates from glassware as effectively as potassium dichromate. A furnace time of two hours was sufficient to destroy the organic carbon content and kill organics in the volatile solids test and two hours was adopted for the use in this project. This ware was detergent washed, rinsed with general purpose laboratory water, dried, and placed in the muffle furnace at a temperature of 550°C for at least two hours. They were then removed, placed in a desiccator for cooling, and sealed with appropriate covers before being stored for further use.

Many of the container caps could not be acid washed or furnace cleaned. These caps were detergent washed, rinsed with general purpose laboratory water, and rinsed repeatedly with Type II laboratory water, allowed to stand overnight in Type II water in a chromic acid washed container, rinsed twice more in the morning, dried in the 60°C oven, and immediately placed on their matching containers which had received acid washing or furnace cleaning.

3.5.2 Analytical Methods

The methods used were generally as listed in Table 16 and as further described in the following section.

TABLE 16: ANALYTICAL METHODS USED DURING THE STUDY.

Parameter	Method
Temperature	APHA 2550-B
Turbidity	APHA 2130-B, and manufacturer's literature.
Particle counts	Manufacturer's literature.
pH	APHA 4500-H
Dissolved oxygen	APHA 4500-OG
Nonpurgeable dissolved organic carbon	APHA 5310-C
Biodegradable organic carbon	Servais et al., (1987)
UV absorbance	Fenstermacher, (1988) (Now available in APHA, 1995)
Settleable solids	APHA 2540-F
Total and volatile suspended solids	APHA 2540-D
Coliform	APHA 9222-B
Total and volatile solids	APHA 2540-G
Folin reactive material	Spanos, (1989)
Carbohydrates	Chesbro, (1992)
Acriflavine direct count	Spanos, (1989)
Metals	USEPA, (1991)
Grain size	ASTM D422-63(1990)

Temperature– All temperatures were measured at the sampling locations using glass-mercury laboratory thermometers, calibrated in °C, and reported to the nearest whole degree. Data taken at times of sampling at Portsmouth, Gorham, Newport, Newark, West Hartford, and the UNH laboratory were taken using the same thermometer. Routine monitoring data on plant operations at the Portsmouth, Gorham, Newport, Newark, and West Hartford facilities were taken from plant operating reports. Temperatures were measured on grab samples in one liter beakers in which the thermometer was allowed to stand for not less than one minute to reach equilibrium with the sample.

Turbidity-- Measurements on field samples of water from Newport, Newark, West Hartford, and the column studies were performed on a laboratory turbidimeter (Hach, Loveland, CO). Measurements on Gorham samples were performed by Gorham using a Hach Model 2100A. Samples from the Portsmouth pilot plant were performed using a Hach Ratio Turbidimeter belonging to the Portsmouth Water Treatment Plant laboratory. Daily turbidity records at all plants were provided from plant records. The turbidimeters were allowed to warm for not less than I hour and were tested against secondary standards of formazine in the 0 to 2 NTU range. All samples were taken by grab sampling and stored in glass or plastic containers which had been chromic-acid cleaned. Samples were stored, when necessary between point of collection and laboratory analysis, in cooled containers using ice or frozen "blue-ice" blocks.

Particle Counts-- Particle counts were made using a Met-One (Grants Pass, Oregon) Model 250 Particle Counter system with the Model 250 batch sampler, Model 214 single sensor counter, and LB 1010 light-blocking sensor. Samples were stored in chromic acid washed polyethylene containers or sterile twirl bags. Studies by Flax (1993) indicated that storage in a refrigerator for up to five days did not cause a significant change in particle count on filtered water samples, but counting for the present study was generally completed within 24 hours. The particle counter was set up with a maximum combined count not to exceed 30,000 counts per mL and samples with counts in excess of this limit were diluted with Type II laboratory water. Particle counts for various sizes were collected in "bins" as listed in Table 17. Data were saved to the computer disk and plotted in counts per mL for each size range. Each counting series was performed in triplicate and the results for the three runs averaged. Background counts of Type II laboratory water were also performed before and after a series of counts for quality control and to determine the particle

TABLE 17: PARTICLE COUNTING SIZE RANGES AND MAXIMUM COUNTS PER SIZE RANGE.

Bin Number	Particle size range	Counting limit per mL
1	1.00 - 1.25	5000
2	1.25 - 1.50	3500
3	1.50 - 1.75	3500
4	1.75 - 2.00	3500
5	2.00 - 5.00	3000
6	5.00 - 7.50	3000
7	7.50 - 10.00	2000
8	10.00 - 17.50	2000
9	17.50 - 25.00	2000
10	25.00 - 30.00	2000

content of water used for diluting samples with high particle counts.

pH-- All measurements were made with electronic pH meters. Meters were calibrated at two points (4.0 and 7.0) with prepared buffers (VWR, Bridgeport, NJ) before each day's use (APHA, Method 4500-H+B).

Dissolved Oxygen (DO)-- All values were made using electronic meters. Meters were calibrated against air (APHA, 1989). Samples were analyzed in 300 mL BOD bottles.

Organic Carbon (Nonpurgeable; Total and Dissolved)-- Organic carbon was determined by the UV-persulfate oxidation method with a Dohrmann DC-80 TOC Analyzer (Dohrmann, Santa Clara, CA). Total organic carbon (TOC) was determined in unfiltered samples. Dissolved organic carbon (DOC) was measured in samples which had been filtered through a 0.22 or 0.45 um prewashed filter. TOC or DOC was determined by acidifying samples with concentrated phosphoric acid and purging the sample with nitrogen for a minimum of 5 minutes. Three 1 mL hypodermic injections were made for each sample and standard unless, on some samples, the limits of instrument accuracy were met with only two injections. Storage times for the stock and working standards were two months and one month, respectively. Field samples were stored in 10 mL amber or clear glass vials with Teflon septa in plastic caps, stored in the refrigerator at 4°C under dark conditions.

Samples were preserved by acidification with two drops of concentrated phosphoric acid to lower the pH to 2 or less. Working standards, consisting of four concentrations of anhydrous potassium biphthalate and a blank of Type II laboratory water, were prepared immediately before analysis by being placed into 10 mL vials identical to the standards, two drops of concentrated phosphoric acid were added, and all samples and working standards then warmed by standing to room temperature. An additional two drops of concentrated phosphoric acid were added to each vial before sparging with nitrogen.

Vials were cleaned in the early stages of the laboratory investigation in a chromic acid solution. After March 1993, the vial cleaning process was revised and, instead of chromic acid washing, the vials were furnace- cleaned. There were no significant differences between standards prepared with the acid-cleaned glassware and those with furnace-cleaned glassware.

Standard curves were prepared using replicates of the working standard dilutions and "blanks" both before and after a series of measurements. "Blanks" and "readback" samples were used about every ten samples. Individual injections or samples demonstrating values outside 90% probability were rejected and the remaining values utilized.

Biodegradable Dissolved Organic Carbon (BDOC)- - BDOC was determined using the method of Servais et al. (1987), as modified by Royce (1994). This method compares the dissolved organic carbon concentration of a sample between the time shortly after collection and again after it has been held at 20°C in the dark for a period of 28 to 30 days. Field samples were preserved by refrigeration at 4°C before analysis. All glassware was acid-cleaned and sterilized by autoclaving. Filters were sterilized by autoclaving or purchased in an already sterile condition.

Samples were filtered using a filter apparatus (Kontes, Vineland, NJ) and 0.22 um filters (Sartoris, Bohemia, NY) to filter sterilize the sample. At least 250 mL of sterile Type II water was used to rinse filters of any detergents and then to rinse the flask. The filter was then rinsed with at least 50 mL of sample to flush the laboratory water from the filter and flask. At least 200 mL of sample was then filtered and the filtrate collected and transferred to a sterile, covered 250 mL Erlenmeyer flask. For some samples, more than one filtering operation was necessary to recover at least 200 ml of filtrate; when required, the same washing operations were performed on the new filters.

After all samples had been filtered and flasks prepared, 2.0 um filters were then used to remove organisms larger than bacterial size from the sample. "Seed" water was prepared by utilizing the above mentioned prewash, rinse, and filtering operation. 10 to 20 ml of seed water was then transferred to a sterile container. Four mL of the seed water was transferred to each flask and the flasks mixed by swirling. TOC vials were filled from each flask for the "zero day" sample, acidified with two drops of concentrated phosphoric acid, and stored at 4°C for later analysis. The covered flasks were placed in cardboard boxes and closed to prevent light and possible algal development, and kept in a constant temperature room at 20°C.

The flasks, rather than being held static as in the Servais method, were placed on a shaker table to ensure complete mixing during the storage period. The flasks were taken from the constant temperature room at designated periods and aliquates transferred into clean TOC vials as above. Normally, samples were taken at 0 and 28 days for determination of BDOC, although on occasion, samples were taken at intermediate times to determine the rate of development.

Analyses were normally prepared in duplicate and the results averaged.

Ultraviolet Light Absorbance at 254 nm (UV at 254 nm)-- This parameter is a surrogate for estimating trihalomethane formation potential and depends upon the absorption of ultraviolet light at 254 nm (Amy, et al., 1986). Field samples were stored at 4°C before analysis and analyzed within 7 days of collection . The samples were warmed to room temperature. Samples were filtered through Whatman GF/F filters (which have been ashed in the muffled furnace for one-half hour before use), using disposable syringes, and filter holders. Filters and equipment had been pre-rinsed with approximately 50 mL of Type II laboratory water and at least 20 mL of sample prior to use. The filtered sample were discharged directly into clean quartz cuvette, the pH adjusted to 7.0 by the addition of two drops of pH buffer solution, and placed in the spectrophotometer for reading. Results are reported as absorption per cm.

The spectrophotometer (Bausch & Lomb Spectronic 2000, Rochester NY) was allowed to warm up for a period of at least 1 hour before analysis. All samples were analyzed using matched quartz cuvettes. Triplicate analyses were made on each sample with sample blanks of Type II laboratory water used before and after each series of analyses and as readbacks during the course of analysis to detect instrument drift.

Settleable Solids-- This test was performed in the field on aqueous samples of wash water from the harrowing process. Grab samples were collected on a timed basis from the wash water flow. One liter of sample was mixed in the sampling container and poured into the Imhoff cone to the l liter mark. The sample was settled for approximately 45 minutes. The cone was then rotated to gently dislodge solids which had adhered to the sloping sides of the cone. After an additional 15 minutes of settling, the volume was read at the upper surface of the settled solids.

Total and Volatile Suspended Solids-- Suspended solids were measured on aqueous samples of wash water from the harrowing process as described above. Grab samples were collected on a timed basis, stored in polyethylene sample containers, and refrigerated until time of analysis in the laboratory. Settleable solids were removed prior to filtration and the supernatant from the settleable solids test was used. Whatman GF/F, 47 mL diameter, glass fiber filters were used for all measurements.

Coliform Bacteria-- All coliform bacterial testing was performed by a laboratories certified by the Department of Environmental Services of the State of New Hampshire or the Connecticut Department of Health. These laboratories were: Gorham, NH, Wastewater Treatment Plant, Claremont, NH, Water Treatment Plant, Portsmouth, NH, Water Treatment Plant, and West Hartford, CT, Water Treatment Plant.

Flow-- Flow rates at the respective facilities were measured by a variety of methods. Flow measurements at the Gorham Water Treatment Facility utilized the plant Venturi tube flow meters which had been calibrated at the start of the testing program. Flow measurements at the Newport Water Treatment Facility were by insert flow meters (Data Industrial Item 71-000472). The main meter on the plant output is a Venturi meter. Flow measurements at the Newark Water Treatment Facility were by Venturi-type flow meters.

Flow measurements at the West Hartford Water Treatment Facility also used Venturi flow meters. Some of these flow meters were known to be highly inaccurate but a "master" Venturi flow meter for the combined flow from each section of the plant was used to adjust the estimated rates for individual filters in that section of the plant. Wastewater flows were estimated by measuring the cross section area of the stream channel carrying the flow and surface velocity across the width of the flow. The surface velocities of segments across the stream were related to mean velocities using curves of equal velocity in various channel sections (Chow, 1959).

Flows for the pilot plants and the column studies were measured with a stop watch for the time to fill graduated cylinders.

Total and Volatile Solids-- The procedure was from Spanos, (1989 with Method 2540G (APHA, 1989) as a secondary reference. Duplicate analyses were run on each sample., using approximately 5 grams, wet weight, of sample.

Folin Reactive Material-- Folin reactive material, FRM, was used to estimate the protein content and, from that, the active microbiological mass within the sand samples. FRM was determined based on the method by Spanos (1990) and based also on the methods by Lowry (1951) and Gerhardt et al. (1981). All glassware was washed with chromic acid or furnace-cleaned. Pipet tips and temperature sensitive equipment were washed repeatedly with Type II laboratory water and air dried.

All tests were performed in duplicate. Approximately 3 grams, wet weight, of samples were weighed into 50 mL Erlenmeyer flasks. The initial step in the analytical process was to remove FRM from the sand grains by adding 40 mL of neutralized 0.1% (w/v) sodium pyrophosphate to each flask and mixing the sample on a MaxiMixer for 30 seconds, off for 30 seconds, and again for 30 seconds, before being allowed to settle. The FRM was converted from protein with caustic by adding 3.5 mL of the extract in a clean 12 mL disposable glass vial and 7 mL of 1.0 N sodium hydroxide The samples were heated for 10 minutes in a 90°C water bath to increase the rate of reaction. Vials with Type II laboratory water as blanks and standard concentrations prepared with crystalline bovine albumin were prepared as for samples, including the dilution with 2 volumes of 1.0 n sodium hydroxide and heating in the water bath. One mL aliquots of all standards, samples, and replicates were then transferred to clean 12 mL disposable glass vials for analysis. The mixture of the sodium carbonate and potassium tartrate copper sulfate solution was used the same day it was prepared and not held for other tests. The sodium carbonate and potassium tartrate solution were prepared in advance. The Folin-Ciocalteu reagent was 1.95 normal and was diluted to half strength with Type II laboratory water. This solution was also diluted daily for testing purposes. The color was allowed to develop for 20 minutes before being read at a wavelength of 750 nm with the spectrophotometer.

The bovine albumin used for the standard was stored in a tightly closed vial in the refrigerator until the day before use. Approximately 0.075 grams of the crystalline bovine albumin serum was placed in an acid washed 25 mL volumetric flask to which 2 mL of one normal sodium hydroxide was added with sufficient Type II laboratory water to bring the volume up to the mark. The actual weight of albumin was recorded and used for the adjustment of the final standard curve. Concentrations used to prepare a standard curve were 3, 30, and 60 ug/L. Calculations were performed using the standard curve and corrected for the actual weight of albumin and the percent of protein in albumin (97%).

Carbohydrates-- Biomass in the sand media samples was also estimated by analyzing for carbohydrates which are contained in capsular material (Liu, et al., 1992). Carbohydrates were measured using the phenol-sulfuric acid determination (Chesbro, 1992). All glassware was washed with chromic acid or furnace-cleaned. Pipet tips and temperature sensitive equipment were washed repeatedly with Type II laboratory water and air dried.

The analytical procedure was run in triplicate on each sample. Approximately 0.3 grams of sand was weighed into the disposable glass 12 mL vials, the weight recorded, and two mL of Type II laboratory water was added. Blanks and standards were prepared using 2 mL of Type II laboratory water for appropriate dilution of sucrose as a standard carbohydrate. Standard solutions were prepared from a stock made of 0.375 grams of sucrose per 100 mL and then diluted to produce concentrations of 1.5, 15, and 30 mg/L carbon. A concentration of 60 mg C/L carbon exceeded the range of the spectrophotometer. Blanks and standards were placed into the disposable vials also using volumes of 2 mL. When ready for analysis, the equipment was placed under a fume hood for safety and then 0.15 mL of analytical grade 89 percent Phenol was added and followed immediately by 5.0 mL of analytical grade concentration sulfuric acid. The vial was capped, mixed by inversion five times, and allowed a minimum of 15 minutes to develop color. The vials were then read with the spectrophotometer at the wave length of 489 nm.

Acriflavine Direct Count-- Acriflavine Direct Counts (AFDC) were carried out using the method of Spanos (1989), Balkwill and Ghiorse (1985) and Mooney (1993). Before the organisms were stained for epifluorescent microscopy, they were removed from the surface of the sand grains. The organisms and other coatings were removed using the same extraction procedure as for the Folin reactive material test but using glassware which had also been autoclaved for sterilization and reagents which had been prepared using aseptic techniques and filter sterilized water. Blank samples of solutions were carried through the extraction, filtration, and counting steps to determine the background levels of organisms that were present through contamination of materials.

The procedure involved several steps. One mL of extract for each sample, replicate, and a "blank" was transferred to a sterile dilution tube. The dilution tubes were mixed with a Maxi-Mixer and held for filtration. The final dilution was fixed with 1 mL of glutaraldehyde solution per 10 mL of diluted sample. The tube was remixed, recapped, and then stored at 4°C for up to several weeks.

The organisms in the dilution tubes were filtered so that the organisms were retained on the black polycarbonate filters for epifluorescent staining and counting. The filter apparatus was not suitable for sterilization and so it was washed with phosphorus-free detergent and rinsed thoroughly with Type II water. Backing filters, with 0.45 um openings, were first placed in the filter apparatus to support the 0.2 um polycarbonate filters and both were washed with 2 mL of citrate solution which was discarded. One mL of sample was then added, filtered, and an additional 2 mL of citrate solution was added and filtered, One mL of acriflavine stain was added and allowed to stand for 10 minutes before filtration. A final 2 mL of citrate solution was added and filtered. The filters were then removed from the apparatus, placed on laboratory paper towels with the organism on top so as not to be in contact with contaminated surfaces. After drying, the filters were transferred to microscope slides, I drop of immersion oil added, and the cover slip placed to complete the procedure. The slide could then be stored in the dark at 4°C for later counting. The filtrate was discarded.

Sodium citrate solution was a 0.I M solution, acidified to a pH of 4 with concentrated hydrochloric acid. The glutaraldehyde solution was a 25% solution in Type II laboratory water with I.99 grams of Cacodylic acid added, and filter sterilized with a disposable syringe and filter. The acriflavine solution was a 1.0 mM solution. Filters for the test were 0.2 um, 25 mL black polycarbonate filters (Nuclepore) and placed on a backing support filter which was a 0.45 micron 25 mL (Gilman Sciences) Metricel membrane filter. The black polycarbonate filters were purchased gas-sterilized while the backing filter was sterilized by autoclaving.

The organisms on the filters were counted by students in the Department of Microbiology at the University of New Hampshire for bacteria, fungal fragments, and protozoa. Bacteria and protozoa were differentiated by visual size in the experience of the counter. Fungal fragments were identified as filaments. The counts were expressed in numbers of organisms per field of a measured diameter microscopic view.

Metals-- Metals were analyzed using the USEPA Contract Lab Program Statement of Work for Inorganic Analyses/Soil/ Sediment Digestion Procedure (USEPA, 1991) as modified by Vaughan (1993) and by the Inductively Coupled Plasma (ICP) Analytical Technique at the New Hampshire Materials Testing Laboratory. All samples were run in duplicate, with analytical standards and blanks included for quality assurance. Blanks were prepared using the same techniques but without any sand sample being added, and standards were prepared using appropriate laboratory metal standards. Metal tests were performed on all samples for total iron, total manganese, total calcium, and total aluminum. All glassware was acid washed with 50 percent nitric acid for a minimum of one hour, and then rinsed with Type II laboratory water.

Sand samples were mixed in the plastic storage bags, and approximately one gram by wet weight was transferred to acid washed beakers for analysis (Vaughan, 1993). Ten mL of 1:1 nitric acid was added to each beaker, the beaker covered with a watch glass, and placed on a hot plate to heat at approximately 95°C for 10 minutes without boiling. At the end of 10 minutes, the samples were removed, allowed to cool, and 5 mL of concentrated nitric acid was added. The watch glasses were replaced, samples returned to the hot plates, and boiled gently (refluxed) for 30 minutes. Although Type II laboratory water could have been added to maintain the volume at greater than 5 mL, the step was not necessary. The sample was then cooled, 2 mL of Type II laboratory water added, and 3 mL of 30 percent hydrogen peroxide added, the watch glasses replaced, and the beakers returned to the hot plate to be warmed at approximately 95°C until the effervescence substantially subsided. Additional I mL volumes of 30 percent hydrogen peroxide were added and the samples continued to be warmed until the effervescence again substantially subsided. No more than 10 mL of the 30 percent peroxide was used for any of the samples. The beakers were again cooled, and 5 mL of one to one hydrochloric acid and 10 mL of Type II laboratory water then added to the beaker. The cover glass was replaced and the samples returned to the hot plate for an additional 10 minutes of warming at 95°C. The beakers were again cooled, the contents of the beaker (including the sand) was transferred to acid washed 100 mL volumetric flasks, diluted to the mark with Type II laboratory water and allowed to settle overnight. A portion of the flask supernatant was carefully decanted to acid washed polyethylene sample containers without transfer of any sediment. These samples in the polyethylene vials were then sent to the contract laboratory for analysis.

Grain Size Analysis-- Samples were prepared for sieve analysis by air drying at 103°C overnight. The sand samples were cooled to room temperature and placed in sealed plastic bags for storage prior to sieve analysis. Sample sizes were approximately 500 grams minimum. Sieves used were the 3/8th, No. 8, No. 10, No. 20, No. 40, No. 60, No. 140, No. 200, and pan. Samples were usually run without duplicates but, because of overlapping analyses and filter runs, there were duplications for certain samples. These data have been used for determinations of accuracy and precision.

3.6 DATA ANALYSIS METHODS

3.6.1 Analytical Tools

Data analysis was performed using a IBM-Compatible Personal Computer and with the following programs:

Microsoft Windows Version 3.1 (Microsoft Corporation, Redmond, WA)
WordPerfect Version 6.0a for Windows (WordPerfect Corporation, Orem, Utah)
Microsoft Excel Version 4.0 Spreadsheet (Microsoft Corporation, Redmond, WA)
Jandel Scientific Sigma Plot 5.0 for Windows (San Rafael, CA)

The SigmaPlot program was used for laboratory data conversions and plotting. The Excel program was used for general spread sheet calculations and basic statistical analyses, such as means, standard deviation, ANOVA, and t-tests.

3.6.2 Quality Assurance and Quality Control

A quality assurance and control plan (Collins et al., 1992) was used as a guide for sampling, analysis, and use of data. Sampling locations have been described earlier in this Section. Sampling containers and storage methods are summarized in Table 18. Samples were labeled in the field, for location, time, site, and preservation used. Chain of custody forms were attached and the samples shipped or transported by the sampling personnel in refrigerated foam chests to the laboratory.

Analytical methods have been described elsewhere in this Chapter, but detailed

TABLE 18: SAMPLING CONTAINERS, PRESERVATION TECHNIQUES, AND HOLDING TIMES.

Parameter	Container type	Preservation	Maximum Holding Time
pH	G, P washed	None	Immediately
Turbidity	G, P acid washed	Cool, 4°C	48 hrs
Particle Count	P, acid washed	Cool, 4°C	48 hrs
Dissolved Oxygen	G, washed	None	Immediately
Organic Carbon	P, acid washed	Cool, 4°C, H_2SO_4 or HCl to pH<2.0	48 hrs
Biodegradable Organic Carbon	P, acid washed	Cool, 4°C	48 hrs
UV Absorbance	P, acid washed	Cool, 4°C	7 days
Settleable Solids	P, washed	Cool, 4°C	24 hrs
Total and Volatile Suspended Solids	P, washed	Cool, 4°C	24 hrs
Alkalinity	P, washed	None	18 days
Hardness	P, acid washed	Cool, 4°C	14 days
Ammonia-N	P, washed	Cool, 4°C, H_2SO_4 to pH<2.0	28 days
Phosphorus	P, washed	Cool, 4°C, H_2SO_4 to pH<2.0	28 days
Coliform	P, acid washed, sterile	Cool, 4°C	24 hrs
Grain Size Analysis	P, washed	None	No limit
Total and Volatile Solids	P, acid washed	Cool, 4°C	7 days
Folin Reactive Material	P, acid washed	Cool, 4°C	48 hrs
Carbohydrates	P, acid washed	Cool, 4°C	72 hrs
Acriflavine Direct Count	P, acid washed, sterile	Cool, 4°C	As soon as possible, less than 48 hrs.
Metals, in sand media	P, washed	None	No limit
Metals, in water	P, acid washed	Cool, 4°C, HNO_3 to pH<2.0	6 mo.

instructions for the procedures were maintained in a notebook at the laboratory. Data were recorded in multi-form bound laboratory notebooks.

Data were analyzed using standard statistical methods. The Grubbs test (Taylor, 1987) was used for rejecting outlying observations. The Student's t-test was used to determine if results were significantly different, and a confidence limit of 90 percent was used unless otherwise noted. The standard deviation of sample populations were compared and pooled (Taylor, 1987; Collins et al., 1992a). Method Detection Limits were based on "one-tailed" 99 percent confidence level using the standard deviation estimated on reagent blanks.

Water quality analyses are reported as the mean value of the individual analyses, with standard deviations when the analyses were performed in replicate on the same sample. Water quality analyses over extended periods are reported with the mean value and the standard deviation of the individual analyses over the period.

The filter media was cored using a 3.8 cm (1.5-in.) diameter polyvinyl chloride tube. The tube was open at both ends with the coring end bevelled on the inside to facilitate insertion into the sand media. The tube was inserted at predetermined locations (Collins et al., 1992) to depths as marked on the outside of the tube and the tube withdrawn from the media. The full length of the sample cores at Gorham, NH were removed from the filter room and extracted, with tapping of the tube and pressing from the top with a wooden rod, onto a clean plastic sheet for subsampling by depth intervals. Sample cores at the other plants were taken with the same tube to the bottom of the individual depth intervals, removed from the media, and the media sample for that depth removed directly from the open bottom of the tube. All media samples were taken within one cm (0.5-in.) of the designated sample depth. Samples were deposited directly into sterile 56 gm (2-ounce) "Whirl-Pak" bags and stored in ice chests until they could be returned to the laboratory for refrigeration. The analyses were performed in replicate for each subsample. Results of the analyses for each subsample were compared for statistical outliers, then the resultant mean and standard deviation for each was compared with those for other cores within the same filter to determine if there were statistically significant differences at the 90 percent level. All analyses for the three cores in each filter for the same subsample depth, excluding outliers, were then used to determine the mean and standard deviation for the sample set representing the filter at this depth.

The media was analyzed for grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, and aluminum.

Quality control was maintained by: 1) adherence to the written laboratory procedures based on the referenced methods and instrument manufacturers instruction, 2) use of duplicates on all filter media and many aqueous samples, 3) use of spikes, replicate analyses, reagent blanks, analytical "readbacks", and 4) comparison of the results with others from the same source and with those from the other sources. The methods are summarized in Table 19. Information on the limits of detection, method detection limits, and distribution of variance between processing steps is presented in Appendix B.

The laboratories at each plant were visited at the start of the project and again near the end of the work. Communications were maintained with both plant superintendents and with the laboratory manager and sampling staff at each plant.

3.7 COSTS

3.7.1 Labor

Labor requirements for the various cleaning operations were determined by observation of the numbers of personnel and the time involved for cleaning.

3.7.2 Equipment

Equipment and personnel time were recorded at the time of the cleaning event. It should be noted that equipment at some plants might be used only for cleaning operations and remain out of service for long periods. Other plants, specifically the West Hartford plant, use the equipment daily because of the large number of filters being cleaned on a regular basis.

TABLE 19: QUALITY CONTROL METHODS.

Parameter	Lab Spike	Reagent Blanks	Replicates	Read-backs
Flow	-	NA	NA	NA
Headloss	-	NA	NA	NA
Temperature	-	Thermometer calibrated		-
pH	-	Yes	-	-
Turbidity	-	Yes	-	Yes
Particle Count	-	Yes	3	Yes
Dissolved Oxygen	-	Yes	-	-
Organic Carbon	-	1/10	2	1/10
Biodegradable Dissolved Oxygen Demand	-	1/set	2	-
UV Absorbance	-	1/10	7	-
Settleable Solids	-	-	-	-
Total and Volatile Suspended Solids	-	1/set	2	-
Coliform	-	-	-	-
Grain Size Analysis	-	-	Occasionally	-
Total and Volatile Solids	-	1/8 or more	2	1/set
Folin Reactive Material	-	3/set	2	1/set
Carbohydrates	-	3/set	3	1/set
Acriflavine Direct Count	-	3/set	2	-
Metals	Yes	1/set	2	-

3.7.3 Materials

The only materials required for cleaning operations were water, both raw and filtered, and sand where required for make-up.

3.7.4 Wastes

Wastes produced by the scraping operations consisted of the sand being removed from the filters. At some plants, this sand may be used for fill or for sanding streets. At most plants, however, the sand was stockpiled until sufficient sand was in storage to justify hydraulic cleaning operations after which the sand may be reused for make-up in other filters. It was not possible to measure the wastes from hydraulic cleaning while the filter was being resanded at West Hartford. Estimates were made based on the differences in quality between "dirty" sand being removed and the clean sand which replaced it.

Additional wastes are generated from the harrowing operations in the form of wash water. Measurements of flow volumes during the cleaning operations were made at Newport, NH using the flow meters. Measurements at West Hartford were based on the cross sectional areas and estimated mean velocity of flow in the drainage channels. Measurements of settleable and suspended solids in the wastewaters were made as discussed earlier.

3.7.4 Filter Time

Records of filter times and throughput were taken from plant records.

3.7.5 Administration

Estimates of administrative time involved with the cleaning of filters were prepared from discussions with the plant staff.

CHAPTER 4

RESULTS AND DISCUSSION FOR INDIVIDUAL PLANTS

Operating results are presented in this chapter from each of the plants visited during this study. The plants include Gorham, NH, Newport, NH, Newark, NY and the slow sand filter plant at West Hartford, CT. The design details of the individual plants are summarized in Table 20.

TABLE 20: SUMMARY OF PLANT FILTER DETAILS.

Item	Gorham, NH	Newport, NH	Newark, NY	West Hartford, CT
Year constructed	1991	1992	1951	1922,-27,-41,-53, -60
Capacity, ML/d (MGD)	3.8 (1.0)	2.6 (0.7)	7.6 (2.0) (Slow-sand filters only)	18.9 (50)
Filter sizes, meters (ft)	3-23x19 (77x64)	3-21x17 (68x56)	4-42x12 (139x39)	#1 52x43(170x140) #18 67x36(220x120) #21 82x40(270x130)
Water depth over sand, meters (ft)	1.4 (4.6)	1.5 (5.0)	1.3 (4.2)	2.0 (6.5)
Media depth, m (in) effective size,mm uniformity coef.	 0.68 (27) 0.26 1.9	 0.68 (27) 0.27 2.2	 0.91 (36) 0.39 2.5	 0.68 (27) 0.30-0.34 2.5-2.6
Application rate design, m/hr (gpm/sf) avg, m/hr (gpm/sf)	 0.12 (0.047) 0.072 (0.030)	 0.11 (0.045) 0.087 (0.035)	 0.16 (0.064) 0.16 (0.063)	 0.16 (0.064) #1 0.10 (0.040) #18 0.15 (0.062) #21 0.27 (0.11)
Empty bed contact time, design, hr.	5.7	6.2	5.7	4.2

4.1 GORHAM, NEW HAMPSHIRE

The Gorham, New Hampshire slow sand filtration facility began filtering water to waste January 21, 1991 and to the distribution system February 12, 1991. Sampling and analyses for this study were carried out from May 1992 until July 1993. The filter losses over the period of sampling increased from a low of 1.4 cm in June 1992 to a high of 48 cm in January 1993 and and then declined to 20 cm at the end of the evaluation period. The filters were not cleaned between startup and the end of sampling for this study, although cleaning was necessary in November 1993 and since that time. The data does include information on the filter performance and the accumulation of materials within the filters during this study period.

4.1.1 Raw Water Quality and Filter Performance

Tables 21 and 22 present data on raw and filtered water quality at the Gorham plant. Water samples from the raw water supply and from the individual filters were collected over the period from June 15, 1992 to July 13, 1993. Raw water turbidity ranged from 0.17 to 0.84 NTU. The pH ranged from 6.6 to 7.0 during the study period from May 1, 1993 through January 10, 1994. Concentrations of iron were below the MDL of 0.03 mg/L on all sampling events. Manganese concentrations were 0.175 and 0.168 mg/L on August 31 and November 3, 1992, respectively, but below 0.01 on all other sampling events. The data are summarized in Table 23.

TABLE 21: WATER QUALITY DATA FOR GORHAM, NH, TEMPERATURE, TURBIDITY, AND UV ABSORBANCE.

Date	Water Temp. °C	Turbidity, NTU			UV Absorbance, cm^{-1}		
		Raw	Filter 1	Filter 2	Raw	Filter 1	Filter 2
June 15, 1992	11	0.44	0.19	0.18	0.034	0.031	-
June 22	11	0.17	0.18	0.18	-	-	-
June 29	11	0.31	0.21	0.17	0.034	0.038	0.034
July 6	11	0.49	0.23	0.19	0.042	0.032	0.031
July 13	12	0.16	0.18	0.17	0.037	0.036	0.035
July 20	12	0.16	0.19	0.15	0.040	0.036	0.037
July 27	12	0.13	0.20	0.15	0.034	0.031	0.032
August 3	13	0.40	0.19	0.16	0.049	0.047	0.050
August 10	13	0.40	0.15	0.16	0.044	0.036	0.038

TABLE 21 CONTINUED ON NEXT PAGE

TABLE 21 CONTINUED

August 17	13	0.30	0.16	0.16	0.036	0.034	0.034
August 25	13	0.34	0.16	0.18	-	-	-
August 31	15	0.36	0.17	0.16	-	-	-
Sept. 9	14	0.34	0.16	0.16	0.053	0.056	-
Sept. 22	13	0.42	0.15	0.16	0.045	0.047	0.043
Oct. 7	8	0.35	0.14	0.14	0.031	0.031	0.033
Oct. 21	8	0.41	0.15	0.17	-	-	-
Nov. 3	6	0.08	0.19	0.17	0.050	0.044	0.044
Nov. 17	4	0.36	0.16	0.18	-	-	-
Dec. 15	3	0.32	0.16	0.18	0.038	0.034	0.035
Dec. 29	3	0.56	0.16	0.17	-	-	-
Jan.12, 1993	3	0.45	0.16	0.16	-	-	-
Feb. 4	2	0.35	0.09	0.08	-	-	-
Feb. 17	2	0.26	0.08	0.12	-	-	-
March 2	2	0.22	0.10	0.11	-	-	-
March 16	2	0.33	0.13	0.12	-	-	-
March 30	2	0.66	0.12	0.13	-	-	-
April 13	3	0.84	0.15	0.17	-	-	-
May 3	-	-	-	-	0.077	0.079	0.077
May 6	7	0.43	0.14	0.16	-	-	-
May 18	8	0.44	0.14	0.13	-	-	-
June 1	8	0.38	0.16	0.16	-	-	-
June 15	10	0.43	0.19	0.17	-	-	-
June 29	11	0.43	0.19	0.18	-	-	-
July 13	15	0.49	0.21	0.20	-	-	-
July 27	-	-	-	-	0.041	0.033	-
Mean(c)	-	**0.37**	**0.16**	**0.16**	**0.043**	**0.040**	**0.041**
Std.Dev.(c)	-	**0.15**	**0.03**	**0.02**	**0.011**	**0.012**	**0.012**

TABLE 22: WATER QUALITY DATA FOR GORHAM, NH, NPDOC AND BDOC.

Date	NPDOC, mgC/L			BDOC, mg/L		
	Raw	Filter 1	Filter 2	Raw	Filter 1	Filter 2
June 15,1992	1.63	1.57	1.42	-	-	-
June 22	1.53	1.4	1.56	-	-	-
June 29	1.49	1.41	1.48	0.13	0.19	0.16
July 6	1.60	1.36	1.34	-	-	-
July 13	1.69	1.43	1.28	-	-	-
July 20	1.58	1.34	1.30	-	-	-
July 27	1.20	1.06	0.99	0.16	0.10	0.06
August 3	1.66	1.85	1.72	-	-	-
August 10	1.72	1.57	1.36	-	-	-
August 17	1.10	1.09	1.11	-	-	-
August 25	1.33	1.17	1.44	-	-	-
August 31	2.00	1.70	1.60	-	-	-
Sept. 9	1.39	1.40	1.36	0.05	<0.01	0.08
Oct. 7	1.27	1.54	1.10	0.12	0.14	0.17
Oct. 21	1.98	1.79	2.14	0.25	0.10	0.34
Nov. 3	1.81	1.43	1.43	0.44	-0.07	0.03
Jan. 17, 1993	1.40	1.39	1.34	0.06	0.14	0.08
May 3	1.97	1.96	2.16	-	-	-
July 27	1.68	1.28	-	0.35	0.15	-
Mean	**1.57**	**1.46**	**1.45**	**0.20**	**0.09**	**0.13**
Std. Dev.	**0.26**	**0.23**	**0.30**	**0.14**	**0.08**	**0.10**

The filters had been in operation for the same period and treating the same volumes of water from a common supply. As expected, the data on turbidity removals for the respective filters were not significantly different between the two filters at the 90 percent confidence level, with an overall mean removal rate of 60 percent. Removals for NPDOC and UV absorbance were also essentially the same for each of the filters at the 90 percent confidence level, with mean removal rates of 6 percent for both parameters. The pilot testing carried out before the design of this plant

TABLE 23: SUMMARY OF WATER QUALITY AT GORHAM, NH.

Parameter	June 15,'92-October 21,'92, May 18,'93-July 27,'93 (Raw water temp.≥8°C)	November 3,'92-May 6,'93 (Raw water temp.<8°C)
Turbidity, NTU		
Raw	0.35 ± 0.11 (22)	0.40 ± 0.20 (n=11)
Filtered	0.17 ± 0.02 (44)	0.14 ± 0.03 (n=22)
Removals, %	56.4 ± 7.2 (44)	64.9 ± 11.6 (n=22)
NPDOC, mg/L		
Raw	1.5 ± 0.2(n=20)	1.7 ± 0.3(n=3)
Filtered	1.4 ± 0.2(n=39)	1.6 ± 0.4(n=6)
Removals, %	6.6 ± 11.3 (n=39)	6.3 ± 12.3 (n=6)
UV Absorbance, cm^{-1}		
Raw	0.040 ± 0.006(n=13)	0.052 ± 0.017(n=4)
Filtered	0.037 ± 0.007(n=23)	0.050 ± 0.019(n=6)
Removals, %	6.0 ± 9.6 (n=23)	6.6 ± 6.4 (n=6)

(Collins, 1990) had not resulted any removal of NPDOC or UV absorbance during the 190 day pilot study, indicating the possibility that the eventual removal of these parameters by the full scale facility would be low. The BDOC concentrations were generally in the range of the method detection level for the analysis for NPDOC used in the determination for BDOC indicating the assimilable carbon in the raw water supply was very low and unreliable. These concentration were generally less than 15 percent of the NPDOC as expected (Collins and Vaughan, 1993; Klevens, 1995). The extremely low values and variance of laboratory methods are believed to account for the negative values. The analytical results for BDOC were not significantly different between the inlet and the outlets of the filters over the evaluation period, averaging between 0.1 to 0.2 mg/L which was, as previously noted, in the range of the MDL for this test.

No particle counts were made on these water samples. There were no significant differences between data summarized for the periods during which the water temperatures were warmer than ≥8°C and periods during which temperatures were cooler.

4.1.2 Filter Media

Although the filters were not cleaned during the evaluation period, samples were taken on two occasions. Sample cores from this filter were difficult to extract and, while the filter was flooded, could not be taken at depths into the filter greater than the person taking the samples could reach to manually cover the lower end of the sample tube after it had been inserted to the desired depth. At the time of the May 1992 sampling, the media was also apparently "air-bound" in different locations of the filter and would not support the weight of a person walking on these isolated pockets. The water level was subsequently lowered and the filter slowly backfilled, and the media was able to support a person's weight afterward.

The surface of these filters were covered by a thick layer of schmutzdecke material unlike that observed in the other full-scale filters in this study or in the pilot-scale filters at Portsmouth, NH. In the other filters, the schmutzdecke layer visible on top of the sand media was thin and gelatinous. At Gorham, the layer was as much as one to two cm thick but similar in appearance to moss or lichen growing in a woodland environment. This layer easily separated from the surface of the media if the water above it were disturbed. The information on the media is presented in Table 24.

The data on the subsample relicates was analyzed using two-factor ANOVA methods to determine if the variation between replicates exceeded that between core subsamples by depth or that between cores at the same depth. A statistical probability of 90 percent was used for determining significance. A sample of this calculation for the July 27, 1993 analyses for volatile solids is attached in Appendix B. The results of such statistical analyses for the Gorham, NH media samples taken July 27, 1993 indicated that the variations between replicates were not significant, that the variations between cores were not significant, but the variation between depth was significant for volatile solids and FRM. The variations for carbohydrates were significant between replicates, depth, and cores, showing this analytical parameter should not be considered further for this sample event. The variations for these factors, as well as AFDC, iron, manganese, calcium, aluminum, are also summarized in Table 24.

These results were generally consistent with the data collected by Spanos (1989) indicating AFDC counts of 10^8 to 10^9 per gram dry weight in the schmutzdecke and upper 30 cm of media at the West Hartford, CT plant, Springfield, MA plant, and New Haven, CT plant, and ratios of FRM to AFDC of 0.4 to 2 x 10^{-12} g FRM per cell as counted by AFDC. The comparable results at the Gorham plant for AFDC counts were also 10^8 to 10^9 per gram dry weight in the schmutzdecke and upper 30 cm of media, but 5 to 6 x 10^{-12} g FRM per cell as counted by AFDC which was more than twice those indicated. The ration of carbohydrate to protein concentrations were in the range of 0.2 to 0.3 percent which was low relative to the 2 to 3 percent expected from the literature (Charackis and Marshall, 1990).

This information should also be considered relative to the history of the filters. The filters had been in operation only since January, 1991 and had never been cleaned. It is estimated that the annual flow of water through the filter had been approximately 1.6 ML/sm with an estimated load of 2.6 kg/sm NPDOC. The estimated NPDOC removal was six percent, or an estimated removal of less than 0.1 kg/sm. The load of turbidity and UV Absorbing materials, calculated as the NTU or UVA times the flow in ML, are estimated as 0.66x10^6 NTU units/sm and 0.08x10^6 UVA units/sm, respectively.

4.2 NEWPORT, NEW HAMPSHIRE

The Newport, New Hampshire facility was first visited in May 1993. At that time, the filters were ready to be cleaned for the first time since they had been put in operation in October, 1992. The subsequent cleaning operations were sampled through January, 1994. The filters at this plant were operated using both of the two principal cleaning methods, scraping and harrowing, to compare their effects on plant performance and media development. The evaluation period ended

TABLE 24: SAND MEDIA CHARACTERISTICS AT GORHAM, NH.

Depth below surface	Total Solids percent		FRM	Carbohydrate	AFDC	Iron	Manganese	Calcium	Aluminum
cm	Total	Volatile	mg protein/ gdw	mgC/gdw	10^6/ gdw	mg/kgdw	mg/kgdw	mg/kgdw	mg/kgdw
Filter No. 3, May 28, 1992 (Unused)									
Mixed	97.52 ±0.33	0.11 ±0.01	-	-	-	-	-	-	-
Filter No. 2, May 28, 1992 (16 months after initial flow)									
Top 1.2	77.78 ±2.00	0.77 ±0.16	-	-	-	-	-	-	-
4-7	80.86 ±1.37	0.34 ±0.12	-	-	-	-	-	-	-
15-25	80.58 ±1.89	0.15 ±0.04	-	-	-	-	-	-	-
Mean	79	0.46	-	-	-	-	-	-	-
Filter No. 2, July 27, 1993 (30 months after initial flow) Effective size = 0.26 mm, Uniformity coefficient = 1.9									
Schmutz-decke	74.73 ±4.09	1.38 ±0.34	3.72 ±1.12	0.60 ±0.15	649 ±514	2280 ±160	285 ±1	527 ±13	2160 ±40
Top 1.2	80.92 ±1.84	0.18 ±0.02	1.48 ±0.48	0.0049 ±0.0011	308 ±164	1820 ±420	40 ±1	258 ±14	1080 ±80
15- 25	80.99 ±1.08	0.12 ±0.01	0.51 ±0.16	0.0011 ±0.0002	118 ±64	1900 ±340	32 ±2	242 ±19	1030 ±40
Weighted Mean,(a)	79.41	.45	1.56	0.15	300	1980	97	317	1320

(a) Weighted mean = [(Schmutz./4) +(Level 1/4) + (Level 2/2)] in January 1994, however, before the filters could be repeatedly cleaned with the respective cleaning methods. Consequently, long-term comparative treatment performance data were limited. The data does include comparative information on the costs of the methods and on the accumulation of materials within the filters during the first year of operation.

4.2.I RAW WATER QUALITY AND FILTER PERFORMANCE-

Tables 25 through 27 present the collected data on raw and filtered water quality. Water samples from the raw water supply and from the individual filters were collected over the period from May 12, 1993 to January 10, 1994. There were no samples taken from Filter 2 after it had been harrowed except during the first 17.5 hours of ripening. Raw water turbidity ranged from 0.2 to 0.7 NTU except during the runoff periods when it reached 1.2 to 1.6 (Newport, 1993). The pH ranged from 6.6 to 7.0 during the study period from May I, I993 through January 10, I994. The data on turbidity removals for the respective filters were not significantly different between the filters at the 90 percent confidence level, with an overall mean removal rate of 80 percent. Removals for NPDOC and UV absorbance were also compared and found to be essentially the same for each of the filters at the 90 percent confidence level, with mean removal ratesof 22 percent for both parameters. The BDOC concentrations were below the MDL levels in the raw water and filter discharges.

The data showed differences were significant at the 90 percent condidence level for removal of UV absorbance between the samples before June and after November 20 which corresponded with water temperatures in the raw water supply at or above 8°C, or below 8°C. The data was separated around these dates and reanalyzed with the results presented in Table 28.

The differences between the filters in the removal of all parameters were not significant at the 90 percent level except between July and November 20 when the mean removal of particles in the Filter No. 1 were lower than those in the other two filters. None of the data contributing to this

TABLE 25: WATER QUALITY DATA FOR NEWPORT, NH, TEMPERATURE, TURBIDITY, AND PARTICLE COUNT.

Date	Water Temp. °C	Turbidity, NTU				Particle Count, per mL			
		Raw	Filter 1	Filter 2	Filter 3	Raw	Filter 1	Filter 2	Filter 3
May 12, 1993	14	0.50	-	-	-	-	-	-	-
May 19	13	0.43	0.24	0.27	0.39 (a)		-	-	-
June 27	20	0.22	0.12	0.14	0.11	5058	-	-	1890
July 23	21	0.20	-	0.12	0.10	-	-	-	-
July 27	21	0.22	0.12	0.14	0.13(a)	5058	-	1447(b)	1065(a)
Aug.31	20	0.25	0.12	0.12	0.09	3393	468	284	252
Sept.23	18	0.38	0.07	0.08	0.07	3722	283	322	320
Nov.10	8	0.59	0.20(a)	0.06	0.06	3257	876(a)	222	259
Nov.20	8	0.52	0.07	0.06	0.06	2629	315	170	205
Nov.30	7	0.52	0.06	-	0.05	3838	345	-	349
Jan.11	4.5	0.38	0.05	0.25(a)	0.14(b)	4018	499	1980(a)	1622(b)
Mean(c)	-	**0.44**	**0.07**	**0.08**	**0.07**	**3393**	**382**	**250**	**277**
Std.Dev.(c)	-	**0.12**	**0.03**	**0.03**	**0.02**	**470**	**96**	**67**	**57**

(a) Sample taken during ripening and not considered in mean and standard deviations.

(b) Sample value determined to be an "outlier" and not considered in mean and standard deviation.

(c) Mean and standard deviation computed on period of August 31, 1993 to January 11, 1994.

TABLE 26: WATER QUALITY DATA FOR NEWPORT, NH, NPDOC AND UV ABSORBANCE.

Date	NPDOC, mgC/L				UV Absorbance, cm^{-1}			
	Raw	Filter 1	Filter 2	Filter 3	Raw	Filter 1	Filter 2	Filter 3
May 12, 1993	-	-	-	-	-	-	-	-
May 19	2.28	-	-	1.78	-	-	-	-
June 27	-	-	-	-	-	-	-	-
July 23	2.50	-	1.98	1.78	0.047	-	0.039	0.037
July 26	-	-	-	-	-	-	-	-
Aug.31	2.31	1.54	1.35	1.52	0.039	0.030	0.024	0.026
Sept.23	2.63	1.64	1.98	1.94	0.040	0.029	0.032	0.030
Nov.10	2.15	1.86(a)	1.74	1.70	0.043	0.046(a)	0.043	0.043
Nov.20	2.00	1.59	1.56	1.64	0.043	0.033	0.033	0.033
Nov.30	-	-	-	-	0.043	0.037	-	0.035
Jan.11	2.12	1.96	2.13(b)	1.87	0.045	0.040	0.043(a)	0.040
Mean(c)	**2.28**	**1.68**	**1.66**	**1.74**	**0.043**	**0.034**	**0.033**	0.034
Std.Dev.(c)	**0.22**	**0.19**	**0.27**	**0.14**	**0.003**	**0.005**	**0.008**	0.006

(a) Sample taken during ripening and not considered in mean and standard deviations.

(b) Sample value determined to be an "outlier" and not considered in mean and standard deviation.

(c) Mean and standard deviation computed on period of August 31, 1993 to January 11, 1994.

TABLE 27: WATER QUALITY DATA FOR NEWPORT, NH, BDOC AND MISCELLANEAOUS PARAMETERS.

Date	BDOC, mgC/L				Miscellaneous, mg/L			
	Raw	Filter 1	Filter 2	Filter 3	Raw	Filter 1	Filter 2	Filter 3
May 12, 1993	-	-	-	-	Fe=0.01 Mn=0.019	-	-	Fe=0.00 Mn=0.000
May 19	-	-	-	-	-	-	-	-
June 27	-	-	-	-	-	-	-	-
July 23	0.24	-	0.14	0.12	Fe=0.00 Mn=0.001	-	Fe=0.01 Mn=0.000	Fe=0.00 Mn=0.002
July 26	-	-	-	-	-	-	-	-
Aug.31	0.03	-0.06	0.04	-0.22	-	-	-	-
Sept.23	0.43	0.06	0.15	0.30	-	-	-	-
Nov.10	0.13	0.14(a)	0.06	<MDL	Fe=0.07 Mn=0.037 NO_3-N=0.06 P=-0.01	Fe=0.03 Mn=0.004	Fe=0.08 Mn=0.002	-
Nov.20	0.15	0.15(c)	0.22(c)	0.08	-	-	-	-
Nov.30	-	-	-	-	-	-	-	-
Jan.11	-	-	-	-	-	-	-	-
Mean(c)	**0.11(<MDL)**	**0.05(<MDL)**	**0.08(<MDL)**	**0.04(<MDL)**	-	-	-	-
Std.Dev.(c)	**0.24**	**0.08**	**0.06**	**0.18**	-	-	-	-

(a) Sample taken during ripening and not considered in mean and standard deviations.
(b) Sample value determined to be an "outlier" and not considered in mean and standard deviation.
(c) Mean and standard deviation computed on period of August 31, 1993 to January 11, 1994.

TABLE 28: SUMMARY OF WATER QUALITY AT NEWPORT, NH.

Parameter	July-Nov.20 (Raw water temp.≥8°C.)	Nov.30-May (Raw water temp.<8°C.)
Turbidity, NTU		
Raw	0.36 ± 0.16 (n=6)	0.45 ± 0.10(n=2)
Filtered	0.09 ± 0.03(n=13)	0.05 ± 0.01(n=4)
Removals, %	70.4 ± 18.9 (n=13)	88.6 ± 1.8 (n=4)
Particles, /mL (≥1 um)		
Raw	3612 ± 900(n=5)	3678 ± 481(n=2)
Filtered	282 ± 79 (n=11)	398 ± 88 (n=3)
Removals, %	91.3 ± 2.2 (n=11)	88.9 ± 2.2 (n=3)
NPDOC, mg/L		
Raw	2.3 ± 0.3(n=3)	2.1 (n=1)
Filtered	1.7± 0.0(n=12)	1.9 ± 0.1 (n=2)
Removals, %	24.2 ± 5.3 (n=11)	10.0 ± 2.0 (n=2)
UV Absorbance, cm^{-1}		
Raw	0.042 ± 0.003(n=5)	0.044 ± 0.001(n=2)
Filtered	0.033 ± 0.006(n=13)	0.038 ± 0.002(n=4)
Removals, %	25 ± 6 (n=11)	14 ± 4 (n=4)

conclusion were obtained after that filter was scraped on November 10, 1993. When separated on the basis of raw water temperature, only the differences in removals of NPDOC and UV absorbance are significant. There were no significant diffrences in performance on removal of any of the parameters by the filters during the short period after the filters had been cleaned by different methods.

The BDOC concentrations in the raw and filtered water were below the MDL concentrations. The BDOC concentrations were approximately five percent of the NPDOC of the water which was at the low end of the ranges previously reported (Collins and Vaughan, 1993; Klevens, 1995).

Iron was present in the raw water at very low concentrations and concentrations in the effluent were below the detection level of 0.007ug/L. Manganese was present in the raw water at up to 0.037 mg/L but no more than 0.002 mg/L was found in the effluent. The concentrations of

NO_3-N and PO_4-P were 0.08 mg/L and 0.01 mg/L, respectively. These concentrations, relative to the concentration of BDOC, were 100: 72:9 which exceed the usual ratios of nutrients required for conventional satisfaction of biochemical oxygen demand on highly organic substrates, 100:5:1 (WEF, 1992) or 100:15:3 if the ratio for the oxygen demand to BDOC present is 32:12.

4.2.2 Cleaning

Filters were cleaned according to the schedule shown in Table 29 which includes the dates and cleaning methods employed.

TABLE 29: FILTER CLEANING SCHEDULE AT NEWPORT, NH.

Month	Filter 1	Filter 2	Filter 3
May 1993	5/7 (a)	5/12 (a)	5/18 (a)
June	-	-	-
July	7/22(a)	-	7/26 (a)
Aug.	-	-	-
Sept.	-	-	-
Oct.	-	10/12 (b)	10/7 (b)
Nov.	11/9 (c)	11/30 (b)	-
Dec.	-	-	-
Jan 1994	-	1/10 (d)	-

(a) Filter hand raked with cross-flow but not harrowed due to soft surface.
(b) Not wet harrowed due to soft surface, but dry harrowed to incorporate accumulated deposits.
(c) Filter cleaned by scraping.
(d) Filter cleaned by wet harrowing and dry harrowing.

Hand raking- Filter 1 was first cleaned by hand raking while a cross-flow of wash water was maintained across the filter to the effluent channel, carrying off the resuspended solids. Hand raking was used as a temporary measure since the sand surface was so soft that the tractor sunk to the depth of the axles when the operators first tried to use the tractor for wet harrowing,. The operator of the West Hartford, CT facility, the plant at which the harrowing method had been developed, was consulted and reported that the filters at that plant needed to operate for a time before the media became firm enough to support a tractor (Petraitus, 1993). Since filter cleaning was needed, a flow of 4.9 ML/m (900 gpm) of raw water was maintained across the surface of the sand to the effluent weir for the time it took for five men to hand rake the sand surface, suspending the accumulated materials and allowing the majority of the suspension to be carried over the overflow weir. The sand surface was raked twice during this time as the suspended materials would settle behind the advancing line of rakes and it had to be resuspended to get the majority of it to pass over the weir. The filter was refilled and run to waste until the next morning when it was returned to regular service. After the raking was finished, the other two filters, which had been placed on hold during the cleaning operation, were returned to service. The flow used for the cross-flow during hand raking, and later when wet harrowing, was the entire raw water flow available at the plant. The velocity of the flow across the filter during the hand raking was approximately 0.91 m/min (0.05 fps) , or 2.7 L/s/meter (13.1 gpm/ft) of filter length, with a depth of 0.18 cm (7 in).

Scraping- Filter No. I was cleaned with the scraping method on November 9, I993. On the morning a filter was to be cleaned, the supernatant water above the sand was drained from the filter to the creek. When the filter was to be scraped, the filter was further drained to several centimeters (inches) below the surface of the sand to provide a firm base for laborers to walk and for vehicles to enter to carry out scraped sand. Scraping was carried out by four shovellers and an equipment operator. For the first load, a dump trailer was used to haul sand from the filter but it was inconvenient and a tractor-mounted front-end loader was used for the rest of the cleaning event. Sand was "scraped" (removed from the filter surface) using long handled, flat blade shovels and then thrown into the bucket of the front loader, and hauled out of the filter and dumped on to a plastic sheet for temporary storage. It was planned that it would be replaced into a filter later after it was washed. The filter was refilled with filtered water from the underdrain system until the surface was up to the effluent weir, and then raw water was introduced from the inlet pipe to complete filling the filter box. The working cycle is outlined in Table 30.

TABLE 30: WORK SCHEDULE FOR SCRAPING NEWPORT FILTER 1, NOVEMBER 9, 1993.

Time interval	Activity	Labor and Equipment
7:00- 8:30	Drain filter	1 person, none
8:30- 9:15	Scraping	5 persons, loader
9:15-10:30	Smoothing surface by dragging	4 persons, tractor
10:30-15:30	Refill filter	Brief visit by 1 person.
15:30-7:30	Filter to waste	Brief visit by 1 person.
7:30	Return to service	

The total volume of sand removed was 3.2 cubic meters (4.2 cy) as measured at the dump site. No wash water was generated except for the volume of raw water drained from the filter before cleaning and the water filtered to waste. None of this water required treatment before discharge to the receiving stream.

Harrowing- Filter No. 2 was cleaned by the wet harrowing method and monitored for this study. Before the sand would support the tractor, however, the filter had to be cleaned twice without the wet harrowing step. Dry harrowing the accumulated material into the filter media hastened the rate at which the filter surface became sufficiently firm to support the tractor and allowing the wet harrowing method to proceed. The West Hartford plant uses this same procedure after a filter bed is "reconditioned" (Petraitus, 1993). There was no wastewater or waste sand generated during dry harrowing operations except while the filter was ripened over night.

The final wet harrowing/dry harrowing operation was similar to that of hand raking except a small rubber-tired tractor pulled a harrow around the filter surface while flow was maintained from the influent pipe across the filter surface to the overflow weirs. The harrow penetrated approximately 0.2 m (8 in) below the surface of the sand and suspended the accumulated materials so they could be carried to the holding pond. After the wet harrowing, the filter water level was drawn down to about 30 cm (12 in) below the surface of the sand and the surface was "dry harrowed" to smooth the sand surface. The filter was then filled with filtered water from the underdrain system until the water surface reached the overflow weir level, and then raw water was again introduced from the inlet pipe to complete filling the filter box. A small tractor was used to pull the harrow. The working cycle for the harrowed filter is presented in Table 31.

TABLE 31: WORK SCHEDULE FOR HARROWING NEWPORT FILTER 2, JANUARY 10, 1994.

Time interval	Activity	Labor and Equipment
7:30- 9:00	Drain filter	1 person, none
9:00- 9:30	Sampling media for study	NA
9:30-10:30	Wet harrowing	1 person, tractor and harrow
10:30-13:40	Drain to below sand surface	1-person, none
13:40-14:15	Dry harrowing	1 person, tractor and harrow
14:15-14:30	Smoothing surface by dragging	1 person, tractor
14:30-16:45	Refill filter	Brief visit by 1 person.
16:45-8:30	Filter to waste	Brief visit by 1 person.
8:30	Return to service	

The cross-flow during wet harrowing was at the same velocity and depth as during hand raking. The cleaning method generated 0.19 ML (51,400 gal) of water which required treatment before discharge to the receiving stream. This water was sampled every 15-minutes and analyzed for turbidity, settleable solids, and suspended solids. The results and the flows at the time of sampling are presented in Table 32. Table 33 summarizes the labor and equipment used in cleaning the filters at Newport, NH and the total volumes of wash water resulting from the different cleaning operations. The scraping and harrowing operations monitored were being performed for the first time at this plant.

TABLE 32: ANALYSES ON WASH WATER FROM WET HARROWING AT NEWPORT,NH, JANUARY 10, 1994.

Minutes from start	Flow L/m (gpm)	Turbidity NTU	Settleable Solids mL/L	Suspended Solids mg/L	UV Absorbance cm^{-1}
1	3260 (860)	42	5	117	0.044
15	3260 (860)	115	16	286	0.044
30	3260 (860)	120	10	253	0.046
45	3220 (852)	136	7	247	0.046
60	3030 (800)	46	1.2	80	0.046

TABLE 33: SUMMARY OF DATA ON CLEANING FILTERS AT NEWPORT, NH.

Cost Item	Costs			
	Scraping (Nov. 9, 1993)	Harrowing (Jan. 10, 1994)	Hand raking (May 18, 1993)	Hand raking (July 26, 1993)
Direct labor, in person-hrs	9	4	3	6.7
Administrative labor, in person-hrs	1	1	1	1
Equipment, in operating hrs	2	2	None	None
Sand, in cubic meters (cy)	3.2 (4.2)	None	None	None
Raw water drained, ML (gal)	0.515 (136,000)	0.511 (135,000)	0.511 (135,000)	0.51 (135,000)
Wash water, flow settleable solids, L (gal) suspended solids, kg (lb) suspended solids, % vol.	None	0.19(51,000) 1800(465) 43(95) 28	0.17(45,000) 602(159) 12(6) 34	0.17(45,000) 685(181) 18(8) 65
Filtered water, ML (gal)	1.0 (280,000)	0.93 (247,000)	1.38 (365,000)	1.42 (376,000)
Time out of service, hrs Actual cleaning time Total	 2(a) 24.5	 2(a) 25	 1(a) 23	 1.7(a) 23

(a) The actual time for cleaning shown is for the hours that labor is being performed and does not include time to drain supernatant water, drain filters between wet and dry harrowing, refill the filter, or ripen before returning to service.

4.2.3 Ripening

The water from the filters was monitored after most of the cleaning events to determine the rate at which the treatment performance recovered. The results are presented in Tables 35 and 36. The iron and manganese were also monitored after one cleaning event and the data, including the information on the wash water, is presented in Table 34. The data for turbidity in the water filtered to waste after each of three hand raking operations are presented in Figure 8. The data for the turbidity and particle count from the November 9, 1993 scraping operation is presented in Figure 9, and the data for the January 10, 1994 harrowing operation is presented in Figure 10. The coliform bacteria data for both the scraping and harrowing operations are shown together in Figure 11. The water quality parameters has been plotted against both the time after filtration begins, either to waste or to service, and against he number of bed volumes of filtered water which has passed through the filter. The initial volume indicated is that corresponding to the volume of the underdrain system and gravel layers.

TABLE 34: WASHWATER IRON AND MANGANESE CONCENTRATIONS FROM HAND RAKING OPERATIONS AT NEWPORT, NH, MAY 18, 1993.

Time	Iron, mg/L	Manganese, mg/L
Raw water	<0.03	0.019
Filtered effluent, before cleaning	<0.03	0.01
Composite 1, first 1/3 of Hand raking period	3.42	1.146
Composite 2, second 1/3 of Hand raking period	7.19	2.666
Composite 3, final 1/3 of Hand raking period	3.51	1.301
Composite 4, first hour of ripening period	0.05	0.017
Composite 5, second hour of ripening period	<0.03	0.005

Filtered water parameters generally increased over the time to discharge a volume of water corresponding the that in the underdrain system and gravel layer. Following hand raking

TABLE 35: RIPENING TRENDS AFTER HAND RAKING AT NEWPORT, NH.

Time, hrs	May 12, 1993 Filter 2		May 18, 1993 Filter 3					July 26, 1993 Filter 3				
	Turbidity NTU	UV Absorbance	Turbidity NTU	UV Absorbance	Coliform /100mL			Turbidity NTU	Particle Count/mL	UV Absorbance	Coliform /100mL	
					Total	Fecal	Non-				Total	Non-
Raw water	0.26	-	0.43	-	4	2	>200	0.20	5060	-	12	-
0	-	-	3.0	-	-	-	-	3.0	-	-	-	-
0.17	-	-	0.40	-	-	-	-	-	-	-	-	-
0.33	40	-	0.45	-	0	0	>200	3.0	-	-	-	-
0.5	-	-	0.45	-	-	-	-	-	-	-	-	-
0.67	-	-	0.45	-	-	-	-	-	-	-	-	-
0.83	43	-	-	-	-	-	-	-	-	-	-	-
1	-	-	0.44	-	-	-	-	-	-	-	-	-
1.33	0.52	-	0.46	-	-	-	-	-	-	-	-	-
1.67	-	-	0.44	-	0	0	27	-	-	-	-	-
1.83	0.46	-	0.45	-	-	-	-	-	-	-	-	-
2	-	-	0.45	-	-	-	-	-	-	-	-	-
2.17	-	-	-	-	-	-	-	0.15	-	-	0	TNTC
2.33	0.50	-	-	-	-	-	-	-	-	-	-	-
2.67	-	-	0.63	-	-	-	-	0.14	1056	-	0	-
3	-	-	0.55	-	-	-	-	-	-	-	-	-
3.17	-	-	-	-	-	-	-	0.13	-	-	0	TNTC

TABLE 35 CONTINUES ON NEXT PAGE

TABLE 35 CONTINUED

3.67	-	-	0.49	-	-	-	-	-	-	-	-	-
4.17	-	-	0.46	-	-	-	-	0.14	1773	-	0	TNTC
5.17	-	-	0.44	-	-	-	-	-	-	-	-	-
6.2	-	-	0.43	-	-	-	-	-	-	-	-	-
7.7	-	-	0.43	-	-	-	-	-	-	-	-	-
9.7	-	-	0.41	-	-	-	-	-	-	-	-	-
12	-	-	0.41	-	-	-	-	-	-	-	-	-
17	-	-	0.40	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	0.11	1890	-	-	-
21	-	-	0.39	-	2	1	72	-	-	-	-	-
3 day	-	-	-	-	-	-	-	-	-	-	-	-
7	0.27	-	-	-	-	-	-	-	-	-	-	-
37	-	-	0.11	-	-	-	-	0.09	252	0.026	-	-
40	-	-	0.11	-	-	-	-	-	-	-	-	-
46	0.14		-	-	-	-	-	-	-	-	-	-
59	-	-	-	-	-	-	-	0.07	320	0.030	-	-
66	-	-	0.10	0.037	-	-	-	-	-	-	-	-
69	-	-	0.13	-	-	-	-	-	-	-	-	-
72	0.12	0.039	-	-	-	-	-	-	-	-	-	-
75	0.14	-	-	-	-	-	-	-	-	-	-	-
111	0.12	0.024	-	-	-	-	-	-	-	-	-	-
134	0.08	0.032	-	-	-	-	-	-	-	-	-	-

TABLE 36: RIPENING TRENDS AFTER SCRAPING AND HARROWING AT NEWPORT, NH.

Time hrs	Scraping, Nov.9, 1993					Wet/dry harrowing, Jan.10, 1994			
	Turbidity NTU	Particle Count /mL	UV Absorbance cm^{-1}	Coliform /100mL		Turbidity NTU	Particle Count /mL	Coliform /100mL	
				Total	Non-			Total	Non-
Raw water	0.57	-	-	-	-	0.38	-	-	-
0	-	-	-	-	-	0.09	762	1	3
0.5	0.83	1636	-	5	>200	0.24	1170	7	23
0.67	-	-	-	-	-	-	-	-	-
1	1.43	-	-	8	>200	0.52	1743	10	135
1.16	1.52	-	-	-	-	-	-	-	-
1.25	-	-	-	-	-	0.72	-	-	-
1.33	1.41	2213	-	-	-	-	-	-	-
1.5	1.27	2275	-	13	>200	0.90	2418	19	151
1.78	1.05	-	-	-	-	-	-	-	-
2	0.91	-	-	-	-	1.02	2625	-	-
2.5	0.53	1261	-	9	144	1.12	2651	-	-
3	0.38	-	-	-	-	1.02	2558	43	138
3.5	0.31	869	-	0	>200	-	-	-	-
4	-	-	-	-	-	0.77	-	-	-
5	-	-	-	-	-	0.62	2003	19	60
5.5	0.24	840	-	1	>200	-	-	-	-
6	-	-	-	-	-	0.56	-	-	-
7	-	-	-	-	-	0.52	2059	12	65
17.5	-	-	-	-	-	0.25	1980	7	31
19	0.20	876	-	1	24	-	-	-	-
days	-	-	-	-	-	-	-	-	-
11	0.07	315	0.033	-	-	-	-	-	-
21	0.06	345	0.037	-	-	-	-	-	-
63	0.05	499	0.040	-	-	-	-	-	-

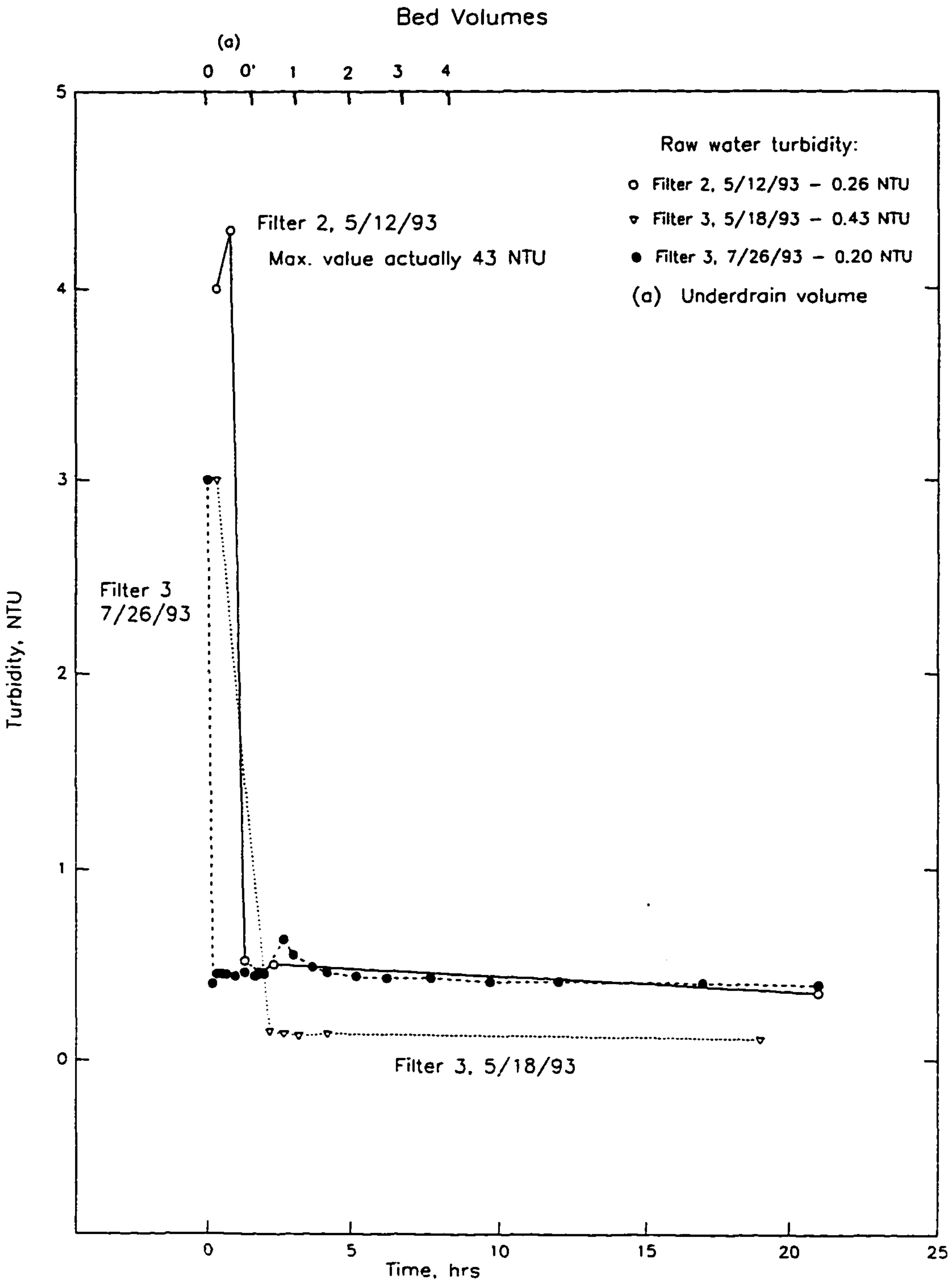


Figure 8: Ripening trends as measured by turbidity after hand raking at Newport, NH.

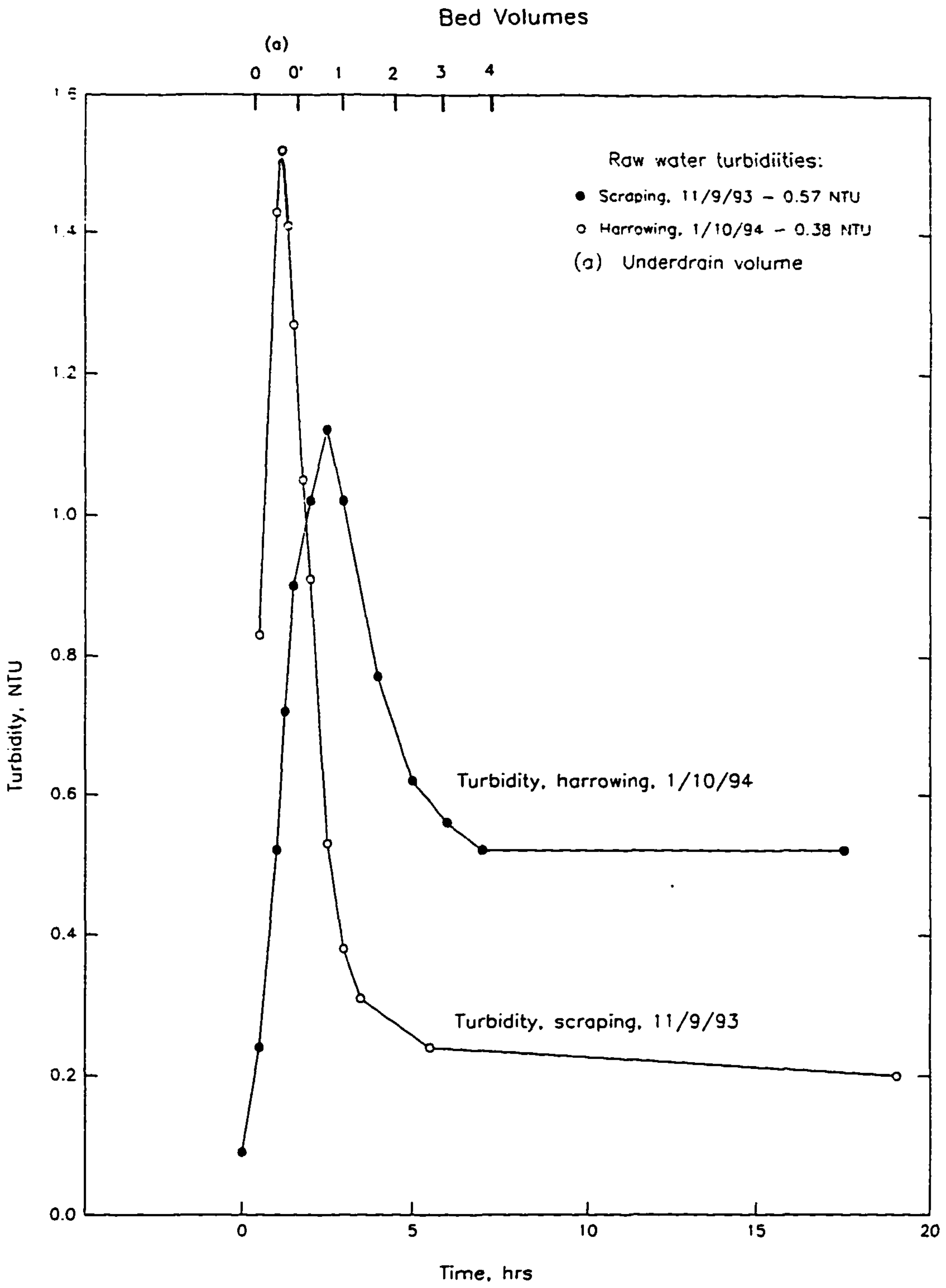


Figure 9: Ripening trends as measured by turbidity after scraping and harrowing at Newport, NH.

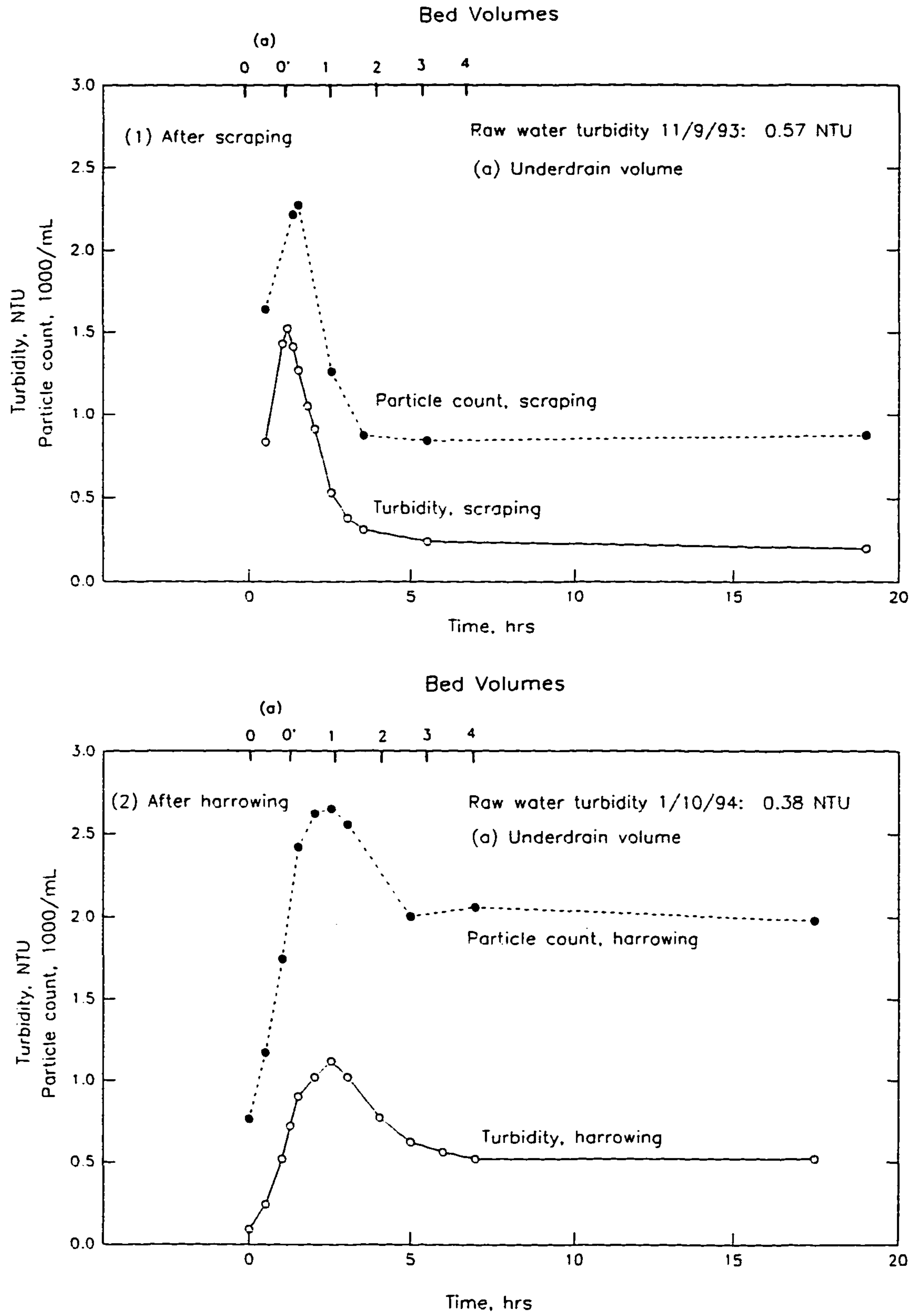


Figure 10: Ripening trends as measured by turbidity and particle count after (a) scraping and (b) harrowing at Newport, NH.

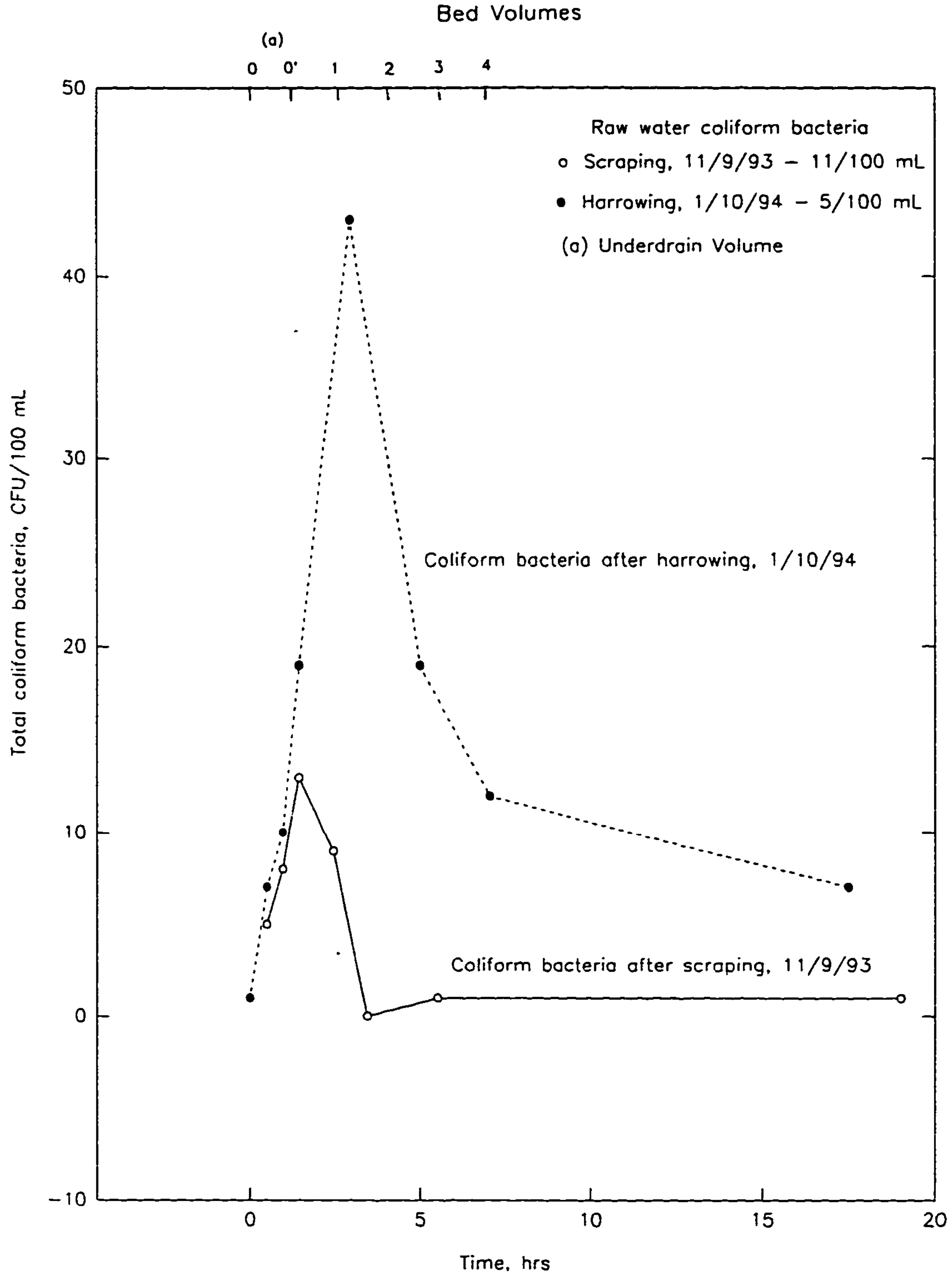


Figure 11: Ripening trends as measured by total coliform bacteria after scraping and harrowing at Newport, NH.

the filter surfaces, the turbidity rapidly declined to normal filtered water concentrations. Ripening trends for particles and coliform bacteria were not monitored following hand raking. This operation disturbed the filter media to a depth of less than one centimeter and while an reverse flow was maintained and little impact was expected.

Ripening trends after scraping and harrowing were more pronounced. Filtered water turbidities had recovered after 8 hours following hand raking or harrowing and after five hours following raking. Both turbidity and particle count were higher after harrowing than after scraping, but this data represents only the ripening period following the first time these cleaning operations were carried out on the filters. Total coliform removal recovered within about four hours after hand rakingor scraping but coliforms were still present after 17.5 hours following the first time this filter was harrowed.

4.3.5 Filter Media

Samples of the sand at different depths in the filters were taken immediately before the filters were cleaned. These data are presented in Table 37 and represent the changes in the upper 30 cm (12 in) of the filter media during the first year of operation.

Media Sampling-- The three cores taken from Filter 3 on May 18 and July 26 were separated by depth, and the subsamples at the same level of the three cores composited before analysis. The remaining filter sampling events were sampled and the subsamples at the separate depths of each core analyzed separately.

Volatile Solids-- The cores from each filter sampling event show significant differences in volatile solids concentrations between cores at different locations within the filter but no significant differences at the respective depths between the events of May 18, July 26, and November 10. The cores taken January 9, 1994 contained significantly less volatile solids at all levels in the sand

TABLE 37: SAND MEDIA CHARACTERISTICS AT NEWPORT, NH.

Depth below surface cm	Total Solids percent		FRM mg protein/ gdw	Carbohydrate mgC/gdw	AFDC 10^6/ gdw	Iron mg/kgdw	Man-ganese mg/kgdw	Calcium mg/kgdw	Aluminum mg/kgdw
	Total	Volatile							
Filter No. 2, May 18, 1993 (13 months after initial flow)									
Top 1.2	72.11 ±0.09	0.40 ±0.05	0.51 -	-	148 ±101	2350 ±85	83 ±5	304 ±34	1230 ±82
5-10	-	-	-	-	-	-	-	-	-
25-30	80.67 ±0.80	0.15 ±0.02	0.05 -	-	0.16 ±0.10	2540 ±39	61 ±1	269 ±8	1300 ±166
Weighted Mean	76.38	0.20	0.26	-	74	2440	72	287	1270
Filter No. 3, July 26, 1993 (15 months after initial flow)									
Top 1.2	81.73 ±0.46	0.36 ±0.02	4.36 ±0.96	0.0110 ±0.001	203 -	-	-	-	-
5-10	-	-	-	-	-	-	-	-	-
25-30	85.18 ±0.94	0.19 ±0.05	1.32 ±0.46	0.001 ±0.001	163 -	-	-	-	-
Weighted Mean	83.45	0.27	2.84	0.006	183	-	-	-	-

TABLE 37 CONTINUED ON NEXT PAGE

TABLE 37 CONTINUED

Filter No. 1, November 9, 1993 (19 months after initial flow) Effective size = 0.27 mm, Uniformity coefficient = 2.2									
Top 1.2	87.85 ±1.57	0.38 ±0.09	2.52 ±0.07	0.40 ±0.057	-	2680 ±121	152 ±1	235 ±38	1080 ±101
5-10	92.61 ±0.44	0.20 ±0.02	0.73 ±0.02	0.18 ±0.009	-	2640 ±132	653 ±19	252 ±14	1130 ±105
25-30	93.58 ±0.12	0.16 ±0.01	0.29 ±0.01	0.15 ±0.017	-	2030 ±68	41 ±3	208 ±33	1020 ±24
Weighted Mean,1.2 & 25-30	90.72	0.25	1.55	0.29	-	2360	96	222	1050
Weighted Mean, all	92.38	0.19	0.72	0.32	-	2420	67	233	1060
Filter No. 2, January 9, 1994 (21 months after initial flow)									
Top 1.2	81.02 ±1.98	0.18 ±0.05	0.23 ±0.10	0.052 ±0.027	-	-	-	-	-
5-10	77.98 ±0.61	0.16 ±0.05	0.31 ±0.15	0.053 ±0.028	-	-	-	-	-
25-30	78.27 ±1.22	0.11 ±0.02	0.11 ±0.08	0.015 ±0.023	-	-	-	-	-
Weighted Mean,1.2 & 25-30	79.65	0.12	0.14	0.04	-	-	-	-	-
Weighted Mean, all	78.5	0.11	0.18	0.04	-	-	-	-	-

Weighted mean = {[(Level 1 + Level 2)/2] x 7.5 cm} + {[(Level 2 + Level 3)/2] x 22.5 cm} / 30 cm
at the Gorham plant or as reported in earlier studies (Spanos, 1989). Concentrations declined before sampling in November and January.

filter than at the times of sampling in May, July, and November.

Folin Reactive Material-- The proteinaceous material in the media samples varied considerably, between cores, depths, and with season. The results of the analyses on the samples of May 18, 1993 and January 9, 1994 were consistent with each other, but there were not sufficient replicates of the May 18 analyses for statistical evaluation. Both sets of samples had been taken after several months of treating water under winter conditions, but there is insufficient evidence to confirm that cold weather operation was the cause of the lower concentrations. The FRM concentrations in the top 1.2 cm (1/2 in) and in the middle of the harrowing depth at 5-10 cm (2-4 in) were significantly higher than in the lower level just below the harrowed depth, at 25-30 cm (10-12 in), by a factor of over 4. The concentrations at the top and the mid-level were not significantly different from each other, however.

The protein content of the samples of July 26 and November 9, 1993, at all core locations and depths are significantly higher than at the time of the other samples of sand collected from "cold water" conditions. There were significant differences between the cores and between the different depths of the November 9 sampling. The difference between depths was more pronounced at the time of the November 9 sampling, by a factor of 12, than at the time of the July sampling when the top 1.2 cm was 3.4 times higher in concentration than at the 25-30 cm level.

The FRM concentrations detected in the filters were increasing between May and July. During this period, the filter surfaces were cleaning by hand raking, without scraping or harrowing, in order to promote the development of interstitial material which might consolidate the media so it would bear the weight of mechanical cleaning equipment. The development of such material was indicated by the increasing FRM. The initial concentrations in May at a depth of 25-30 cm was approximately one-tenth of the concentrations at the Gorham plant, yet they increased at both this depth and at the surface to concentrations greater than been previously reported (Spanos, 1989;

Eighmy et al. 1988).

Carbohydrates-- Carbohydrate concentrations, like the FRM concentrations, differ between cores, depths, and with time, but with less variation between them than with the FRM analyses. The concentration at the 25-30 cm (10-12 in) level did decrease after the November 9 sample as had the FRM concentration, but by only about one-third instead of the nearly 80 percent for FRM. The carbohydrate concentration at the top 1.2 cm (1/2 in) decreased by 70 percent in the same period, relative to the 90 percent reduction in FRM.

Acriflavine Direct Count (AFDC)-- The only two sets of AFDC measurements were on the early samples from May 18 and July 26, 1993. The results indicated a bacteria count of 2 x 10^8 per gram dry weight and about 0.6 x 10^{11} per gram volatile solids in the top 1.2 cm. The results at the 25-30 cm depth were not consistent, with only 0.2 x 10^6 in May and 2 x 10^8 in July, per gram dry weight of solids, and 10^8 and 10^{11} per gram volatile solids, respectively. The count per gram volatile solids at the top for both dates, and at the bottom level for the July sample appear consistent at about 0.6 to 1 x 10^{11}. The counts per gram FRM for the July sample are 5 x 10^{10} in the top 1.2 cm and 10^{11} at the 25-30 cm depth. The count per gram carbohydrate (as carbon) were 2 x 10^{13} at the top 1.2 cm and 1 x 10^{14} at the 25-30 cm depth.

Metals-- The concentrations of iron, calcium, and aluminum at the top 1.2 cm and the 25-30 cm depth did not change substantially, but the manganese concentrations increased between May and November in the top 1.2 cm (1/2 in) but not at the depth of 25-30 cm (10-12 in).

4.3 NEWARK, NEW YORK

The Newark plant was visited from August 17 to November 16, 1993 to record the costs of cleaning with the scraping method and to monitor water quality. The cleaning and resanding operations at this plant, and the ripening periods after them, have also been studied by Letterman (1985). The filters at this plant have only been cleaned by scraping. The cleaning schedule for each of the filters over the past five years is summarized in Table 38.

TABLE 38: FILTER CLEANING SCHEDULE AT NEWARK, NY.

Month	Filter 1	Filter 2	Filter 3	Filter 4
Jan. 1991	1/23	-	-	-
Feb.	-	2/26	2/28	-
Mar.	3/20	-	-	-
Apr.	-	-	-	4/3
May	5/30	5/29	-	-
June	6/27	-	-	-
July	-	7/8	7/11	-
Aug.	8/8	8/20	-	8/22
Sept.	-	-	-	-
Oct.	10/1	-	-	-
Nov.	-	11/22	-	-
Dec.	Resanded, 12/3	-	-	-
Jan. 1992	-	-	Resanded, 1/6	-
Feb.	-	2/14	-	2/6
Mar.	-	-	-	-
Apr.	-	4/22	-	-
May	-	-	-	5/13
June	6/3	6/10	6/18	6/18
July	7/7	7/8	-	-
Aug.	-	-	-	8/4
Sept.	9/2	-	9/3	-
Oct.	-	-	-	-
Nov.	-	-	-	-
Dec.	-	12/9	-	-
Jan. 1993	1/19	-	-	1/21
Feb.	-	-	2/19	-

TABLE 38 CONTINUED ON NEXT PAGE

TABLE 38 CONTINUED

Mar.	-	-	-	-
Apr.	-	-	-	-
May	-	-	-	-
June	-	6/3	6/10	6/17
July	7/8	7/29	-	-
Aug.	-	-	8/17	8/17
Sept.	-	9/23	-	-
Oct.	10/20	-	-	10/26
Nov.	-	-	-	-
Dec.	-	-	12/10	-

Resanding normally reduces the frequency of cleaning as may be seen from Table 38. Cleanings per 12 month period declined from 8/year to 3/year after resanding Filter 1, from 9/year to 4/year for Filter 2, and from 10/year to 1/year for Filter 4. Cleanings for Filter 3, on the other hand, remained the same at 2/year. All the filters had been resanded in October 1986. Filter 1 has never been rebuilt down to the drains, but Filters 2 (1979) and 3 (1980) have been entirely rebuilt and Filter 4 (1979) also had the pea stone and sand levels replaced.

4.3.1 Raw Water Quality and Filter Performance

The results of water analyses on raw and finished water samples for the slow sand filters in Newark, NY are presented in Tables 39 through 41. The water is prechlorinated at a rate of 0.5 mg/L throughout the year for algae control. All raw water samples were collected where the raw water line enters the plant, approximately 14.4 km (7.8 miles) downstream of the point of chlorination.

The raw water supply for the plant is from the northeastern side of Canandaigua Lake, one of the "Finger Lakes" in central New York. The summaries of the history, geography, hydrology,

TABLE 39: WATER QUALITY DATA FOR NEWARK, NY, TEMPERATURE, TURBIDITY AND PARTICLE COUNT.

Date	Water Temperature °C	Turbidity, NTU			Particle Count/mL		
		Raw	Filter 3	Filter 4	Raw	Filter 3	Filter 4
Aug.17, 1993	10	1.90(b)	0.13(a)	0.16(a)	23,660(b)	318(a)	744(a)
Oct.4	13	0.76	0.05	0.06	3,457	83	69
Oct.26	15	0.56	0.04	0.06	4602	49	70
Nov.16	10	-	-	-	5053	-	-
Mean	-	0.66	0.04	0.06	4,371	66	70
Std.Dev.	-	0.14	0.01	0	823	24	1
Mean Removal, %	-	-	93.1	91.0	-	98.25	98.25

(a) Sample taken during ripening and not considered in mean and standard deviations.

(b) Sample value would be considered an "outlier" except the raw water supply is known to have algae growths at this period of the year. Value not used in mean and standard deviation as they would not be comparable without data on filter effluents for the same period.

TABLE 40: WATER QUALITY DATA FOR NEWARK, NY, NPDOC AND BDOC.

Date	NPDOC, mg/L			BDOC, mg/L (c)		
	Raw	Filter 3	Filter 4	Raw	Filter 3	Filter 4
Aug.17, 1993	2.32(b)	2.14(a)	-	0.0 (a)	0.0 (a)	-
Oct.4	1.53	1.27	1.24	0.17	0.18	0.06
Oct.26	2.18	1.79	1.7	0.0	0.17	0.0
Nov.16	2.11	-	-	0.05	-	-
Mean	1.94	1.53	1.47	0.07	0.12	0.03
Std.Dev.	0.36	0.37	0.32	0.08	0.01	0.04
Mean Removal,%	-	17.5	20.5	-	Negative	32.5

See footnotes (a) and (b) with preceeding table.

(c) All values less than MDL for analysis method. Seeded glucose/glutamic acid solution (TOC = 3.0 mg/L) indicated BDOC range of 2.6 - 2.9 mg/L for these sets of analyses.

TABLE 41: WATER QUALITY DATA FOR NEWARK, NY, UV ABSORBANCE AND MISCELLANEOUS PARAMETERS.

Date	UV Absorbance, cm^{-1}			Miscellaneous, mg/L		
	Raw	Filter 3	Filter 4	Raw	Filter 3	Filter 4
Aug.17, 1993	0.030(b)	0.029(a)	-	-	-	-
Oct.4	0.106	0.078	0.097	-	-	-
Oct.26	0.032	0.027	0.027	Fe=0.03 Mn=0.005 NO_3-N=0.12 PO_4-P<0.01	Fe<0.007 Mn<0.002	Fe<0.007 Mn=0.002
Nov.16	0.028	-	-	PO_4-P=0.01	-	-
Mean	0.055	0.052	0.062	-	-	-
Std.Dev.	0.043	0.036	0.049	-	-	-
Mean Removal, %	-	21.0	12.1	-	-	-

See footnotes (a) and (b) with preceeding table.

and water quality characteristics of the lake are available (Bloomfield, 1978; Canandaigua Lake Watershed Task Force, 1994). The lake has been given an overall classification as "oligo-mesotrophic" with signs of cultural eutrophication (Canandaigua Lake Watershed Task Force, 1994). The water has a mean hardness of 128 mg/L with a mean alkalinity of 96 mg/L (both as CaCO3). The nutrient levels in the eplimnion vary seasonally due to algal activities, but those of the hypolimnion stay relatively constant (Bloomfield, 1978). The nitrate-nitrogen and soluble reactive phosphorus concentrations of raw water were reported as about 0.3 and 0.01 mg/L, respectively. Analyses on the raw water sample of October 26, 1993 indicated concentrations of 0.12 mg/L NO_3-N and less than 0.01 mg/L PO_4-P. A second analysis showed 0.01 mg/L PO_4-P, on the November 16, 1993 raw water sample. The intake is at approximately 14 meters (46 ft) (Lozier, 1947) and is within the normal range of 10 to 15 meters for the thermocline.

The only parameter to test different between filters at 90 percent significance by the Student's t-test would have been on the BDOC data but the results were below the MDL of the test and thus unreliable. It is concluded that there was no significant difference between the performances of the two filters. The mass ratio of BDOC:NO_3-N: PO_4-P is 11:10:0.5 which is sufficient to avoid nitrogen and phosphorus nutrient deficiency from these sources, and confirms the observation that organic carbon substrate is the rate limiting nutrient (WEF, 1992).

4.3.2 Cleaning Procedures

The flow to a filter was halted the evening before cleaning so that the water surface could fall to near the level of the sand surface by the next morning without wasting the supernatant water. The next morning, the filtered water line was closed and the drain opened to complete the drawdown to 2 to 3 cm (1 in) or more below the sand. The cleaning procedures used during those visits are summarized below. Filters 3 and 4 were both cleaned on August 17, 1993 and Filter 4 was again cleaned on October 27.

The scraping operation was carried out with a crew of 4 persons using a small truck refitted locally with a hydraulically operated, low-sided, dump body having a capacity of approximately 0.8 cubic meter (1.1 cy). The crew proceeded in a line over a width of about 6 meters (20 ft) down one long side of the filter with two men ahead and one on each side of the truck. The crew removed the top 1 to 2 cm (1/2 to 3/4-in.) of the schmutzdecke/sand using long-handled, aluminum, flat-blade shovels, and threw it into the dump body of the truck parked behind them. As the crew advanced, the driver periodically left his shovel, moved the truck back up to the edge of the area being scraped, and returned to his position scraping. The width of filter scraped by each crew member varied with the rate of shovelling by each member and the need to keep the line progressing in an even pattern around the truck, adjusting for the time lost by the driver. When the truck was filled, at about every 6 meters (20-ft), the truck was driven out of the filter on a concrete ramp built as part of the original plant design to dump the sand with sand saved from previous cleanings on a paved area within 30 meters (100-ft) of the ramp. The truck then returned to the scraping area and the crew resumed scraping. As the work reached the end of the filter, the work line moved to the other side of the 12 meter wide filter and worked back toward the end where they had started. When the scraping was finished, the tire marks and ridges left in the sand were smoothed by dragging a piece of wire mesh fencing with the lawn tractor. The filter was then refilled, first from the bottom with filtered water until it covers the sand, and then from the top with raw water. No water was filtered to waste before the filter was returned to service. The schedules for the cleaning operations monitored on the two occasions are outlined in Tables 42 and 43.

The volume of scraped sand was not measured due to the lack of a storage area at which the sand could be measured separately from sand from previous cleaning operations. The number of truck loads was also regarded as unsuitable due to non-uniform loads. The volume was therefore estimated on the basis of the filter area and the depth to which the sand was to be removed. No wastewater was generated except when draining the last foot of supernatant water and the water within the filter media before scraping. The data on the cleaning operations for each of the 504 sq. meter (5,420 sf) filters are summarized in Table 44.

TABLE 42: WORK SCHEDULE FOR NEWARK, NY, AUGUST 17, 1993.

Time interval	Activity	Labor and Equipment
22:00 prev. day - 7:00	Drain Filter No. 4	Brief visit, 1 person
7:15-10:45	Scraping filter	4 persons, truck
10:45-11:00	Smooth surface	1 person, tractor
11:00-14:35	Refill Filter No. 4	Brief visit, 1-person
14:35	Return Filter No. 4 to service	Brief visit, 1-person
7:00-10:45	Drain Filter No. 3	Brief visit, 1 person
10:45-14:15	Scraping filter	3.5 persons, truck
14:15-14:30	Smooth surface	1 person, tractor
14:30-21:45	Refill Filter No. 3	Brief visit, 1-person
21:45	Return Filter No. 3 to service	Brief visit, 1-person

TABLE 43: WORK SCHEDULE FOR NEWARK, NY, OCTOBER 26, 1993.

Time interval	Activity	Labor and Equipment
22:00 prev. day- 8:00	Drain Filter No. 4	Brief visit by 1 person
9:00-12:000	Scraping surface, smoothing	4 persons, truck and tractor
12:00-16:00	Refill Filter No. 4	Brief visit by 1 person.
16:00	Return to service	Brief visit by 1 person.

Letterman and Cullen(1985) found the labor requirements for scraping the Newark filters to be half that of the median for the 7 central New York plants studied, and that the labor requirements varied with the depth of sand removed and the type of equipment used to remove the sand. The data from this study essentially confirmed the level of effort he reported for this plant, although the specific equipment used to haul sand had been changed from a motorized buggy to a small, dump-body truck.

TABLE 44: SUMMARY OF DATA ON CLEANING FILTERS AT NEWARK, NY.

Cost Item	Costs			
	Aug.17 Filter 4	Aug.17 Filter 3	Oct.26 Filter 4	Letterman (1985)
Direct labor, person-hrs	16	12	13	10.5
Administrative labor, person-hrs	1	1	1	Not reported
Equipment, operating hrs				
Truck	3.5	3.5	3	2
Tractor	0.5	0.5	0.5	0.5
Sand, in cubic meters (cy)	9.2 (12)	9.2 (12)	9.2 (12)	6.1 (8)
Raw water drained, ML (gal)	0.151 (40,000)	0.151 (40,000)	0.151 (40,000)	Not reported
Wash water, flow	None	None	None	None
Filtered water, L (gal)	None	None	None	None
Time out of service, hrs				
Actual cleaning time (a)	3.8	4.1	3	2.2
Total	8	13	18	24

(a) The actual time shown is the time that labor is being used in cleaning the filter and does not include time to drain supernatant water or refill the filter. No ripening time was required.

4.3.3 Ripening

The flow from both filters was monitored after cleaning on August 17, 1993. The changes in water quality occurring after cleaning are presented in Table 45. The bed volumes of water filtered during the sampling period were calculated and are shown with Figures 12 and 13. No analyses were run for NPDOC, UV absorbance, or coliform bacteria in 1993. The turbidity and particle count results substantiate that no ripening period was necessary, although coliform testing should be performed periodically to reconfirm ripening is unnecessary. This conclusion also confirms that of Letterman (1985), although that report found ripening was necessary after a filter was resanded. The turbidities in the filtered water after scraping are presented in Figure 12, including the data by Letterman (1985). The turbidity and particle count for each of the ripening periods are presented in Figure 13. As previously noted in this study and by Letterman, there is no

TABLE 45: RIPENING TRENDS AFTER SCRAPING AT NEWARK, NY.

Time	August 17, 1993 Filter 3		August 17, 1993 Filter 4		August, 1983 Filter 1 (Letterman, 1985)		
hrs	Turbidity NTU	Particle Count/mL	Turbidity NTU	Particle Count/mL	Turbidity NTU	Particle Count/mL	Stnd. Plate Count/mL
Raw	1.9	23,660	1.9	23,660	3.0	-	4
0.17	0.20	1,077	0.20	2,330	0.35	-	3
0.75	0.20	869	-	-	-	-	-
1	-	-	-	-	0.35	-	16
1.5	0.17	730	-	-	-	-	-
2	-	-	-	-	0.45	982	27
2.25	-	-	0.19	1,571	-	-	-
3	-	-	-	-	0.40	-	25
3.25	-	-	0.20	1,632	-	-	-
4	-	-	-	-	0.35	483	9
5	-	-	-	-	0.35	-	2
6	-	-	-	-	0.35	-	2
7	-	-	0.19	1,589	0.23	-	12
8	-	-	0.18	1,267	0.30	-	7
10	0.13	318	-	-	0.23	199	3
12	-	-	-	-	0.25	329	2
14	-	-	-	-	0.2	-	7
16	-	-	-	-	0.2	622	27
17	-	-	0.16	744	-	-	-
20	-	-	-	-	0.25	-	380
1 day	-	-	-	-	0.25	-	12
2	-	-	-	-	0.25	-	12
49	0.05	-	0.06	-	-	-	-
76	0.04	49	0.06	70	-	-	-

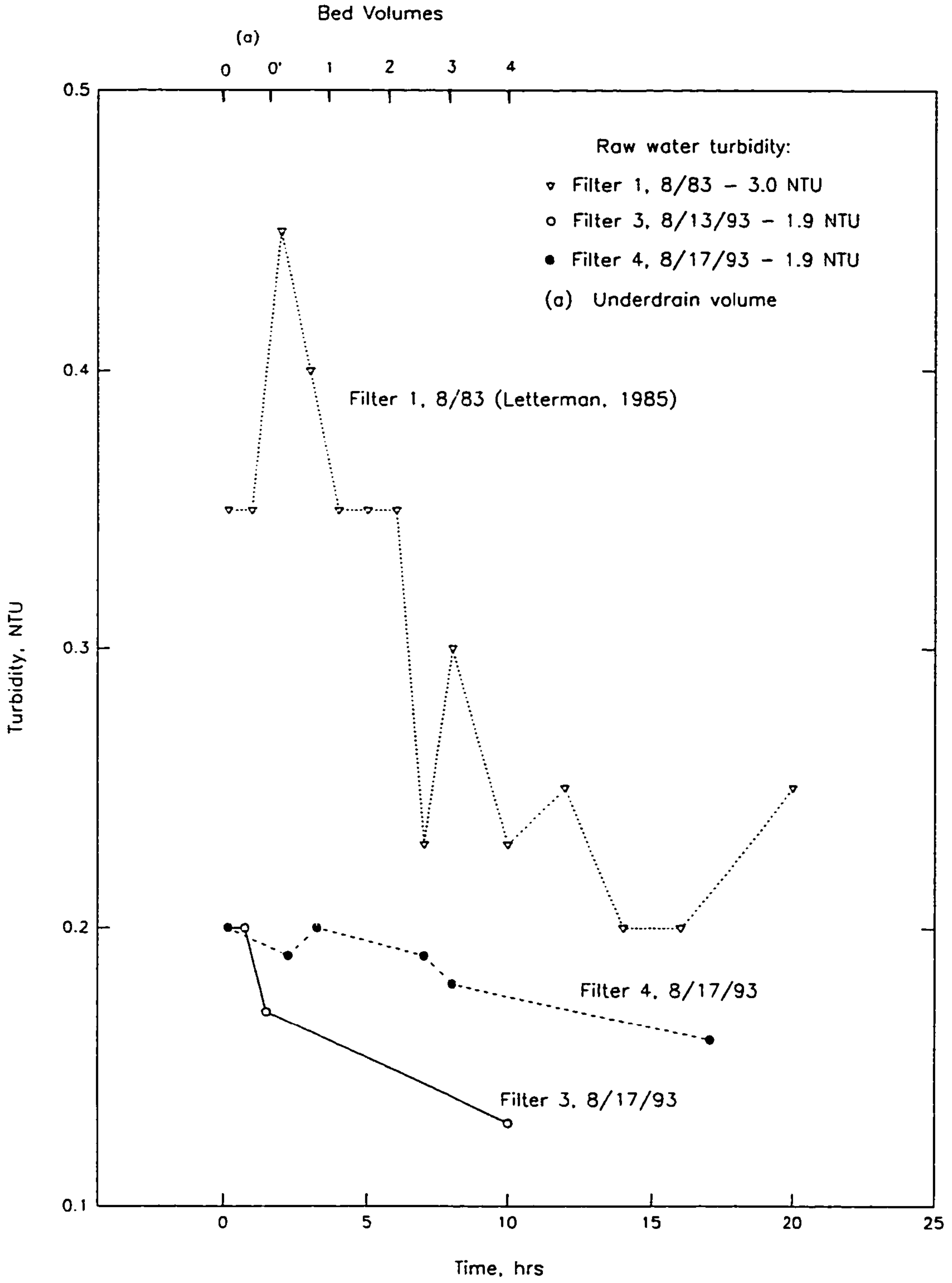


Figure 12: Ripening trends as measured by turbidity after scraping at Newark, NY.

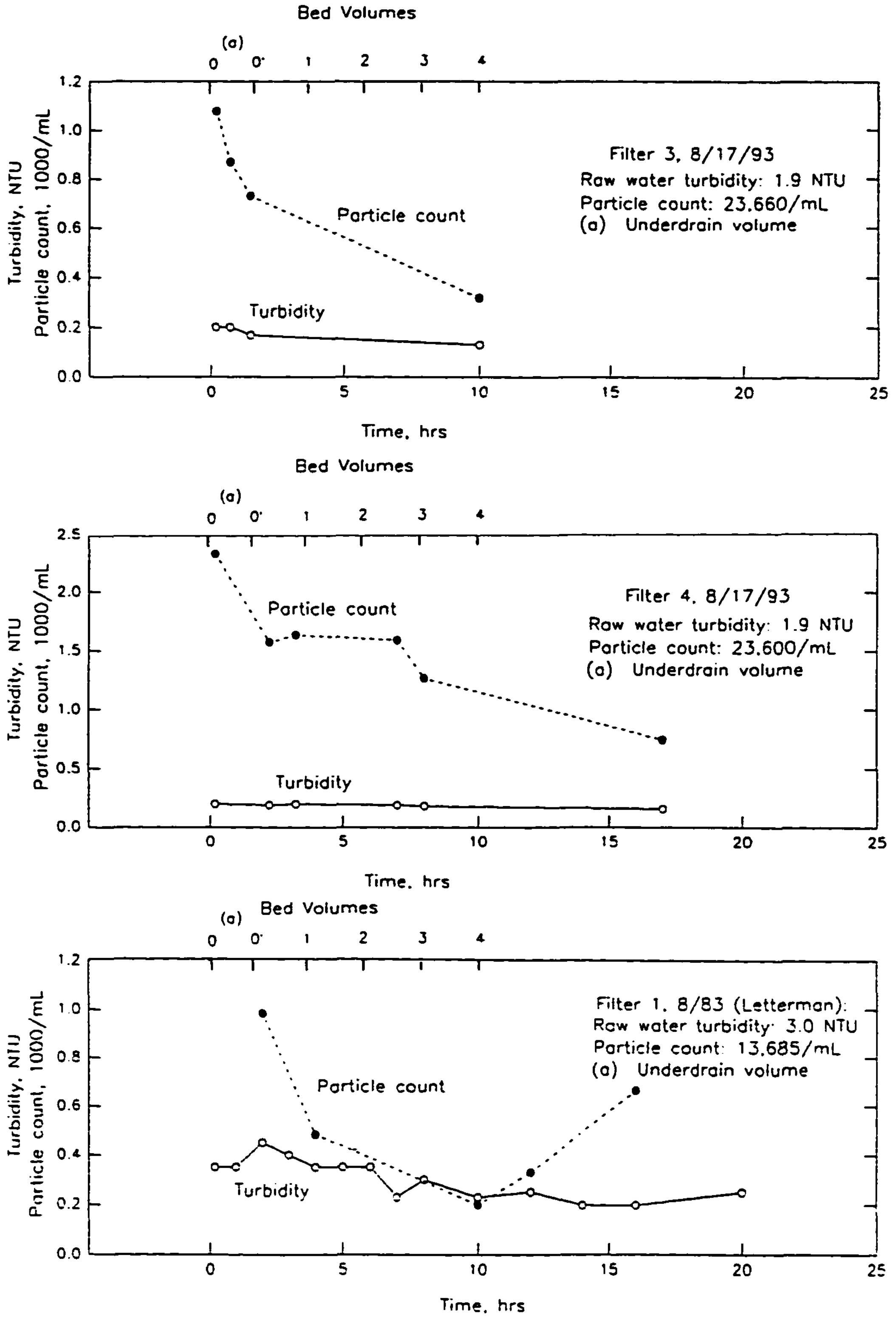


Figure 13: Ripening trends as measured by turbidity and particle count after scraping at Newark, NY.

ripening at this plant after a filter is scraped as based on the turbidity data. The particle count data, however, indicats that there is a further increase in the removal rate over the ripening period even though the particle count on the filtered water is always well below the count on the raw water. Head losses through the filter also decline by 0.1 m (0.3 ft) over a period of several days of operation after a filter is scraped and reaches their minimum about 3 to 5 days after being returned to service.

4.3.4 Filter Media

Filters 3 and 4 were cored for samples at the top 1.2 cm (1/2 in) and for the interval between 25-30 cm (10 and 12 in) at the time they were scraped August 17. Filter 4 was again cored and sampled on October 27, 1993. A summary of the analytical results are presented in Table 46.

Sand-- The sand used in the filters was a local natural sand and was purchased without a limit on acid-soluble materials. Letterman found (1985) that the weight loss in the sand dissolution test was 36 percent, instead of the maximum of 5 percent permitted under AWWA Standard B100. The effective sizes and uniformity coefficients in Filter 4 are also different from the 1985 results for Filter 1, 0.39 mm and 2.2, respectively, instead of the 0.35 mm and 1.7, respectively, reported by Letterman and Cullen (1985) but the filters have been resanded several times since that earlier study.

Volatile Solids-- The volatile solids concentrations of the samples were compared by 2-factor ANOVA. The results indicated that the variations between the filters at the same depth were not significant at the 90 percent level but the variation with depth, between the top 1.2 cm (1/2 in) and the 25-30 cm (10-12 in) depth, was significant. A single factor ANOVA analysis of the data within each filter indicated that the variation between cores was not significant for Filter 4, but was significant at 99 percent for the cores from Filter 3. The volatile solids concentrations in all levels

TABLE 46: SAND MEDIA CHARACTERISTICS AT NEWARK, NY.

Depth below surface	Total Solids percent		FRM	Carbohydrate	AFDC	Iron	Man-ganese	Calcium	Aluminum
cm	Total	Volatile	mg protein /gdw	mgC/gdw	10^6/ gdw	mg/kgdw	mg/kgdw	mg/kgdw	mg/kgdw
Filter No. 3, August 17, 1993 (19 months after resanding)									
Top 1.2	87.21 ±1.86	1.04 ±0.20	1.26 ±0.40	0.15 ±0.04	180 ±25	9100 ±1030	486 ±26	97700 ±2350	4480 337
5-10	-	-	-	-	-	-	-	-	-
25-30	91.05 ±0.85	0.85 ±0.12	0.56 ±0.34	0.06 ±0.01	46 ±16	9440 ±961	533 ±90	109000 ±7550	4130 174
Weighted Mean	89.18	0.94	0.91	0.10	114	9270	510	103400	4300
Filter No. 4, August 17, 1993 (39 months after resanding)									
Top 1.2	84.68 ±2.26	1.23 ±0.12	1.91 ±0.19	0.13 ±0.05	184 ±24	-	-	-	-
5-10	-	-	-	-	-	-	-	-	-
25-30	91.04 ±0.79	0.84 ±0.12	0.41 ±0.20	0.06 ±0.01	42 ±10	-	-	-	-
Weighted Mean	87.86	1.04	1.16	0.09	113	-	-	-	-

TABLE 46 CONTINUED ON NEXT PAGE

TABLE 46 CONTINUED

Filter No. 4, October 26, 1993 (41 months after resanding)

Top 1.2	85.73 ±1.29	1.32 ±0.13	2.21 ±0.25	0.39 ±0.07	8 ±6	11000 ±584	624 ±99	92200 ±5980	5110 ±102
5-10	92.69 ±0.67	0.93 ±0.07	0.63 ±0.03	0.12 ±0.01	2 ±1	8850 ±837	502 ±35	11400 ±2500	3890 ±629
25-30	92.16 ±0.85	0.93 ±0.18	0.72 ±0.11	0.11 ±0.02	0.7 ±0.1	9210 ±88	425 ±31	96400 ±4570	3970 ±711
Weighted Mean, 1.2 & 25-30 cm	89.04	1.12	1.55	0.56	4.47	10100	524	94300	4540
Weighted Mean, all	91.66	0.97	1.07	0.63	2.29	9270	488	104000	4080

Grain size analysis: Effective size = 0.39 mm, Uniformity coefficient = 2.5

Weighted mean = $\frac{\{[(\text{Level 1} + \text{Level 2})/2] \text{ x } 7.5 \text{ cm}\} + \{[(\text{Level 2} + \text{Level 3})/2] \text{ x } 22.5 \text{ cm}\}}{30 \text{ cm}}$, or as appropriate for the number of levels.

of Core 3 from that filter were significantly lower than in Cores 1 and 2. The significant difference between levels in the cores taken from Filter 4 on October 26 occurred between the top 1.2 cm (1/2 in) and the 5-10 cm (2-4 in) depth and not between the 5-10 cm (2 to 4 in) and the 25-30 cm (10 to 12 in) depth.

Folin Reactive Material (FRM)-- Results for protein content were similar to that for volatile solids concentration. The concentration differences were not significant on an overall basis between filters or between cleaning dates but the variation between levels was significant whether based on dry weight or volatile solids. Differences in FRM concentrations with depth were predominately in the change between the top 1.2 cm (1/2 in) and the 5-10 cm (2 to 4 in) level and not between the 5-10 cm (2 to 4 in) and the 25-30 cm (10 to 12 in) levels. FRM concentration increased between the 5-10 cm (2 to 4 in) level and the 25-30 cm (10 to 12 in) level rather than decreasing as had volatile solids concentrations. The variation between filters was not significant. Variations between cores within each filter were not significant except in filter 3 where results for Core 2 were atypical, rather than Core 3 which had been atypical for volatile solids concentrations. The concentration in the Newark, NY filters were similar to the concentrations determined for the West Hartford, CT filters by Spanos (1989).

Carbohydrates-- The carbohydrates data indicated significant differences in concentrations between filters and between depths within filters. The differences between filters occurred between the August and October sampling events for Filter 4 and which indicated the concentrations of carbohydrate at both top and bottom levels increased over the time period. The difference between depths was significant in the data from all three samplings but the data from the October 26 cleaning indicated the predominant change was between the top 1.2 cm (1/2 in) and the 5-10 cm (2 to 4 in) level and not between the 5-10 cm (2 to 4 in) and the 25-30 cm (10 to 12 in) levels. This agrees with the results for volatile solids and FRM, as the schmutzdecke material is included in the top 1.2 cm (1/2 in) of material. A comparison between the cores for the individual filters indicated that the differences between cores in each filter were not significant except between the cores of Filter 4 taken in October, for mgC/g dry wt for which Core 2 was at higher concentrations as it had been also for FRM concentrations.

Acriflavine Direct Counts (AFDC)-- The counts per gram volatile solids, FRM, and carbohydrate are summarized in Table 47. The bacteria population is lower in the October samples in comparison with those in August, in the filters at Gorham and Newport, and in the filters reported by Spanos (1989). Those AFDC results for the October samples were also low with respect to the concentrations of FRM for October as indicated by the ratios of FRM to AFDC in the range of 10^{-10} rather than the more typical ratio of 10^{-12} for the August analyses of samples from the Newark plant and the Gorham and Newport plants. The ratio of 10^{-12} grams FRM per AFDC was also similar to the ratio s reported by Spanos (1989) and Eighmy et al. (1988). The ratios of carbohydrate to FRM were within reasonable ranges (Charackis and Marshall, 1990) for all three

TABLE 47: MEAN AFDC PER UNIT SOLIDS, AND RELATIVE CONCENTRATIONS BETWEEN FRM, CARBOHYDRATE AND AFDC FOR NEWARK, NY.

Depth below surface, cm	AFDC per gram dry weight	AFDC per gram volatile solids	gram FRM per AFDC	gram carbohydrate, as C, per gram FRM
Filter No. 3, August 17, 1993				
Top 1.2	$2x10^8$	$2x10^{10}$	$7x10^{-12}$	0.12
25-30	$5x10^7$	$6x10^9$	$1x10^{-11}$	0.11
Filter No. 4, August 17, 1993 (39 months after resanding)				
Top 1.2	$2x10^8$	$2x10^{10}$	$1x10^{-11}$	0.07
25-30	$4x10^7$	$5x10^9$	$1x10^{-11}$	0.15
Filter No. 4, October 26, 1993 (41 months after resanding)				
Top 1.2	$8x10^6$	$7x10^8$	$3x10^{-10}$	0.18
5-10	$2x10^6$	$2x10^8$	$3x10^{-10}$	0.19
25-30	$7x10^5$	$8x10^7$	$1x10^{-9}$	0.15

sampling dates and so it must be presumed the October analyses for AFDC were should not be considered reliaable.

Metals-- Each of the metal concentrations in all samples and all depths are generally constant, showing no strong associations with depth or filter. The calcium concentration is high due to the use of "calcium sand" in the filters at this plant.

4.4 WEST HARTFORD, CONNECTICUT

The initial plan was to study the performance and cleaning of filters which had sand of varying ages since they had been reconditioned. The sand had been in the filters since being reconditioned as summarized in Table 48. The filters have been cleaned with the harrowing process since the mid-1950's. The cleaning cycle for each of the 22 filters is normally just over once a month.

TABLE 48: HISTORY OF WEST HARTFORD, CT FILTERS.

Filter No.	Year reconditioned	Years since reconditioning
1	1974	19
18	1980	13
21	1993	<1

4.4.1 Raw Water Quality and Filter Performance

The results of water analyses on the raw and finished water samples during the project study period are presented in Tables 49 through 51. Analysis of the data was divided between two raw water temperature conditions, $\geq$ 8°C and <8°C. The raw water can enter this plant from either of two reservoirs or as a mixture. The three influent conditions were analyzed separately for the major parameters and compared to determine if the quality was significantly different. Similarly, the removal of turbidity, particles, etc. for the filters were calculated based on the respective

TABLE 49: WATER QUALITY DATA FOR WEST HARTFORD, CT, TEMPERATURE, TURBIDITY, AND PARTICLE COUNT.

Date	Water Temp. °C	Turbidity, NTU				Particle Count/mL			
		Raw	Filter 1	Filter 18	Filter 21	Raw	Filter 1	Filter 18	Filter 21
Sept.26,'92	17	-	-	-	-	-	-	-	-
Nov.16	10	-	-	-	-	-	-	-	-
Dec.14	-	-	-	-	-	-	-	-	-
Jan.26,'93	4	-	-	-	-	27,008	-	952	-
Sept.15	21	1.08	-	0.12(a)	0.13(a)	10,136	-	-	-
Sept.16	18	-	-	-	-	-	-	318(a)	395(a)
Oct.5	16	-	-	-	-	-	-	-	-
Oct.6	16	-	-	-	-	6,202	344(a)	348	66
Oct.11	14	-	-	-	-	-	-	-	-
Oct.12	14	1.00	0.05	0.05	-	-	-	-	-
Oct.14	14	1.15	0.02	-	0.05	9,630	-	-	-
Oct.16	14	0.97	0.05	0.05	0.05	-	-	-	-
Oct.29	12	0.58	0.02	0.01	0.06	-	-	-	-
Nov.2	11	0.83	0.02	0.01	0.03	5,770	41	10	174
Nov.8	10	0.68	0.05	0.05	0.05	-	-	-	-
Nov.15	9	0.68	0.05	0.05	0.05	-	-	-	-
Nov.16	-	-	-	-	-	5,714	-	-	-

(a) Sample taken during ripening and not considered in mean and standard deviations.

(b) Analytical result considered an "outlier" and not considered in mean and standard deviations.

TABLE 50: WATER QUALITY DATA FOR WEST HARTFORD, CT, NPDOC AND BDOC.

Date	NPDOC, mg/L				BDOC, mg/L			
	Raw	Filter 1	Filter 18	Filter 21	Raw	Filter 1	Filter 18	Filter 21
Sept.26,'92	2.8	1.5	1.7	-	0.8	0	0.1	-
Nov.16	2.5	2.0	-	-	0.4	-0.8(b)	-	-
Dec.14	2.3	-	-	-	-0.6(b)	-	-	-
Jan.26,'93	2.1	-	1.7	-	0.0	-	-	-
Sept.15	2.2	-	1.3	1.3	-	-	-	-
Sept.16	-	-	-	-	-	-	-	-
Oct.5	1.2	0.7	0.8	0.8(a)	0.3	0.1	0.1	.1
Oct.6	-	-	-	-	-	-	-	-
Oct.11	-	-	-	1.2	-	-	-	-
Oct.12	-	-	1.2	-	-	-	-	-
Oct.14	1.7	1.1	-	-	0.2	-	-	-
Oct.16	-	-	-	-	-	-	-	-
Oct.29	1.7	1.0	1.0	1.3	-	-	-	-
Nov.2	1.5	1.0	1.0	1.1	0.0	0.0	-0.1	0.0
Nov.8	-	-	-	-	-	-	-	-
Nov.15	-	-	-	-	-	-	-	-
Nov.16	1.6	-	-	-	-0.1	-	-	-

(a) Sample taken during ripening and not considered in mean and standard deviations.
(b) Analystical result considered an "outlier" and not considered in mean and standard deviations.

TABLE 51: WATER QUALITY DATA FOR WEST HARTFORD, CT, UV ABSORBANCE AND MISCELLANEOUS PARAMETERS.

Date	UV Absorbance, cm^{-1}				Miscellaneous, mg/L				
	Raw	Filter 1	Filter 18	Filter 21	Parameter	Raw	Filter 1	Filter 18	Filter 21
Sept.26,'92	0.064	0.044	0.034	-	Samples of October 18, 1993.				
Nov.16	0.058	0.03	-	-	Fe	0.10	0.22	0.03	0.02
Dec.14	-	-	-	-	Mn	0.052	0.005	0.002	0.001
Jan.26,'93	0.056	-	0.056	-	PO_4, as P	0.01	<MDL	<MDL	<MDL
Sept.15	0.049	-	0.014(a)	0.035(a)	Samples of October 25, 1993.				
Sept.16	0.048	-	0.022	0.030	NH_3-N	0.040	<MDL	0.03	<MDL
Oct.5	0.037	0.02	0.021	0.026	NO_3-N	0.002	0.03	0.03	<MDL
Oct.6	-	-	-	-	-	-	-	-	-
Oct.11	-	-	-	-	-	-	-	-	-
Oct.12	0.035	0.02	0.02	0.022	-	-	-	-	-
Oct.14	-	-	-	-	-	-	-	-	-
Oct.16	-	-	-	-	-	-	-	-	-
Oct.29	0.043	0.022	0.021	0.033	-	-	-	-	-
Nov.2	0.043	0.026	0.025	0.031	-	-	-	-	-
Nov.8	-	-	-	-	-	-	-	-	-
Nov.16	0.045	-	-	-	-	-	-	-	-

(a) Sample taken during ripening.

raw water supply to the filter and compared. The results of the analysis, using the tests for outliers, variance, and differences between mean values, were at the 90 percent confidence levels as established for the project. The results of the comparisons are presented in Table 52.

TABLE 52: SUMMARY OF WATER QUALITY PARAMETERS AT WEST HARTFORD, CT.

Parameter	Raw water temp.≥8°C.	Raw water temp.<8°C.
Turbidity, NTU		
Raw	0.82 ± 0.24 (n=37)	0.50 ± 0.11(n=12)
Filtered	0.05 ± 0.02 (n=33)	0.11 ± 0.06(n=11)
Removals, %	93.3 ± 3.4	76.9 ± 13.5
	Not significant between filters.	Not significant between Filters 1 & 18, no data on Filter 21.
Particles,/mL (≥1 um)		(a)
Raw	6999 ± 2081(n=7)	27088
Filtered	128 ± 138 (n=5)	962
Removal, %	98 ± 2 (n=5)	96
	Not significant between filters.	Insufficient data.
NPDOC, mg/L		(a)
Raw	1.9 ± 0.6(n=17)	2.1 ± 0.1(n=2)
Filtered	1.2 ± 0.3(n=16)	1.7
Removal, %	34 ± 13 (n=16)	18
	Not significant between filters.	Insufficient data.
UV Absorbance, cm^{-1}		(a)
Raw	0.045 ± 0.007(n=17)	0.056 ± 0.006(n=2)
Filtered	0.024 ± 0.006(n=17)	-
Removal, %	43 ± 11 (n=17)	-
	See discussion	
BDOC, mg/L (<MDL)		(a)
Raw	0.1 ± 0.2 (n=12)	0.1
Filtered	0.0 ± 0.1 (n=9)	0.1
Removal, %	-	0.0
	Not significant	
Iron, mg/L		(a)
Raw	0.09 ± 0.05(n=3)	0.08
Filtered	0.02 ± 0.01(n=6)	0.01
Removal, %	77 ± 20 (n=6)	88
	Not significant between filters.	Insufficient data.
Manganese, mg/L		
Raw	0.060 ± 0.016(n=3)	0.023 ± 0.001(n=2)
Filtered	0.004 ± 0.006(n=3)	0.003 ± 0.002(n=4)
Removal, %	95 ± 7 (n=3)	88 ± 7 (n=4)
	Not significant between filters.	Not significant between filters.

(a) Only data for this parameter at <8°C was from samples on January 23, 1993.

The differences in raw water quality as measured at the different filters were not significant and the data from the separate sources could be combined for the period of the data for this study. The removal efficiencies of the several filters were also not significantly different except for the removal of UV absorbance between Filters 1 (46±4 percent), 18 (51±11 percent) and Filter 21 (34±8 percent) during the September to November period. These removals compare favorable with those reported from mean results in 1987 (Spanos, 1989) as shown in Table 53.

TABLE 53: COMPARISON OF 1993 RESULTS COMPARED WITH RESULTS BY SPANOS (1989).

Parameter	1993 Results		SPANOS (1989)	
	Raw water temp.≥8°C.	Raw water temp.<8°C.	Sept.24, 1987 (Raw water temp.>8°C.)	Feb.11, 1987 (Raw water temp.<8°C.)
Turbidity, NTU				
Raw	0.82	0.50	0.50	0.50
Filtered	0.05	0.14	0.15	0.25
Removal, %	93	77	70	50
NPDOC, mg/L				
Raw	1.86	2.15	2.26	1.82
Filtered	1.18	1.70	1.56	1.22
Removal, %	34	18	31	33
UV Absorbance, cm^{-1}				
Raw	0.045	0.056	0.056	0.042
Filtered	0.024	0.056	0.032	0.032
Removal, %	43	7	43	24
Iron, mg/L				
Raw	0.09	0.07	0.38	0.1
Filtered	0.02	0.01	0.04	<0.1
Removal, %	77	88	90	-
Manganese,mg/L				
Raw	0.060	0.024	0.08	0.05
Filtered	0.004	0.003	0.01	0.02
Removal, %	95	88	88	60

The filters sampled in 1987 had last been renovated in 1974 and 1972 (13 and 15 years before they were sampled), respectively, which was between the ages of Filters 1 and 18 which were sampled in 1993. The data confirm the high levels of removal for NPDOC and UV absorbance at this plant relative to that at the other plants studied (Fenstermacher, 1988; Spanos, 1989; Eighmy et al, 1991). The filter with the lowest removal of UV absorbance was the filter which had been renovated less than one year before sampling, as opposed to Filters 18 and 1 which had not been renovated in 13 and 19 years, respectively, and which was operating at an application rate of twice that of Filters 1 and 18.

4.4.2 Cleaning

The schedule for cleaning West Hartford Filters 1, 18, and 21 during the study period are given in Table 54. The first cleaning operations to be monitored were on Filters 18 and 21. Filter

TABLE 54: CLEANING SCHEDULE FOR WEST HARTFORD, CT.

Filter 1	Filter 18	Filter 21
9/16-7/92	9/17-8/92	9/24-5/92
10/14-5/92	10/23-4-5/92 (Dry harrowed 3x)	10/29-30/92 (Began reconditioning)
11/12-3/92	-	-
12/15-6/92	12/1-2/92	-
1/25-6/93	-	-
2/27-8/93	2/10-1/93	-
3/30-1/93	3/9-10/93	-
4/30-5/1/93	4/1-3/93 4/27-8/93	(Returned to service, 4/26/93)
5/27-8/93	-	5/24/93 (dry harrowed)
6/29-30/93	6/21-2/93	-
7/27-8/93	7/16-7/93	-
8/29-30/93	8/10-2/93	8/2-3/93
-	9/12-4/93	9/14/93
10/5-6/93	10/13-4/93	10/12-3/93
11/2-3/93	11/19-20/93	11/29-30/93
12/16-7/93	12/17-8/93	12/27-8/93

18 had been wet harrowed on September 12, but there was a power failure at 9:30 AM on the 13th which stopped the exhaust ventilators and prevented dry harrowing that day. As a result, dry harrowing had to be delayed until the 14th and the time for it was reduced so that Filter 21, which did not need intensive cleaning before returning to service, could also be dry harrowed the same day and both filters returned to service as quickly as possible to meet the needs of a community water shortage. Filter 18 was cleaned again on October 13, 1993, with a normal dry harrowing operation. The schedule outlined in Table 55 has been put together using the combined information from the two dates.

TABLE 55: SEPT 15/OCT.13, 1993 WORK SCHEDULE FOR WEST HARTFORD FILTER 18.

Time interval	Activity	Labor and Equipment
3:00- 8:00	Drain filter	Brief visit by 1 person
8:00-10:00	Move tractor into filter	2 persons, tractor and harrow
10:00-15:30	Wet harrowing	2 persons, tractor and harrow
15:30- 8:00	Drain to below sand surface	-
8:00-10:20	Dry harrowing	2 persons, tractor and harrow
10:30-16:00	Refill filter	Brief visit by 1 person.
10:30-16:00	Move equipment	2 persons, tractor and harrow
16:00	Return to service at 1.9 ML/d	Brief visit by 1 person.
8:00	Increase to normal flow	Brief visit by 1 person.

The wash water was sampled on October 14 from the filter drain. The flow rate was estimated by measuring the cross section of the stream channel receiving the flow and surface velocity measurements made across the stream. The surface velocity of segments of stream width were related to the mean velocities (Chow, 1959). There was no velocity in the stream channel before the wash water flow was initiated. The measurements for flow rate were labor-intensive and could not be taken for each sample but were taken at two separate times during the cleaning event and the results averaged. The wash water flow from this 2,250 sq. meter (24,200 sf) filter contained 5.5 ML (1.45 MG) of water, 12,700 liters (3,360 gal) of settleable solids, and 357 kg (785 lb) of suspended solids which were 44 percent volatile. The cross-flow in this filter was 0.38 m deep and had a calculated velocity of 0.65 meter/min (0.036 fps).

As noted above, the cleaning of Filter 21 scheduled for the September 15, 1993 was changed due to a water shortage in the service area. The wet harrowing was eliminated and only the dry harrowing phase was used. Filter 21 was cleaned again on October 12, 1993 following the normal procedures. The schedule in Table 56 outlines the information combined from these two events.

TABLE 56: SEPT.15/OCT.12, 1993 WORK SCHEDULE FOR WEST HARTFORD FILTER 21.

Time interval	Activity	Labor and Equipment
3:00- 8:30	Drain filter	Brief visit by 1 person
8:30-10:30	Move tractor into filter	2 persons, tractor and harrow
10:00-16:10	Wet harrowing	2 persons, tractor and harrow
16:10- 8:00	Drain to below sand surface	-
8:00-15:10	Dry harrowing	2 persons, tractor and harrow
15:20-21:00	Refill filter	Brief visit by 1 person.
15:10-16:00	Move equipment	2 persons, tractor and harrow
21:00	Return to service at 3.8 ML/d	Brief visit by 1 person.
8:00	Increase to normal flow	Brief visit by 1 person.

As for the data on Filter 18 taken October 13, the wash water flow from the wet harrowing operation was estimated by measuring the cross section of the receiving stream channel and measuring the surface velocity. There was a flow in the stream prior to the harrowing operation and that flow was first estimated and then subtracted from the flow rate during the cleaning operation, 0.071 cubic meters/s (2.1 cfs) of the total 0.35 cubic meters/s (12.5 cfs). Samples had to be taken from the stream as there was no other point to be used. The loading was estimated on the total flow as the stream flow was clear before cleaning began. There was no upflow through the filter during the wet harrowing operation according to the flow meter. The total wash water load from the six hours of wet harrowing was calculated to be 6.5 ML (1.7 MG) water containing 26,800 liters (7,080 gal) of settleable solids and 612 kg (1,346 pounds) of suspended solids which were 34 percent volatile. The cross-flow velocity was calculated to be 0.62 meters/min. (0.034 fps) and was about 0.38 m (15 in) deep.

Filter 1 was cleaned October 5, 1993 following a schedule similar to those for filters 18 and 21. The wash water produced during the wet harrowing operation was sampled. The flow was estimated by measuring the cross section area of the flow in the drain channel in the filter building and its surface velocity as described earlier. Unlike the arrangements for introducing the wash water during wet harrowing Filters 18 and 21, Filter 1 is an older filter which does not have flow channels along the long sides for inlet and outlet of the cross-flow. Instead, raw water must be introduced from the inlet corner of the filter to a depth of about 0.3 m (1 ft), the flow turned off, and the drain located in the same corner is opened to draw the water back with the resuspended materials produced while the tractor harrows. This operation results in a continuing variation in the rate of wash water flow and characteristics. The cross-flow velocity varied from zero to about 1 m/min (3 fps) across the area of the filter and over the time to drain off the surface.

The calculated total wash water load was 0.33 ML (87,000 gal) containing 5,200 liters (1,380 gal) of settleable solids and 120 kg (260 lb) of suspended solids which were 37 percent volatile. Filter 1 was again cleaned on 11/2/93 after cores had been collected but the wash water flow was not monitored. The load and its flow pattern are presented in Table 57. The information collected on the cleaning operations for the filters is presented in Table 58.

4.4.3 Ripening

The filtered water from the filters was monitored after several of the cleaning events to determine the rates at which the removal performance recovered. The results of these analyses

TABLE 57: WASH WATER FROM WEST HARTFORD FILTER 1, OCTOBER 5, 1993.

Time	Flow rate Liters/sec.	Turbidity NTU	Settleable Solids mL/L	Suspended Solids	
				mg/L	% Volatile
11:10	28	130	7	177	37
11:30	28	>200	28	782	36
12:00	6	45	0.1	80	44
12:30	0	36	0.4	50	46
13:00	0	-	-	-	-
13:25	28	170	13	292	38
14:00	28	57	1.5	103	41
14:30	0	-	-	-	-
14:49	26	>200	26	472	38
15:10	28	>200	50	992	37
15:45	6	50	<0.01	84	38
16:10	0	39	<0.01	63	48

are presented in Table 59. The data on turbidity for all three ripening periods are presented in Figure 14. The data for turbidity and particle count for each of the ripening periods are presented in Figure 15. The data on total coliform for all three ripening periods are presented in Figure 16. The number of bed volumes of water passing through the filters in these times were also calculated and this information is shown in the figures.

There was a ripening effect on each of these filters after the cleaning events. Although turbidities, particle counts, NPDOC, and UV absorbance are consistently below raw water concentrations throughout the period after the filters are returned to service, total coliform counts have increased and at least 4 to 8 hours of filtering is needed before the count returns to levels below the 1 to 2 counts per mL present in the raw water. Two to four hours (three to five bed volumes) are also needed before the turbidity, particle count, and UV absorbance return to the

TABLE 58: SUMMARY OF DATA ON CLEANING FILTERS AT WEST HARTFORD, CT.

Cost Item	Costs			
	Filter 1 2,250 sq meters (24,200 sf)	Filter 18 2,250 sq meters (24,200 sf)	Filter 21 3,260 sq meters (35,100 sf)	Average/100 sq meters (/1000 sf) (b)
Direct labor, in labor-hrs (a)	14	14	21	0.79 (0.58)
Administrative labor, in labor-hrs	2	2	2	0.08 (0.07)
Equipment, operating hrs				
Truck	0	0	0	0
Tractor	7	7	10.5	0.31 (0.29)
Sand, in cubic meters (cy)	None	None	None	None
Raw water drained, ML (gal)	None	None	None	None
Wash water, flow, ML (gal)	0.33 (87,000)	5.5 (1,450,000)	6.5 (1,700,000)	0.22 (5,130)
settleable solids, L (gal)	5,200 (1,380)	12,700 (3,360)	26,800 (7,080)	690 (180)
suspended solids, kg (lb)	120 (260)	357 (785)	612 (1,350)	18 (38)
suspended solids, % vol.	37	44	34	38
Filtered water, L (gal)	None	None	None	None
Time out of service, hrs	Not recorded			
Actual cleaning time (a)		7	11.2	0.32 (0.30)
Total time		32	36.5	34

(a) The actual hours of labor spent cleaning the filters are shown but the actual time cost is higher, to allow for the time to drain supernatant water before cleaning, drain the filter between wet and dry harrowing, and move equipment between filters and the assignment of personnel by standard shift lengths. The assigned time for cleaning is 32 person hours.

(b) The wash water load averages are based on Filter 18 and 21 which have inlet and outlet channels for the wash water. The percent volatile solids are based on the average of all filters.

TABLE 59: RIPENING TRENDS AFTER HARROWING AT WEST HARTFORD, CT.

Time hours	Turbidity NTU	Particle Counts /mL	NPDOC mg/L	UV Absorbance cm^{-1}	Coliform bacteria /100 mL	
Filter 18, Sept. 15, 1993. Wet and dry harrowing on same day.					Total	Non-
Raw water	1.16	10,136	2.0	0.046	2	-
0.17	0.21	187	-	-	0	560
0.50	0.21	-	-	-	-	-
1.0	0.16	135	-	-	-	-
1.5	0.40	-	-	-	-	-
2.0	0.19	130	-	-	3	480
4.0	0.17	138	1.3	0.019	2	230
6.0	0.10	124	1.3	0.018	2	212
8.0	0.10	110	1.1	0.021	5	180
18.7 (a)	0.12	318	1.5	0.030	1	350
21 days	-	348	0.84	0.021	-	-
Filter 21, Sept.15, 1993. Dry harrowed only.						
Raw water	0.99	10,100	2.3	0.050	1	-
0.33	0.47	-	1.8	0.035	2	1200
0.50	0.40	-	-	-	-	-
1.25	0.32	690	2.3	0.031	-	-
1.5	0.26	-	-	-	-	-
2.0	0.26	523	1.5	0.029	0	880
4.0	0.19	427	1.3	0.026	2	660
14.0	0.14	395	1.3	0.030	1	460
21 days	-	66	0.85	0.026	-	-

TABLE 59 CONTINUED ON NEXT PAGE

TABLE 59 CONTINUED

Filter 21, Oct.13, 1993. Normal cleaning cycle.

Raw water	1.26	-	-	-	1	TNTC
0.25	0.25	-	-	-	5	TNTC
0.75	0.21	336	-	-	5	180
1.25	0.11	496	-	-	3	240
1.75	0.11	-	-	-	2	180
2.25	0.10	-	-	-	2	250
4.25	0.11	-	-	-	0	190
13.75	0.05	-	-	-	0	67
16 days	0.06	-	1.30	0.033	-	-
20 days	0.03	174	1.13	0.031	-	-

(a) This sample was taken shortly after filter rate had been increased from 1.9 to 3.8 ML/d.

normal ranges for filtered water. Instead of returning filters to operation immediately after cleaning, a ripening period would be appropriate for normal operation. As at all plants, however, total coliform tests should be performed on the first filtered water sent to the system as a minimum check on the adequacy of water quality.

4.4.4 Filter Media

Cores were taken of the filter media prior to cleaning operations and analyzed at the UNH laboratory. Results of the analyses are summarized in Table 60. The data given in the table are the means of values from laboratory replicate analyses for each of the cores, and calculated as:

$$\text{weighted mean} = \frac{\{[(\text{Level 1} + \text{Level 2})/2] \times 7.5\ \text{cm}\} + \{[(\text{Level 2} + \text{Level 3})/2] \times 22.5\ \text{cm}\},}{30\ \text{cm}} \quad (5)$$

or as appropriate for number of levels sampled.

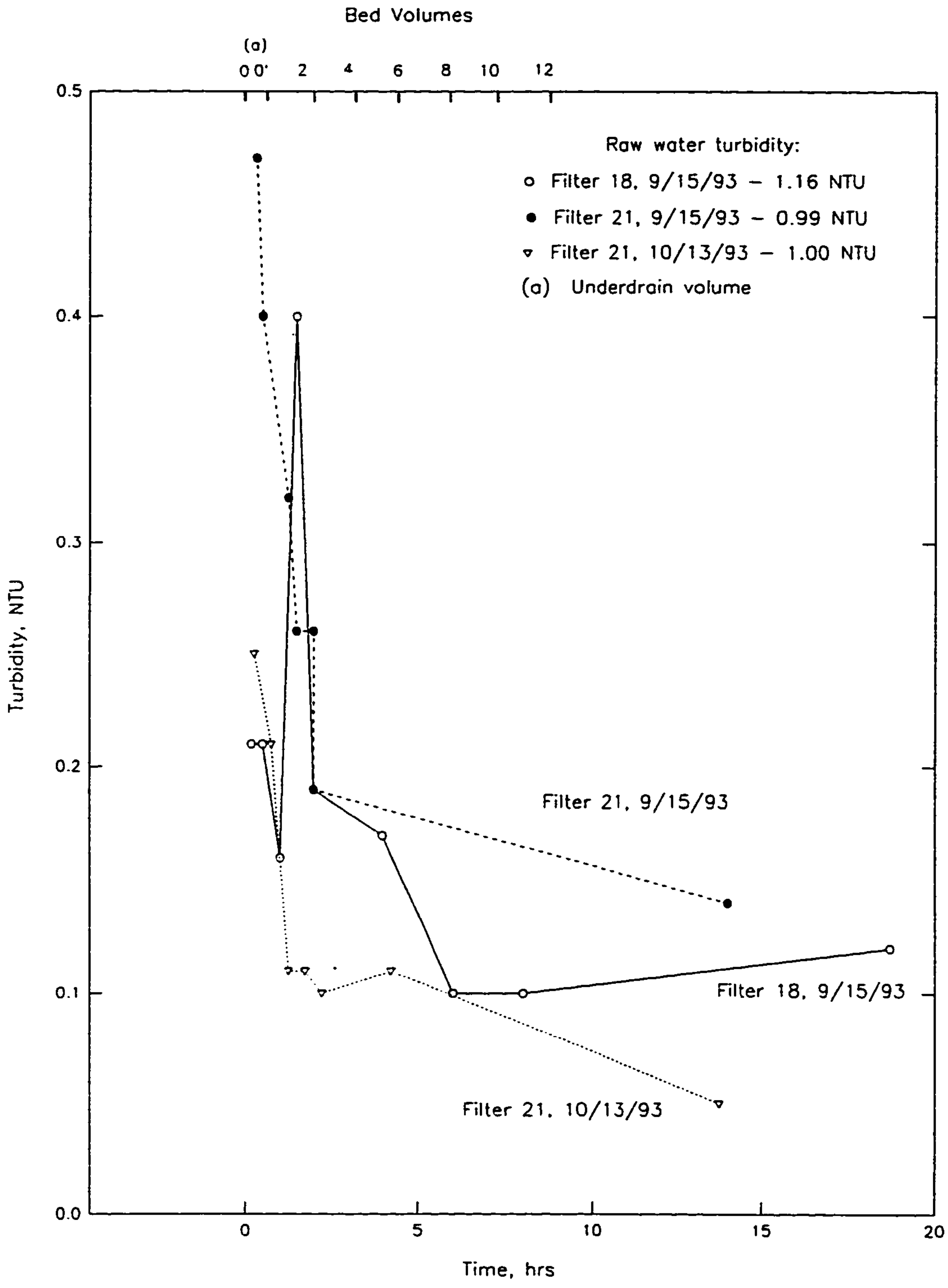


Figure 14: Ripening trends as measured by turbidity after harrowing at West Hartford, CT.

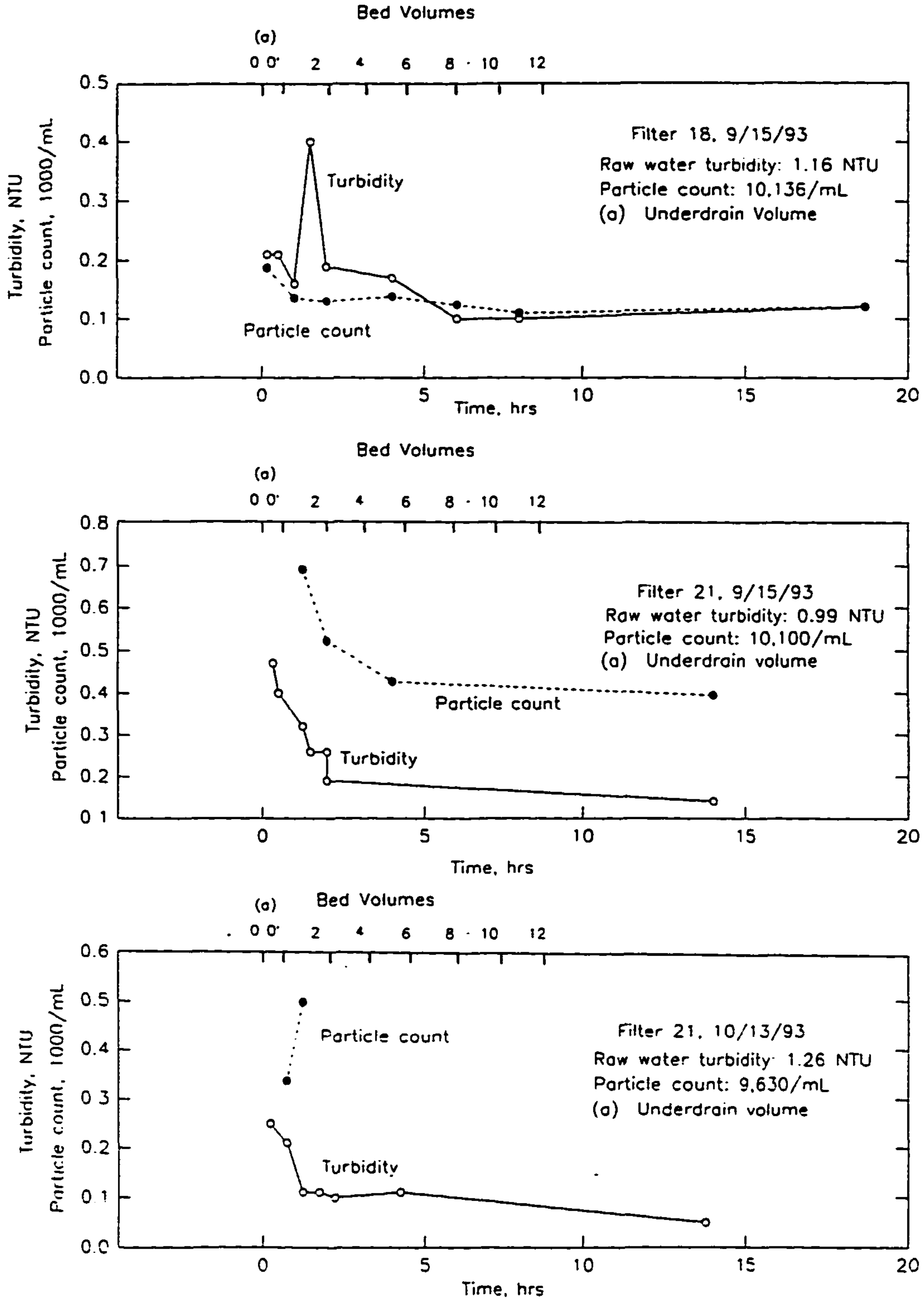


Figure 15: Ripening trends as measured by turbidity and particle count after harrowing at West Hartford, CT.

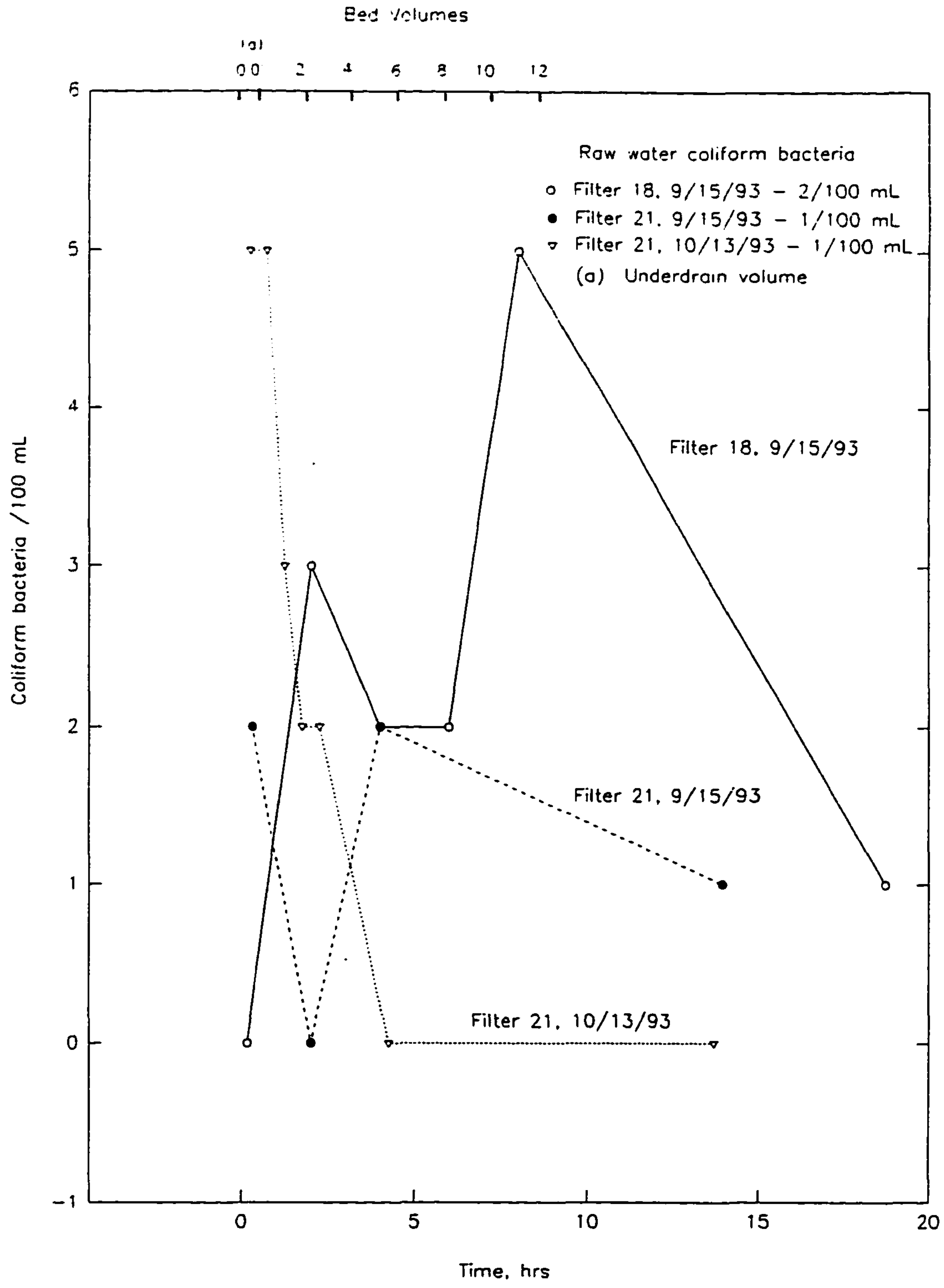


Figure 16: Ripening trends as measured by total coliform after harrowing at West Hartford, CT.

TABLE 60: SAND MEDIA CHARACTERISTICS AT WEST HARTFORD, CT.

Depth below surface cm	Total Solids percent		FRM mg protein /gdw	Carbohydrate mgC/gdw	AFDC 10^6/ gdw	Iron mg/kgdw	Man-ganese mg/kgdw	Calcium mg/kgdw	Aluminum mg/kgdw
	Total	Volatile							
Filter 21, January 26, 1993. Reconditioned sand. Effective size = 0.34 mm, Uniformity Coeff.= 2.6.									
Mixed	95.76 ±0.14	0.23 ±0.04	-	-	-	2390 ±604	184 ±29	245 ±45	1660 ±191
Filter 21, September 15, 1993. Before cleaning. (7 months after resanding)									
Top 2.5	74.09 ±3.65	0.65 ±0.13	2.05 ±0.68	0.24 ±0.13	143 ±5	-	-	-	-
5-10	-	-	-	-	-	-	-	-	-
25-30	82.92 ±2.26	0.34 ±0.04	0.45 ±0.06	0.033 ±0.004	97 ±47	-	-	-	-
Weighted Mean, 0-30	77.50	0.50	1.25	0.14	120	-	-	-	-
Filter 21, October 12, 1993. Before cleaning. (8 months after resanding)									
Top 1.2	74.09 ±0.92	0.75 ±0.06	2.24 ±0.47	0.26 ±0.02	92 ±8	4200 ±83	899 ±1	480 ±37	1670 ±99
5-10	-	-	-	-	-	-	-	-	-
25-30	80.92 ±1.84	0.29 ±0.02	0.21 ±0.02	0.063 ±0.013	16 ±11	2790 ±6	177 ±8	486 ±127	1530 ±86
Weighted Mean, 0-30	77.50	0.52	1.22	0.16	54	3500	538	483	1600

TABLE 60 CONTINUED ON NEXT PAGE

TABLE 60 CONTINUED

Filter 21, October 13, 1993. After cleaning. (8 months after resanding)									
Top 1.2	95.03 ±0.76	0.39 ±0.10	0.34 ±0.18	0.020 ±0.002	22 ±2	-	-	-	-
5-10	-	-	-	-	-	-	-	-	-
25-30	95.23 ±0.38	0.28 ±0.08	0.22 ±0.24	0.16 ±0.02	7 ±6	-	-	-	-
Weighted Mean, 0-30	95.13	0.34	0.28	0.09	14	-	-	-	-
Filter 18, October 13, 1993. Before cleaning. (162 months after resanding)									
Top 1.2	74.46 ±.	0.65 ±0.09	1.40 ±0.15	0.27 ±0.05	99 ±81	4300 ±414	581 ±33	318 ±51	1670 ±222
5-10	-	-	-	-	-	-	-	-	-
25-30	81.36 ±0.34	0.67 ±0.02	1.08 ±0.21	0.037 ±0.014	52 ±48	4580 ±442	187 ±2	413 ±19	2030 ±421
Weighted Mean, 0-30	77.91	0.66	1.24	0.15	76	4440	384	366	1850
Filter 18, September 15, 1993. After wet harrowing. (162 months after resanding)									
Top 2.5	95.84 ±0.26	0.29 ±0.02	0.68 ±0.14	0.052 ±0.005	56 ±39	-	-	-	-
5-10	-	-	-	-	-	-	-	-	-
25-30	87.40 ±0.54	0.56 ±0.05	1.38 ±0.44	0.18 ±0.02	17 ±18	-	-	-	-

TABLE 60 CONTINUED ON NEXT PAGE

TABLE 60 CONTINUED

Weighted Mean, 0-30	91.62	0.42	1.03	0.12	36	-	-	-	-
Filter 1, January 26, 1993. Before cleaning. (220 months after resanding)									
Top 5.0	94.34 ±0.04	0.38 ±0.04	-	-	-	-	-	-	-
5-10	-	-	-	-	-	-	-	-	-
25-30	88.81 ±0.01	0.48 ±0.01	-	-	-	-	-	-	-
38-53	88.51 ±0.07	0.52 ±0.08	-	-	-	-	-	-	-
Weighted Mean, 0-30	90.39	0.43	-	-	-	-	-	-	-
Filter 1, October 5, 1993. Before cleaning (228 months after resanding). Effective size = 0.30 mm, Uniformity Coeff.= 2.5.									
Top 1.2	83.14 ±2.40	0.67 ±0.07	1.93 ±0.62	0.19 ±0.03	123 ±78	4200 ±226	559 ±42	392 ±102	1890 ±199
Top 2.5	85.29 ±2.54	0.60 ±0.06	1.38 ±0.74	0.16 ±0.04	126 ±53	-	-	-	-
5-10	-	-	-	-	-	-	-	-	-
25-30	85.18 ±5.07	0.60 ±0.10	0.83 ±050	0.12 ±0.04	54 ±29	4060 ±1540	329 ±22	206 ±50	1430 ±319
Weighted Mean,1.2 & 25	84.16	0.64	1.38	0.15	88	4130	444	299	1660

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Filter 1, November 2, 1993. Before cleaning. (229 months after resanding)									
Top 1.2	83.16 ±1.48	0.47 ±0.09	0.99 ±0.33	0.17 ±0.04	-	4270 ±142	494 ±10	270 ±23	1640 ±204
5-10	85.92 ±5.19	0.43 ±0.06	0.54 ±0.23	0.12 ±0.06	-	3470 ±892	347 ±15	246 ±24	1570 ±215
25-30	83.10 ±1.47	0.67 ±0.06	1.09 ±0.22	0.30 ±0.06	-	4880 ±622	287 ±26	427 ±169	2710 ±338
Weighted Mean, 1.2 & 25	84.06	0.57	0.87	0.19	-	3870	420	258	1600
Weighted Mean, all	84.52	0.52	0.80	0.19	-	4100	342	316	2010
Filter 19, March 3, 1994. After wet/dry harrowing and during reconditioning. (259 months after resanding) Effective size = 0.32 mm, Uniformity Coeff.= 3.0.									
Top 1.2	-	-	-	-	-	-	-	-	-
5-10	95.56 ±1.12	0.36 ±0.05	0.58 ±0.16	0.082 ±0.046	-	3170 ±788	276 ±30	411 ±68	1260 ±239
25-30	89.63 ±0.92	0.58 ±0.02	1.68 ±0.07	0.22 ±0.05	-	4880 ±457	98 ±11	593 ±101	2010 ±256
41-46	92.79 ±0.38	0.38 ±0.02	0.94 ±0.22	0.10 ±0.01	-	4660 ±543	91 ±12	649 ±132	1990 ±154
56-61	89.61 ±1.68	0.37 ±0.05	0.77 ±0.21	0.098 ±0.020	-	4080 ±442	81 ±10	670 ±341	1850 ±215
Weighted Mean, all	90.34	0.52	1.19	0.19	-	4120	134	592	1810

Volatile Solids-- Analyses for total and volatile solids at different depths in the cores taken from the respective filters showed significant variance at the 90 percent level between cores, depths, and filters. The concentrations at the top 1.2 cm of the filters sampled were approximately the same immediately before the filters were cleaned. This concentration was not related to the length of time since the filter had been reconditioned. The volatile solids concentrations at the 25-30 cm depth of the filters did increase over time since the filters had been reconditioned, from a mean of 0.23 percent in the sand after reconditioning to 0.58 to 0.67 percent after 19 to 24 year of operation. The concentrations in the intermediate depth of 5-10 cm (2-4 in) were lower than in the top or lower levels.

The concentration differences between the top 1.2 cm (1/2 in) and top 5 cm (1 in) of cores taken from Filter 1 on October 5, 1993 were not significantly different. The concentration of volatile solids in the top 1.2 cm (top 1/2 in) and at the depth of 25-30 cm (10-12 in) in Filter 1, sampled in January 1993,were lower than at the same depths and in the same filter in October and in November of the same year. This was evident in Filter 18 media, sampled in October, which had operated 66 months less than Filter 1. Folin Reactive Material-- The concentration of protein in the separate samples varied significantly between cores within a filter, between depths in the cores, and between filters. The samples of January 1993 had not been analyzed for FRM so there was no basis for comparison between seasons. Such differences had been reported by Spanos (1989), who also found that there were differences relative to media depth in a filter and between filters at different plants. No differences were reported by Spanos between FRM concentrations in cores from the same filter or between filters at the same plant. Significant differences also were found in this study in FRM concentrations with the age of sand following reconditioning.

The effects of cleaning were also significantly different in FRM concentration in the upper 30 cm (12 in) of filter media between cores taken before and after harrowing. As indicated in Table 50, the mean FRM concentration in Filter 21 was reduced from 1.22 mg/g dry wt before cleaning to 0.92 mg/g dry wt after cleaning in October 1993. The mean concentration in the upper 30 cm (12 in) of Filter 18 was reduced from 1.24 mg/g dry wt to 1.03 mg/g dry wt after wet harrowing

The FRM concentration, per gram volatile solids, did not vary significantly in the top 1.2 cm 91/2 in) of the filter media over the age of the sand in filters, but did increase at the 25-30 cm (10-12 in) depth over the age of filter sand from 16 ± 24 mg/g volatile solids to 292 ± 12 mg/g volatile solids. These data are summarized in Table 61.

Carbohydrates-- Carbohydrate concentrations, expressed as elemental carbon per gram volatile solids, varied between cores, depths, filters, and age of sand. The carbohydrate concentration did not vary significantly in the top 1.2 cm (1/2 in) of the filter media over the age of the sand in filters, but did change at the 25-30 cm (10-12 in) depth, increasing over the age of filter sand as summarized in Table 62.

Acriflavin Direct Count (AFDC)-- The bacteria counts variations were significant only with the depth of the sample in the filter. The results did not significantly change with the age of the sand.

Metals-- Iron concentrations did not vary over the age of the sand in the top 1.2 cm (1/2 in) of filter media, but the concentration for iron and manganese at the lower depths increased with increasing sand age. The iron concentration at the 25-30 cm (10-12 in) depth increased from 2390 mg/kg dry wt in the reconditioned sand to 4580 mg/kg dry wt after 162 months of service but did not increase further. The concentrations at the lower depths were sampled at the beginning and end of resanding. The concentration of iron increased significantly over that period.

The manganese concentrations varied widely. The concentration in the top 1.2 cm (1/2 in) was relatively constant, except for that in Filter 21 after 8 months of operation when it was

TABLE 61: FRM CONCENTRATIONS, IN MG, PER GRAM VOLATILE SOLIDS AT WEST HARTFORD, CT.

Depth cm	Recon-ditioned sand	Filter 21		Filter 18	Filter 1		Filter 19
		Sept.15,'93 7 mo.	Oct.12,'93 8 mo.	Oct.13,'93 162 mo.	Oct.5,'93 228 mo.	Nov.2,'93 229 mo.	March 3,'94 259 mo.
Top 1.2	16±24	296±64	280±73	271±85	289±95	208±38	-
5-10	16±24	-	-	-	229±118	123±40	160±41
25-30	16±24	130±13	73±7	155±21	131±70	166±29	292±12
41-46	16±24	-	-	-	-	-	271±28
56-61	16±24	-	-	-	-	-	218±21

TABLE 62: CARBOHYDRATE CONCENTRATIONS, IN MGC, PER GRAM VOLATILE SOLIDS AT WEST HARTFORD, CT.

Depth cm	Recon-ditioned sand	Filter 21		Filter 18	Filter 1		Filter 19
		Sept.15,'93 7 mo.	Oct.12,'93 8 mo.	Oct.13,'93 162 mo.	Oct.5,'93 228 mo.	Nov.2,'93 229 mo.	March 3,'94 259 mo.
Top 1.2	10±2	32±12	33±5	46±10	29±4	36±7	-
5-10	10±2	-	-	-	29±5	27±12	23±2
25-30	10±2	10±1	22±6	5±2	27±7	45±9	39±8
41-46	10±2	-	-	-	-	-	27±2
56-61	10±2	-	-	-	-	-	25±2

approximately twice that observed during other sampling periods. The manganese concentrations at the 25-30 cm (10-12 in) depth increased with sand age except in Filter 19 which had been sampled during reconditioning. Calcium and aluminum concentrations did not change significantly, with depth or sand age.

4.4.5 Reconditioning

The reconditioning procedure normally begins with the plant operators harrowing the filter, moving the hydraulic washing equipment and hoses into the appropriate filter building, and draining the filter. The contractor who is to do the reconditionnning moves the equipment from the building into the filter and is reinstructed on cleaning procedures. Sand is manually shoveled into ejector boxes which move the sand hydraulically through hoses to vortex washing tanks. Wash water from the vortex tanks is discharged to the filter effluent channel and drains to the holding reservoir used to settle wash water from the harrowing process. Entrained solids settle in the reservoir and the overflow is discharged to a creek under a discharge permit. The sand from the tanks is dumped onto the surface of the filter nearby. Later the sand is again shoveled into a ejector box, through another vortex washing tank, and discharged to an area of the filter which has previously been emptied. The cleaned sand dewaters on the gravel supporting layer and remains. The depth of sand is built up to the normal operating depth of 0.68 meters (27 in) and, when the entire filter area has been recovered, the filter is ready to be put back into use.

Although this description outlines the basic procedures, the filter is full of sand when work begins and no area is available to place the reconditioned sand. During the early stages of the operations, partially reconditioned sand is conveyed (after the first washing step) onto the surface of a portion of the bed that will be reconditioned later and stored. When a sufficient area has been cleared to the gravel supporting layer, fully reconditioned sand is replaced.

Water for the ejectors and washing operations is taken from the raw water supply of the plant. The waste water from the vortex tanks and from the filter underdrains is discharged to a holding reservoir as previously described. The volumes of water used and solids produced have never been measured.

The upper few centimeters of the gravel supporting layer is manually shoveled into a mechanical screening apparatus so that the gravel can be separated from sand which has mixed with it during filter operation and during the reconditioning procedure. The separated gravel is replaced as the operations move across the filter and the relatively small volume of sand thrown back onto uncleaned areas for reconditioning.

Sand losses from successive harrowing operations and the reconditioning procedures are made up as reconditioning reaches the end of the filter and an area of the supporting gravel layer remains uncovered with cleaned sand. This portion of the filter is refilled with virgin sand purchased for that purpose. Replacement sand is currently purchased with an effective size of from 0.32 to 0.38 mm with uniformity coefficient of less than 2.3 from Holliston Sand & Gravel in Slatersville, Rhode Island. Makeup sand for the last two 0.2 hectare (1/2 acre) filters cleaned, No. 12 and 14 in 1989-90, was a combined total of 2.7 million kg (620 tons). Make up sand for the last four 0.3 hectare (3/4 acre) beds, No. 19 through 22, was 1, 0.5, 2.4, and 1 million kg (250, 120, 544, and 240 tons), respectively.

Reconditioning normally takes from 4 to 6 months: I to 2 weeks during which the sand filter is awaiting the reconditioning crew, from 9 to 20 weeks while the filter is being reconditioned, and then 1 to 2.5 months while the filter is run to waste and "ripened." The progress of ripening is monitored by sampling the filtered water for turbidity, total and fecal coliform, and total plate count. When the total coliform count drops to 0 to 1 colony forming units (CFU) per 100 mL, the filter is placed back into service. The actual time for filters to be out of service, exclusive of preliminary time awaiting the reconditioning crew, is summarized in Table 63.

TABLE 63: RECONDITIONING RECORDS FOR WEST HARTFORD, CT.

Year	Filter No.	Area hectares (acres)	Reconditioning time weeks[a]	Ripening period weeks
1989	11	0.2 (1/2)	14	6 (April-May)
1989	13	0.2 (1/2)	9	5 (May)
1990	14	0.2 (1/2)	14	4 (April-May)
1990	12	0.2 (1/2)	9	3 (June)
1991	20	0.3 (3/4)	19	6 (March-April)
1992	22	0.3 (3/4)	18	7 (March-April)
1993	21	0.3 (3/4)	14	4 (April-May)
1994	19	0.3 (3/4)	12	8 (April-June)

[a] Crew size during the reconditioning procedure is approximately 20 persons, or 800 labor hours per week.

Two filters, No. 19 and 21, were reconditioned during the study period. Both had been constructed in 1960 and reconditioned in 1973. Filter 21 was again reconditioned in early 1993. Filter 19 was again reconditioned between January through April 1994. Grab samples were taken from different layers in both filters during their reconditioning. Samples from Filter 21 were taken January 26, 1993. A single grab sample was taken from mid-depth in the top 30 cm (12-in) of material and another at mid-depth in the bottom 30 cm (12-in) of material, with an additional sample taken of the reconditioned sand.

The samples from Filter 19 were taken on March 21, 1994 to represent three vertical cores in a unreconditioned section of the filter. Two samples were taken of sand being reconditioned after only the first washing, and five samples from the fully reconditioned sand, after the second washing. The vertical sections representing the cores through the unreconditioned sand represent sand at depths of 5 to 10, 25 to 30, 41 to 46, and 56 to 61 cm (2 to 4 in, 10 to 12 in, 16 to 18 in, and 22 to 24 in) below the approximate original sand surface. No samples was taken at the top 1 cm (1/2 in) level as the original sand surface had been thoroughly disturbed by cleaning operations and mixed with partially reconditioned sand stored on it. The results of analyses on the samples from Filter 19 are shown in Table 64.

Sieve Analyses-- The effective sizes for the sand samples at all levels and for all samples were not significantly different at the 95% probability level using 2-factor analysis of variance (ANOVA) calculations. A comparison of the different levels between the different cores in the unreconditioned sand showed a probability of inequality of only about 40% between levels. A comparison between the mean effective size of each separate core of unreconditioned sand with the two samples of once- washed sand and the three samples of reconditioned sand showed only a 65% probability of inequality. This result was surprising as it had been expected that the vortex sand washing process would remove very fine materials and result in a larger effective grain size. This was not true based on mean values of 0.318 mm for the unreconditioned sand, 0.283 mm after the first wash and 0.306 mm for the reconditioned sand. The variance between samples at each level for the few samples analyzed overshadowed the relatively small differences in grain size.

A similar 2-factor ANOVA on the uniformity coefficients from these data demonstrated greater probabilities for inequality. The analysis indicated a 92 percent probability of inequality between uniformity coefficients at the different depths for the unreconditioned sand and just under a 90% probability of inequality between uniformity coefficients of the unreconditioned, once-washed, and reconditioned sands. The uniformity coefficients of the two grades of reconditioned sands were not significantly different at the 90 percent confidence level, but the difference between the unconditioned and reconditioned sands was significant.

Since the effective size of the sand was not changed but the uniformity coefficient decreased, the vortex sand washing and reconditioning process apparently reduced the proportion

TABLE 64: SUMMARY OF WEST HARTFORD FILTER 19 MEDIA ANALYSES, MARCH 21, 1994.

Depth below surface cm	Effective size in mm, & Uniformity coef.	Solids percent		FRM mg protein/g dw	Carbo-hydrate mgC/gdw	Iron mg/kgdw	Man-ganese mg/kgdw	Calcium mg/kgdw	Alum-inum mg/kgdw
		Total	Volatile						
Unreconditioned sand.									
Top 1.2	-	-	-	-	-	-	-	-	-
5-10	0.29 2.94	95.56 ±1.12	0.36 ±0.05	0.58 ±0.16	0.082 ±0.046	3170 ±788	276 ±30	411 ±68	1260 ±239
25-30	0.30 3.28	89.63 ±0.92	0.58 ±0.02	1.68 ±0.07	0.22 ±0.05	4880 ±457	98 ±11	593 ±101	2010 ±256
41-46	0.34 2.99	92.79 ±0.38	0.38 ±0.02	0.94 ±0.22	0.10 ±0.01	4660 ±543	91 ±12	649 ±132	1990 ±154
56-61	0.32 2.91	89.61 ±1.68	0.37 ±0.05	0.77 ±0.21	0.098 ±0.020	4080 ±442	81 ±10	670 ±341	1850 ±215
Weighted mean, all	0.31 3.05	90.34	0.52	1.19	0.19	4120	134	592	1810
Reconditioned sand after 1st wash.									
-	0.28±0.04 2.13±0.21	97.03 ±0.99	0.30 ±0.01	0.12 ±0.05	0.044 ±0.013	2400 ±387	186 ±20	287 ±27	1210 ±124
Reconditioned sand after both washes.									
-	0.31±0.03 2.53±0.06	97.03 ±0.12	0.31 ±0.11	0.05 ±0.08	0.031 ±0.005	2750 ±366	165 ±30	308 ±128	1330 ±118

of D-60 grain size material in the sand which narrowed the relation between the D-60 and D-10 sizes. This is contrary to expectation but was consistent with the analyses of the five partially or fully reconditioned samples and the twelve unreconditioned samples.

Volatile Solids-- The sample cores were found to be affected by their locations. The sites for the three cores of the "dirty sand" (before reconditioning) were determined by taking random numbers between zero and 13 as the length of the exposed sand face available for sampling was 4.0 meters (13 feet). The first number was "one" and resulted in taking the core for D-1 adjacent to a column where the harrowing equipment could not loosen the sand when it was harrowed just before starting the reconditioning process. The sample at the 5-10 cm (2 to 4 in) level from this core was significantly darker and contained more organic material than samples from comparable levels at cores D-2 and D-3. These latter samples were taken at a distance from columns and had been regularly traversed with the harrow. The results from the analyses on Core D-1 at the depth of 5-10 cm (2 to 4 in), and to a lesser extent at the depth of 25-30 cm (l0 to 12 in), were statistically atypical in comparison to the results from Cores D-2 and D-3. The effective sizes and uniformity coefficients of the respective cores did not show any differences, but those for total and volatile solids did. Results of analyses on Core D-1 were different from those on Cores D-2 and D-3 because of the location next to the column.

Two-way ANOVA results showed very high probabilities of inequalities between the total and volatile solids concentrations between the levels, between the different cores, but only 89 percent probable between the unreconditioned and reconditioned sand samples if all three cores of the "dirty sand" were considered. The volatile solids content of the media adjacent to the column at depths of 5-10 cm and 25-30 cm were approximately double (0.80 percent vs 0.34 percent, and 0.82 percent vs 0.58 percent) those of samples taken where the media wass accessible to the harrow. When the results of core D-1 next to the column were omitted, the probabilities of inequality between the unreconditioned and reconditioned sands increased to greater than 95%.

One-tailed t-Tests on the mean values for percent volatile solids in each of the unreconditioned, first wash, and reconditioned samples indicated that differences between means for the unreconditioned samples (0.483+/-0.007 percent, n=3) and the first wash samples (0.301+/-0.000 percent, n=2) is 97 percent probable. The similar test between the first wash samples and the reconditioned samples (0.315+/-.005 percent, n=3) indicated that, while the mean percent of volatile solids appeared to be increased by the second washing step and storage in place, the probability was not significant (P=0.66).

A pattern of accumulation within the filter emerges, beginning with the data on volatile solids but continuing through the data for protein, carbohydrates, and metals. Generally, the concentration of volatile solids in the level near the top of the sand filter, 5-10 cm (2-4 in), are below those at 25-30 cm (l0 to 12-inches), the level just below the depth reached by the harrowing. The characteristics of the sand at the 5-10 cm level (2-4 in) are relatively similar to those at depths of 41-61 cm (l6 to 24-inches). The sample adjacent to the column, on the other hand, indicates much higher concentrations of volatile solids to the depth just below the depth of harrowing than for the samples taken where the sand has been harrowed regularly.

Folin Reactive Material (FRM)-- Two-factor ANOVA results on the unreconditioned sand samples showed greater than 99% probability of inequality between the FRM concentrations between different depths in the filter bed, whether including the results of the high organic layer in core D-1 or not. When the results for FRM concentration were corrected from mg of protein per g dry wt of filter media to gram of protein per gram of volatile solids within the sand filter sample, the ANOVA results showed less effect from interactions between the selection of the core location and depth of sample and less variation within these replicate samples.

Results from ANOVA calculations consistently showed over 98% probability of inequality in or between the FRM concentration in the unreconditioned and reconditioned sands. Whereas sieve analyses and solids analyses showed almost no improvements in quality of sand before and after reconditioning, FRM analysis shows very significant removal of protein material by reconditioning.

Carbohydrates-- An ANOVA on the results of the carbohydrate tests, reported as carbon on a dry weight basis, showed significant differences between all samples, at all depths, and between the unreconditioned and the reconditioned sands. There is high probabilities of difference (>99.9) between the different locations of unreconditioned sand cores, between the different depths within each core, and for interactions between these two factors but with very low variance between replicate analyses. The data which had been corrected for volatile solids concentration also showed equally high probabilities of differences between the samples, depths, and interaction whether the results of core D-1 were included or not.

4.5 PILOT PLANT STUDIES

Laboratory scale sand filter tests were carried out to compare filter characteristics that could not be made in the field. The tests were in three phases, an initial ripening period of three cycles during which all three parallel filters were cleaned by scraping, the principal study period of five cycles during which the filters were cleaned by different methods, and a final period during which the filters ripening was studied after cleaning. The filter media was then sampled to determine if differences had developed as a result of the respective cleaning methods. These filters, unlike the field scale plants, were near the UNH laboratory and more extensive testing was feasible.

4.5.1 Raw Water Quality and Filter Performance

Analytical results of raw and filtered water samples during the first two phases of study are presented in Tables 65 through 69. Performance was compared between the filters for phase 1, when all were cleaned by scraping. The only significant differences found in performance were between turbidity removals when the filtered water was greater than or equal to 8°C and when it was less than 8°C. Little data was collected for NPDOC and BDOC removal during this period as the time was intended primarily maturing the filter media.

The cleaning methods were changed for the second phase of this study beginning June, 1993. Scraping continued to be used to clean Filter 1, but a harrowing process was used for Filters 2 and 3 as described in the section on "Methods and Materials." Performance was also compared between the filters for this phase of the study. The results showed no significant differences between filter performance except for headlosses. Headlosses for the filters are shown graphically in Figure 17. The filter cleaned by harrowing showed greater head losses than the filter cleaned by scraping after the third cleaning cycle, with increasing losses developing in each of the two subsequent cycles the filters were operated. The harrowing method used in the pilot filters, however, could not reproduce the full operation of plant scale cleaning. The filers were cleaned while an upflow was maintained through the media, but no cross flow could be maintained. The suspended materials were removed by bailing, however. Because the cleaning methods could not be entirely reproduced in the pilot scale, however, observations from this part of the research concerning the rate of head loss development are not conclusive.

4.5.2 Ripening

At the end of the second phase, the filters were cleaned and operated for a short period to compare their ripening characteristics. The results are summarized in Tables 70 to 72.

The quality of the filtered water from Filters 2 and 3 showed increases in turbidity and UV absorbance in the first 120 minutes after cleaning. NPDOC increased during the first 90 minutes after cleaning, but at a lower rate. The qualtiy of water from Filter 1 was also affected during

TABLE 65: WATER QUALITY DATA FOR PILOT SCALE FILTERS DURING PHASE 1, TEMPERATURE AND TURBIDITY.

Date	Water Temp. °C	Turbidity, NTU			
		Raw	Filter 1	Filter 2	Filter 3
Sept.14, '92	19	-	0.93	0.74	0.78
Sept. 23	19	5.04	0.41	0.37	0.45
Oct. 4	18	4.98	0.84	1.08	1.06
Oct. 12	14	3.2	0.49	0.47	0.59
Oct. 21	12	2.0	0.29	0.27	0.27
Oct. 31	10	1.71	0.46	0.35	0.40
Dec. 7	7	2.51	0.90	0.62	0.89
Jan. 6, '93	7	2.9	.095	0.81	0.82
Jan. 18	10	2.46	0.71	0.72	0.82
Mar. 1	7	2.13	1.02	1.12	1.13
Mar. 13	7	2.25	0.84	0.86	0.82
Mar. 24	7	2.27	0.94	1.02	1.11
Mar. 31	-	2.02	0.71	0.76	0.84
Apr. 16	6	1.06	0.28	0.26	0.25
Apr. 28	-	1.04	0.53	0.31	0.39
Mean ≥8°C		**3.00**	**0.56**	**0.51**	**0.56**
Mean < 8°C		**2.20**	**0.79**	**0.77**	**0.84**

Filters cleaned Sept. 23, Oct. 5, Oct. 21, Nov. 21, Feb. 11, Apr. 4, and June 23.

TABLE 66: WATER QUALITY DATA FOR PILOT SCALE FILTERS DURING PHASE 2, TEMPERATURE AND TURBIDITY.

Date	Water Temp. °C	Turbidity, NTU			
		Raw	Filter 1	Filter 2	Filter 3
July 1, '93	23	1.93	0.27	0.25	0.29
July 20	23	3.73	0.29	0.25	0.32
July 24	23	3.56	0.36	0.27	0.31
Aug. 2	23	2.56	-	0.56	0.35
Aug. 8	23	2.03	0.31	0.30	0.31
Aug. 19	23	1.95	0.28	0.28	0.27
Aug. 27	24	1.80	0.26	0.28	0.24
Sept. 1	24	1.88	0.26	0.27	0.22
Mean ≥8°C		**2.43**	**0.29**	**0.28**	**0.29**
No data < 8°C		-	-	-	-

Filters cleaned June 23, July 12, July 24, Aug. 8, Aug. 22, Sept. 6.

TABLE 67: WATER QUALITY DATA FOR PILOT SCALE FILTERS DURING PHASE 1 AND 2, COLIFORM BACTERIA.

Date	Water Temp. °C	Total Coliform/100mL			
		Raw	Filter 1	Filter 2	Filter 3
Oct. 7, '92	16	100	14	4	10
Oct. 13	12	180	5	2	0
Oct. 28	11	140	4	0	0
Nov. 17	9	7	2	0	1
Dec. 3	7	65	1	0	0
Jan. 21, '93	8	16	8	0	0
Mar. 4	7	9	4	3	5
Mar. 18	7	13	2	0	1
Mar. 29	7	26	10	0	0
Apr. 13	5	82	0	1	0
Mean ≥8°C	-	**106**	**6.2**	**2**	**3**
Mean < 8°C	-	**74**	**5.3**	**2**	**5**
Phase 2, Filter 1 cleaned by scraping, Filter 2 by harrowing to 5 cm, Filter 3 by harrowing to 15 cm.					
July 8	23	160	8	4	14
July 20	23	100	15	5	0
July 25	23	200	12	4	0
Aug. 25	23	67	10	7	3
Mean	-	**132**	**11**	**5**	**4**

TABLE 68: WATER QUALITY DATA FOR PILOT SCALE FILTERS DURING PHASE 1 AND 2, NPDOC AND BDOC.

Date	NPDOC, mg/L				BDOC, mg/L			
	Raw	Filter 1	Filter 2	Filter 3	Raw	Filter 1	Filter 2	Filter 3
Phase 1, all pilot filters cleaned by scraping.								
Jan. 7, '93	8.5	8.5	8.8	8.7	0.8	0.7	0.2	0.7
Mar. 30	5.5	4.5	-	-	0.6	0.2	-	-
Apr. 8	6.8	4.8	-	-	-	-	-	-
Apr. 15	6.0	5.0	-	-	1.0	0.3	-	-
Mean	**6.0**	**5.7**	-	-	**0.8**	**0.4**	-	-
Phase 2, Filter 1 cleaned by scraping, Filter 2 by harrowing to 5 cm, Filter 3 by harrowing to 15 cm.								
July 1	7.1	5.4	5.1	5.5	-	-	-	-
July 20	7.2	5.2	5.5	5.1	-	-	-	-
Sept. 1	6.4	5.4	5.2	5.2	0.4	0.1	-0.1	0.0
Sept. 3	6.6	5.6	5.3	5.3	0.5	0.2	0.2	0.2
Sept. 6	6.5	5.5	5.4	5.2	0.3	0.1	0.1	0.0
Mean of Sept. Data	**6.5**	**5.5**	**5.3**	**5.3**	**0.4**	**0.2**	**0.2**	**0.1**

TABLE 69: WATER QUALITY DATA FOR PILOT SCALE FILTERS DURING PHASE 2, UV ABSORBANCE AND PARTICLE COUNT.

Date	UV Absorbance, cm^{-1}				Particle Count/mL			
	Raw	Filter 1	Filter 2	Filter 3	Raw	Filter 1	Filter 2	Filter 3
July 6, '93	0.360	0.245	0.241	0.248	-	-	-	-
Aug. 2	0.354	-	0.253	0.248	-	-	-	-
Aug. 8	0.330	0.238	0.228	0.228	-	-	-	-
Aug. 21	0.319	0.234	0.231	0.221	-	-	-	-
Sept. 1	-	-	-	-	7,923	268	280	263
Sept. 3	0.233	0.221	0.220	0.212	-	-	-	-
Sept. 6	-	-	-	-	12,130	235	199	190

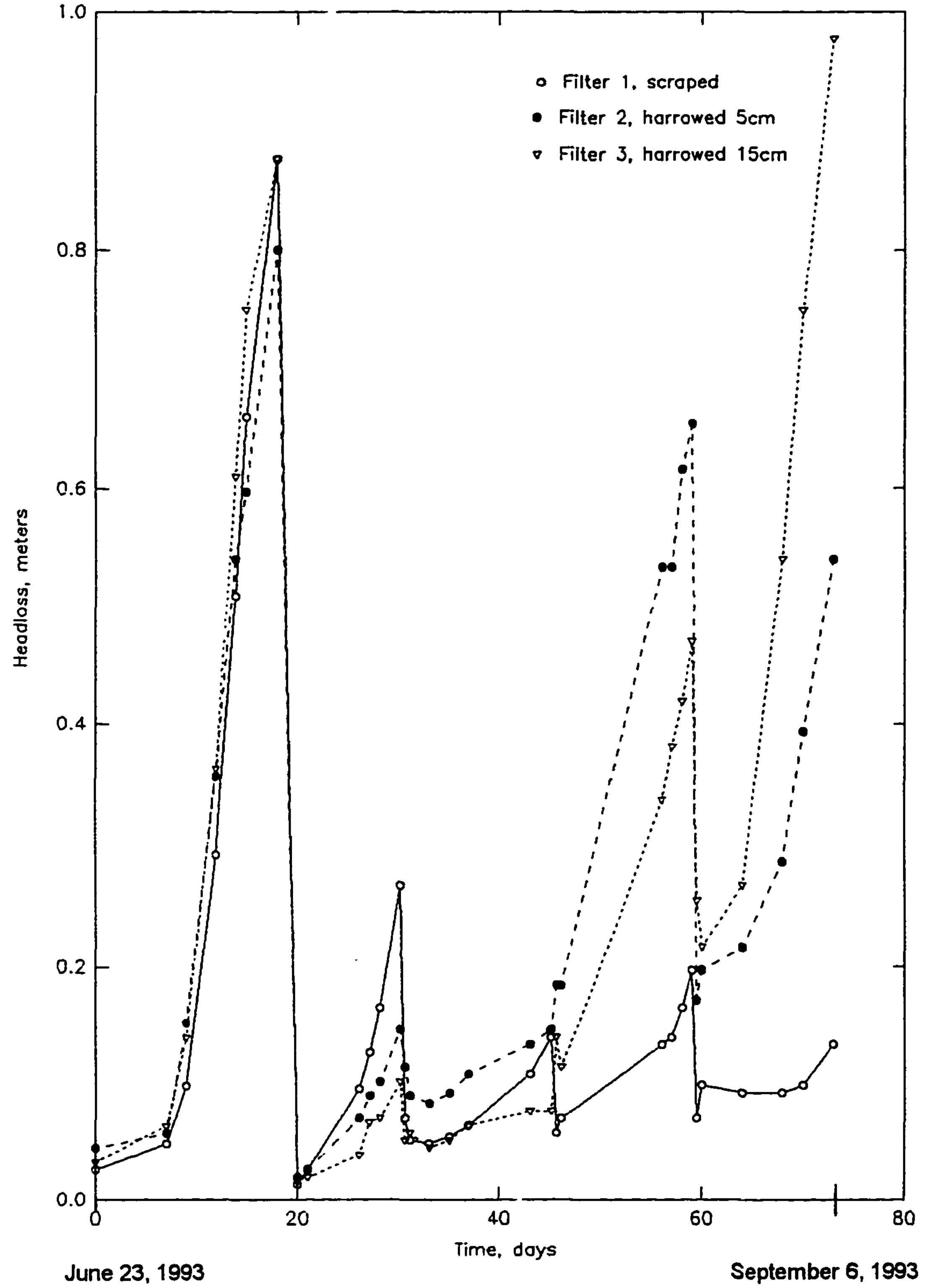


Figure 17: Headloss development as a function of cleaning technique in pilot filters at Portsmouth, NH.

TABLE 70: WATER QUALITY DATA FOR PILOT SCALE FILTERS DURING RIPENING, TEMPERATURE AND TURBIDITY.

Time, bed volumes	Water Temp. °C	Turbidity, NTU			
		Raw	Filter 1	Filter 2	Filter 3
Sept. 6, '93 All filters cleaned by respective methods. Flow restarted at 3:00 P.M.					
0 minutes	23	2.25	-	-	-
30 minutes, = bed volume of underdrain system	23	2.33	0.49	6.0	1.61
60 minutes, = one-half bed volume (a)	23	2.48	0.97	6.84	20.6
90 minutes, = one bed volume	23	2.40	0.64	4.33	13.0
120 minutes, = 1.5 bed volumes	23	2.44	0.55	2.75	6.5
240 minutes, = 3.5 bed volumes	23	2.60	0.48	1.20	1.27
360 minutes,= 5.5 bed volumes	23	2.36	0.45	0.92	0.79
24 hours, = 23.7 bed volumes	23	2.06	0.36	0.58	0.43

(a) Volumetric flow at end of 60 minutes equalled the estimated volume of voids in the underdrain system and one-half the volune of voids in the media bed. Void space was taken as 42 percent of the total volume.

TABLE 71: WATER QUALITY DATA FOR PILOT SCALE FILTERS DURING RIPENING, NPDOC AND UV ABSORBANCE.

Time, bed volumes	Water Temp. °C	NPDOC, mg/L				UV Absorbance, cm^{-1}			
		Raw	Filter 1	Filter 2	Filter 3	Raw	Filter 1	Filter 2	Filter 3
Sept. 6, '93 All filters cleaned by respective methods. Flow restarted at 3:00 P.M.									
0 minutes	23	6.7	-	-	-	0.248	-	-	-
30 minutes, = bed volume of underdrains	23	6.6	5.1	5.6	5.2	0.216	0.233	0.518	0.280
60 minutes, = one-half bed volume	23	6.6	5.0	5.7	7.0	0.312	0.246	0.500	0.727
90 minutes, = one bed volume	23	6.4	5.1	6.0	6.3	0.307	0.241	0.404	0.674
120 minutes, = 1.5 bed volumes	23	7.0	5.1	5.4	5.7	0.305	0.242	0.325	0.425
240 minutes, = 3.5 bed volumes	23	7.4	5.8	5.4	5.2	0.303	0240	0.247	0.238
360 minutes, = 5.5 bed volumes	23	6.8	5.3	5.6	5.1	0.314	0.244	0.247	0.240
24 hours, = 23.7 bed volumes	23	6.7	5.1	5.3	5.1	0.307	0.237	0.234	0.221

TABLE 72: HEADLOSSES FOR PILOT SCALE FILTERS DURING RIPENING.

Time	Water Temp. °C	Head Loss, cm		
		Filter 1	Filter 2	Filter 3
Sept. 6, '93 All filters cleaned by respective methods. Flow restarted at 3:00 P.M.				
0 minutes	23	1.03	3.44	3.54
30 minutes	23	1.13	3.35	3.44
60 minutes	23	-	-	-
90 minutes	23	1.08	3.35	3.35
120 minutes	23	1.03	3.25	3.15
240 minutes	23	0.98	2.16	2.80
360 minutes	23	0.98	2.71	2.76
24 hours	23	0.98	2.16	2.36
56 hours	23	1.57	3.74	3.64
93 hours	23	1.72	4.33	4.13

these periods but the turbidity, NPDOC, and UV absorbances did not exceed the values for the raw water quality.

Particles were counted for water samples taken during the ripening period to determine if the higher turbidities would be indicative of sizes comparable to those of Giardia cysts and Cryptosporidium oocysts. This information is summarized in Table 73. Unexpectedly, the data showed none of the pilot filters showed overall removal of particles, in the size range between 5 and 10 um, at a 2-log rate prior to cleaning. Some of the effluent particles might have been produced or sloughed from the media, however. The scraped filter showed the most rapid recovery in this size range, within 120 minutes. The "harrowed" filters exhibited very high

TABLE 73: PARTICLE COUNTS FOR PILOT SCALE FILTERS DURING RIPENING, SEPTEMBER 6-7, 1993.

Time from start Water source	Particles per mL for particle size range, in um									
	1-1.25	1.25-1.5	1.5-1.75	1.75-2	2-5	5-7.5	7.5-10	10-17.5	17.5-25	25-30
Precleaning										
Raw	7510	2393	1131	472	802	68	14	3.8	0.4	0.3
Filter 1	152	40	18	7.8	15	1.9	0.5	0.2	0.05	0.01
Filter 2	130	36	16	6.0	9.6	0.8	0.2	0.04	0.01	0.01
Filter 3	122	34	17	6.7	9.2	0.9	0.2	0.08	0.01	0.01
30 minutes, = bed volume of underdrains										
Raw	7394	2274	1020	417	691	47	16	5.6	0.03	0
Filter 1	1221	370	177	74	91	4.3	0.6	0.3	0.01	0
Filter 2	1730	244	86	28	39	4.4	1.7	1.5	0.6	0.08
Filter 3	967	140	59	23	32	1.1	0.2	0.09	0.01	0
60 minutes, = one-half bed volume										
Raw	8454	2654	1254	529	948	87	14	8.4	0.5	0.1
Filter 1	546	114	45	(1)	26	(1)	(1)	(1)	(1)	(1)
Filter 2	1533	281	111	42	90	23	23	12	2.7	0.6
Filter 3	3622	731	282	106	168	12	2.9	2.4	0.7	0.1
90 minutes, = one bed volume										
Raw	7001	2101	956	397	634	57	13	6.6	0.5	0.4
Filter 1	386	77	36	(1)	23	(1)	(1)	(1)	(1)	(1)
Filter 2	1440	296	115	41	54	2.3	0.6	0.6	0.2	0.03
Filter 3	1735	146	60	29	46	1.0	0.2	0.2	0.05	0.01

Table 73 continued on following page.

Table 73 continued from preceeding page.

120 minutes, = 1.5 bed volumes										
Raw	9564	2846	1239	512	866	87	21	8.6	1.1	0
Filter 1	498	120	53	24	38	2.0	0.4	0.2	0.07	0.01
Filter 2	858	171	65	22	29	1.6	0.3	0.3	0.04	0
Filter 3	897	137	58	25	37	1.3	0.4	0.2	0.09	0.01
240 minutes, = 3.5 bed volumes										
Raw	8886	2616	1182	464	716	49	11	6.9	0.2	0
Filter 1	513	111	43	16	22	1.1	0.2	0.2	0.05	0
Filter 2	3776	1216	506	164	143	6.6	2.3	2.1	0.6	0.2
Filter 3	459	89	37	15	21	1.2	0.1	0.2	0.09	0.04
360 minutes, = 5.5 bed volumes										
Raw	9534	3066	1432	636	1070	80	14	7.1	1.3	0
Filter 1	320	65	26	10	16	1.9	0.6	0.4	0.1	0
Filter 2	526	127	49	18	27	3.9	1.7	1.6	0.5	0.2
Filter 3	371	83	35	16	17	0.9	0.4	0.04	0.04	0
24 hours, = 23.7 bed volumes										
Raw	7252	2324	1171	524	886	84	16	8.2	0.9	0.4
Filter 1	275	67	30	13	20	2.0	0.6	0.4	0.05	0
Filter 2	495	126	54	22	32	2.9	1.0	0.7	0.2	0.03
Filter 3	286	67	31	12	18	0.99	0.2	0.2	0.01	0

(1) This data not recorded by computor during analysis for unidentified reason. Operator error believed responsible. Data for other size ranges in this sample taken from hand written backup record.

particle releases after cleaning, as also evidenced by the turbidity and color, but the removal had recovered the precleaning level within 360 minutes for Filter 3, but not within 24 hours for Filter 2. This was surprising as Filter 3 had been disturbed more deeply than Filter 2, to 15 cm vs 5 cm.

The greatest increases in particle release after cleaning occurred between 0 and 60 minutes after the flow was restarted in the scraped filter. The rates of increase were approximately 10-fold in the sizes up to 2 um. The greatest releases for the "harrowed" filters occurred slightly later, at about 60 minutes after the flow was restarted. Although the highest releases from Filter 2 were detected 240 minutes after the flow was restarted, this "peak" occured after an earlier peak had begun to decline and is suspected as atypical in a theoretical hydraulic flow through porous media. This might occure in a plant scale application, however, due to effects of short-circuiting, underdrain detention time, and/or intermittent release of deposits. Particle counting showed its importance to operation control during the ripening period.

4.5.3 Sand Media

After the filters had operated for five cleaning cycles, Phase 2 of the pilot study was ended and the sand media analyzed as for the plant scale filters. The results are summarized in Table 74. The data on media sample analyses was statistically analyzed. Volatile solids, in a 2-way ANOVA between the top 2.5 cm and the level between 12-15 cm and between filters, showed significant differences at the 90 percent confidence level. Differences within samples (interactions) were not significant in 1-way ANOVA comparions, the differences between the filters were not significant in the top 2.5 cm (p=0.34) but they were at the 12-15 cm level (p=.05). Similar comparisons were made for FRM and carbohydrates, with results as summarized in Table 75. There was no data on AFDC and there were no replicates on the analyses for metals. The schmutsdecke sample was composited from the surface of all three filters to provide for sufficient sample for analyses.

TABLE 74: SAND MEDIA CHARACTERISTICS IN PILOT PLANT FILTERS

Depth below surface cm	Total Solids percent		FRM mg protein /gdw	Carbo-hydrate mgC/gdw	AFDC 10^6/ gdw	Iron mg/kgdw	Man-ganese mg/kgdw	Calcium mg/kgdw	Aluminum mg/kgdw
	Total	Volatile							
Schmutzdecke (all filters)	53.54 ±1.53	3.10 ±0.11	1.56 ±0.10	2.94 ±0.07	-	6520	2610	302	3870
Filter 1. Filter cleaned by scraping.									
Top 2.5	85.89 ±0.21	1.62 ±0.02	0.74 ±0.22	0.85 ±0.06	-	1440	105	57	4790
12-15	81.63 ±0.26	0.85 ±0.01	0.66 ±0.14	1.01 ±0.06	-	2540	161	197	3430
Filter 2. Filter cleaned by harrowing to depth of 5 cm.									
Top 2.5	84.18 ±0.12	1.68 ±0.01	0.67 ±0.04	1.28 ±0.08	-	2210	150	202	3120
12-15	83.06 ±2.09	1.12 ±0.13	0.55 ±0.03	1.15 ±0.06	-	1120	23	46	3950
Filter 3. Filter cleaned by harrowing to depth of 15 cm.									
Top 2.5	83.24 ±0.11	1.74 ±0.11	0.43 ±0.03	0.92 ±0.03	-	1640	128	42	5220
12-15	82.94 ±0.19	1.19 ±0.04	0.58 ±0.05	1.20 ±0.04	-	1460	64	273	4170

TABLE 75: STATISTICAL COMPARISON OF MEDIA CHARACTERISTICS AT END OF PILOT PLANT TESTING.

Parameter	Results of 2-way ANOVA between levels and filters	Results of 1-way ANOVA between filters at top 2.5 cm	Results of 1-way ANOVA between filters at 12-15 cm
Volatile Solids	Significant both ways; Between levels, p=6x10^-6 Between filters, p=0.01 Interactions, p=0.11	Not significant, p=0.34	Significant, p=0.04
FRM	Significant between filters and interactions; Between levels, p=0.38 Between filters, p=0.02 Interactions, p=0.06	Significant, p=0.03	Not significant, p=0.62
Carbohydrates	Significant both ways and with interactions; Between levels, p=4x10^-4 Between filters, p=8x10^-8 Interactions, p=5x10^-6	Significant, p=10^-7	Significant, p=2x10^-3

(1-p) x 100 = percentf probability of significance. Example, if p=0.1, then probability of significance is 90 percent.

The cleaning methods resulted in different media coating characteristics although the various parameters were not consistent in this conclusion. The differences between filters, shown by the 2-way ANOVA, were consistenly significant for all parameters at probabilities greater than for the interaction, demonstrating the filters had established separate characteristics, although they may need to be operated for additional cleaning cycles for the differences in coating characteristics to become consistently statistically significant at the respective levels.

4.6 LABORATORY SCALE STUDIES

Laboratory scale sand filter tests were carried out to compare filtration factors that could not be made in the field. These factors included the influence on filter performance from age of media and its position within the filter bed (i.e., top vs bottom), the effects of applying raw water from one plant's source to the sand media from another plant, removing coating on the sand grains in the media, and changing the rate of flow through the filter. The laboratory-scale tests were able to compare these factors under constant temperature conditions and, unless intended otherwise, at equal flow rates.

4.6.1 Influence of Sand Media Age

The first series of tests were made using filter sand from the West Hartford, CT plant where it had been determined that there were differences in performance between filters. The sand was taken from Filter 1 and Filter 21 which represented nearly the longest (19 years) and shortest (less than one year) periods since reconditioning of any of the filters at this plant. Separate samples of the sand were also taken from the selected filters at the top 1 cm (1/2 in) and at a depth of 25-30 cm (10-12 in) to compare differences that may be related to depths of media within filters.

Information on the media characteristics, as collected from the filters and after preparation for the filter column, is presented in Table 76. The effective sizes were increased from

TABLE 76: EFFECTS OF SIEVING ON MEDIA USED IN COLUMNS COMPARING SAND AGE, DEPTH, AND CARBON SOURCE.

Media age years	Depth cm	Condition	Grain size		Iron mg/kgdw	Mn mg/kgdw	Calcium mg/kgdw	Aluminum mg/kgdw
			Effective size mm	Uniformity coefficient				
19	Top 1 cm	From filter	0.29	2.5	4200±226	559 ±42	392±107	1890±199
		Sieved	0.49	2.6	2780±244	274±9	181±3	1740±3
	25-30	From filter	0.3	2.5	4060±1540	329±22	206±5	1460±319
		Sieved	0.49	2.8	2550±268	233±21	237±1	1680±59
<1	Top 1 cm	From filter	0.3	2.3	2900±227	295±34	289±48	1480±44
		Sieved	0.5	2.3	2360±418	69.2±2.6	250±67	1420±33
	25-30	From filter	0.3	2.3	2480±451	96.1±5.1	275±120	1420±184
		Sieved	0.52	2	2510±270	63.4±9.8	381±198	1480±22

(Sand media collected from Filter No. 1 at West Hartford, CT on November 2, 1993 and stored at 4°C. until prepared for the columns.)

approximately 0.30 mm to 0.50 mm by wet sieving. The uniformity coefficients did not change significantly. Removing the fine materials also reduced the concentrations of iron and manganese, particularly in the samples from the top 1 cm of the older sand.

Two types of water were used, the natural water source from West Hartford which contained NOM in soluble and particulate forms and a prepared solution of glucose/glutamic acid (G/GA). The G/GA solution was used to test the viability of the biofilm in the columns. Eight columns were operated with the feed water and media combinations listed in Table 77. The concentrations for volatile solids and FRM in the media were also determined after operation and that information are also presented in Table 77. No carbohydrate or AFDC analyses were performed on these media.

The filter columns were mounted in the constant temperature room and the water recycled at a constant rate of 45.4 ± 1.5 mL/minute. This arrangement resulted in an uniform temperature

TABLE 77: DESCRIPTIONS OF COLUMNS COMPARING SAND AGE, DEPTH, AND CARBON SOURCE.

Column No.	Media age years	Depth in filter cm	Grain size		Volatile solids %	FRM mg/gdw	Carbon source
			Effective size, mm	Uniformity coefficient			
1	19	Top 1	0.49	2.6	0.46±0.10	0.28±0.05	Natural water
2	19	25-30	0.49	2.8	0.44±0.16	0.14±0.08	Natural water
3	<1	Top 1	0.50	2.3	0.21±0.01	0.053±0.012	Natural water
4	<1	25-30	0.52	2.0	0.24±0.08	0.0067±0.0036	Natural water
5	19	Top 1	0.49	2.6	0.37±0.07	0.050±0.060	Glucose/ glutamic acid
6	19	25-30	0.49	2.8	0.40±0.04	0.06±0.08	Glucose/ glutamic acid
7	<1	Top 1	0.50	2.3	0.25±0.02	0.028±0.029	Glucose/ glutamic acid
8	<1	25-30	0.52	2.0	0.26±0.02	0.0068±0.0003	Glucose/ glutamic acid

and filter application rate, with an empty bed contact time (EBCT) proportional to the length of time the system was operated and the relative volumes of the filter column and the reservoir. The contact time in the filter was calculated to be 20 percent of the time the system was in operation. The water was recirculated continuously and sampled over 5 days of operation, equivalent to an EBCT of one day. Samples were analyzed for TOC and UV absorbance. TOC, rather than NPDOC, was used for organic carbon analysis to minimize the loss of liquid volume in the system. The sand media had been analyzed for grain size and metals prior to being placed in the columns. Media samples were taken from the inlet end of the columns at the end of the operation and analyzed for total and volatile solids and FRM. The FRM results on this set of samples were not significant beyond one figure due to the particular reagent dilution used. The FRM concentrations were very low relative to those of samples from the plant scale filters as a result of the wet sieve separation used to prepare the media for the laboratory columns. The results of the TOC and UV absorbance analyses are presented in Figures 18, 19, and 20.

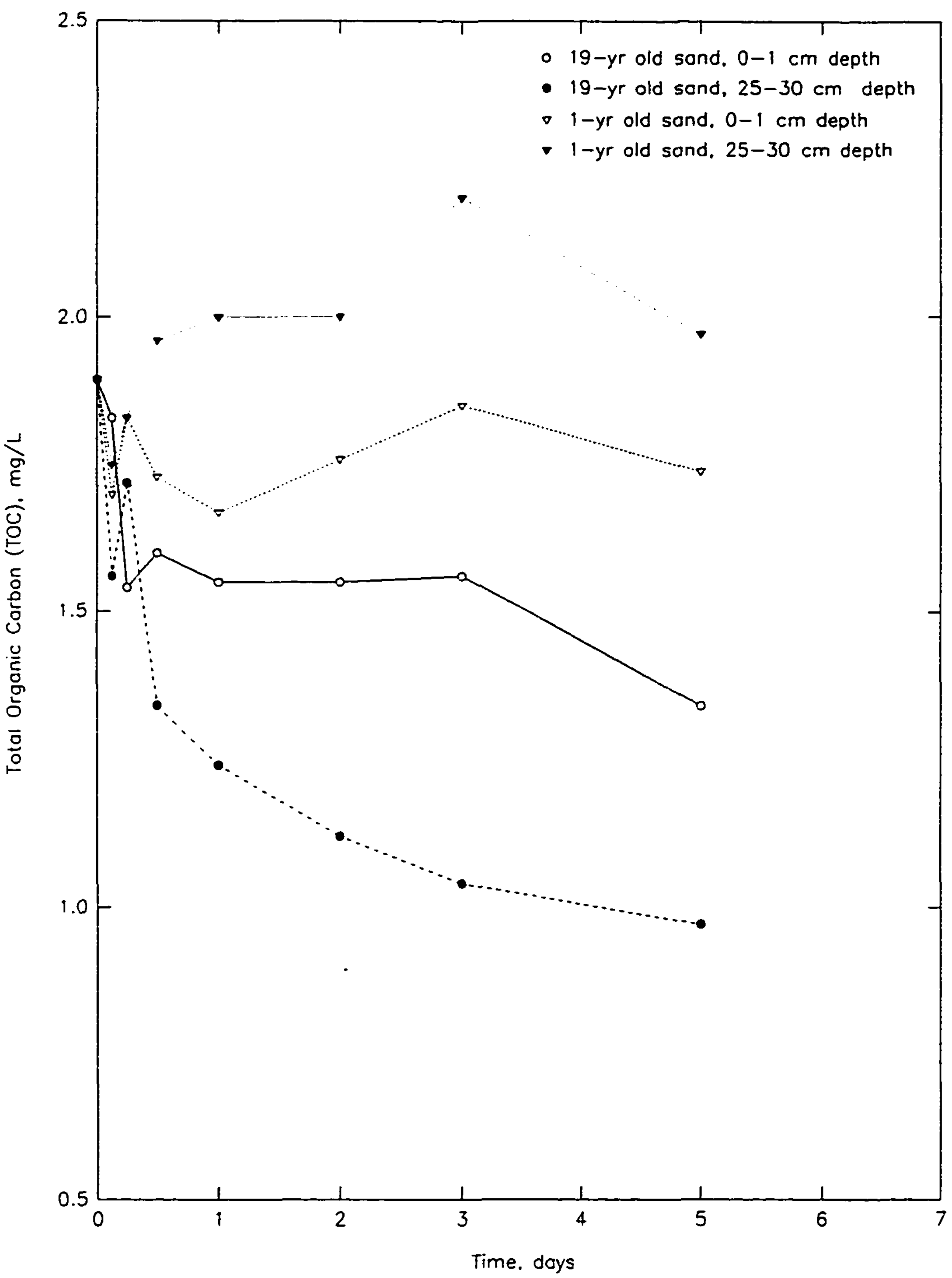


Fig. 18: Influence of sand media age and depth in filter on TOC removal.

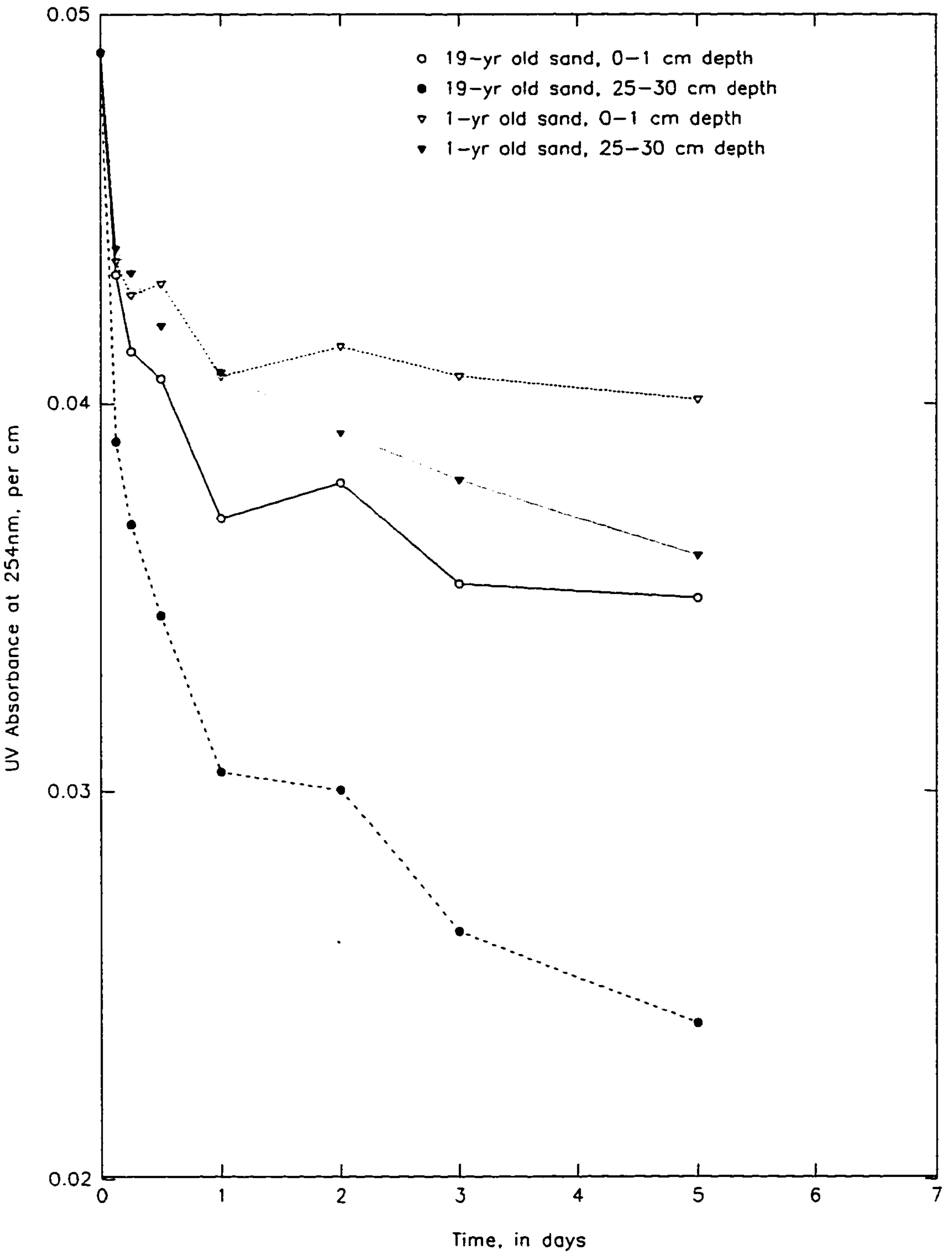


Fig. 19: Influence of sand media age and depth in filter on UV absorbance removal.

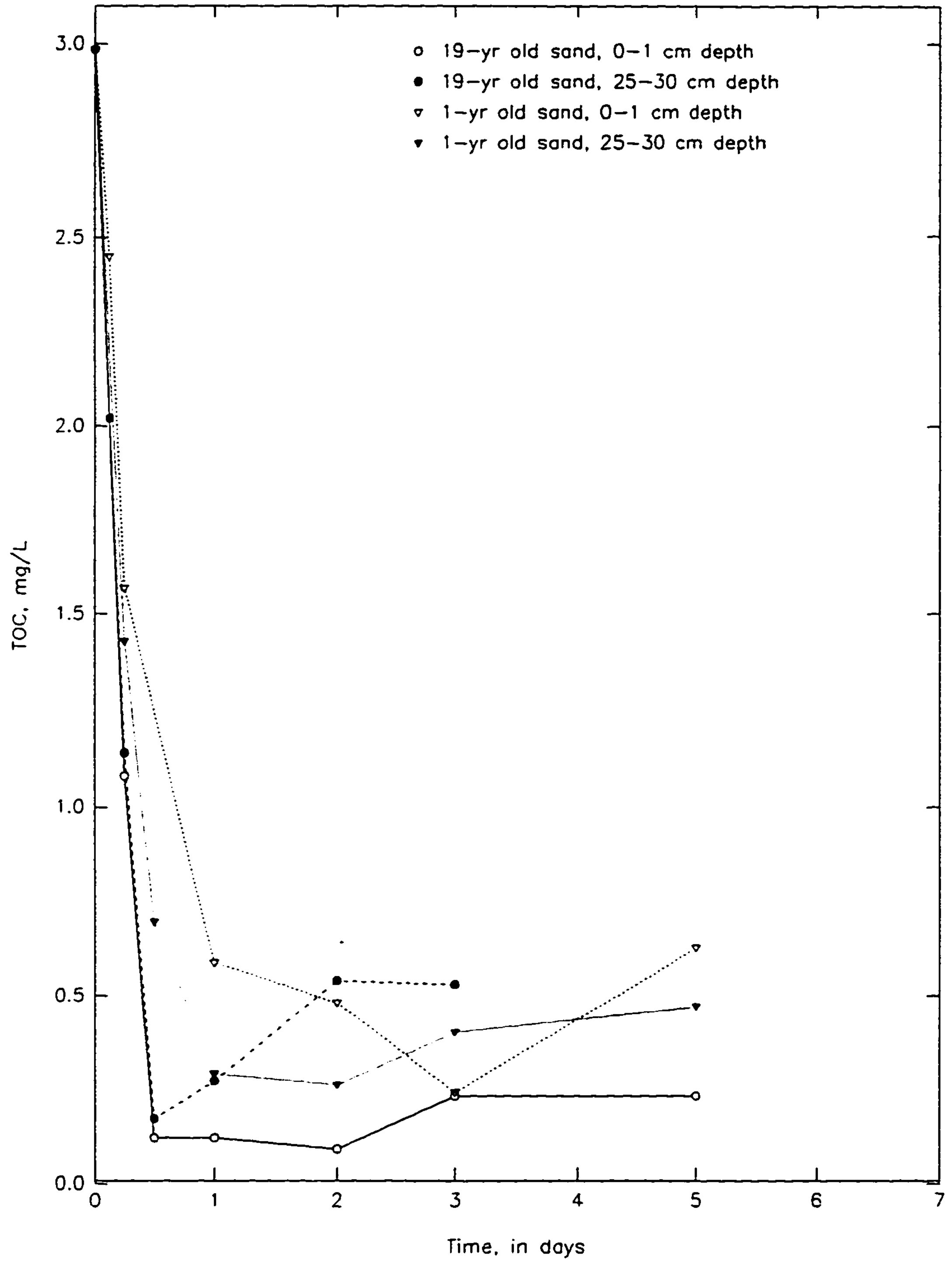


Fig. 20: **Influence of sand media age and depth in filter on TOC removal from Glucose/Glutamic acid solution.**

Removals of both TOC and UV absorbance from the natural water source were greater for the columns containing sand that had been in service for 19 years than for the columns containing "younger sand", regardless of depth, and greater for the sand taken at a depth of 25-30 cm in the filters than for the sand taken from the top 1 cm of a filter, regardless of age. The removal rates for TOC were similar to those for UV absorbance except in the column circulating the natural water and containing sand collected from the top of a filter which had been in operation less than 1 year. In that column, the TOC concentration initially decreased but, after the first 3 hours of operation (EBCT = 0.6 hours), the TOC concentration increased and then remained slightly above the concentration in the raw water for the remainder of the 5 days operation. Only one column showed an increase in UV absorbance after the initial reduction. It appeared that there was an initial removal of both NOM and G/GA followed by a period when the filters were releasing material. The released materials also appeared primarily aliphatic as they do not cause UV absorbance but are detected by the TOC test which detects both aliphatic and aromatic compounds. A study of the source and significance of these releases should be made, perhaps using water sources labelled with radiocarbon to determine if the released material has first been metabolized.

Removal of TOC from the glucose/glutamic acid solution was similar in certain respects to removals from natural water though the rate and percentages removed were higher. The influent TOC concentration was reduced by 96 percent within 12 hours (EBCT = 2.4 hours) by the 19 year old sand taken from a filter at a depth of 25-30 cm as compared to a 16 percent reduction in TOC from the natural water over the same time period by the same sand and depth. Removals of TOC from the G/GA solution by media in the other columns were less rapid but they each reduced the TOC to less than 10 percent of the initial concentration in 12 to 76 hours (EBCT = 2.4 to 15 hours). The relative performances of the individual sand media were in the same order as for removal of TOC and UV absorbance from natural water.

The relative performances of the individual sand media and water types are summarized in Table 78 using the data corresponding to an EBCT of 4.8 hours, approximately the same as the

TABLE 78: INFLUENCE OF MEDIA AGE AND DEPTH IN FILTER ON REMOVAL OF TOC AND UV ABSORBANCE.

Carbon source	Analysis method	Removals, 4.8 hr EBCT	19 years		< 1 year	
			Top 1 cm	25-30 cm	Top 1 cm	25-30 cm
NOM	TOC	%	18.2	34.6	11.8	-5.5
		mg/L	0.34	0.66	0.22	-0.10
		g TOC/ g Vol Solids	0.079	0.16	0.11	-0.046
		g TOC/ g FRM	5,800	22,000	11,000	-52,000
		g TOC/equiv.Fe	21	43	16	-7.0
		g TOC/equiv.Mn	280	620	710	-360
		g TOC/equiv.Ca	150	220	72	-22
		g TOC/equiv.Al	16	32	13	-5.7
	UV Absorbance	%	24.4	37.8	16.9	16.7
		Absorbance, cm^{-1}	0.012	0.018	0.0083	0.0082
		Abs./ g Vol Solids	2.7	4.1	4.2	3.6
		Abs./ g FRM	200	580	420	4,100
		Abs./equiv.Fe	0.72	1.1	0.59	0.55
		Abs./equiv.Mn	9.6	16	26	28
		Abs./equiv.Ca	5.3	5.9	2.7	1.7
		Abs./equiv.Al	.56	.84	.47	.45
G/GA	TOC	%	96.0	91.0	80.2	90.3
		mg/L	2.6	2.7	2.4	2.7
		g TOC/ g Vol Solids	0.80	0.71	0.99	1.1
		g TOC/ g FRM	290,000	68,000	240,000	900,000
		g TOC/equiv.Fe	170	180	170	180
		g TOC/equiv.Mn	2,300	2,600	7,600	9,300
		g TOC/equiv.Ca	1,300	920	770	570
		g TOC/equiv.Al	130	130	140	150

actual loading rate of the filters monitored at West Hartford, CT. This corresponded with the samples taken from the laboratory filter columns after 1 day.

The removal of NOM, measured both as TOC and UV absorbance, is higher for the sand taken at the greater depth from the filter that had been in operation longer. The removals, measured as TOC and UV absorbance, by the sand from the filter in operation less than one year old, were lower for the sand taken at both depths. The sand from the upper 1 cm of the younger filter was as effective as the sand from 25-30 cm in the same filter in removing UV absorbance from the normal source water (NOM) and TOC from the G/GA solution, but the sand from 25-30 cm failed to remove TOC from the normal source water. There is no explanation for this except for experimental error as that sand was effective in removing TOC from the G/GA solution.

The "younger" sand from the upper cm of the filter bed indicated a higher removal efficiency per gram volatile solids, FRM, and manganese equivalents on TOC and UV absorbance of NOM in the normal source water but the "older" sand indicated a greater removal efficiency on TOC and UV absorbance of NOM per gram equivalent iron and calcium. The relative removals were comparable per gram aluminum. The "older" sand from the lower depth was more efficient than the sand from the surface of both filters in removing TOC and UV absorbance per unit of volatile solids, iron, calcium, and aluminum. The sand from both depths of the "younger" filter were more efficient in removal on TOC from the G/GA solution per unit FRM and manganese and UV absorbance of NOM in the normal source water per unit manganese.
The removals of TOC from G/GA solution by the columns indicated the older sands had higher overall removals, though somewhat less efficient per gram volatile solids and FRM.

These results show that the age of the sand in the filters was significant on overall removals and that the removal of NPDOC and UV absorbance, both THM precursors, is more significant with depth in the filter as the sand ages. Both of these results are based on filter sand cleaned by harrowing.

4.5.2 Importance of Source Water Quality

The second series of columns compared the removal of TOC and UV absorbance from different water sources by sand from filters at different plants. The natural water supplies to the West Hartford and Newark plants and G/GA solution were applied to sand from those two plants and the sand from a pilot scale filter at the Portsmouth, NH plant. The sand from West Hartford was a mixture of sand from the top 1 cm and 25-30 cm depth of the 19 year old media in Filter No. 1. The sand from Newark was a similar mixture of the two depths, from Filter No. 4 which had been last resanded 41 months earlier. The sand and filter columns were prepared as described earlier. The eight columns were operated with the feed water and media combinations listed in Table 79. The characteristics of the media after the evaluations period are listed in Table 80.

TABLE 79: DESCRIPTIONS OF COLUMNS COMPARING DIFFERENT WATER SOURCES WITH DIFFERENT SOURCES OF SAND MEDIA.

Column No.	Media source & age years	Grain size		Water source
		Effective size, mm	Uniformity coefficient	
1	Newark, 3.5	0.52	2.7	Newark
2	Newark, 3.5	0.52	2.7	West Hartford
3	Newark, 3.5	0.52	2.7	Glucose/ glutamic acid
4	West Hartford, 19	0.48	2.5	Newark
5	West Hartford, 19	0.48	2.5	West Hartford
6	West Hartford, 19	0.48	2.5	Glucose/ glutamic acid
7	Portsmouth, <1	0.49	2.1	Newark
8	Portsmouth, <1	0.49	2.1	West Hartford

(Sand media collected from Filter No. 1 at West Hartford, CT on November 2, 1993. Sand collected from Filter No. 4 at Newark, NY on October 26, 1993. Sand collected from Portsmouth, NH pilot plant filter on November 5, 1993.)

TABLE 80: CHARACTERISTICS OF SAND MEDIA AFTER COMPARING PERFORMANCE WITH DIFFERING WATER SOURCE AND DIFFERENT SOURCES OF SAND MEDIA.

Column No.	Media source & age in years	Volatile solids %	FRM mg/gdw	Carbo-hydrate mgC/gdw x 1000	AFDC 10^6/ gdw	Iron mg/kgdw	Manganese mg/kgdw	Calcium mg/kgdw	Aluminum mg/kgdw
1	Newark, 3.5	1.19±0.11	0.13±0.04	12.3±1.5	0.9±0.1	9270 ±488	540 ±18	120000 ±8580	3360 ±536
2	Newark, 3.5	1.29±0.07	0.16±0.02	12.0±1.0	1.1±1.3	9610 ±370	544 ±46	116000 ±22800	3900 ±145
3	Newark, 3.5	1.15±0.15	0.21±0.11	13.2±1.0	1.5±0.2	8060 ±620	497 ±71	117000 ±2280	2990 ±352
4	West Hartford, 19	0.34±0.04	0.25±0.01	33.8±4.2	5.7±3.3	2880 ±391	281 ±34	1010 ±587	1870 ±488
5	West Hartford, 19	0.38±0.17	0.23±0.03	29.0±2.5	4.9±0.8	3180 ±157	248 ±2	298 ±58	1880 ±107
6	West Hartford, 19	0.44±0.17	0.19±0.04	34.4±1.3	4.3±0.2	3660 ±266	237 ±12	377 ±128	2020 ±237
7	Portsmouth, <1	0.50±0.04	0.24±0.02	31.4±3.7	2.8±0.8	1900 ±713	31 ±8	217 ±75	2230 ±246
8	Portsmouth, <1	0.51±0.01	0.22±0.01	31.3±0.7	4.8±1.3	1920 ±822	33 ±1	299 ±47	2390 ±76

The columns were operated at a temperature of 20°C and the water recycled at a constant rate of 49 mL/minute. Samples of the water were taken at timed intervals and analyzed for TOC and UV absorbance as described for the series discussed earlier. The results of the TOC and UV absorbance analyses, at the end of 24 hours operation (EBCT = 4.8 hours) are listed in Tables 81

TABLE 81: NOM ORGANIC CARBON REMOVALS COMPARING WATER SOURCES AND SOURCES OF SAND MEDIA.

Carbon source	Analysis method	Removals 4.8 hr EBCT	Newark sand		W. Hartford sand		Portsmouth sand	
			Newark water	W.Hartford water	Newark water	W.Hartford water	Newark water	W.Hartford water
NOM	TOC	%	7.4	44.5	18.6	64.6	-230	38.7
		mg/L	0.16	1.44	0.40	2.10	-2.82	1.26
		g TOC/ g Vol Solids	0.015	0.13	0.13	0.61	-0.65	0.29
		g TOC/ g FRM	1,200	9,000	1,600	9,100	-12,000	5,700
		g TOC/ g Carbohydrate	13	120	12	72	-90	40
		g TOC/ 10^6 AFDC	180	1,300	70	430	-1,000	260
		g/equiv.Fe	2.9	25	23	110	-180	110
		g/equiv.Mn	65	580	310	1,900	-11,000	8,200
		g/equiv.Ca	1.5	10	32	560	-780	340
		g/equiv.Al	3.8	30	17	90	-110	42
	UV Abs.	%	8.3	5.5	3.0	39.1	-360	-110
		Absorbance, cm^{-1}	.003	.002	.001	.018	-.087	-.004
		Abs/ g Vol Solids	0.26	0.22	0.33	5.3	-20	-1.0
		Abs/ g FRM	22	16	4.0	78	-360	-20
		Abs/ g Carbohydrate	0.23	0.21	0.03	0.62	-2.8	-0.14
		Abs/ 10^6 AFDC	3.1	2.3	0.18	3.6	-31	-0.94
		Abs/equiv.Fe	0.051	0.044	0.058	0.94	-5.7	-0.40
		Abs/equiv.Mn	1.1	1.0	00.78	16	-310	-30
		Abs/equiv.Ca	0.026	0.017	0.079	4.8	-24	-1.2
		Abs/equiv.Al	0.067	0.052	0.043	0.77	-3.4	-0.15

and 82 and the removals over the entire period are presented in Figures 21, 22, and 23.

TABLE 82: G/GA ORGANIC CARBON REMOVALS COMPARING WATER SOURCES AND SOURCES OF SAND MEDIA.

Carbon source	Analysis method	Removals 4.8 hr EBCT	Newark sand	W. Hartford sand	Portsmouth sand
			G/GA solution	G/GA solution	G/GA solution
G/GA	TOC	%	90.1	94.6	Not performed
		mg/L	2.94	2.10	-
		g TOC/ g Vol Solids	0.28	0.79	-
		g TOC/ g FRM	14,000	16,000	-
		g TOC/ g Carbohydrate	220	89	-
		g TOC/ 10^6 AFDC	2,000	720	-
		g/equiv.Fe	61	140	-
		g/equiv.Mn	1,300	2,800	-
		g/equiv.Ca	20	650	-
		g/equiv.Al	79	120	-

The greatest removals of TOC were associated with water and sand media from the West Hartford plant. Relative performance in removal of TOC from West Hartford water were, in descending order: West Hartford sand (19 years), Newark sand (3.5 years), and Portsmouth sand (<1 year). The TOC removals from Newark water were also higher when being filtered with the West Hartford sand than with the Newark sand. The filter columns with the Portsmouth sand were unable to remove either TOC or UV absorbance from the Newark water, and rapidly began to release both aliphatic and aromatic materials into the recirculating water. The columns with the Portsmouth sand were able to remove TOC from the West Hartford water but not UV absorbance. Columns with both the Newark sand and the West Hartford sand were better able to remove UV

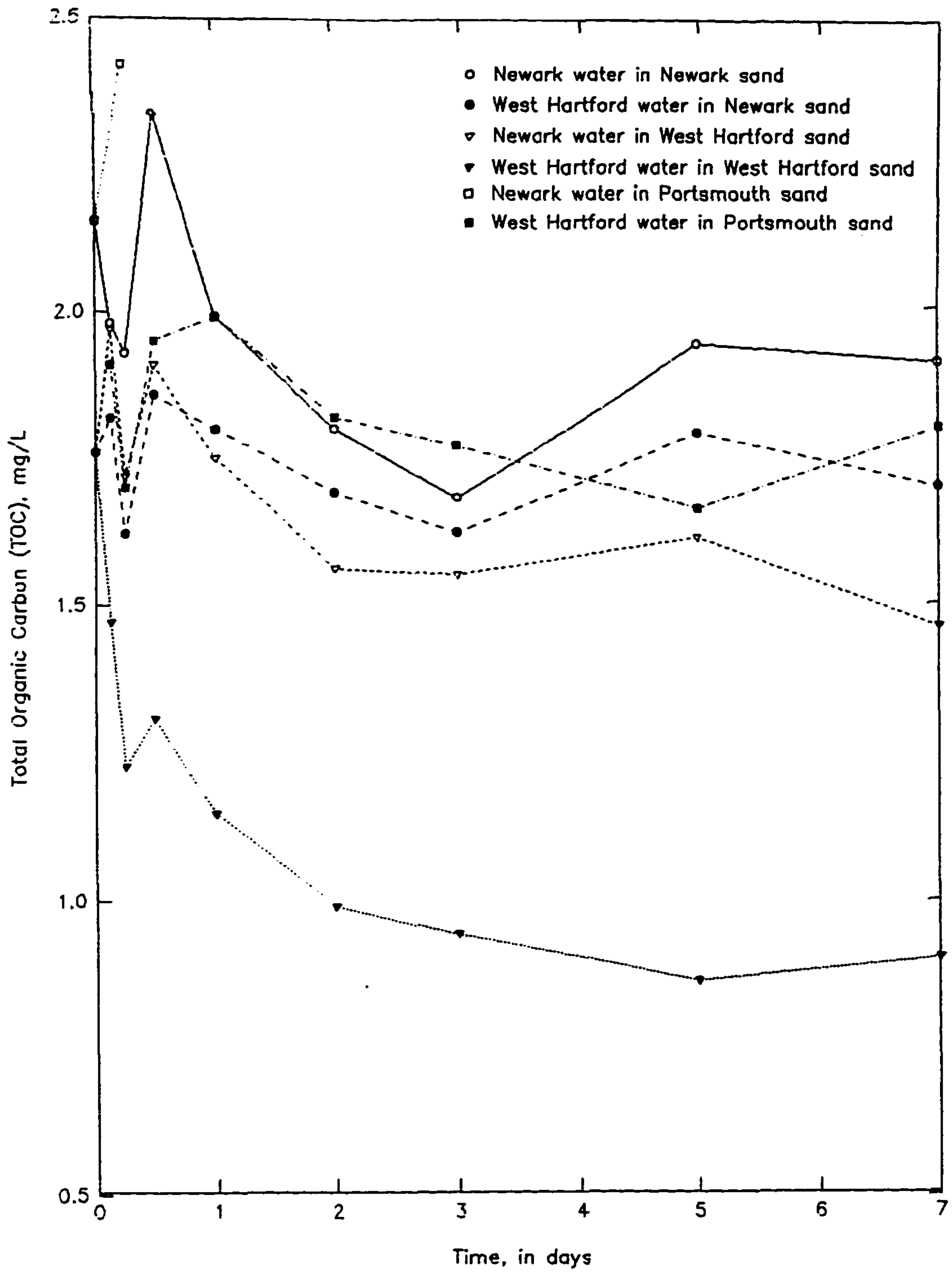


Fig. 21: Influence of different water sources on removal of NOM as measured by TOC by sand from different sources.

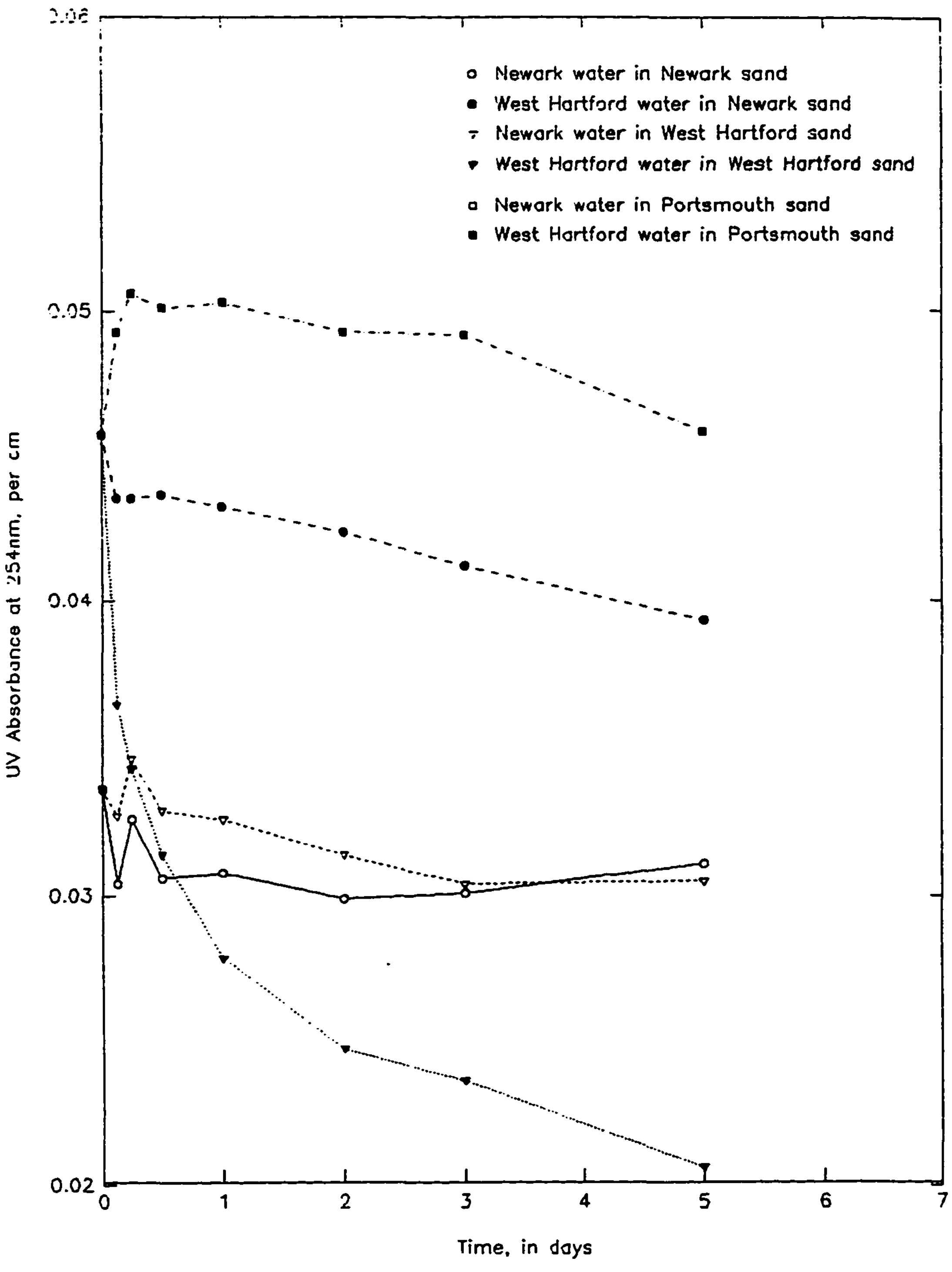


Fig. 22: Influence of different water sources on removal of NOM as measured by UV absorbance by sand from different sources.

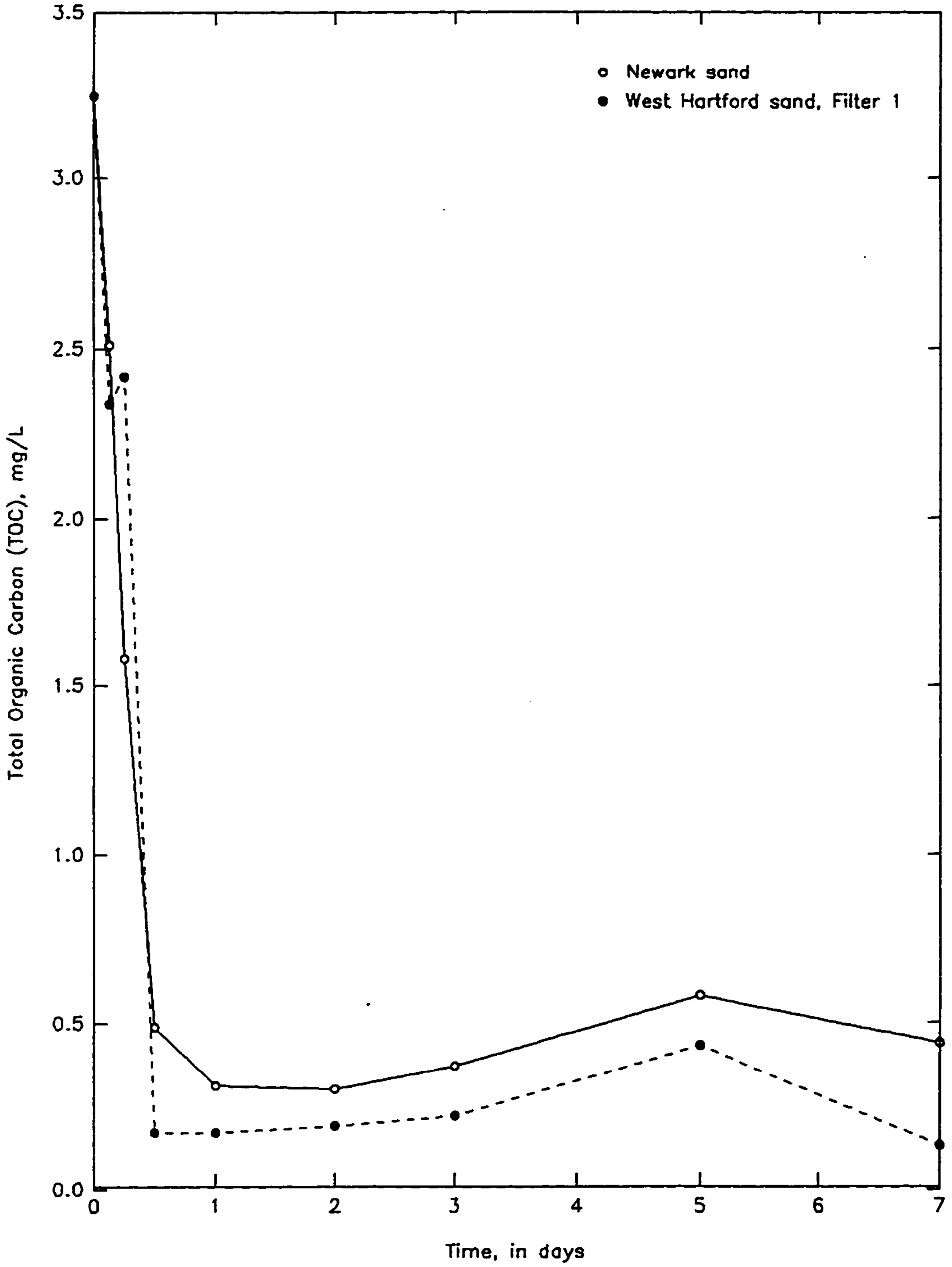


Fig. 23: Removal of TOC from G/GA solution by sand from different sources.

absorbing material from the source water normally supplied to these filter media than from the water from the other source. The West Hartford sand was able to remove 39 percent of the UV absorbing material from its own source water as compared to the Newark sand removing only 8 percent from its own supply, however. TOC in the water from the West Hartford source was more readily removed than that in water from the Newark supply or Portsmouth supply. The UV absorbance also was more readily removed than that in water from the other supplies. Generally the sand media normally used with a water source, and therefore acclimated to it, was able to remove a greater percentage of the NOM and UV absorbance from that supply than the sand media from another plant although the sand media from the West Hartford plant was more effective in removing TOC from the Newark source than was the Newark sand media. Both media removed TOC from the G/GA solution at apprximately the same percentage. The removals per unit of FRM, carbohydrate, and AFDC were higher for the Newark sand media.

4.2.3 Influence of Natural Coating Material on Filter Media

A third set of columns were run to compare removal of TOC and UV absorbance after removing a portion of natural media coating on the sand. Media preparation was described in Chapter 3. Four pairs of columns were prepared. Pairs of columns had all, two-thirds, one-third, or none of the natural coating removed by acid and combustion, as described in "Methods and Materials," and one column of each pair operated water sources as summarized in Table 83. The results of the analyses for TOC and UV absorbance at the end of the first day of the operating period (EBCT equal to 4.8 hours) are summarized in Tables 84 and 85 and the removals over the entire period are presented in Figures 24, 25, and 26.

The respective filters media removed NOM and G/GA, measured both as TOC and UV absorbance, in relative proportion to the amounts of initial biomass on the sand. The columns which contained sand which had all organic coating and metallic coating removed still demonstrated an ability to remove organic carbon. There was no evidence of a lag period before

TABLE 83: DESCRIPTIONS OF COLUMN COMPARING WATER SOURCE AND PROPORTION OF NATURAL COATINGS ON SAND MEDIA.

Column No.	Percent natural coating	Volatile solids %	FRM mg/gdw	Carbo-hydrate mgC/gdw x 1000	AFDC 10^6/ gdw	Iron mg/kgdw	Manga-nese mg/kgdw	Calcium mg/kgdw	Aluminum mg/kgdw	Water source
1	100	0.42±0.01	0.26±0.01	47.6±4.4	3±2	2240±920	41±13	281±167	2240±520	Portsmouth
2	100	0.43±0.02	0.23±0.02	40.1±4.5	3±1	2060±630	42±8	212±17	2080±110	Glucose/ glutamic acid
3	67	0.29±0.02	0.25±<0.00	24.9±1.0	2±<1	1580±780	32±9	154±25	1580±180	Portsmouth
4	67	0.28±0.04	0.23±<0.00	25.1±1.8	3±3	1310±70	31±6	212±61	1640±270	Glucose/ glutamic acid
5	33	0.17±0.02	0.21±<0.00	12.0±1.0	2±1	1090±240	22±3	159±107	883±228	Portsmouth
6	33	0.15±0.01	0.24±0.04	13.7±0.1	3±<1	844±4	21±5	186±2	867±146	Glucose/ glutamic acid
7	0	0.04±0.02	0.22±0.03	15.7±1.0	0.4±0.4	144±69	4±2	74±38	119±53	Portsmouth
8	0	0.04±<0.00	0.21±0.02	17.8±4.0	2±1	163±20	7±4	44±2	117±115	Glucose/ glutamic acid

(All media was taken from the pilot filter at Portsmouth, NH. The effective size was 0.48 mm and the uniformity coefficient was 2.0 after being sieved, and 0.49 and 2.1 after treatment to remove natural coating.)

TABLE 84: NOM ORGANIC CARBON REMOVALS COMPARING PROPORTION OF NATURAL COATINGS ON SAND MEDIA.

Carbon source	Analysis method	Removals 4.8 hr EBCT	Percent of sand with natural coating			
			100	67	33	0
NOM	TOC	%	16.8	8.9	5.6	3.1
		mg/L	1.06	0.56	0.36	0.20
		g TOC/ g Vol Solids	0.31	0.23	0.23	0.57
		g TOC/ g FRM	4,000	2,300	1,700	890
		g TOC/ g Carbohydrate	22	23	30	12
		g TOC/ 10^6 AFDC	370	310	180	470
		g/equiv.Fe	80	60	55	230
		g/equiv.Mn	5,700	3,900	3,500	9,900
		g/equiv.Ca	300	290	180	210
		g/equiv.Al	38	29	32	130
	UV Abs.	%	25.8	15.5	12.5	9.5
		Absorbance, cm^{-1}	0.068	0.041	0.033	0.025
		Abs./ g Vol Solids	0.020	0.016	0.021	0.073
		Abs/ g FRM	260	160	160	110
		Abs/ g Carbohydrate	1.4	1.6	2.8	1.6
		Abs/ 10^6 AFDC	24	23	16	60
		Abs/equiv.Fe	5.1	4.3	5.1	29
		Abs/equiv.Mn	360	280	330	1,300
		Abs/equiv.Ca	19	21	17	27
		Abs/equiv.Al	2.4	2.1	3.0	17

TABLE 85: G/GA ORGANIC CARBON REMOVALS COMPARING PROPORTION OF NATURAL COATINGS ON SAND MEDIA.

Carbon source	Analysis method	Removals 4.8 hr EBCT	Percent of sand with natural coating			
			100	67	33	0
G/GA	TOC	%	86.6	86.0	84.2	56.1
		mg/L	6.44	6.40	6.26	4.18
		g TOC/ g Vol Solids	1.7	2.8	4.6	12.
		g TOC/ g FRM	28,000	28,000	27,000	20,000
		g TOC/ g Carbohydrate	160	260	460	230
		g TOC/ 10^6 AFDC	2,500	2,500	2,100	2,600
		g/equiv.Fe	520	820	1,200	4,300
		g/equiv.Mn	3,300	4,600	6,600	13,000
		g/equiv.Ca	2,400	2,400	2,700	7,600
		g/equiv.Al	250	320	580	2,900

removals occurred for either type of carbon source, possibly due to repopulation of the sand media from biofilm within the tubing used to connect the apparatus. Analyses of the media following the procedure indicated slight or no significant differences between FRM and AFDC characteristics of the columns but the volatile solids, carbohydrates, and metal concentrations were near the concentrations expected from the blending procedure. There was poor replication for the AFDC data and the decreasing FRM trend was not as dramatic as observed for volatile solids and carbohydrate content. However, the relative removal of TOC and UV absorbance for the respective proportion of biomass/natural coating, referered to as "biosand" in Figures 24 and 25, were greater with the higher percentage of biomass/natural coating remaining on the media. Similar trends and observations have been cited elsewhere (Wang and Summers, 1994; Collins et al. 1989).

The media regained normal AFDC population densities and FRM concentrations within five

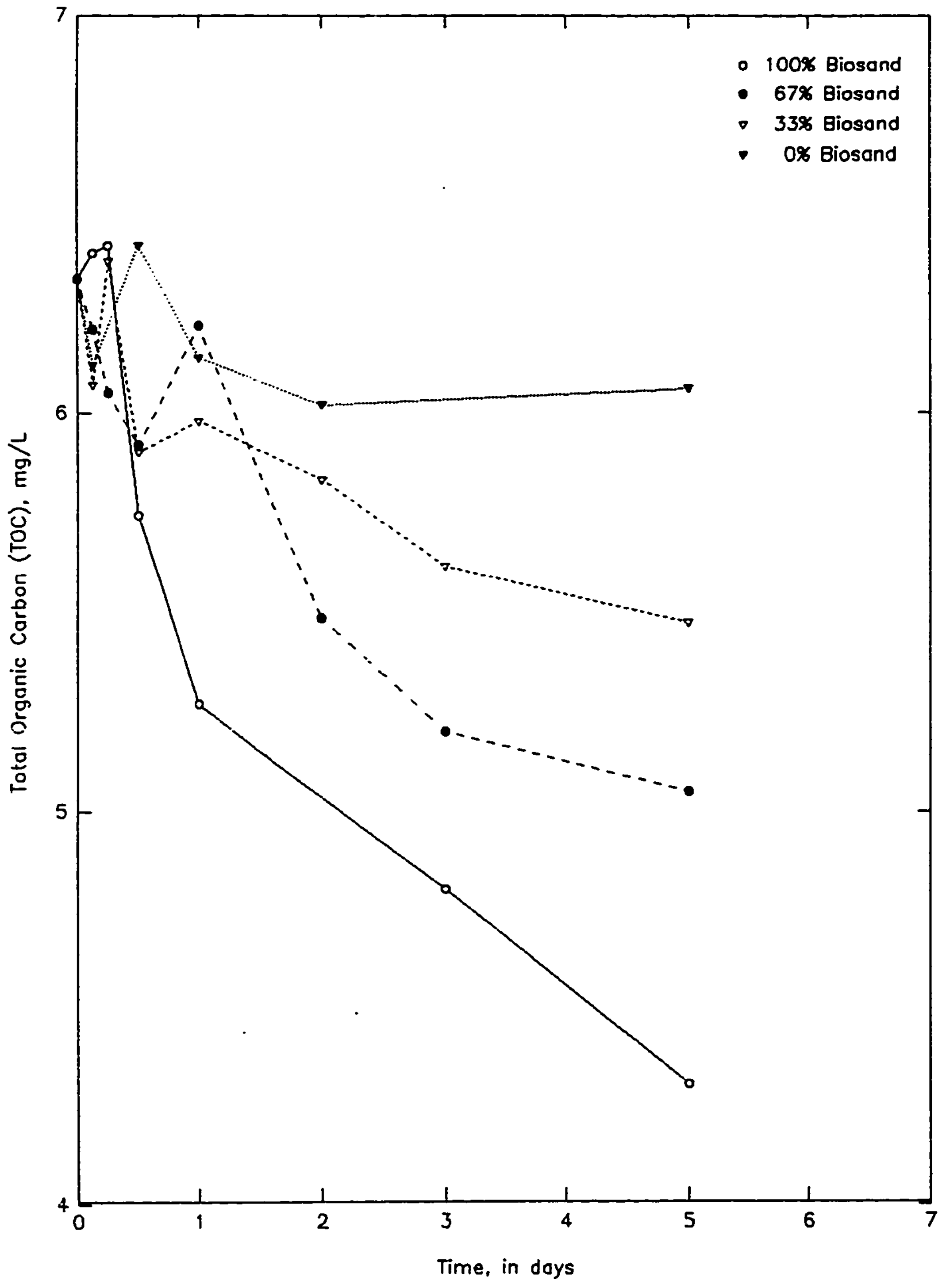


Figure 24: Influence of natural coatings on sand media on removal of NOM measured as TOC.

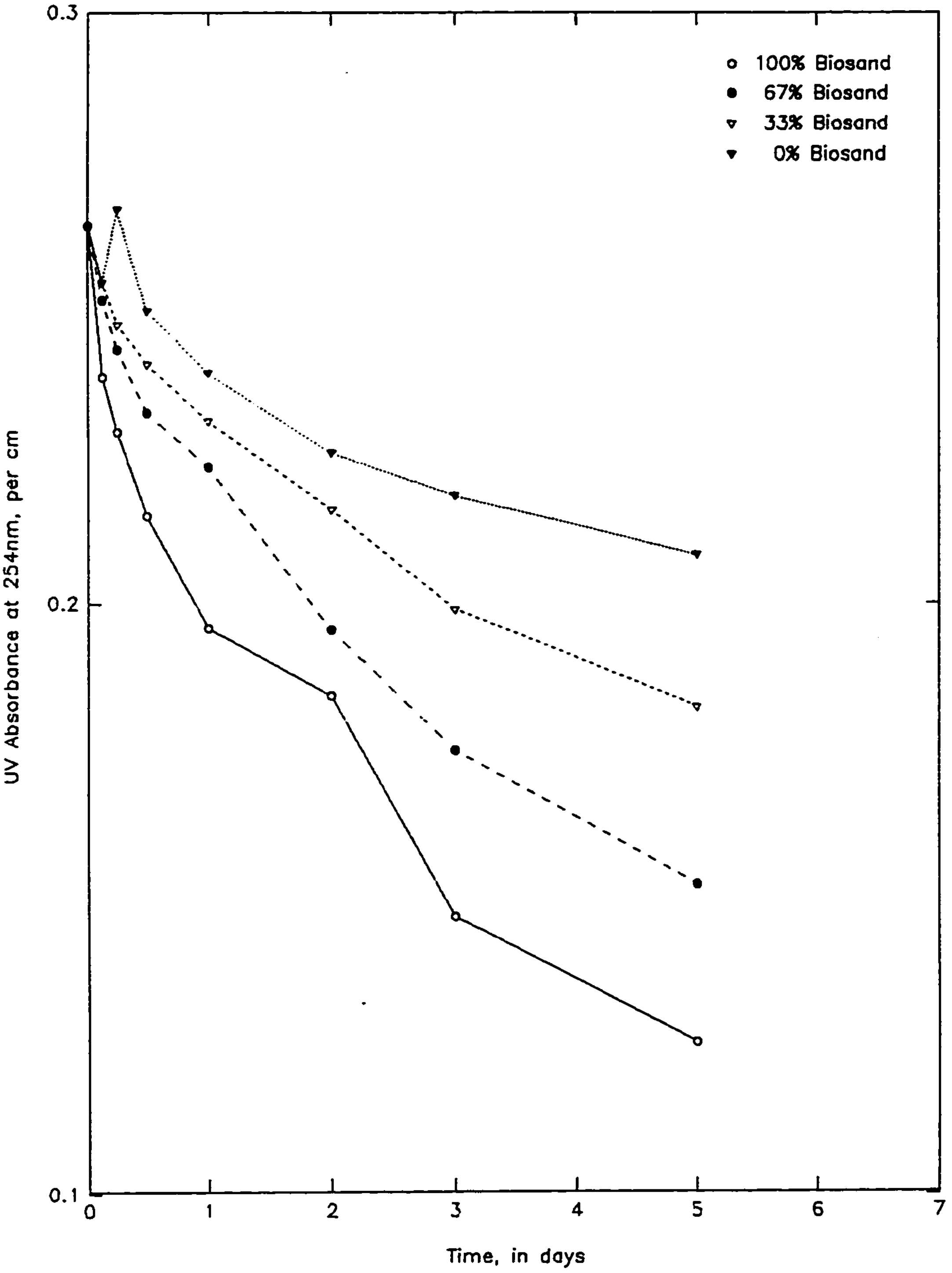


Figure 25: Influence of natural coatings on sand media on removal of NOM measured as UV absorbance.

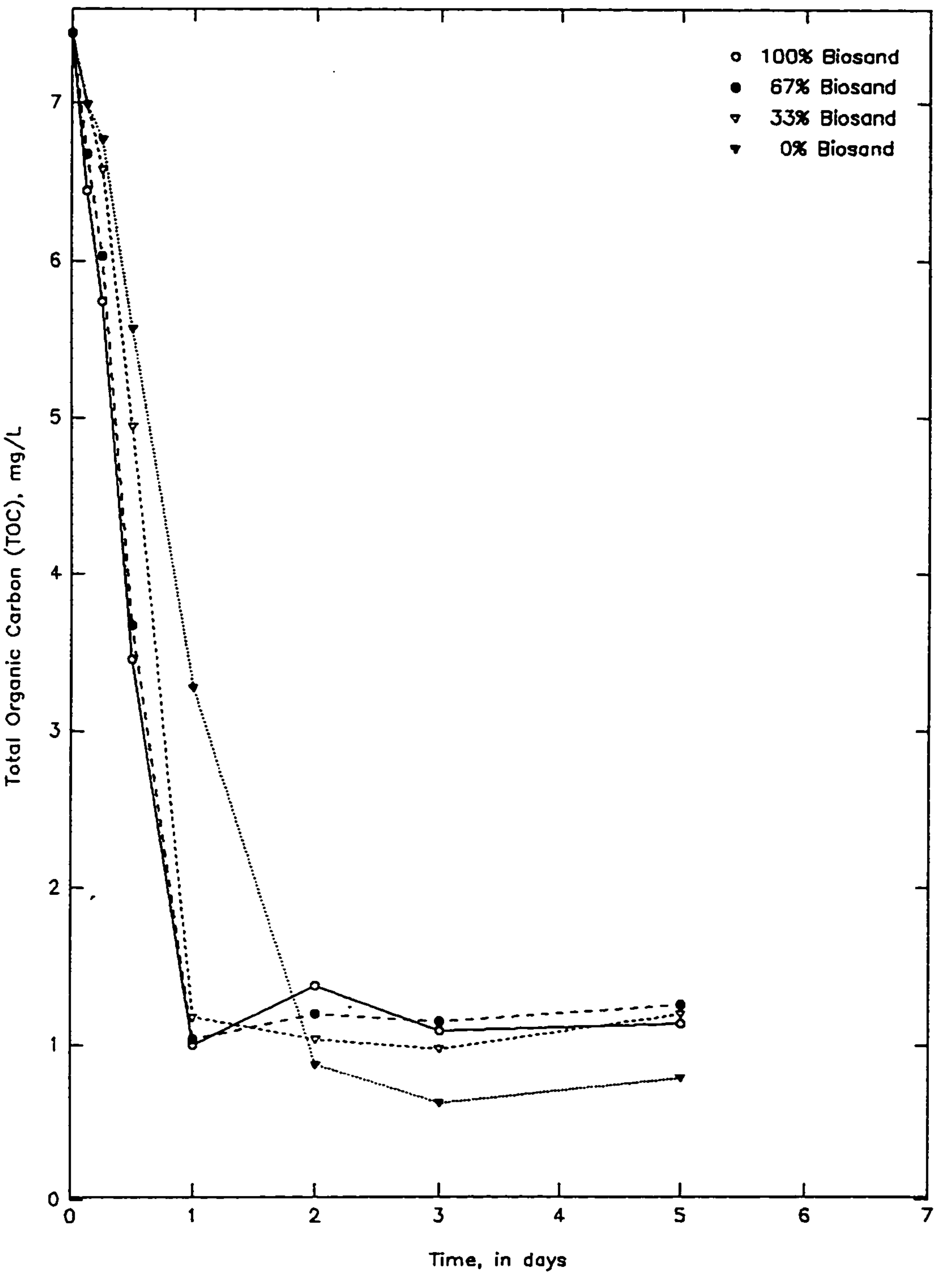


Figure 26: Influence of natural coatings on sand media on removal of TOC from Glucose/Glutamic acid solution.

days after complete destruction of the natural coating although they did not concurrently recover full removal abilities. The recovery was more complete for removal ofTOC from G/GA than from natural water, showing the removal by biodegradation of simple carbon sources recovers more rapidly than the removal of complex NOM, whether by adsorption or biodegradation. The relative ability to remove TOC was approximately the same as the removal of UV absorbance for the different proportions of natural sand coating in the individual filter columns.

4.5.4 Comparison of Filter Loading

The final set of laboratory scale filter columns were prepared to compare the effects of EBCT and filter rate on removal of TOC and UV absorbance from NOM. The columns were prepared with sand from the Portsmouth pilot slow sand filter which had been acclimating to the plant raw water for over 10 months and fed with either the Portsmouth raw water. The variables in the sets were the recirculation rates and the acclimation given to the filter column before the timed experiment began.

The columns were acclimated at the same rate, 49 mL/m, on Portsmouth water for 22 days before adjusting the recirculation pumps to the target rates. The raw water was changed after two and 14 days during the acclimation and again at the start of the 7-day run. The columns were operated with the rates and feed water combinations listed in Table 86. The media

TABLE 86: DESCRIPTIONS OF COLUMNS COMPARING FILTER RATE.

Column No.	Recirculation rate, mL/min.	Volatile solids %	FRM mg/gdw	Carbohydrate mgC/gdw x 1000	AFDC 10^6/gdw	Water source
1	49	0.48±0.09 before columns filled	1.00±0.25 before columns filled	39.3±8.8 before columns filled	0.9±0.0 before columns filled	Portsmouth
2	49					Portsmouth
3	16					Portsmouth
4	90					Portsmouth

characteristics which had been determined are also listed in that table. No metal analyses were made for these sets of columns but the concentrations would be expected to be similar to those for the fully coated material reported with the preceding set of columns. The source and preparation of sand had been the same as discussed previously. All media was taken from the pilot filter at Portsmouth, NH. The effective size was 0.48 mm and the uniformity coefficient was 2.0 after being sieved. As with the preceding sets of columns, the net EBCT was the same for all columns.

The higher removals were associated with the higher flow rates, again for both TOC and UV absorbance. The data for the removals with time are presented in Table 87 and Figures 27 and 28. The differences in removal of TOC, between the lower flow rate and the three higher rates, were proportional to the flow rates yet the differences in removal of UV absorbance was small. The removal of TOC was more sensitive to velocity than was removal of UV absorbance in these flow ranges. The UV absorbing materials are more humic in nature and are less biodegradable.

Higher filter rates increase the interstitial velocity within the media and velocity affects the boundary layer of fluid about sand or other particles within the filter. The pore spaces in a sand filter vary in size and shape, depending on particle size and distribution of sizes, shape, and the extent to which the space may be filled with trapped biological or inorganic debris. A relationship used in the ground water field for flow through porous media is:

$$V = Q/(A^*n) \qquad (6)$$

where A is the cross-section area and n is the porosity of the media. For clean sand the porosity would be approximately 0.42 (AWWA, 1990). The interstitial velocity for a pumping rate of 49 mL/min in the 2.54 cm diameter laboratory-scale filter column would be 0.36 cm/second. The condition of the interstitial flow, laminar or turbulent, can then be determined by the equation for Reynolds number using the equation:

$$R_e = \rho v d/\mu \qquad (7)$$

where d is the mean particle diameter, ρ the density of water, μ the specific viscosity, and flow is

TABLE 87: NOM ORGANIC CARBON REMOVALS FOR INFLUENCE OF FILTER RATE.

Carbon source	Analysis method	Removals 4.8 hr EBCT	Filter rate, mL/min (m/hr)			
			49	49	16	90
NOM	TOC	%	18.2	19.1	8.4	18.0
		mg/L	1.64	1.72	0.76	1.62
		g TOC/ g Vol Solids	0.43	0.45	0.20	0.42
		g TOC/ g FRM	16,000	17,000	7,600	16,000
		g TOC/ g Carbohydrate	42	44	19	41
		g TOC/ 10^6 AFDC	1,800	1,900	840	1,800
		g/equiv.Fe	140	140	63	140
		g/equiv.Mn	8,900	9,400	4,100	8,800
		g/equiv.Ca	730	760	340	720
		g/equiv.Al	63	66	29	62
	UV Abs.	%	20.6	22.5	19.4	21.4
		Absorbance, cm^{-1}	0.084	0.091	0.079	0.087
		Abs/ g Vol Solids	0.021	0.023	0.021	0.023
		Abs/g FRM	840	910	790	870
		Abs/ g Carbohydrate	2.1	2.3	2.0	2.2
		Abs/ 10^6 AFDC	93	100	87	97
		Abs/equiv.Fe	7.0	7.6	6.6	7.2
		Abs/equiv.Mn	460	500	430	470
		Abs/equiv.Ca	37	41	35	39
		Abs/equiv.Al	3.2	3.5	3.0	3.3

laminar if R_e less than a number in the range of 1 and 10 (Freeze and Cherry, 1979). The conditions relating to the laboratory scale filter columns, cleaned sand in an upflow, are such that headloss is low and the mean particle diameter may be taken from the grain size analysis. The value of the Reynolds number, for 20°C, 0.36 cm/s, and d_{50}=0.085 cm is 3.0 and flow is in the

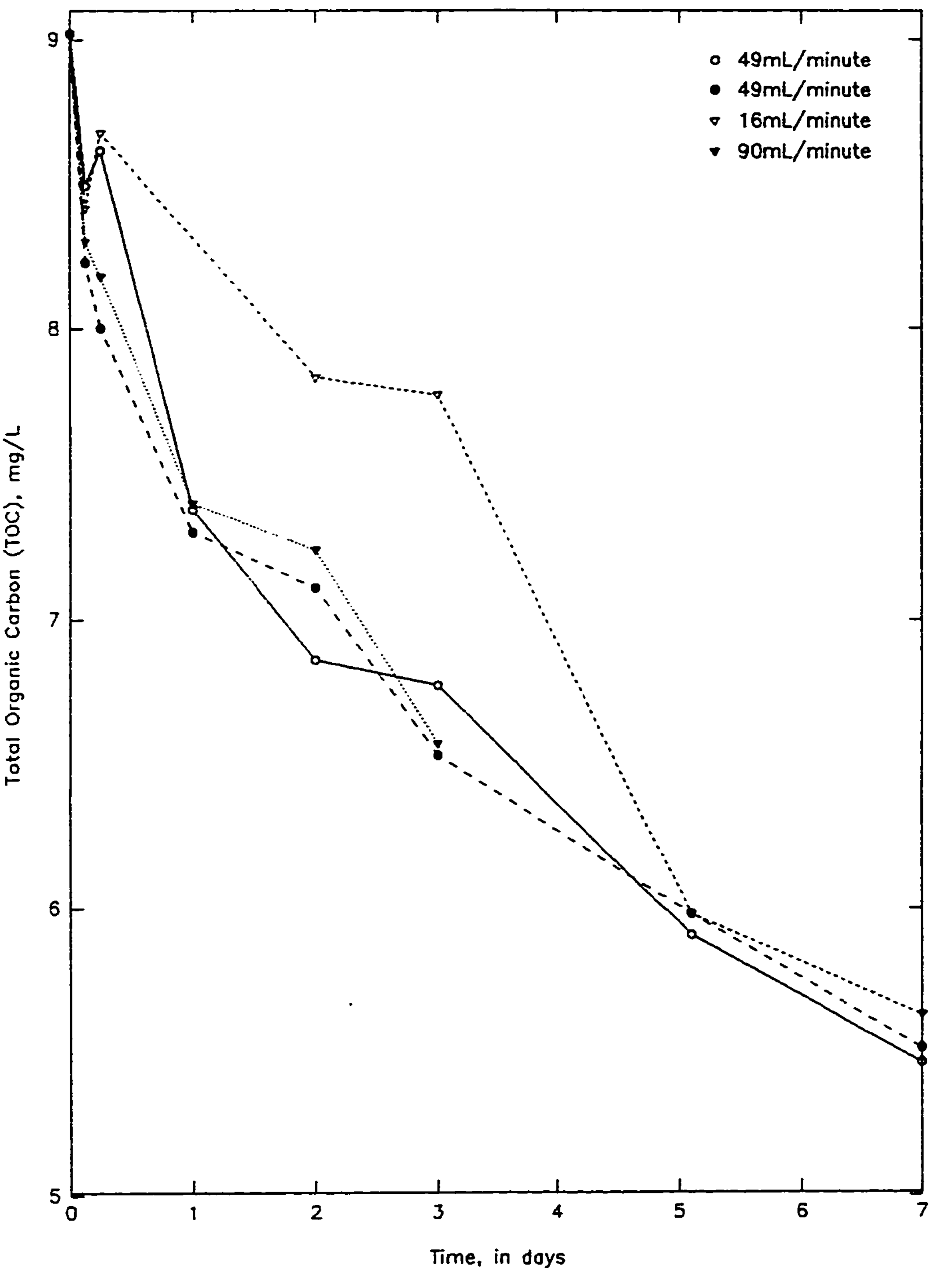


Figure 27: Influence of flow rate on TOC removal.

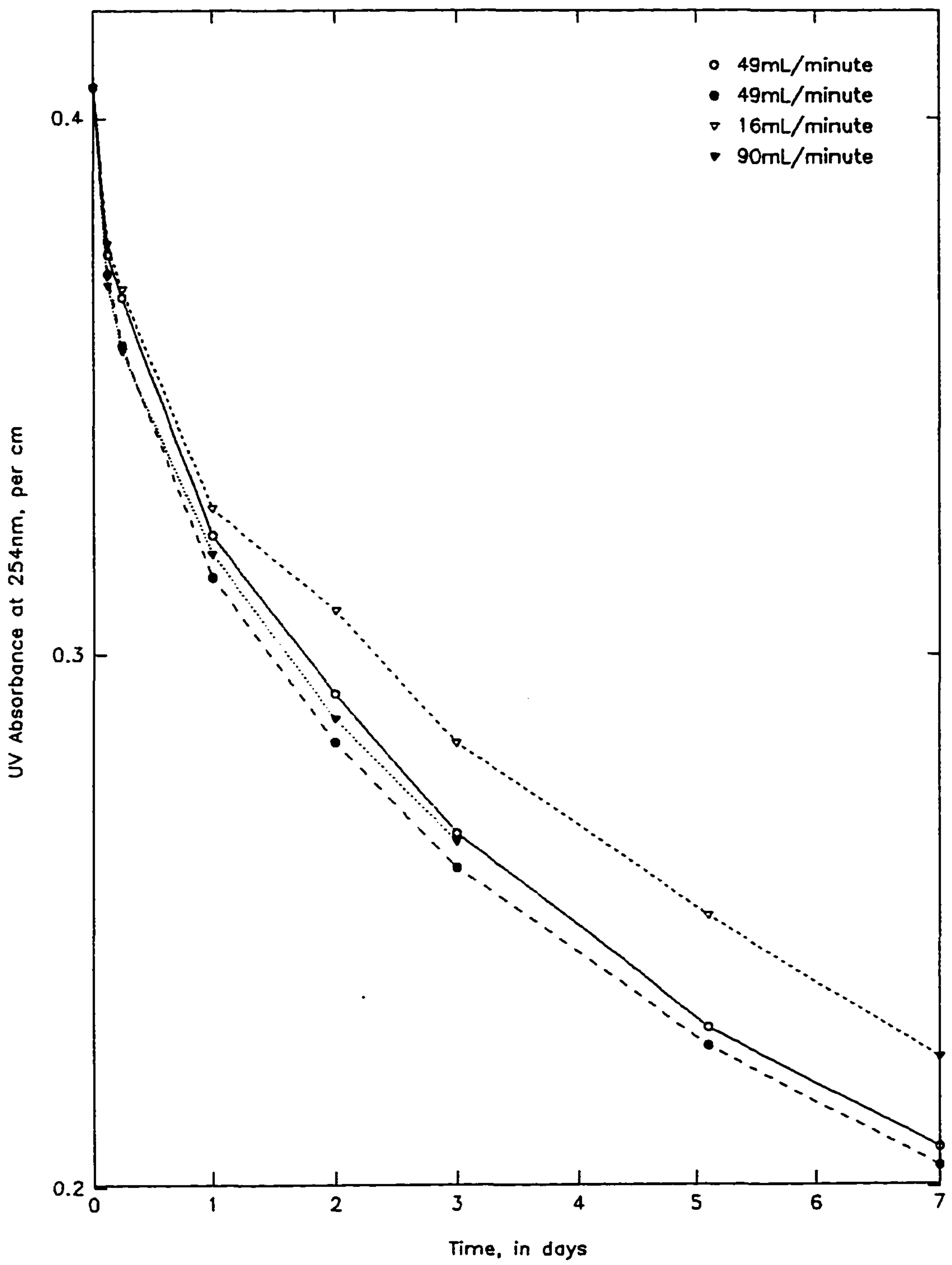


Figure 28: Influence of flow rate on UV absorbance removal.

upper range of values characteristic of laminar flow. Increasing the recirculation rate from 47 or 49 to 90 or 106 would double the Reynolds number to six which is yet higher in the range for laminar flow.

Laminar flow is characterized as an environment in which the viscous forces dominate, unlike the macroenvironment dominated by inertial forces. Viscous flow moves in layers over and around particles and there is little mixing between layers except by diffusion. The layers adjacent to the particle have no relative velocity and the supply of additional organic nutrients or particles that might sorb to the particle is not renewed nor are metabolic wastes removed. As the flow velocity is increased by increasing the recirculation rate, the viscous flow layers move more rapidly and the boundary layer about the coatings on the fixed media particle become thinner, allowing more materials to pass to and away from the coating. With turbulence, the boundary layer becomes negligible in theory and the movement of nutrients and wastes are impeded by only the mass concentrations and the transfer within the coating. In practice, however, laminar and turbulent flow are not stable conditions as the shape and size of the interstitial spaces vary, the patterns of flow change direction, and the coatings on the media are both accumulating particles and debris which fill the spaces and degrading both the accumulated matter and the coatings themselves to change the thickness of the coating and reopen interstitial spaces (Purcell, 1977; Koehl and Strickler, 1981).

The reduced rates for removal of TOC and UV absorbance at the lower flow rates, as summarized in Figures 27 and 28, indicated that the removals were limited by mass transfer, whether to the coatings and/or within the coating, but the higher velocity at the application rates of 47 and 49 and 90 and 106 mL/min reduced the limitation and removals increased. There was little difference in removal between the 47/49 and 90/106 mL/min rates and so it appears that turbulent flow existed at those rates.

CHAPTER 5

DISCUSSION OF RESULTS BETWEEN PLANTS

The operating results from each full-scale slow sand filtration plant were presented in the previous chapter. Results of the pilot scale and laboratory scale studies were also presented in that chapter. The data trends and comparisons demonstrated the importance of temperature, sand media age, sand media biomass/coating content, source water carbon (nutrients) characteristics, empty bed contact time (EBCT), and plant facility management/personnel capabilities on the performance and operation of slow sand filters. Each of these variables will be discussed in this section along with how each cleaning method may impact their influence on performance. The section concludes with a discussion on the cleaning frequency, effectiveness, and costs associated with the scraping and harrowing methods.

5.1 INFLUENCE OF TEMPERATURE

The performance of plant-scale filters relative to temperature, presented earlier by plants, is summarized together in Table 88. No data was collected on the Newark, NY plant during periods when the water temperature was less than 8°C and so no comparisons were made for operation of that plant. Similarly, there was no data collected for certain parameters at other plants and those omissions are indicated in the table. All statistical comparisons for this portion of the study used the two-tailed t-test with a 90 percent confidence limit.

Water temperatures have been found by earlier studies to be important to removals of turbidity, coliform bacteria, and Giardia cysts (Bellamy et al., 1985a, 1985b; Fogel et al., 1993) and Cryptosporidium oocysts removal (Fogel et al., 1993). The removals of turbidity were significantly higher, using the two tailed t-test and a confidence limit of 90 percent, with temperatures at or

TABLE 88: SUMMARY OF PLANT PERFORMANCE RELATIVE TO TEMPERATURE.

Parameter	Raw water temp.≥8°C.	Raw water temp.<8°C.
Turbidity, NTU		
Gorham, NH	56.4 ± 7.4 (n=44)	64.9 ± 11.6 (n=22)
Newport, NH	70.4 ± 18.9 (n=13)	88.6 ± 1.8 (n=2)
Newark, NY	92.1 ± 1.5 (n=4)	-
West Hartford, CT	93.3 ± 3.4 (n=33)	76.9 ± 13.5 (n=11)
Portsmouth, NH (pilot)	87.3 ± 2.8 (n=27)	-
Particles,/mL (≥1 um)		
Gorham, NH	-	-
Newport, NH	91.3 ± 2.2 (n=11)	88.9 ± 2.2 (n=3)
Newark, NY	98.2 ± 0.0 (n=4)	-
West Hartford, CT	98.0 ± 2.0 (n=5)	96 (n=1)
Portsmouth, NH (pilot)	97.4 ± 0.8 (n=6)	-
NPDOC, mg/L		
Gorham, NH	6.6 ± 11.3 (n=39)	6.3 ± 12.3 (n=6)
Newport, NH	24.2 ± 5.3 (n=11)	10.0 ± 2.0 (n=2)
Newark, NY	19.0 ± 2.1 (n=4)	-
West Hartford, CT	34 ± 13 (n=16)	18.0 (n=1)
Portsmouth, NH (pilot)	21.2 ± 4.6	-
UV Absorbance, cm^{-1}		
Gorham, NH	6.0 ± 9.6 (n=23)	6.6 ± 6.4 (n=6)
Newport, NH	25.0 ± 6.1 (n=11)	16.3 ± 3.5 (n=4)
Newark, NY	16.5 ± 7.4 (n=4)	-
West Hartford, CT	43 ± 11 (n=17)	-
Portsmouth, NH (pilot)	29.9 ± 2.0 (n=11)	-

greater than 8°C at the three plants where data was collected. The removals of particles, tested only at two plants, were higher at the Newport, NH plant though not at the West Hartford, CT plant. The removals of NPDOC and UV absorbance were significantly higher during the seasonally warm periods of the year at both the Newport, NH and West Hartford, CT plants than at lower water temperatures but not significantly affected at the Gorham, NH plant. This information is supported by the relative removals of UV absorbance reported by Fenstermacher (1988). That report showed the NPDOC removal was approximately the same between the two seasons reported, "fall" and "winter" both showing a removal of 33 percent, but the filter rates in the fall twice that during the winter sampling event. No reference was made in that report to a temperature effect, but the fall temperatures were reported to be 16 to 17°C and winter temperatures to be 2°C.

Temperature had been previously reported to be significant in the performance of slow sand filters in permanganate consumption (Van de Vloed, 1956), nitrification (Huisman and Wood, 1974), and removal of BDOC (Servais et al., 1992; and Welte and Montriel, 1996). The effect at the Gorham, NH plant appeared to have been present for NPDOC removal, as shown later in Figure 30, but insufficient to be statistically significant due to the wide standard deviation in the data. The effect of temperature at the Gorham, NH plant was not noticeable on the removal of UV absorbance.

The removal of turbidity varied with temperature at all plants and removal of particles varied with temperature at the Newport, NH plant though not at the West Hartford, CT plant. There was no significant difference in removal of either parameter between the two plants which had used the scraping method (Newark, NY) and the harrowing method (West Hartford, CT) to clean filters.

The NPDOC and UV absorbance removals at all plants were plotted against temperature and removals were found higher at temperature at or greater than 8°C. Because of this and because no comparable removal data had been collected for the Newark, NY plant when water temperatures were below this level, the data for all the plants was separated according to temperatures at or above 8°C or below 8°C, Removals at the Gorham plant were not found to be related to temperature but these data also were separated so the data for comparison between plants would be on the same temperature base. The removals during periods when the raw water temperatures equal or exceeded 8°C are summarized in Figure 29. The statistical significance of the removal efficiencies between the plants and temperature ranges are summarized in Table 89. There were significant differences between all plants in the percent of NPDOC and UV absorbance removed.

The data used in Collins et al. (1992) also showed a significant difference in removals of NPDOC and UV absorbance between samples in the "winter" and "fall" but offered no explanation.

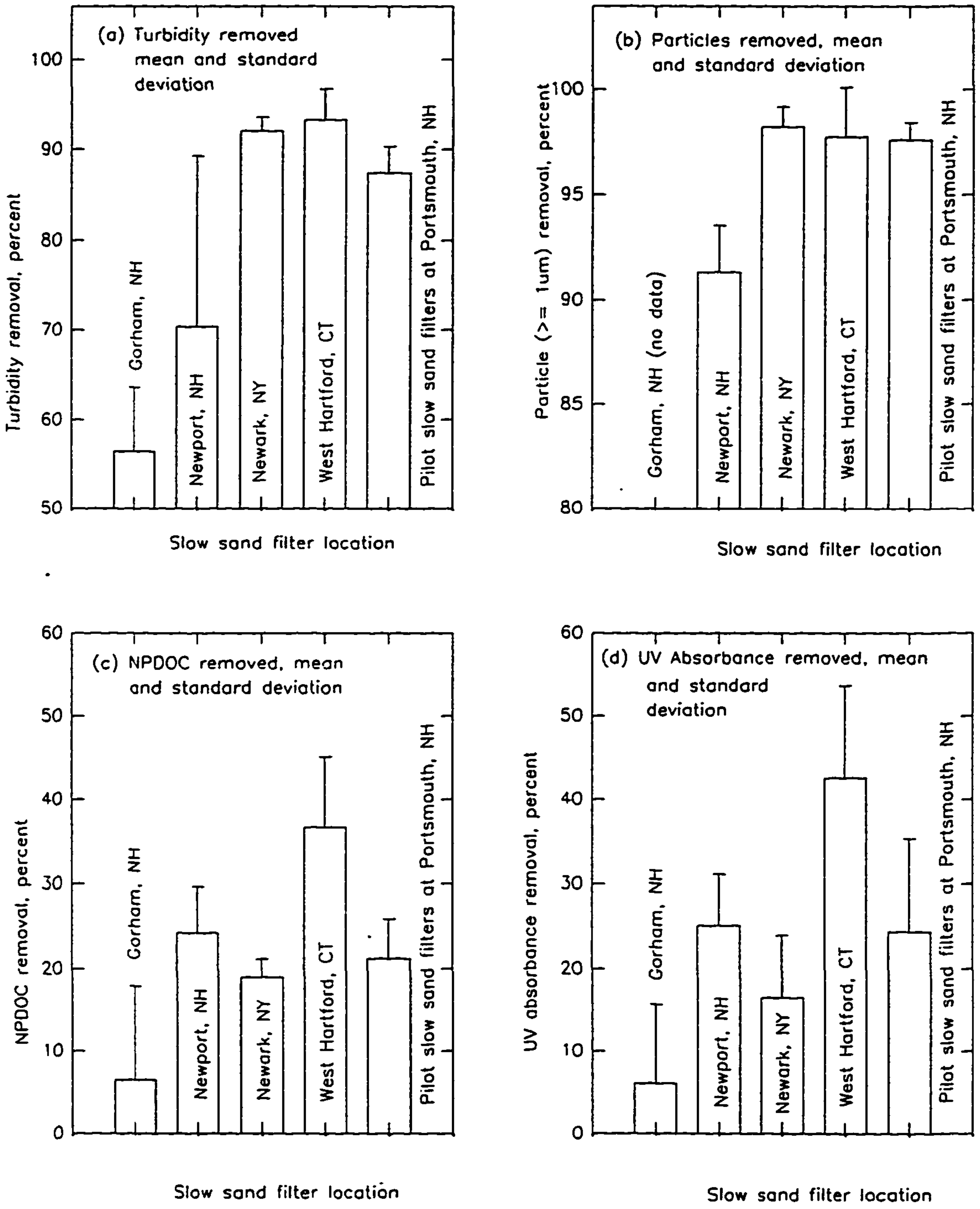


Figure 29: Mean removals of turbidity, particles, NPDOC, and UV absorbance at plants, for water temperatures $\geq 8°C$.

TABLE 89: COMPARISON OF REMOVAL EFFICIENCY BETWEEN PLANTS WHEN TEMPERATURE ≥ 8°C (RELATIVE TO 90 PERCENT SIGNIFICANCE).

Plant (vs plant below)	Gorham, NH	Newport, NH	Newark, NY
Turbidity removal			
Newport, NH	No	-	-
Newark, NY	Sig. diff.	Sig. diff.	-
West Hartford, CT	Sig. diff.	Sig. diff.	No
Particle removal			
Newport, NH	(a)	-	-
Newark, NY	(a)	Sig. diff.	-
West Hartford, CT	(a)	Sig. diff.	No
NPDOC removal			
Newport, NH	Sig. diff.	-	-
Newark, NY	Sig. diff.	Sig. diff.	-
West Hartford, CT	Sig. diff.	Sig. diff.	Sig. diff.
UV absorbance removal			
Newport, NH	Sig. diff.	-	-
Newark, NY	Sig. diff.	Sig. diff.	-
West Hartford, CT	Sig. diff.	Sig. diff.	Sig. diff.

No = no significant difference (Sig. diff.)using two-tailed t-test at 90 percent confidence limit.
(a) No data on Gorham

Review of records for the West Hartford plant reveal the probable water temperatures on the respective sampling dates were in the range of 2-3°C for winter and 16-20°C for fall. Other research (Collins and Vaughan, 1993) concluded that the impact of temperature depended upon the biodegradability of the target organic compound. They found reducing temperatures from 20°C to 5°C significantly affected the rate of biodegradation of glucose/glutamic acid (G/GA) in a recirculation filter columns, but not the eventual total reduction. Natural organic matter removals were also affected by temperature but to a lesser extent than for more readily biodegradable organic compounds.

Temperature effects on nutrient transformation have long been documented, usually related with a simplification of the Arrhenius relationship as follows (Bowie, et al., 1985):

$$K_T = K_{20}\,\theta^{(T-20)} \qquad (8)$$

where K_T = rate coefficient at temperature T,
T = temperature, °C
K_{20} = rate coefficient at , 1/time
θ = temperature adjustment factor.

Removal of NPDOC and UV absorbance for the four plants sampled in this investigation were plotted against the water temperatures at the time of sampling and compared. This information is summarized in Figures 30 and 31. Solution of the equation (8), using the lines of best least square fit for each filter are summarized in Table 90. These coefficients can only be considered qualitative of the trends due to the generally low regression coefficients, particularly relative to the removal of UV absorbance. The data for the Newport, NH, Newark, NY, and West Hartford, CT filters, however, are relatively consistent for NPDOC removal. The mean slopes and Y-intercepts for these three plants, with relative percent standard deviations, were 0.048 ± 31 percent and 2.65 ± 12 percent for NPDOC removal, and 0.038 ± 145 percent and 2.80 ± 35 percent for UV absorbance removal. No data on NPDOC or UV absorbance removal was found in the literature apart from Fenstermacher (1988).

TABLE 90: REGRESSION DATA FOR REMOVAL OF NPDOC AND UVA vs TEMPERATURE.

	Gorham, NH	Newport, NH	Newark, NY	West Hartford, CT		
				Filter 21	Filter 18	Filter 1
NPDOC						
Slope	0.14	0.041	0.051	0.040	0.036	0.074
Y-intercept	0.70	2.55	2.22	2.82	3.05	2.60
regression, r	0.45	0.75	0.51	0.58	0.65	0.60
UV Absorbance, cm^{-1}						
Slope	-0.022	0.033	0.052	0.014	0.12	-0.03
Y-intercept	2.43	2.59	1.99	3.28	2.00	4.14
regression, r	0.12	0.66	0.12	0.25	0.89	0.42

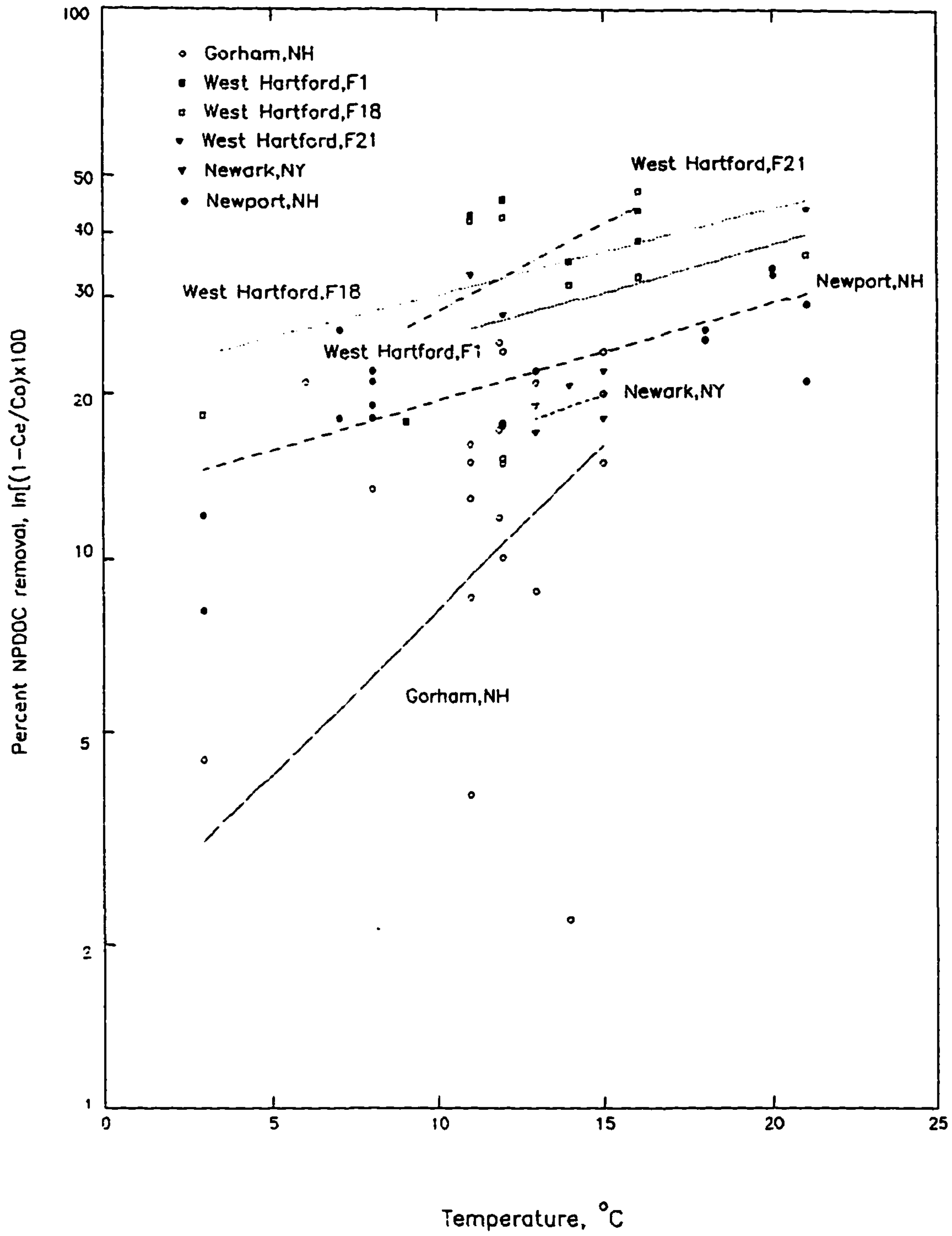


Figure 30: NPDOC removal vs temperature.

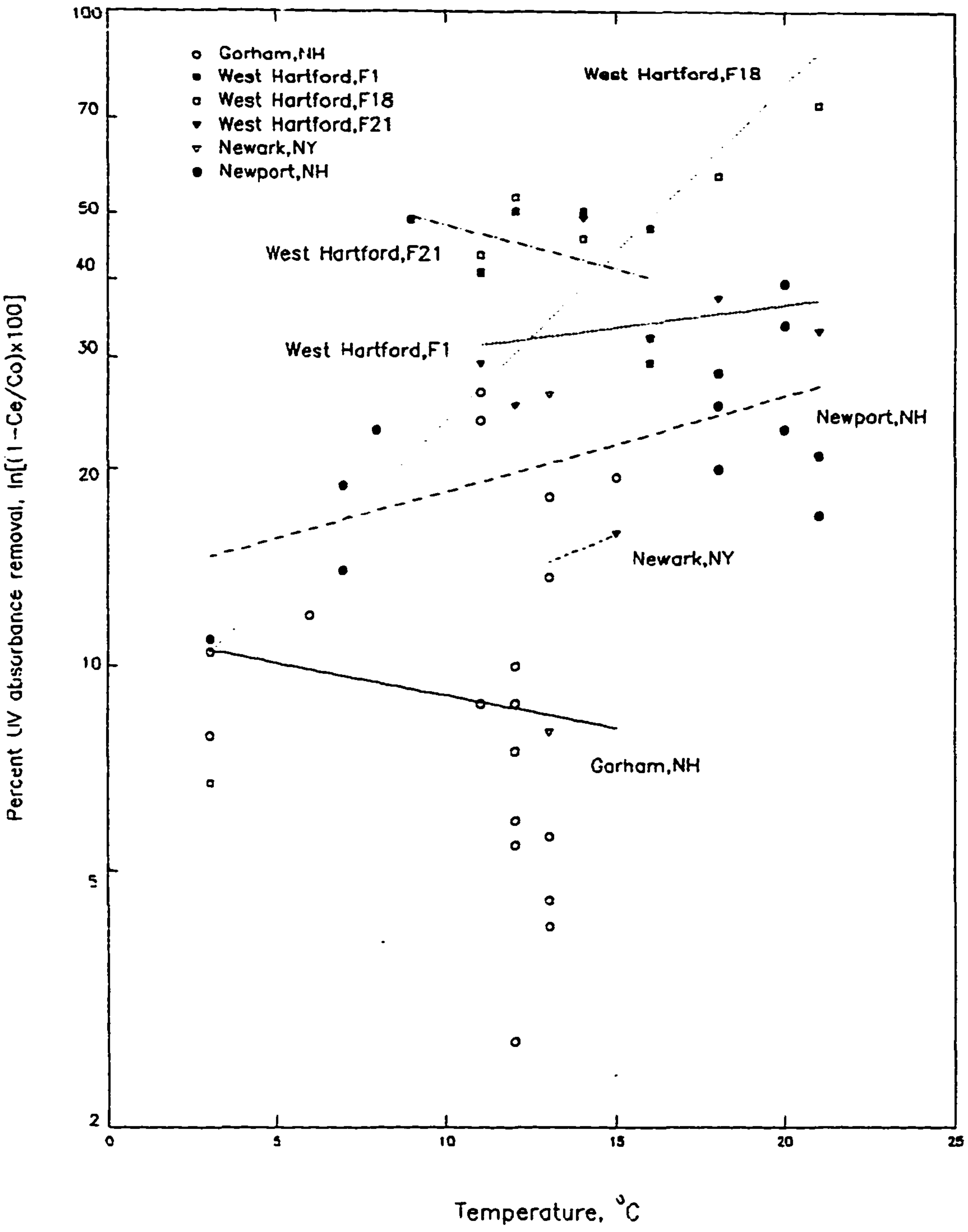


Figure 31: UV absorbance removal vs temperature.

Summary: Temperature significantly influences the performance of slow sand filters on the removal of turbidity and particles and, at some plants, the removal of NPDOC and UV absorbance. A comparison of operating results from slow sand filtration must consider the water temperature at the time of sampling. These temperature related effects on removal of NPDOC and UV absorbance appeared to be independent of the cleaning method utilized.

5.2 SAND MEDIA CHARACTERISTICS

Previous studies (Spanos, 1989; Collins et al., 1989; Eighmy et al., 1991) have discussed sand media characteristics of three operating plants and their relation to performance. The current study also considered sand media characteristics using four operating plants, several filters within those plants, replicate cores within each filter, and subsamples at various depths within the cores.

Results of analyses for FRM and AFDC were generally comparable between this study and those reported in Tables 7 and 8. FRM and AFDC concentrations and ratios of FRM to AFDC for this study and those reported by Spanos (1989) are presented in Table 91. The information in this study was from analyses on cores taken generally from May to October while those previous studies were taken either in February or September. The data was again compared using only those samples taken during the period from June to October when water temperatures were

TABLE 91: COMPARISON OF MEDIA CHARACTERISTICS WITH PREVIOUS STUDIES.

Parameter	This study	Spanos (1989)
FRM, mg/g dry weight at depth of:		
Upper 1.2 cm	0.2 - 4.4	0.4 - 4
25-30 cm	0.1 - 1.3	0.4 - 1.5
AFDC, count/g dry weight at depth of:		
Upper 1.2 cm	1 to 3 x 10^8	10^8 to 10^9
25-30 cm	10^7 to 10^8	10^8 to 10^9
g FRM/AFDC	5 x 10^{-12} to 3 x 10^{-11}	0.8 to 2 x 10^{-12}

above 8°C and the information presented in Table 92. Data was available on three cores from each of the eight filters sampled during period when water temperatures were greater than 8°C in this study. Data was available on one core each of three filters in the previous study. The filters in this study had been in operation for periods of time ranging from less than one year for the filters at Newport, NH and Filter 21 at West Hartford, CT, to two to four years for Gorham, NH and Newark, NY, and to 19 years for Filter 1 at West Hartford, CT. Filters in the previous study (Spanos, 1989) had been in service for 12 (West Hartford Filter 8 to 14 years (New Haven, CT). The time since resanding for the Springfield, MA filters was not reported except for reporting that they were resanded at intervals of no more than 8 years.

TABLE 92: COMPARISON OF MEDIA CHARACTERISTICS WITH PREVIOUS STUDIES, WATER TEMPERATURES GREATER THAN 8°C.

Parameter	This study	Spanos (1989)
FRM, mg/g dry weight at depth of:		
Upper 1.2 cm	0.4 - 4.4	1.1 - 3
25-30 cm	0.2 - 1.3	0.8 - 3.5
AFDC, count/g dry weight at depth of:		
Upper 1.2 cm	1 to 3 x 10^8	$2X10^8$ to $4X10^8$
25-30 cm	0.2 to $2X10^8$	10^8 to $6X10^8$
g FRM/AFDC	4 x 10^{-12} to 2 x 10^{-11}	1 to 8 x 10^{-12}

Other references have noted FRM concentrations in the upper portion of the media, in the material between 2 and 15 cm below the surface, to be between 0.2 and 3 mg/g dry weight and AFDC concentrations of $3x10^8$ to $4x10^9$ (See Table 7). Seger and Rothman (1996) reported bacteria concentrations at this depth in slow sand filters as $1.5x10^7$ CFU/g dry weight using DAPI epifluorscent methods which would correspond to an AFDC count of approximately $2.2x10^7$ /g dry weight using the comparison between methods reported by Spanos (1989). Yardanov et al. (1996) reported a concentration of $2x10^7$ CFU/g dry weight on R2A media.

The ratio of carbohydrate to FRM ranged from 0.003 g/g in the Gorham, NH filter to 0.17

g/g in the West Hartford, CT filters. Carbohydrate materials include cellular polysaccharides at ratios of approximately 2 to 3 percent, if carbon limited, to 19 percent, if ammonia limited (Charackis and Marshall, 1990), but also cellulose and other organic degradation organics. The carbohydrate analyses for the cores in the Gorham, NH filter are at approximately ten percent of the expected concentration relative to the FRM and AFDC concentrations and may not be valid. The carbohydrate concentrations in the Newport, NH, Newark, NY, and West Hartford, CT filters averaged 15, 14, and 17 percent of the FRM concentrations and within the range expected from the literature (Charackis and Marshall, 1990).

Spanos(1989) had reported from analyses of two cores within the same filter at Springfield, MA, using an ANOVA analysis with a 95 percent confidence limit, that there were no significant differences between cores and, from analyses of cores from different filters at that same plant, that there were also no significant differences between the two different filters. He also did not find any significant differences between the cores taken from a Springfield, MA filter in the fall and winter. He did report significant differences (FRM, AFDC, iron, manganese) between depths in cores and between filters at different plants (Springfield, MA, New Haven, CT, and West Hartford, CT) for FRM, iron, and manganese, but not AFDC.

The current study used a confidence level of 90 percent and 2-way ANOVA methods to compare the analyses of three cores from each filter and multiple filters at each of the four plants. Significant differences in volatile solids, FRM, and carbohydrates were found between cores taken from the same filter at all plants except Gorham. Differences in AFDC were present but were not consistently related. Few literature references were found relating to variations between samples at the same depth at different locations within the same filter. Haarhoff and Cleasby (1991) reported from their literature review that "Throughout the slow sand literature, the implicit assumption is made that the vertical biological stratification is the same everywhere in the filter" and that it "may be a reasonable assumption." One reference was reported (Bellinger, 1979) that showed significant variations in algal distribution existed on the filter surface, with variations of about an order of magnitude on two sampling occasions. Factors leading to the variations were hydraulic turbulence at the influent point which prevented uniform schmutzdecke formation, and weather condition (wind and light exposure) on the open filters studied. Minkus (1954) reported that hydraulic permeability of cores from cleaned sand filters varied but did not comment on possible causes. Turneaure and Russell (1924) noted that variations in filtering rate would occur between parts of filters because of scraping, variations in headlosses in the underdrain system, and possible breakage of the underdrains. Intermittent development of schmutzdecke at Gorham and Newport, differences cleaning intensity in corners and adjacent to walls and columns when tractor harrowing was used, variations in cross-flow velocity during wet harrowing, and differences in the depth of sand removed by scraping between individual laborers, and differences in depths of filter sand were observed during this study giving qualitative evidence of possible causes. Filter permeability may also have varied due to localized compaction, deposition, or even blockage of underdrains but these last factors are hypothesized.

The results of these comparisons between cores and filters within plants have been presented earlier with results on the specific plants. Few differences were found between the mean data for the same filter sampled twice within a short time period and within the same season, such as for Filter 21 at West Hartford, CT. or between filters at the same plant which had been operating for approximately the same length of time, as for Filters 3 and 4 at Newark, NY (19 and 39 months) sampled on the same day. Significant differences were found between mean data for the same filter if it were sampled during different seasons, as occurred at all plants, and from different filters at the same plant if the sand in the filters had been in use for significantly different time periods, as for Filters 1,18, and 21 (ages of 19 years, 13 years, and less than one year, respectively since reconditioning) at West Hartford, CT. The filters used by Spanos (1988) at West Hartford, by comparison, had aged 13 years before the fall sampling and 15 years before the winter sampling.

All cores taken in the current study, at Gorham, Newport, Newark, and West Hartford, showed significant differences with depth for volatile solids, FRM, carbohydrates, and AFDC. Differences in iron, manganese, calcium, and aluminum concentrations seldom occurred except with depth and between plants. The media characteristics presented in the preceding chapter were compared between plants, using data on filters sampled during the same general season and filtering water having similar temperatures. The comparisons were made between filters for characteristics of the media in the top 1.2 cm and of the media between 25-30 cm. The surface schmutzdecke was excluded from these comparisons as it could not be collected in a consistent manner. The surface schmutzdecke readily and unavoidably detached from the sand surface at the Gorham and Newport plants when attempting to collect it, but was firmly attached at the Newark and West Hartford plants. The surface schmutzdecke was separated from the surface of the West Hartford filter samples allowing comparison to the samples from Gorham and Newport. The surface schmutzdecke at the Newark, NY filters was very thin and tightly bound to the sand but was scraped, as well as possible, from the sand core surface before analyzing for the media characteristics. The statistical comparison between the respective levels for the filters of the various plants are summarized in Tables 93 and 94. The mean values of the upper and lower levels were averaged and the standard deviations pooled, and the resultant values compared as summarized in Table 95. All comparisons were made using the two-tailed t-test with a 90 percent probability. A separation of variance on the data for the Newark NY plant is presented in Appendix B.

Volatile solids, FRM, carbohydrates, and AFDC were generally different between the filters at all plants for the top 1.2 cm and between the 25 and 30 cm depths and for the mean of the concentrations at those two depths. Volatile solids concentrations were different between filters at both depths, except between the two older filters at West Hartford. FRM concentrations in the surface of the Gorham filters were different only from the Newport and youngest West Hartford

TABLE 93: COMPARISON OF ORGANIC CHARACTERISTICS IN TOP 1.2 CM OF FILTERS.

Plant	Gorham	Newport	Newark	West Hartford, CT		
Filter	F2	F3	F3,4	F21	F18	F1
Date	July 27,'93	July 26,'93	Aug.8, '93	Oct.12, '93	Oct.13, '93	Oct.5, '93
Water temp.	15°C	21°C	10°C	14°C	14°C	16°C
Volatile solids, percent dry weight						
Mean	0.18	0.36	1.13	0.75	0.65	0.67
Stnd.dev.	0.02	0.02	0.17	0.06	0.09	0.07
n	6	2	12	6	6	6
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	No	-
FRM, mg protein/gram dry weight						
Mean	1.48	4.36	1.58	2.24	1.40	1.93
Stnd.dev.	0.48	0.96	0.31	0.47	0.15	0.62
n	12	4	16	6	6	6
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	No	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	No	Sig. diff.	No	Sig. diff.	-	-
vs WH F1	No	Sig. diff.	Sig. diff.	No	Sig. diff.	-
Carbohydrate, mg C/gram dry weight						
Mean	0.0049	0.011	0.14	0.26	0.27	0.19
Stnd.dev.	0.0011	0.001	0.045	0.02	0.05	0.03
n	12	4	21	9	9	9
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-

Table 93 continued on next page

Table 93 continued from preceding page.

Acriflavin direct count, Counts/gram dry weight

Mean	308	203	182	92	99	123
Stnd.dev.	164		23	8	21	78
n	4	1	8	3	3	5
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	No	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	Sig. diff.	No	Sig. diff.	No	No	-

No = no significant difference (Sig.diff.) using two-tailed t-test at 90 percent confidence limit.

filter, but were different from all filters at the greater depth. Carbohydrates were different between all filters at the surface but, at the greater depth, not between Gorham and Newport or between Newark and the youngest of the West Hartford filters. AFDC had fewer differences but there were fewer data points and the statistical tests were less sensitive. The filters that showed the most similarities among the group, even though not consistently for all parameters or depths, were the three filters at the West Hartford, CT plant which treated raw water from the same source and which had each been cleaned by harrowing since they had been resanded although at different times.

Major differences between filters at different plants would occur due to the differences between the quality of the raw water and removal rates in the filters. The application of different loads of either biodegradable or non-biodegradable materials would lead to differing concentrations of organisms and non-biodegradable materials within the filters. These loads have been shown earlier to vary with plant and season, and the performance of the plants have been shown to vary with water temperatures which are also specific to the individual plant locations and water sources. The age of the filters and their cleaning history is also pertinent. The Gorham

TABLE 94: COMPARISON OF ORGANIC CHARACTERISTICS BETWEEN 25-30 CM OF FILTERS.

Plant	Gorham	Newport	Newark	West Hartford, CT		
Filter	F2	F3	F3,4	F21	F18	F1
Date	July 27,'93	Jul.y 26,'93	Aug.8, '93	Oct.12,'93	Oct.13,'93	Oct.5, '93
Water temp.	15°C	21°C	10°C	14°C	14°C	16°C
Volatile solids, percent dry weight						
Mean	0.12	0.19	0.84	0.29	0.67	0.60
Stnd.dev.	0.01	0.05	0.14	0.02	0.02	0.10
n	6	2	12	6	6	6
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	No	-
FRM, mg protein/gram dry weight						
Mean	0.51	1.32	0.48	0.21	1.08	0.83
Stnd.dev.	0.16	0.46	0.28	0.02	0.21	0.50
n	12	4	16	6	5	6
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	No	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	No	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	No	Sig. diff.	Sig. diff.	No	-
Carbohydrate, mg C/gram dry weight						
Mean	0.0011	0.010	0.06	0.063	0.0.7	0.12
Stnd.dev.	0.0002	0.001	0.01	0.013	0.014	0.04
n	12	4	21	9	8	8
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	No	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-

Table 94 continued on next page.

Table 94 continued from preceding page.						
Acriflavin direct count, Counts/gram dry weight						
Mean	118	163	44	16	52	54
Stnd.dev.	64		13	11	48	29
n	4	1	8	3	3	5
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	No	No	No	No.	-	-
vs WH F1	Sig. diff.	Sig. diff.	No	Sig. diff.	No	-

No = no significant difference (Sig.diff.) using two-tailed t-test at 90 percent confidence limit.

filters had not been cleaned in over two years at the time of final sampling at that plant due to the low influent loading and so there would have been little material harrowed into the lower filter media. Similarly, the Newport filters had been cleaned only a few times, generally by raking without scraping or harrowing. Those filters would also have developed little material in the lower filter media. The Newark filters, despite not having been cleaned by harrowing which would distribute surface deposits to greater depth, had been in operation for several years with a water containing higher turbidity, particles, NPDOC, and UV absorbance and would have developed greater deposition below the shallow depth, approximately 1.2 cm, to which they were generally scraped. The filters at West Hartford had also developed different characteristics due to the differences in age, the number of times the filters had been mixed by harrowing, and the decomposition of deposited materials.

TABLE 95: COMPARISON OF ORGANIC CHARACTERISTICS, MEAN FOR UPPER 30 CM OF FILTERS.

Plant Filter Date Water temp.	Gorham F2 July 27,'93 15°C	Newport F3 Jul.y 26,'93 21°C	Newark F3,4 Aug.8, '93 10°C	West Hartford, CT		
				F21 Oct.12 '93 14°C	F18 Oct.13 '93 14°C	F1 Oct.5, '93 16°C
Volatile solids, percent dry weight						
Mean	0.15	0.28	0.98	0.52	0.66	0.64
Stnd.dev.	0.016	0.038	0.16	0.045	0.065	0.086
n	12	4	24	12	12	12
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	No	-
FRM, mg protein/gram dry weight						
Mean	1.00	2.84	1.03	1.22	1.24	1.38
Stnd.dev.	0.36	0.75	0.30	0.33	0.18	0.56
n	24	8	32	12	11	12
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	No	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	No	No	-
Carbohydrate, mg C/gram dry weight						
Mean	0.003	0.006	0.10	0.16	0.15	0.16
Stnd.dev.	0.0008	0.001	0.032	0.017	0.038	0.035
n	24	8	42	18	17	17
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	No	No	-

Table 95 continued on next page.

Table 95 continued from preceding page.

Acriflavin direct count, Counts/gram dry weight

Mean	213	183	113	54	76	88
Stnd.dev.	124	28	19	10	37	59
n	8	2	16	6	6	10
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	Sig. diff.	Sig. diff.	No	No	No	-

No = no significant difference (Sig.diff.) using two-tailed t-test at 90 percent confidence limit.

Similar comparisons were made between filters at the several plants for metal characteristics in the two levels (top 1.2 cm and from 25 to 30 cm) at which the filters were analyzed and mean of the levels in the filters for the metal coating characteristics. This information is summarized in Tables 96 to 98. The differences in iron, manganese, calcium, and aluminum were also generally different between the filters at all plants for the two depths and for the mean of the concentrations at those two depths. The instances of "no significant difference" were more frequent, however, and also included some comparisons between the Gorham and the Newport plants against the filters at West Hartford. The Newark, NY media was distinctly different from the media at all other plants except in relation to the mean of the manganese concentrations against those at the West Hartford, CT plant.

The similarities between the chemical characteristics of the sand media treating New England waters are to be expected in several respects. A principal one, however, is the common source of sand used in the Gorham and Newport plants which had not been in use for prolonged periods of time. The West Hartford sand, too, had been from a similar source in Rhode Island, but had been in service and reconditioned at the plant. All but the sand at Newark were typical of quartz sand as specified by AWWA standards (1989). The Newark sand is a "calcium" sand

TABLE 96: COMPARISON OF METAL CHARACTERISTICS IN TOP 1.2 CM OF FILTERS.

Plant	Gorham	Newport	Newark	West Hartford, CT		
Filter	F2	F3	F3,4	F21	F18	F1
Date	July 27,'93	Jul.y 26,'93	Aug.8, '93	Oct.12 '93	Oct.13,'93	Oct.5, '93
Water temp.	15°C	21°C	10°C	14°C	14°C	16°C
Iron, mg/kg dry weight						
Mean	2280	2350	9100	4200	4300	4200
Stnd.dev.	160	85	1030	83	414	226
n	2	2	2	2	2	2
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	No	No	-
Manganese, mg/kg dry weight						
Mean	285	83	486	899	681	559
Stnd.dev.	1	5	26	1	33	42
n	2	2	2	2	2	2
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	No	Sig. diff.	Sig. diff.	-
Calcium, mg/kg dry weight						
Mean	527	304	97700	480	318	392
Stnd.dev.	13	34	2350	37	51	102
n	2	2	2	2	2	2
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	No	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	No	Sig. diff.	Sig. diff.	-	-
vs WH F1	No	No	Sig. diff.	No	No	-

Table 96 continued on next page.

Table 96 continued from preceding page.

Aluminum, mg/kg dry weight						
Mean Stnd.dev. n	2160 40 2	1230 82 2	4480 337 2	1670 99 2	1670 222 2	1890 199 2
vs Newport		-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	No	Sig. diff.	No	-	-
vs WH F1	No	Sig. diff.	Sig. diff.	No	No	-

No = no significant difference (Sig.diff.) using two-tailed t-test at 90 percent confidence limit.

containing a large percentage of acid soluble material and common to areas with carbonate geological deposits and hard water supplies. Differences between the media among the New England plants were largely in response to the metallic content of the raw water supplies and the length of time in service. Iron and manganese depositing bacteria occur widely in the environment and their presence in filter media has been previously reported (Eighmy et al., 1990). The reduced forms of iron and manganese in the raw water supplies would provide a supplemental source of energy, although Fe^{++} autooxidized rapidly under aerobic conditions at neutral pH (Ghiorse, 1984). Mn^{++} is less likely to autooxidize at pH of less than 9, however, and bacterial oxidation is more likely to be the cause of its deposition. Iron and manganese depositing bacteria are generally associated with low-nutrient conditions and most are aerobes. Usually, too, the deposition of metal oxides occurs in association with extracellular polymers (Ghiorse, 1984). These conditions are typical of the slow sand filter environment.

TABLE 97: COMPARISON OF METAL CHARACTERISTICS BETWEEN 25-30 CM OF FILTERS.

Plant Filter Date Water temp.	Gorham F2 July 27,'93 15°C	Newport F3 Jul.y 26,'93 21°C	Newark F3,4 Aug.8, '93 10°C	West Hartford, CT		
				F21 Oct.12,'93 14°C	F18 Oct.13,'93 14°C	F1 Oct.5, '93 16°C
Iron, mg/kg dry weight						
Mean Stnd.dev. n	1900 340 2	2540 29 2	9440 961 2	2790 6 2	4580 442 2	4060 1540 2
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	No	No	Sig. diff.	No	No	-
Manganese, mg/kg dry weight						
Mean Stnd.dev. n	32 2 2	61 1 2	533 90 2	177 8 2	187 2 2	329 22 2
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-
Calcium, mg/kg dry weight						
Mean Stnd.dev. n	242 19 2	269 8 2	109000 7550 2	486 127 2	413 19 2	206 50 2
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	No	No	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	No	No	Sig. diff.	No	Sig. diff.	-

Table 97 continued on next page.

Table 97 continued from preceding page.

Aluminum, mg/kg dry weight

Mean	1030	1300	4130	1530	2030	1430
Stnd.dev.	40	166	174	86	421	319
n	2	2	2	2	2	2
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	No	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	No	Sig. diff.	No.	-	-
vs WH F1	No	No	Sig. diff.	No	No	-

No = no significant difference (Sig.diff.) using two-tailed t-test at 90 percent confidence limit.

TABLE 98: COMPARISON OF METAL CHARACTERISTICS, MEAN FOR UPPER 30 CM OF FILTERS.

Plant	Gorham	Newport	Newark	West Hartford, CT		
Filter	F2	F3	F3,4	F21	F18	F1
Date	July 27,'93	July 26,'93	Aug.8, '93	Oct.12,'93	Oct.13,'93	Oct.5, '93
Water temp.	15°C	21°C	10°C	14°C	14°C	16°C
Iron, mg/kg dry weight						
Mean	2090	2445	9270	3495	4440	4130
Stnd.dev.	266	64	996	59	428	1100
n	4	4	4	4	4	4
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	Sig. diff.	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	Sig. diff.	No	No	-
Manganese, mg/kg dry weight						
Mean	159	72	510	538	434	444
Stnd.dev.	2	4	66	6	23	34
n	4	4	4	4	4	4
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	Sig. diff.	Sig. diff.	No	-	-	-
vs WH F18	Sig. diff.	Sig. diff.	No	Sig. diff.	-	-
vs WH F1	Sig. diff.	Sig. diff.	No	Sig. diff.	No	-
Calcium, mg/kg dry weight						
Mean	384	286	1034000	483	365	299
Stnd.dev.	16	25	5590	94	38	5080
n	4	4	4	4	4	4
vs Newport	No	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	No	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	No	Sig. diff.	Sig. diff.	No	-	-
vs WH F1	No	No	Sig. diff.	Sig. diff.	No	-

Table 98 continued on next page.

Table 98 continued from preceding page.

Aluminum, mg/kg dry weight

Mean	1695	1265	4305	1600	1850	1660
Stnd.dev.	40	131	268	93	337	266
n	4	4	4	4	4	4
vs Newport	Sig. diff.	-	-	-	-	-
vs Newark	Sig. diff.	Sig. diff.	-	-	-	-
vs WH F21	No	Sig. diff.	Sig. diff.	-	-	-
vs WH F18	No	Sig. diff.	Sig. diff.	No.	-	-
vs WH F1	No	No	Sig. diff.	No	No	-

No = no significant difference (Sig.diff.) using two-tailed t-test at 90 percent confidence limit.

5.3 INFLUENCE OF SAND MEDIA AGE

The importance of media ripening or aging on treatment performance cannot be overemphasized. Earlier studies (Bellamy et al., 1985a) have considered the increased removals of turbidity, coliform, and Giardia cysts as media matured over periods of up to 80 weeks.

Literature references on development of media over a period of years have not been available. Most studies have been based on pilot filters with ripening times ranging from days to months, or on full-scale plants which have been in operation for relatively few years. The time that sand media remains in a filter is limited to only a few years when the filter is cleaned by removing 1 to 3 cm several times each year. The sand in the filters at the West Hartford, CT plant has been in use for varying lengths of time up to nearly 20 years due to the use of harrow cleaning method. This permitted selection of filters for the current sampling study with unusually long run lengths. The information on these filters has been previously presented in tabular form. The information is presented graphically in Figures 32 through 37, showing the changes in volatile solids, FRM, carbohydrates, AFDC, iron, and manganese characteristics from a reconditioned sand (Filter 19 reconditioned in the winter of 1993-4) through a 20 year period. Surface concentration were little changed over the period but the concentrations of volatile solids, FRM, carbohydrates, iron,

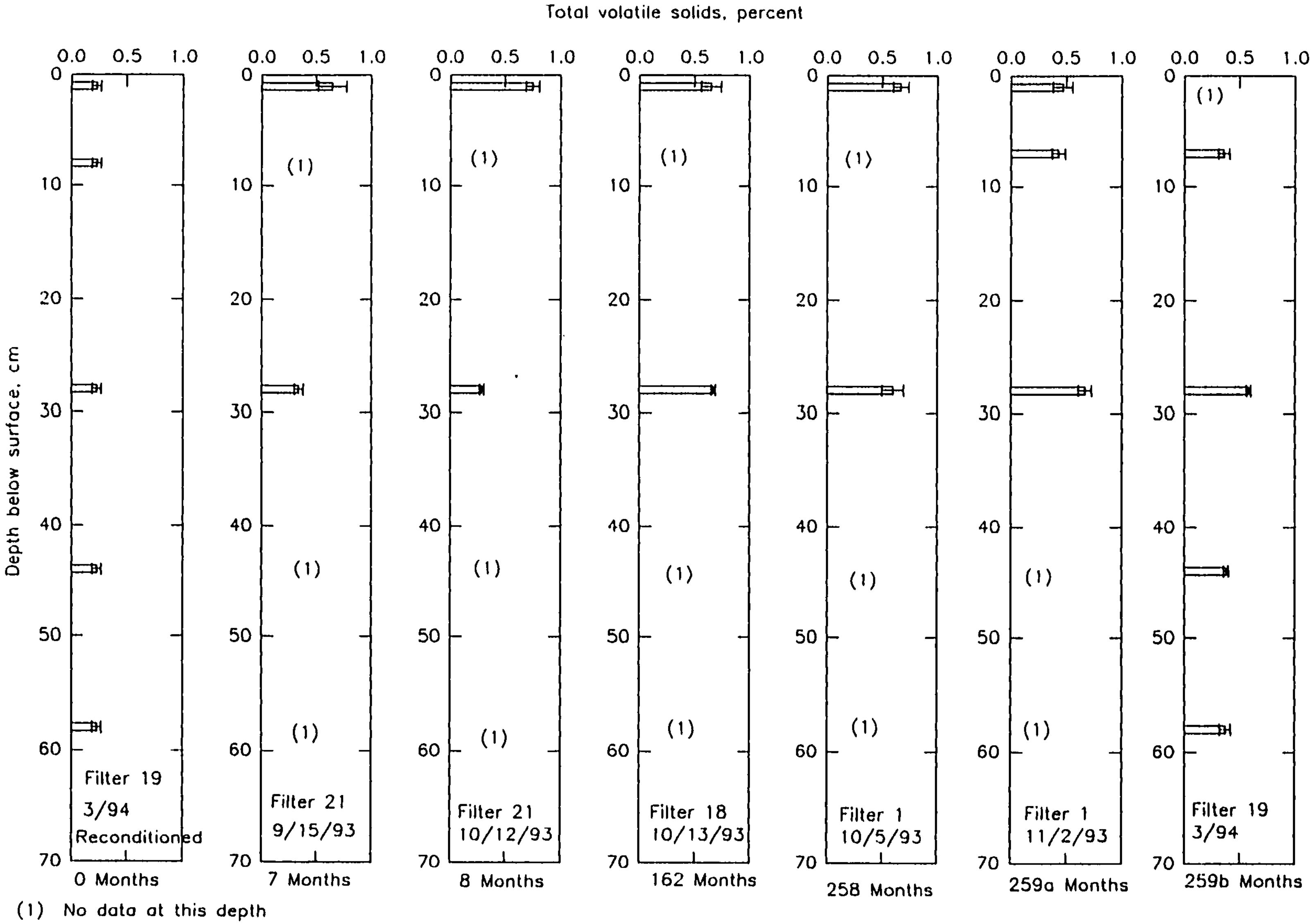


Figure 32: Total volatile solids distribution as a function of filter age and depth for harrowed filters at West Hartford, CT.

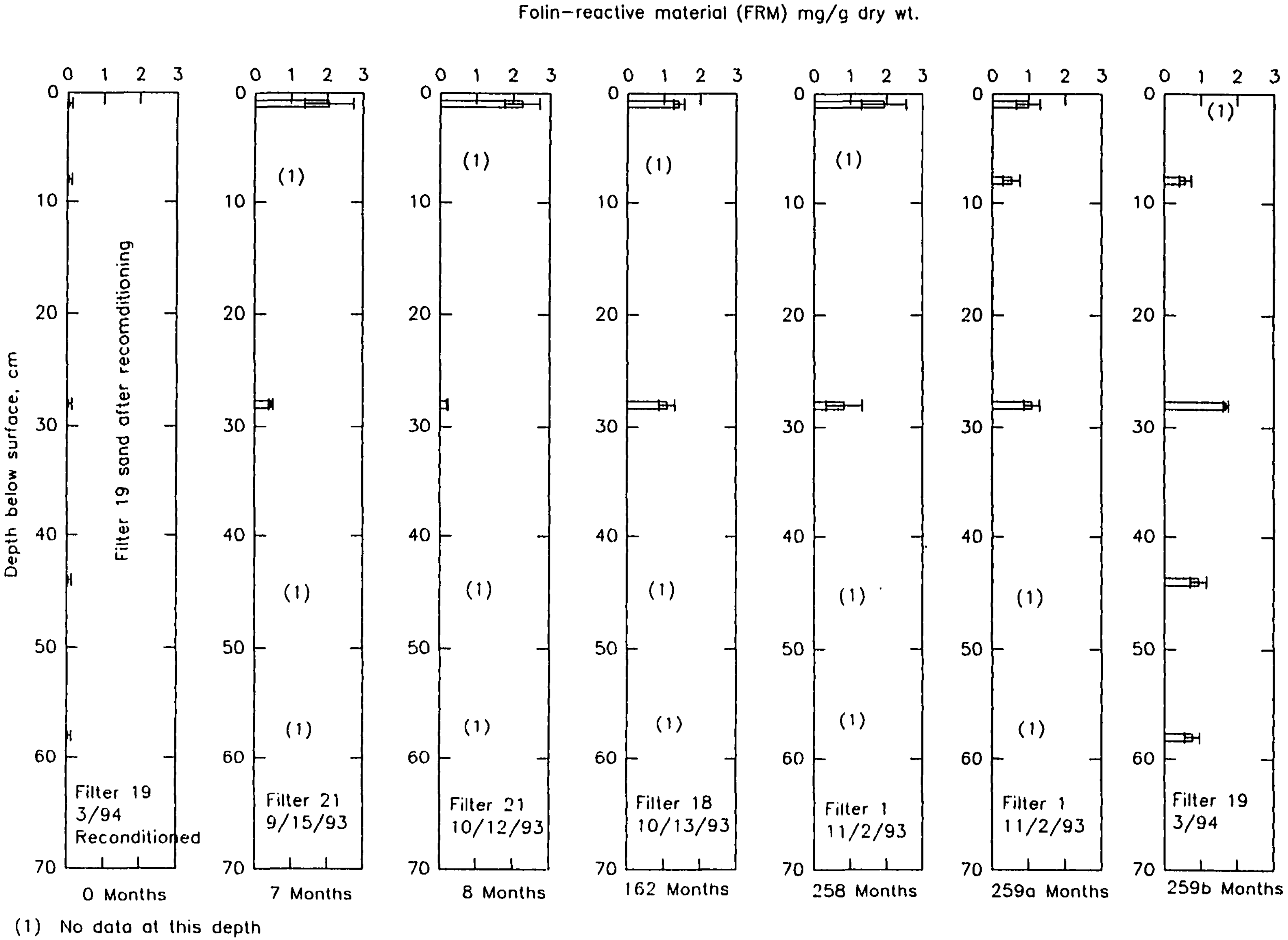
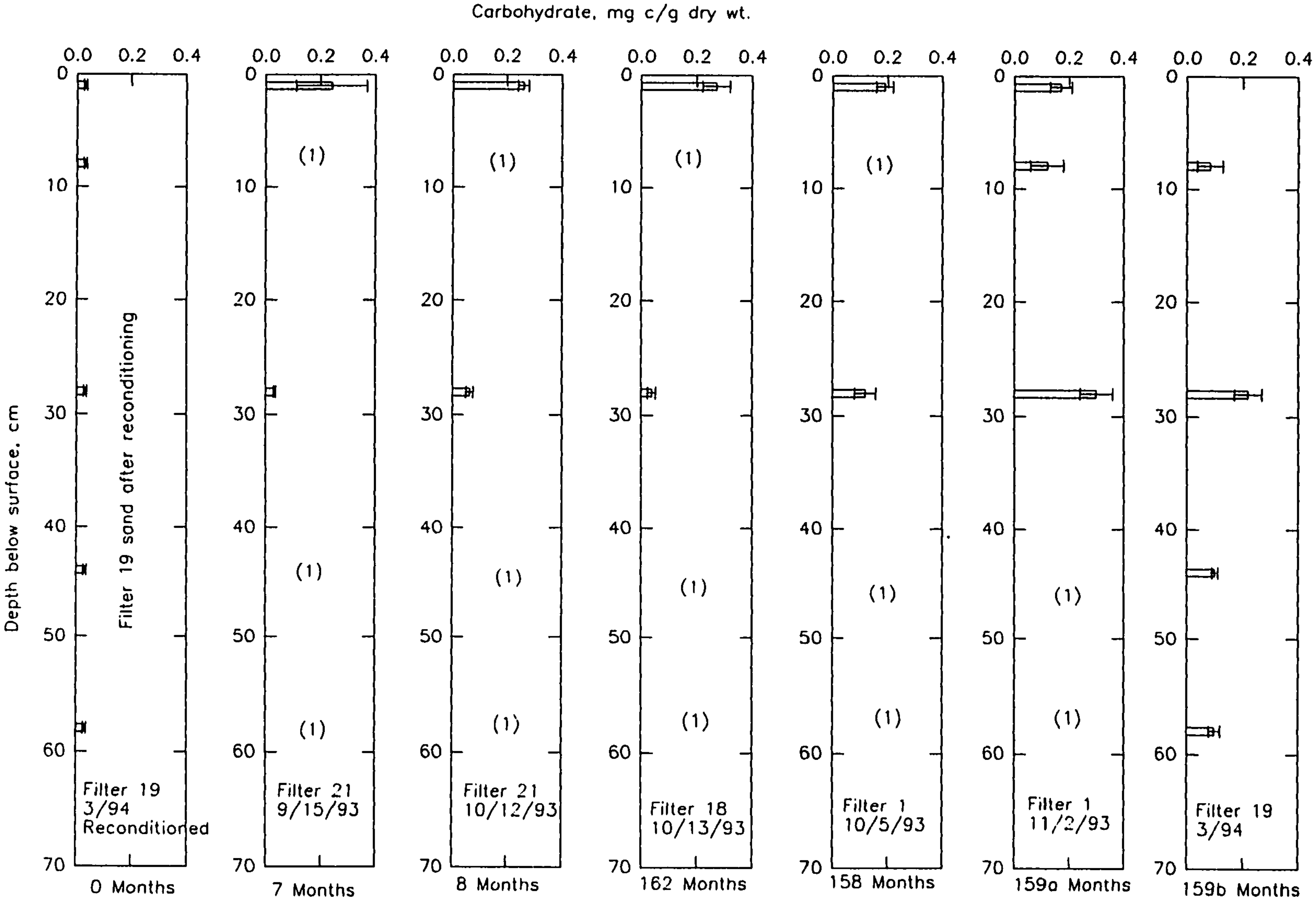


Figure 33: FRM distribution as a function of filter age and depth for harrowed filters at West Hartford, CT.



(1) No data at this depth

Figure 34: Carbohydrate distribution as a function of filter age and depth for harrowed filters at West Hartford, CT.

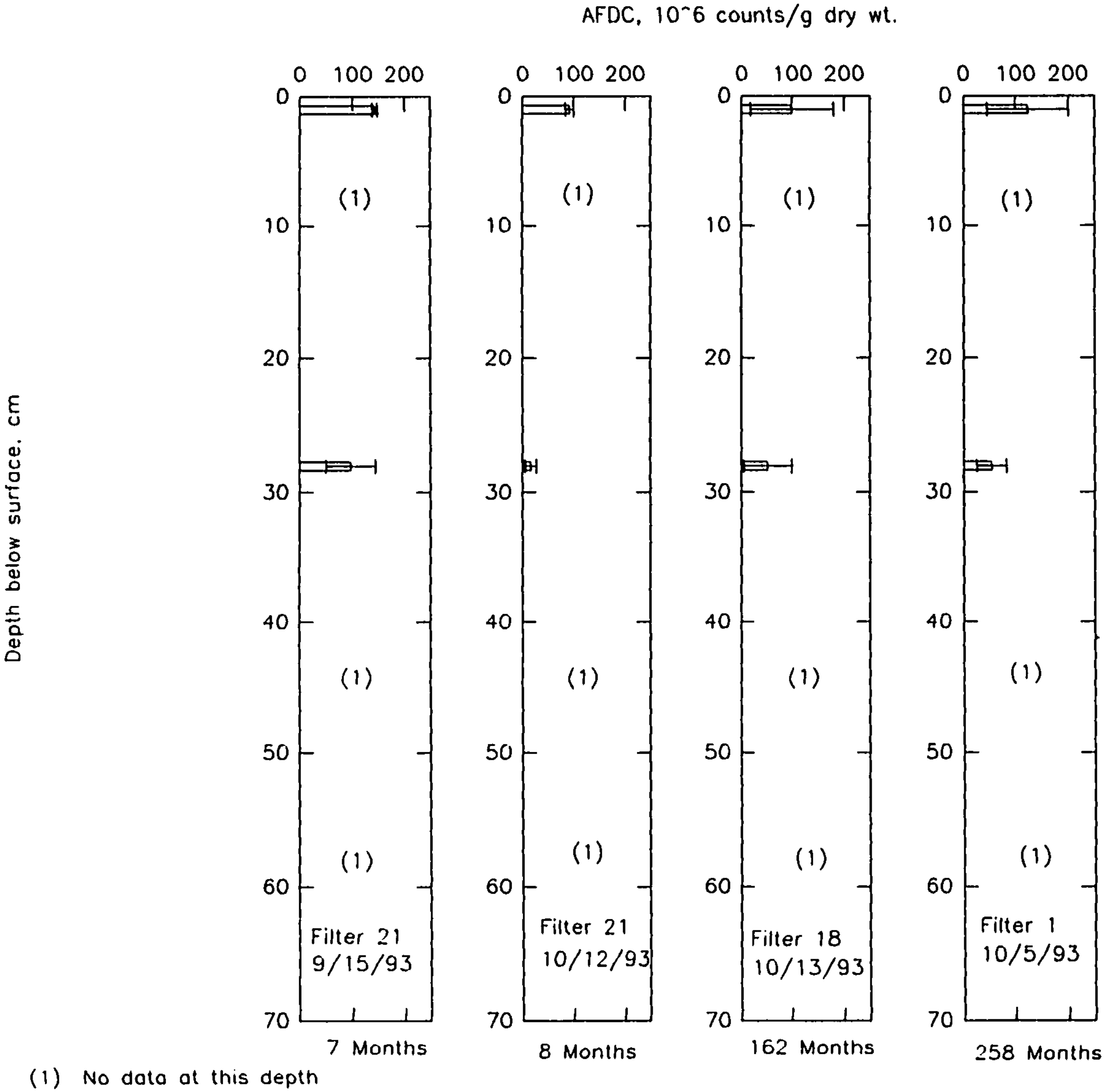


Figure 35: AFDC distribution as a function of filter age and depth for harrowed filters at West Hartford, CT.

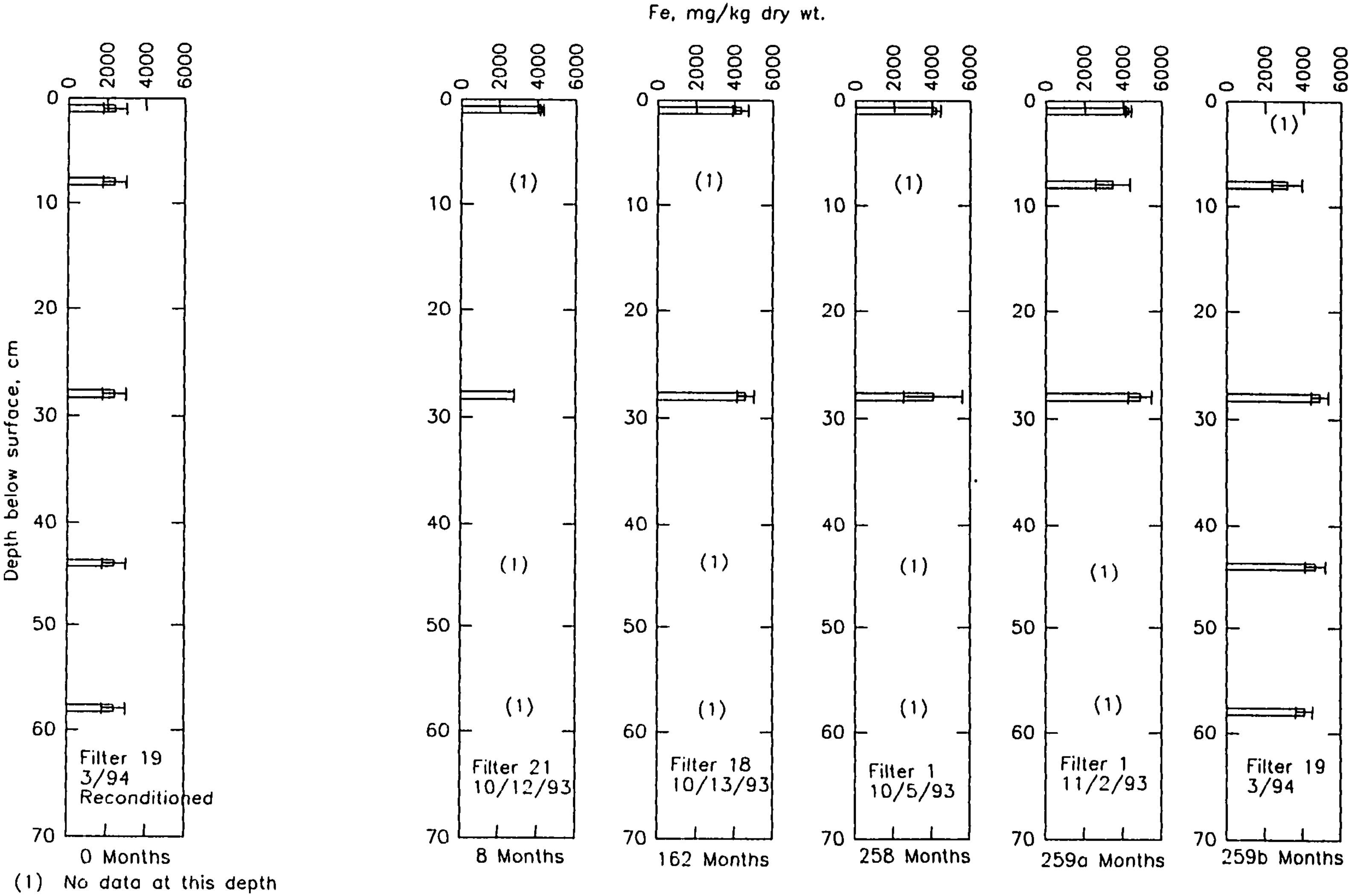
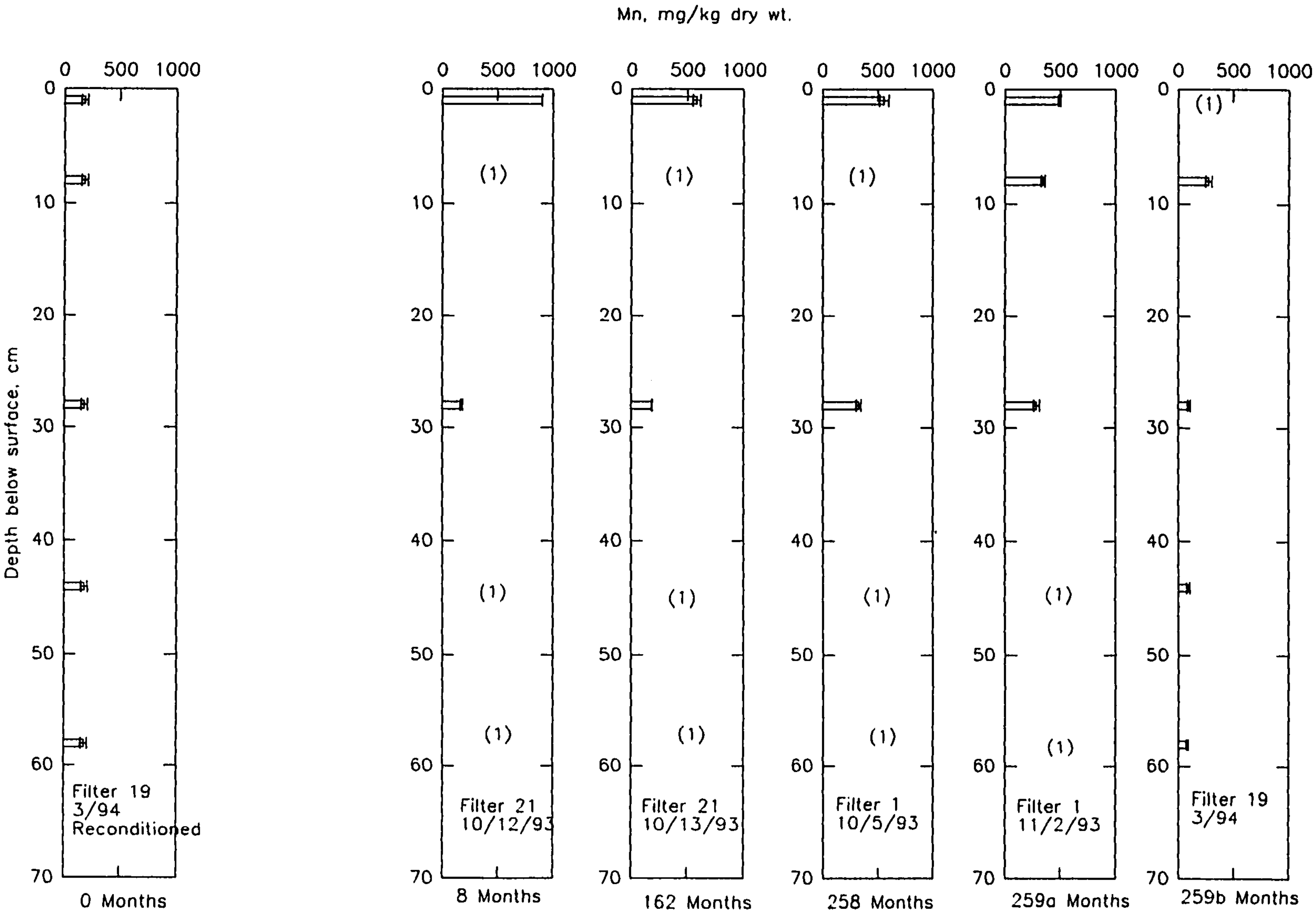


Figure 36: Iron distribution as a function of filter age and depth for harrowed filters at West Hartford, CT.



(1) No data at this depth

Figure 37: Manganese distribution as a function of filter age and depth for harrowed filters at West Hartford, CT.

and manganese increased over the period. AFDC, calcium, and aluminum were not significantly changed. It would be expected that the surface media would not change greatly as the sampling was carried out immediately before filters were to be cleaned. At this time, the filters had accumulated approximately the same mass of organic or inorganic materials as over the preceding filter cycle, generally four to six weeks at this plant. An increase in accumulation would have been indication that the filter had not been sufficiently cleaned over the operating period, yet plant experience had been that even the oldest filter media was generally able to be cleaned to at least one-half of the capacity of its rated capacity (Allen, 1991). Since the filters were not showing increased concentrations of volatile solids, FRM, carbohydrates, iron and manganese in the surface of the filters, then the cleaning technique was achieving its purpose at this level. The development of increasing concentrations at the lower levels indicated that harrow was mixing surface materials into the filter at greater depth than the concentrations developing over a similar time period at the Newark, NY plant which cleaned filters by scraping.

Past research has demonstrated a positive relationship between schmutzdecke age and biomass as quantified by cell protein and bacterial counts (Collins et al., 1992b). Elapsed time or age of a filter media and potential cell growth are considered to be more important in controlling bacterial population levels than filtration of bacteria from the source water (Ripley and Saleem, 1973; Wood, 1980; and Collins et al., 1992b). Wang et al. (1995) also noted that the removal of DBP precursors is likely related to microbial activity rather than the amount of biomass. The growth of the sand media biofilm will be dependent on cell growth potential which, in turn, will be dependent on the availability of the rate limited nutrient, usually organic substrate, and suitable growth environment. Increased surface scraping will inherently limit the age of the schmutzdecke material as compared to the harrowing method which maintains schmutzdecke-like bacterial populations throughout the harrowed portion of filter bed (Collins et al., 1989). The age of sand in a filter cleaned by scraping is also limited by the eventual removal of the media and resanding of the filter.

Sand aging may also relate to changes in non-biological parameters such as metal composition in the sand media coating over time. Biological filters are noted for their exceptional removals of iron and manganese (Degremont, 1991). The older filters in this study accumulated higher iron and manganese, but the most significant differences were between the water supplies to the respective plants. The Newark plant had significantly higher concentrations of iron and manganese than did any of the other plants, but the media had been in the filters for 1.5 to 3 years at Newark as compared to the 19 and 13 years that the media had been in Filters 1 and 18, respectively, at West Hartford. Additional studies have looked more closely at the retention of NOM by artificially coated iron oxide coated media (Benjamin et al., 1993) and naturally occurring iron oxides (Gu et al., 1994; Tipping, 1991; Davis, 1982). Each study has demonstrated the efficacy of NOM adsorption on the metal oxide surface. Consequently, total metal content and composition in the surface coatings of sand media is considered to contribute to the natural aging or ripening of filter media.

The laboratory scale column tests, comparing the removal of TOC and UV absorbance from NOM by sand media of different age (19 years and less than one year) at uniform application rates, EBCT, temperature, and raw water quality confirmed the higher removals with the sand having the greater age and surface coating deposition. The laboratory scale column tests, comparing the removal of TOC and UV absorbance by sand having differing percentages of the natural coatings removed (none to all), also at uniform conditions of application rates, EBCT, temperature, and raw water quality, also confirmed the higher removals with sand having the greater surface coating deposition. In these tests, however, it was also demonstrated that biological coatings as measured by FRM, carbohydrates, and AFDC were capable of rapid replacement. The FRM and carbohydrate concentrations of the media which had all coatings removed prior to the tests had coatings at the end of the five days of testing equal to the media from which two-thirds of the coatings had been removed. The AFDC concentration on the media filtering the G/GA solution was not significantly different after five days between the media with no remaining natural coating and the media with one-third natural coating at the start of the five day test period. The AFDC concentrationon the media filtering the NOM had not recovered, but the ratio of FRM to AFDC was atypical and the AFDC data may not have been valid. Since the FRM and carbohydrate values for the several media analyses were consistent and only the one set of AFDC values were atypical, it was concluded that the media had quickly recovered FRM, carbohydrate, and AFDC during the five day test period. The innoculation for the regrowth would have been the internal surfaces of the tubing using to connect the filter columns and reservoirs as they were not sterilized before the test period.

Summary: The importance of sand media age and subsequent ripening conditions on the treatment performance of slow sand filtration should not be underemphasized. Sand media aging involves the surface accumulation of biological and inorganic constituents that are beneficial to the treatment process. The extent of sand media aging will be a function of how long the sand can be used before resanding and whether the filter cleaning method used at the plant will result in early depletion of the sand in the filter. Filter harrowing appears to accelerate the aging phenomenon as compared to surface scraping by distributing the biomass deposits remaining after cleaning throughout the upper filter layers rather than physically removing the material with the uppermost few centimeters from the filter bed. Furthermore, scraping will limit filter age to four to six years (or as determined by the media depth and length filter cycles as the particular plant in question) as the depth is reduced by one-half to one-inch with each cleaning cycle. The harrowing method of cleaning avoids the reduction in filter depth that is caused by scraping and has allowed filters to remain in service up to 20 years.

5.4 INFLUENCE OF FILTER BIOMASS

A biological process will be more efficient if, for a given volume of media, the concentration of biomass is higher (Collins et al., 1992b) or more active (Wang et al., 1995). Bellamy et al. (1985a and 1985b) found the state of the biological community significantly influenced the ability of slow sand filters to remove coliform bacteria, bacteria as measured by standard plate count, and even inorganic particles, and concluded "the microbiological maturity of the sand bed is the most important variable in the removal of Giardia cysts and coliform bacteria." Those studies considered the maturity of the filters to be"unmeasurable" but defined it as a function of the number of weeks of undisturbed filter operation. Other studies have also considered the population diversity of the filter (Datta and Chaudhuri, 1991; Weber-Shirk, 1992) in relation to the ability of a slow sand filter to remove coliform organisms. Numerous wastewater treatment studies have shown that higher biomass concentrations can lead to a higher rate of biodegradation (Valentis and Lesavre, 1990; Metcalf and Eddy, 1991). Studies evaluating the importance of biomass in drinking water treatment have been fewer, though Rittmann and Huck (1989), Billen et al. (1992), Bonnet et al. (1992), Wang et al. (1995) have studied biological contactors for treatment of public water supplies. A positive relationship was established between filter biomass content , as quatified by protein matter (FRM) and bacterial counts, and organic precursor removals during slow sand filtration (Collins et al., 1989). It was initially thought that biological activated carbon (BAC) would perform better than sand filters for biofiltration of drinking water because the BAC should be able to hold more biomass. However, the results of research studies have been contradictory. Eberhardt (1976) concluded that the GAC filter at quasi-steady-state was much more efficient than a slow sand filter. However, some researchers (Miltner and Summers, 1992) have found that enhanced biological degradation does not appear in the operation of GAC filters at organic carbon substrate levels normally encountered during drinking water treatment. The implication is that bioactivity is more important than biomass in biofiltration performance. More research is needed to distinguish between biomass and bioactivity.

The data from the current study on the relative performance of the filters at the full scale plant was compared to that for the characteristics of the media in the upper 30 cm of the filters. These results are summarized in Figures 38 through 49, showing the removal, as percent, of turbidity, particles, NPDOC, and UV absorbance relative to the volatile solids, FRM, carbohydrates,

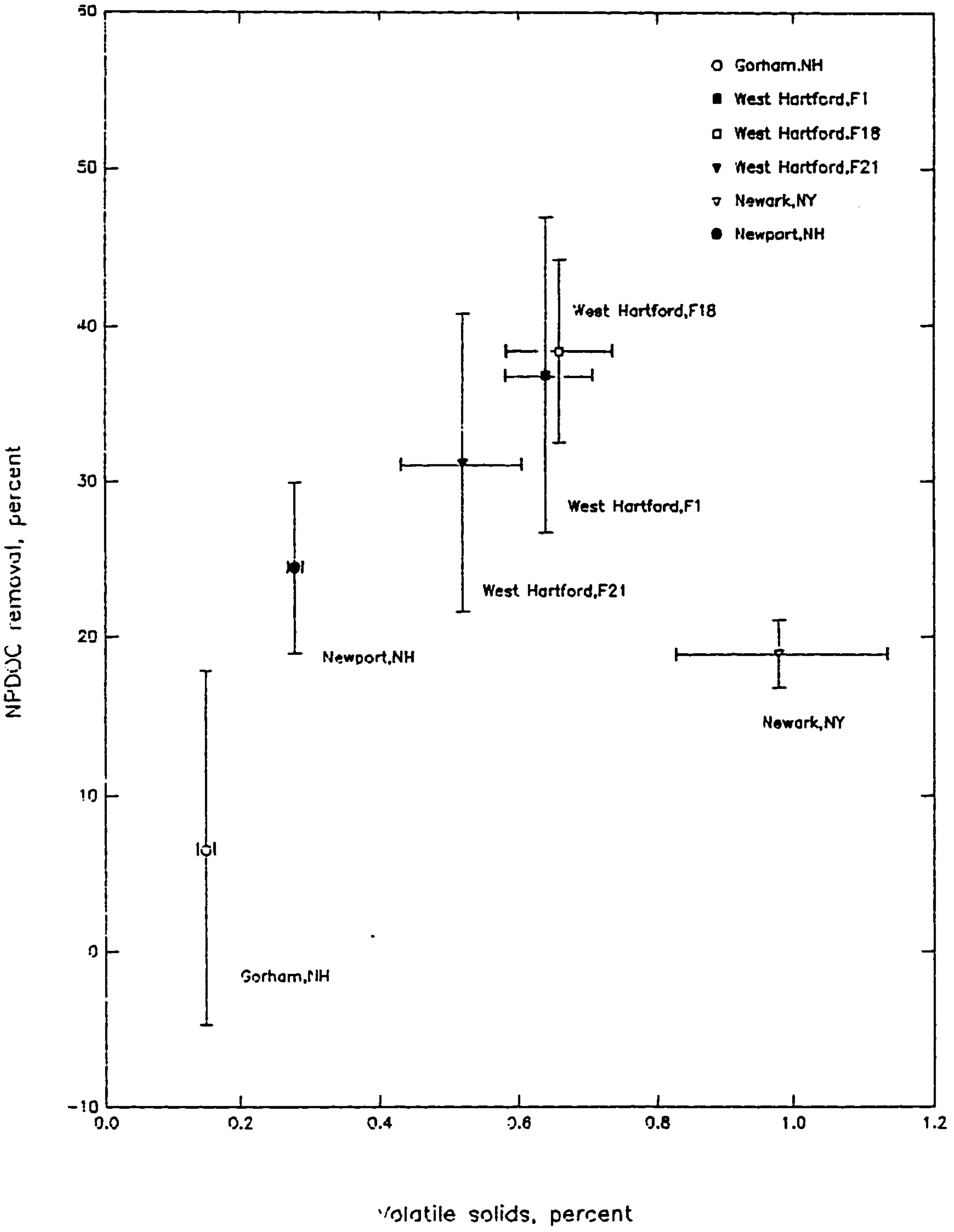


Figure 38: NPDOC removal vs volatile solids in upper 30 cm of filter media.

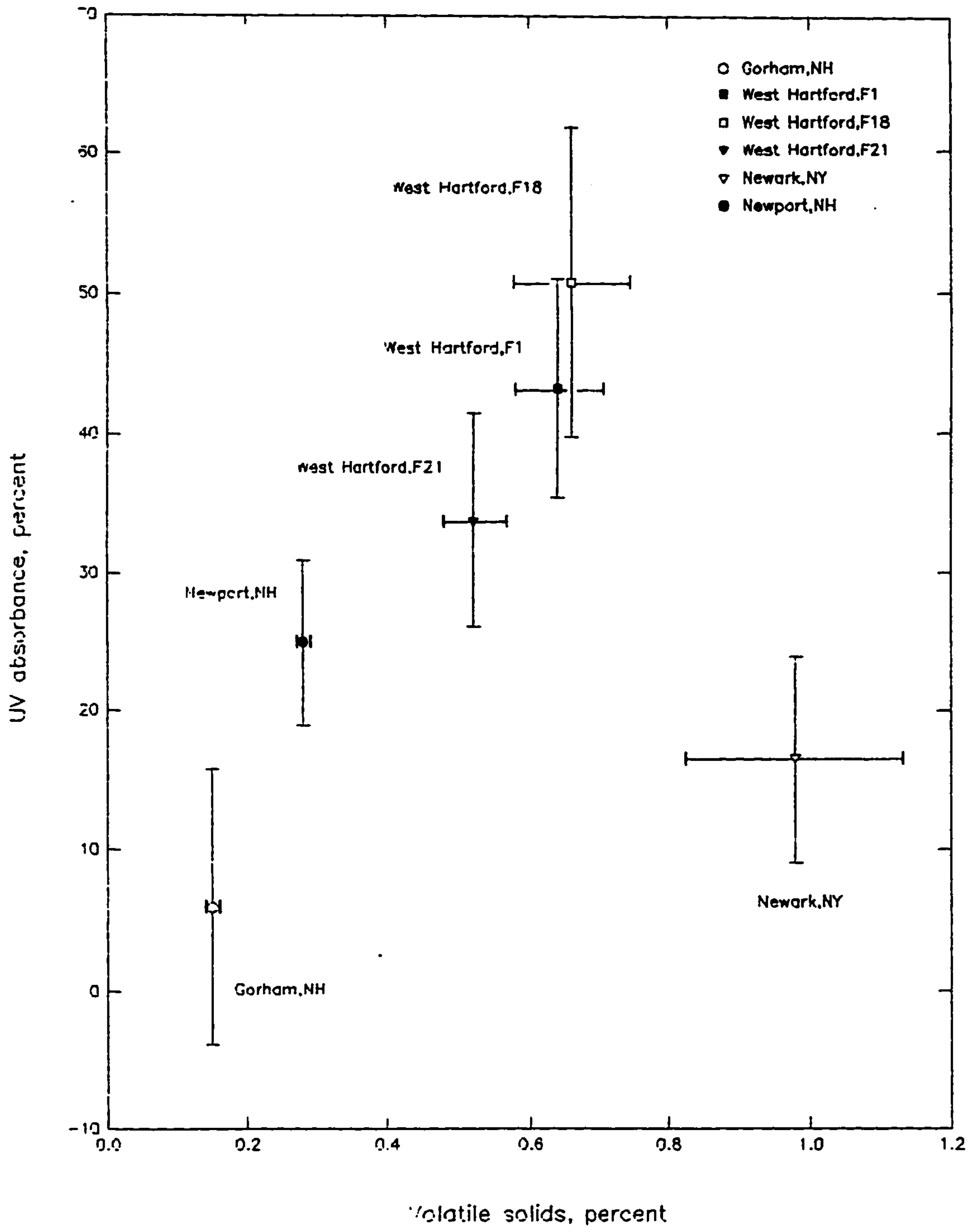


Figure 39: UV absorbance removal vs volatile solids in upper 30 cm of filter media.

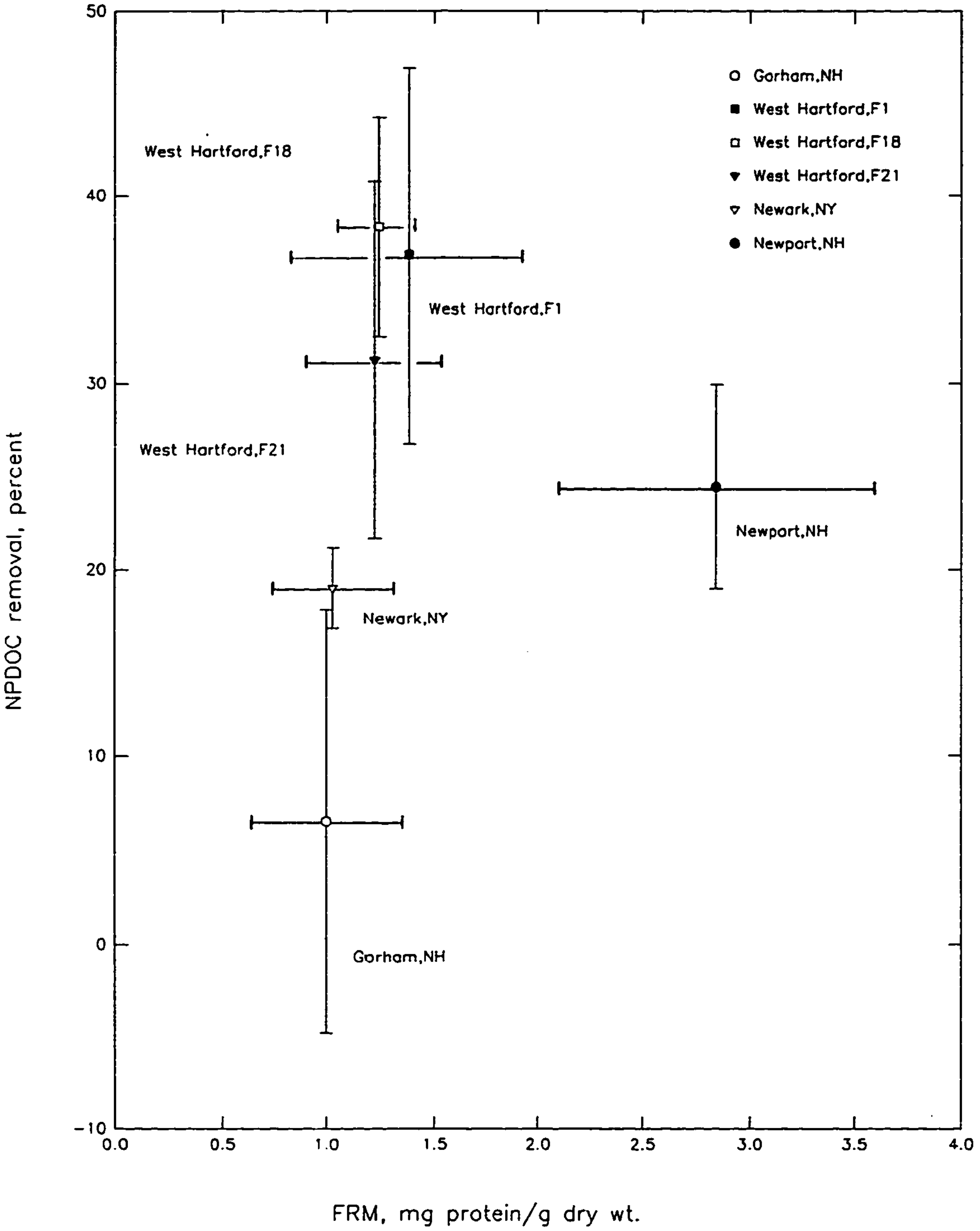


Figure 40: NPDOC removal vs FRM in upper 30 cm of filter media.

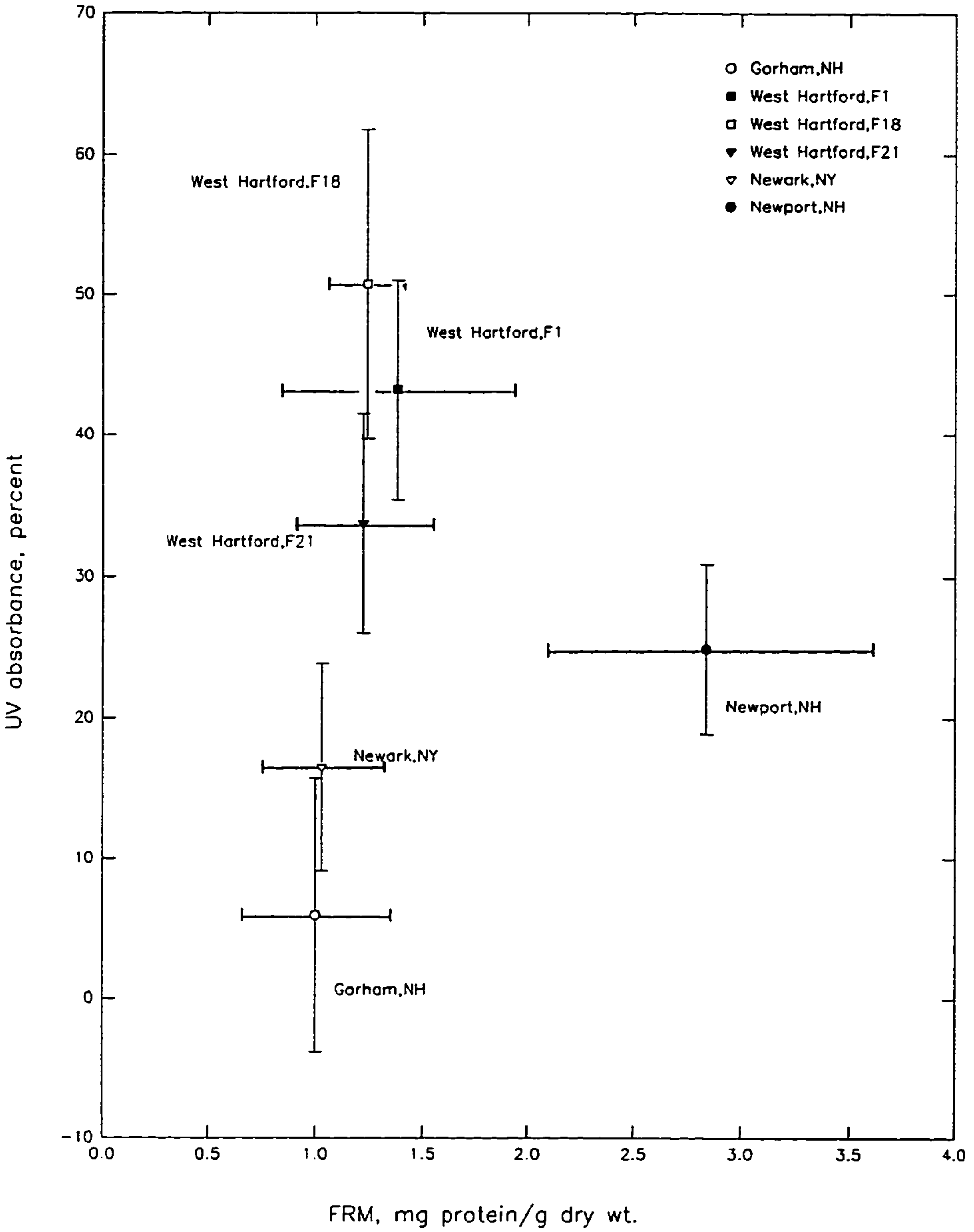


Figure 41: UV absorbance removal vs FRM in upper 30 cm of filter media.

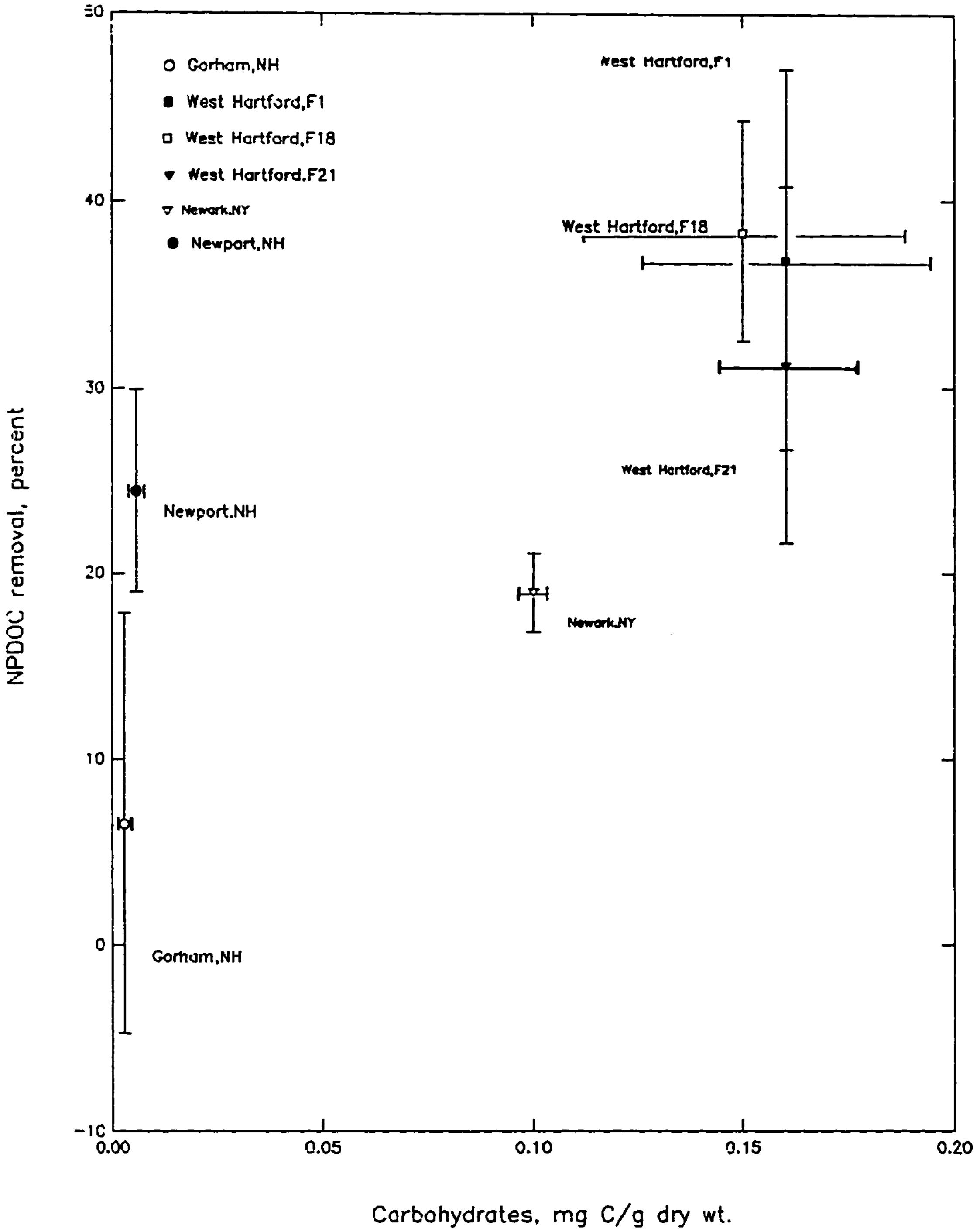


Figure 42: NPDOC removal vs carbohydrate in upper 30 cm of filter media.

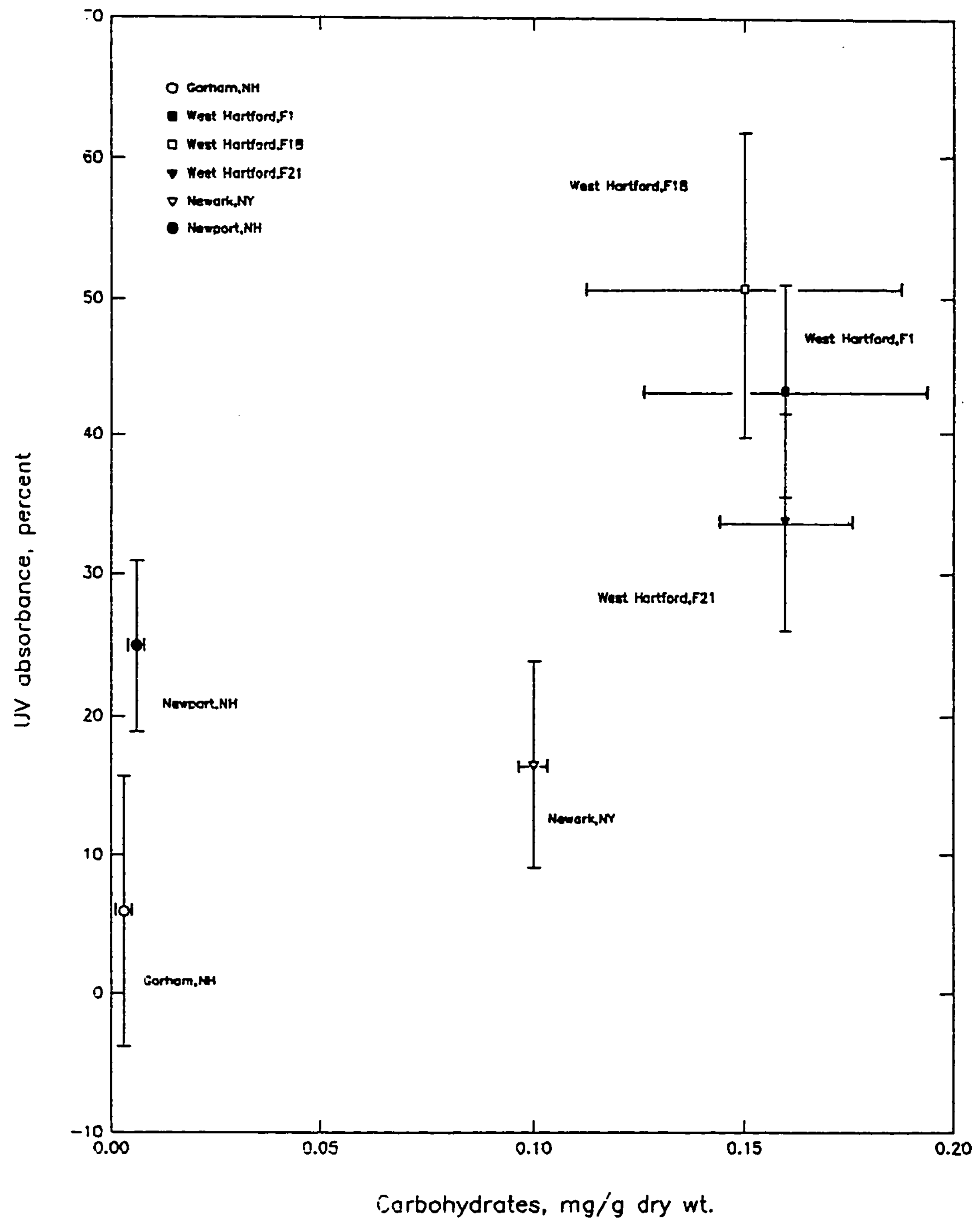


Figure 43: UV absorbance removal vs carbohydrate in upper 30 cm of filter media.

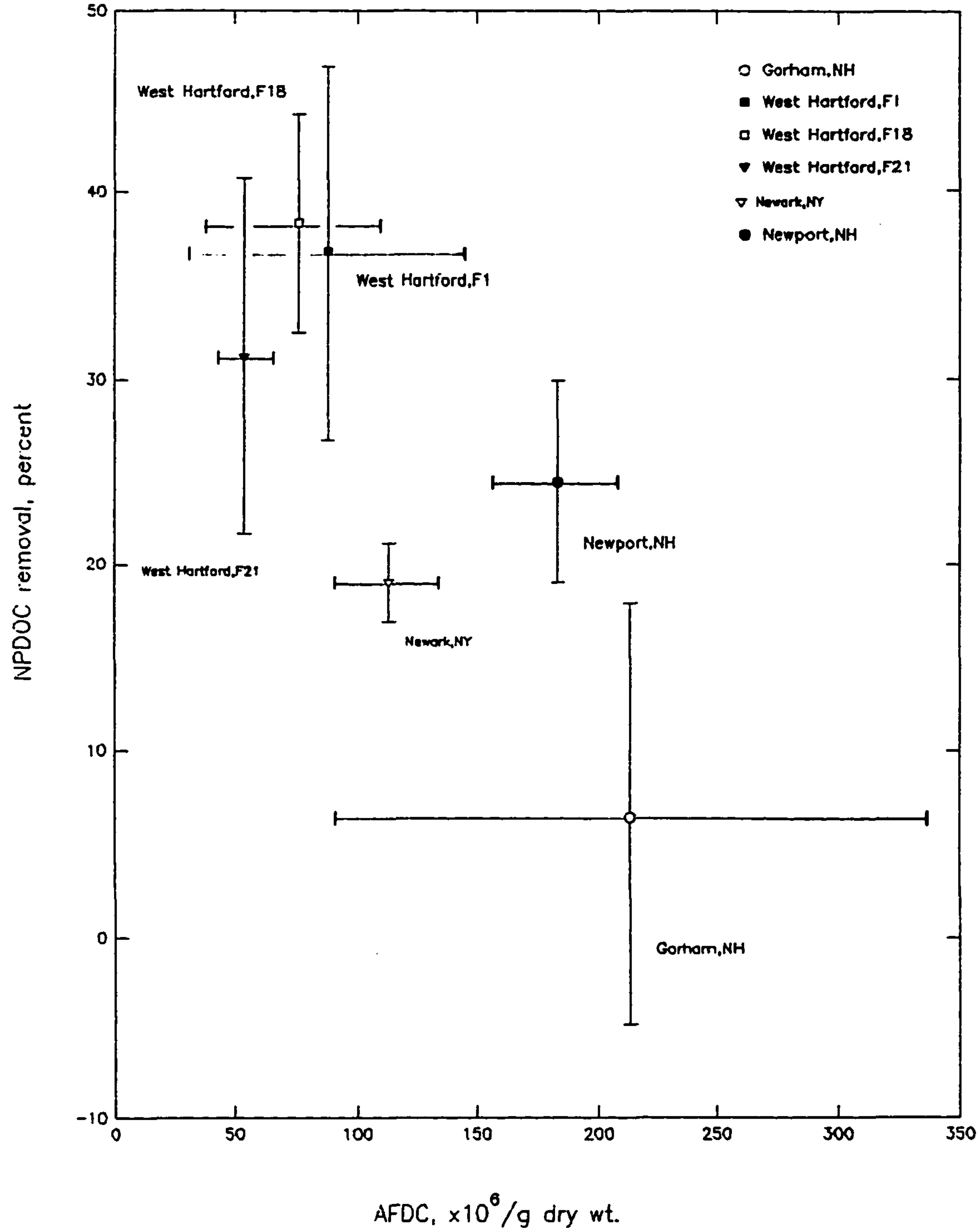


Figure 44: NPDOC removal vs AFDC in upper 30 cm of filter media.

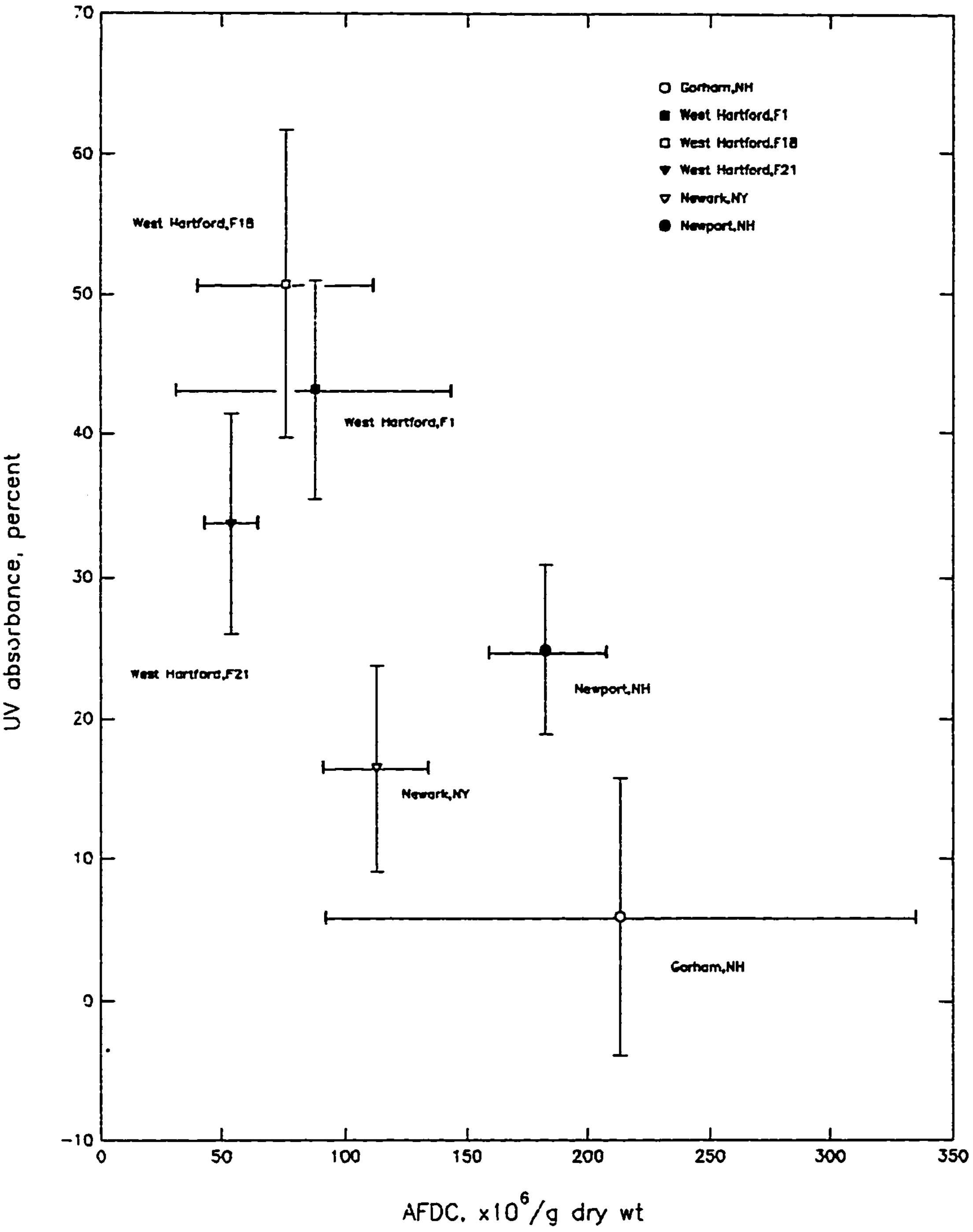


Figure 45: UV absorbance removal vs AFDC in upper 30 cm of filter media.

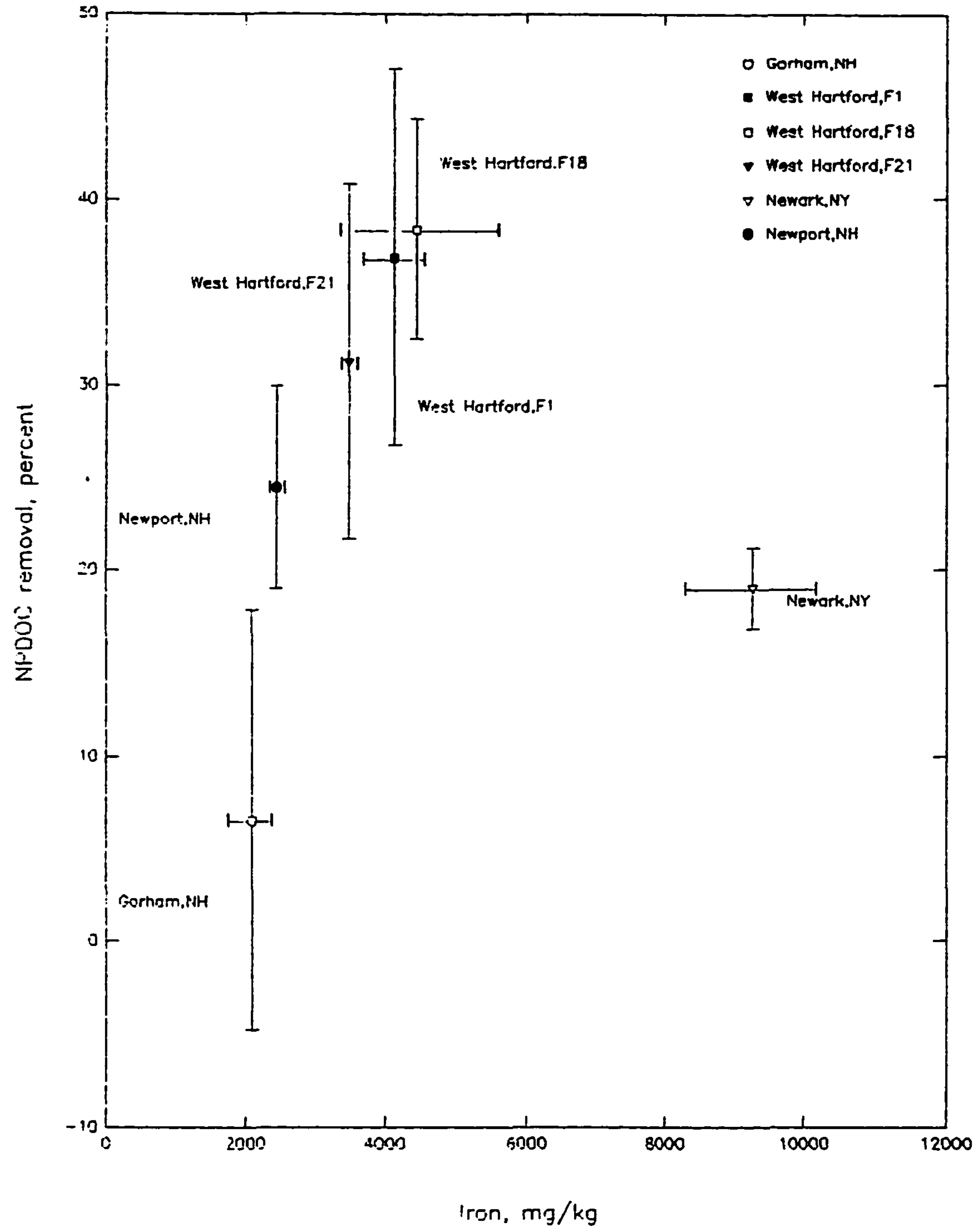


Figure 46: NPDOC removal vs iron in upper 30 cm of filter media.

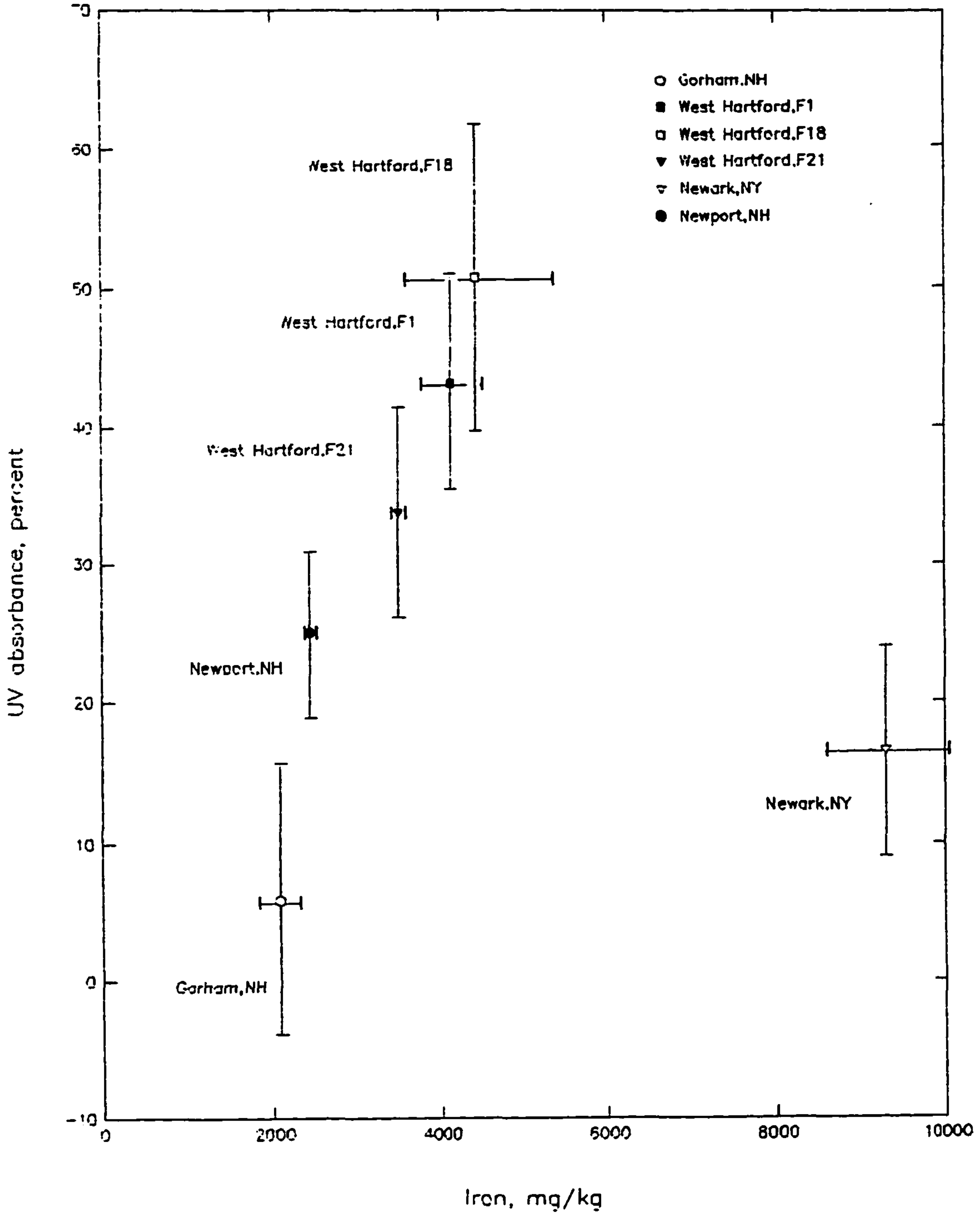


Figure 47: UV absorbance removal vs iron in upper 30 cm of filter media.

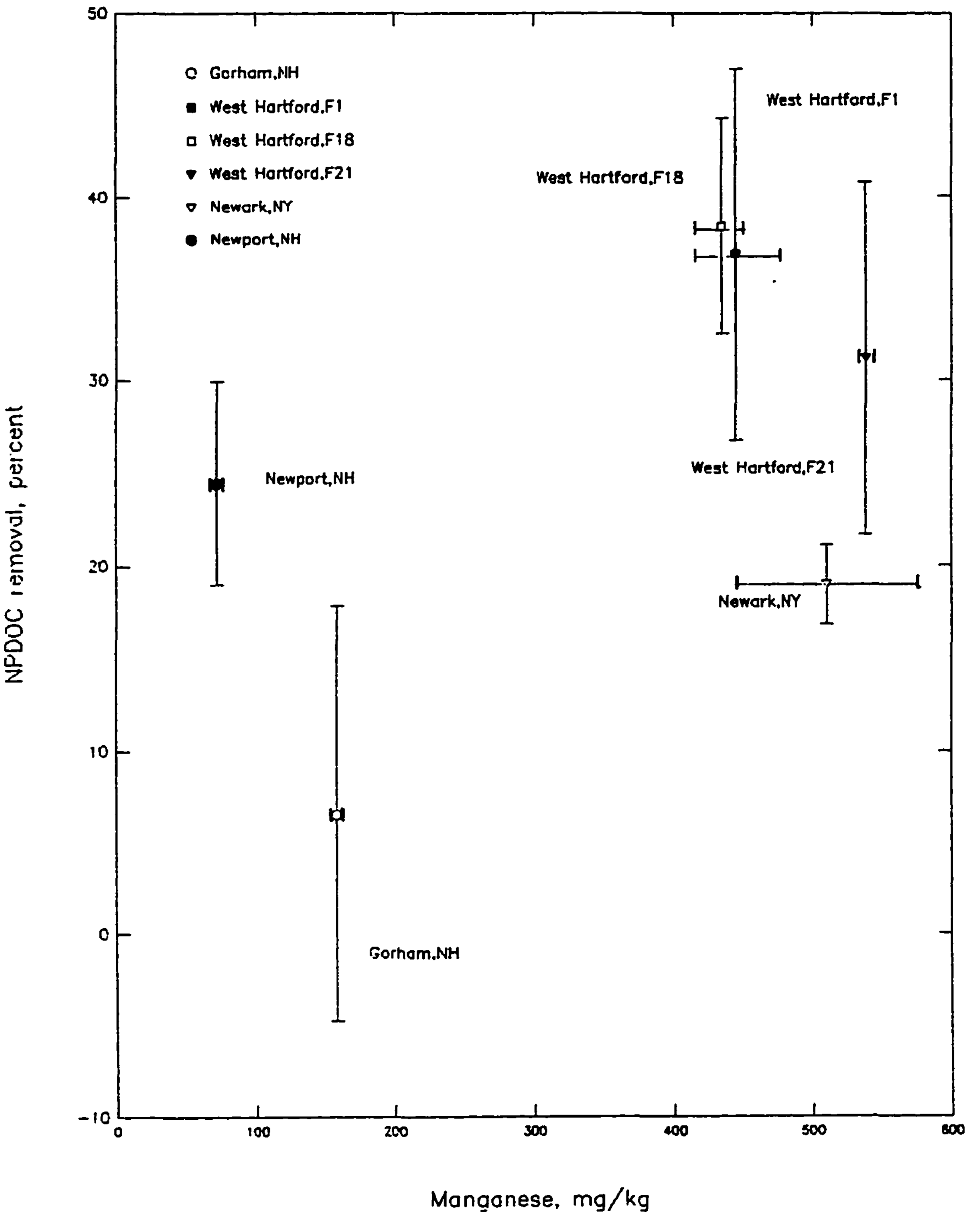


Figure 48: NPDOC removal vs manganese in upper 30 cm of filter media.

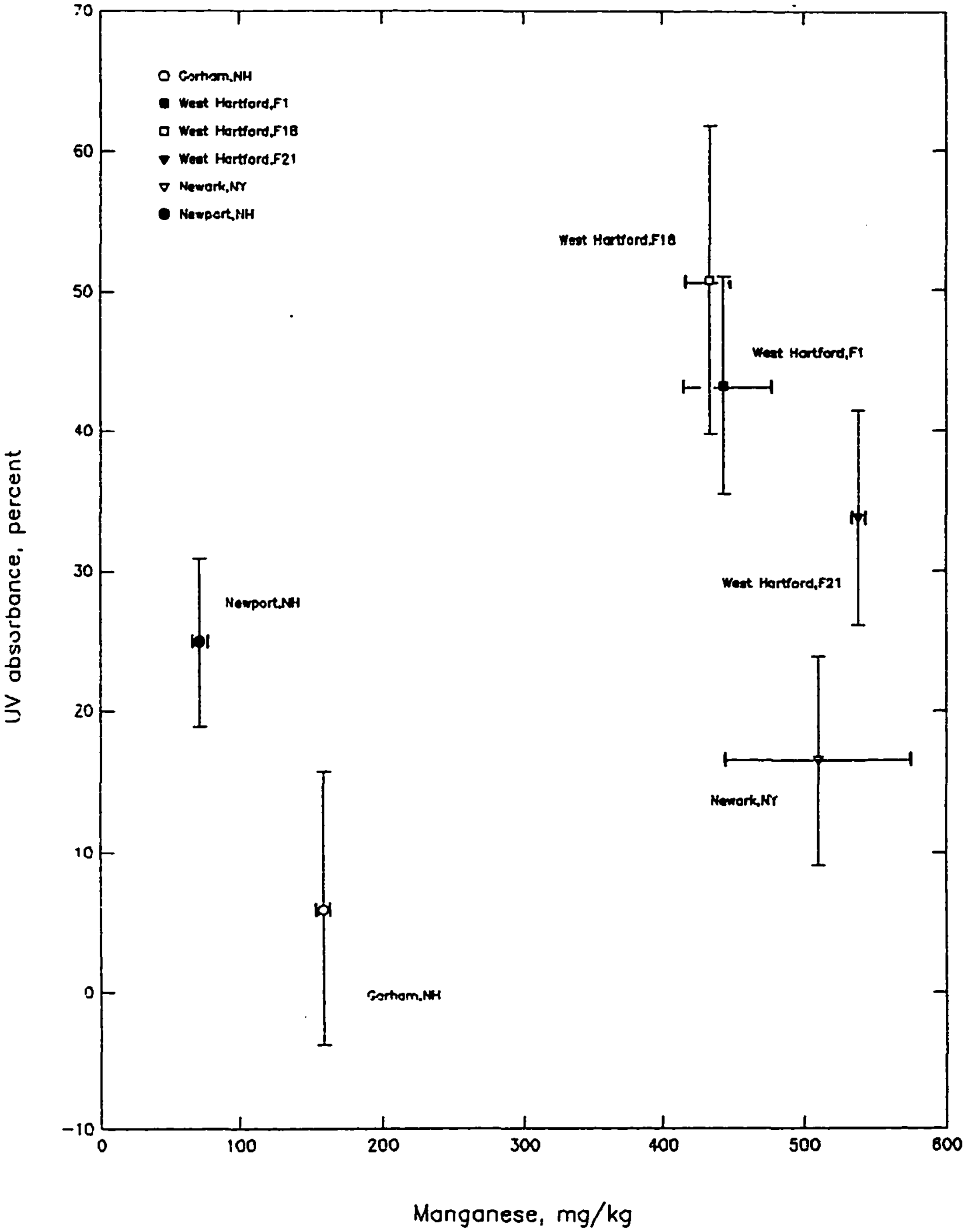


Figure 49: UV absorbance removal vs manganese in upper 30 cm of filter media.

AFDC, iron, and manganese characteristics of those filters.

Comparisons between older and newer/fresher sand media in this study, on both full scale and laboratory scale filters, correlated superior removals of NPDOC and UV absorbance with sand media having ages up to 19 years. This improved performance appeared to be related to the biological and inorganic composition of the sand media coatings as discussed earlier and shown in the preceding figures, 38 to 49.

Neither of the two cleaning methods studied removes such a large proportion of the natural sand coating biomass that they would affect the ability of the cleaned sand to remove TOC or UV absorbing materials. Ripening trends following cleaning events indicate the cleaned filters have substantially recovered pre-event performance levels within a few hours or bed volumes filtered. Scraping may remove a layer of the media in its entirety, but the sand media which is newly exposed has already developed a significant microbiological population (Eighmy et al., 1992). Harrowing removed materials from a greater thickness of the media, agitating, disrupting, and carrying off deposits down to 15 to 20 cm in the media as opposed to removing only the upper 1 to 2 cm, but harrowing also redistributes the remaining sand coating material/biomass throughout this thickness. This generalization is not meant to say that there is no effect from the cleaning methods. Both cleaning methods impact the surface deposits which are often reported to provide the greater part of treatment by slow sand filters. Also, as noted in Chapter 2 and elsewhere, a period of ripening may be necessary after a filter is cleaned to recover the former levels of filter performance (Letterman and Cullen, 1985). The need for ripening new filter media, whether following construction of the facility or resanding, was shown by the relative removal of NPDOC and UV absorbing material. The advantage of trenching and "throwing-over" the lower part of the filter media during resanding is apparent from both the point of retaining natural sand coatings within the filter and increasing the mean age of the filter media. An advantage of the harrowing cleaning method over scraping can also be deduced as it retains the sand within the filter and avoids the need to replace sand every 5 to 10 years. The sand in a harrowed filter will eventually require reconditioning, but the filters at West Hartford have been operated for up to 20 years before reconditioning. They plan to reduce this to 10 years (Allen, 1993).

The rapidity with which AFDC and FRM materials recover in the media and the slower recovery of the removal performance of the media indicates that prolonged ripening of a new sand involves more than the development of a simple biofilm. The information from the laboratory filter columns does not explain whether the longer ripening is necessary for the development of a "thick film" as suggested by Rittmann (1990), a more heterogeneous population of bacteria or microfauna (Weber-Shirk, 1992), or other characteristics necessary for removal. A longer study period and modified experimental design should be used to provide a filter arrangement that could be sampled during the evaluation period to consider these factors.

Summary: The evidence presented in this study, especially from the laboratory-scale filters, support the importance of biomass on slow sand filter performance. Increasing biomass content resulted in a proportional increase in organic carbon removal. As observed in previous studies, the harrowing cleaning method can elevate the biomass content of slow sand filters, measured as protein and carbohydrate, over that in filters cleaned by surface scraping. The scraped filters at the Newark plant, however, contained higher concentrations of volatile solids than did the harrowed filters at West Hartford. The reason for this can not be easily explained by the collected data but may be related to the activity of the materials at the different plants.

5.5 IMPORTANCE OF SOURCE WATER QUALITY

The source of water is also important to biofiltration efficiency. Several studies have mentioned that the organic carbon substrate is usually the rate-limiting nutrient in the biological processes (LeChevallier et al., 1990). For a variety of reasons, the biodegradable content of natural waters will vary from source to source (Aiken and Cotsaris, 1995; Owen et al., 1995).

Nitrogen and phosphorous are not considered rate limiting for established biofilm because the necessary nutrients for biological activity are considered to be already stored in the surface coating (Camper, 1994). However, this may not be the case during the initial start-up stages of a biofiltration process.

Recent research (Wang and Summers, 1993) has proposed that the biodegradable content of the dissolved organic carbon (NPDOC) may be subdivided into a fast biodegradable portion which follows Monod kinetics and a much slower biodegradable portion which follows first-order kinetics. The fast portion would be preferentially removed in an engineered process since detention times for both are generally measured in minutes or hours. The slower biodegradable portion is typically measured in days. Consequently, the fast and slow biodegradable kinetic fractions of natural organic matter in water will be dependent on the relative biodegradability of NOM which, in turn, will be dependent on the groundwater contribution (and other hydrogeologic factors) to the surface raw water. The West Hartford water supply, for example, would appear to be more amenable to biofiltration than the low organic content source waters in New Hampshire.

Another important factor to consider in source water influences is that complex metabolic interactions within the filter bacterial population may be dependent indirectly on the biological characteristics of the source water. Past research (Collins et al., 1989) demonstrated that the greater propensity to metabolize benzoate, and aromatic compound, in the West Hartford filters correlated to superior NOM removals than observed in other slow sand filtration facilities. In that study, raw water quality showed SUVA (Edzwald, 1993) characteristics of the West Hartford water to be more amenable to removal of UV absorbance and THM precursors, and to be more consistent with seasons. The data for these determinations and results are summarized in Table 99. Comparable data from the current study is presented in Table 100.

TABLE 99: PERFORMANCE AND SUVA FROM COLLINS ET AL. (1992).

Plant	Springfield, MA		New Haven, CT		West Hartford, CT	
Season	Winter	Fall	Winter	Fall	Winter	Fall
UV absorbance, cm^{-1}	0.081	0.093	0.042	0.079	0.042	0.056
DOC, mg/L	2.34	2.96	1.16	3.56	1.82	2.26
SUVA, $mg/L{\cdot}m^{-1}$	3.5	3.1	3.6	2.2	2.3	2.5
UVA removal, percent	33	22	17	15	24	43
DOC removal, percent	15	12	13	28	33	31

TABLE 100: SUVA FROM GORHAM, NH, NEWPORT, NH, NEWARK, NY, AND WEST HARTFORD, CT. , AND PERFORMANCE AT 15°C FROM REGRESSION CURVES.

Plant	Gorham, NH	Newport, NH	Newark, NY	West Hartford, CT	Portsmouth, NH
Season	Summer-fall	Summer-fall	Summer-fall	Summer-fall	Summer-fall
UV Absorbance, cm^{-1}	0.040±0.006	0.042±0.003	0.055±0.043	0.045±0.024	0.319±0.051
DOC, mg/L	1.5±0.2	2.3±0.3	1.9±0.4	1.9±0.6	6.5±0.8
BDOC, mg/L	0.2±0.1	0.1±<0.1	0.1±0.1	0.1±0.2	0.3±0.4
SUVA, $mg/L{\cdot}m^{-1}$	2.6	2.3	2.9	2.4	4.9
UVA removal, percent	8.1	21.9	16.0	39.1	24.8(1)
DOC removal, percent	16.1	23.8	19.9	36.0	21.2(1)

(1) This data is for a water temperature of 23°C which existed through the second testing period.

The lower SUVA values were associated with higher UVA and NPDOC removal for the earlier study, but the results were not consistent during the present study. The higher removals of organic carbon from West Hartford raw water were substantiated in the laboratory column tests. Both the Newark and West Hartford sand media removed a higher percentage of TOC from the West Hartford water than from the Newark raw water. The Portsmouth sand was also capable of removing TOC from the West Hartford water but was unable to do so with the Newark raw water.

The pattern for removal of UV absorbance from the respective water sources was essentially the same, although the Newark sand media was able to remove as slightly higher percentage of the UV absorbance from its own water than from the West Hartford water, 8.3 percent vs 5.5 percent.

Summary: With all other factors normalized or cancelled out, the efficiency of slow sand filters appeared to be impacted by the biodegradability characteristics of the raw water supply. Whether the biodegradation process was affected by a rate limited nutrient other than organic substrate could not be determined in this study.

5.6 INFLUENCE OF FILTRATION RATE AND EMPTY BED CONTACT TIME

Filtration rate has an effect beyond the relation to the EBCT of a filter as in the single-pass operation used in full-scale slow-sand filter operation. The effect of filter rate to both full-scale and laboratory-scale filters is to increase the pressure required to cause flow through the filter media and to increase the interstitial velocity within the media. This velocity affects the boundary layer of fluid about sand or other particles within the filter as previously discussed in Chapter 4.5.4 comparing performance of laboratory-scale filters operated at different filtration rates.

This factor may also be considered in relation to full scale filters, such as the filters at West Hartford where Filter 21 operates with a EBCT twice that of Filters 1 and 18 and twice that at any of the other filters monitored. The range of values for temperature, velocity, and mean clean sand size, and Reynolds numbers for the plants are summarized in Table 101. All of these values are very low relative to the range for turbulent flow and interstitial velocities would be important. The range of velocities considered in the laboratory-scale experiment were ten times the velocities in the full-scale filters and the Reynolds numbers greater than ten times those in the plant-scale facilities. Flow through all plant-scale facilities were within the laminar flow range and the removals would be considered limited by transport through the boundary layer around the particles.

TABLE 101: REYNOLDS NUMBERS FOR FLOW AT FACILITIES IN STUDY.

Plant	Mean grain size	Mean velocity with n=0.42	Temperatures °C.		Reynolds No.	
	mm	cm/s	Low	High	Low	High
Gorham, NH	0.42	0.0048	3	23	0.012	0.021
Newport, NH	0.53	0.0058	2	15	0.018	0.027
Newark, NY	0.8	0.010	10	15	0.054	0.07
West Hartford, #1	0.65	0.0066	4	21	0.027	0.044
West Hartford, #18	0.6	0.0099	4	21	0.038	0.060
West Hartford, #21	0.60	0.018	4	21	0.068	0.11
Portsmouth Pilot	0.60	0.0079	4	19	0.030	0.046
Lab-scale, 49 mL/m	0.85	0.161	-	20	-	3
Lab-scale, 16 mL/m	0.85	0.053	-	20	-	1
Lab-scale, 90 mL/m	0.85	0.296	-	20	-	6

The differences in velocity also affect the relative empty bed contact times (EBCT) of the plant scale filters. Those filters have similar media depths and so the EBCT for the filters would beapproximately proportional to the velocities. Considering the filters with as simple reactor model equation of:

$$[(Ci-Ce)/Ci] \times 100 = e\text{^}-Kt \qquad (9)$$

where Ci = influent concentration
Ce = effluent concentration
K = biological reaction rate
t = contact time.

The temperature effect on the reaction rate is related as earlier discussed in this chapter so the rates of removal have been estimated for a temperature of 15°C using the regression factors calculated earlier in this chapter. Empty bed contact time was calculated on the full depth of the filters tested in the study, and estimates of the media characteristics (volatile solids, FRM, carbohydrates, and AFDC) were based on the profiles established from the cores to a depth of 30 cm. The characteristics below that depth were presumed to remain the same below 30 cm. The relative performance of the plant-scale filters is summarized as shown in Table 102. An example of the calculation of one set of the values is presented in Appendix C.

TABLE 102: FIRST ORDER REACTION COEFFICIENTS (HR^{-1}) FOR REMOVAL OF NPDOC AND UVA.

	Gorham, NH	Newport, NH	Newark, NY	West Hartford, CT		
				Filter 21	Filter 18	Filter 1
Loading rate, m/hr	0.072	0.11	0.070	0.14	0.16	0.12
Filter depth, m	0.68	0.68	0.75	0.68	0.68	0.68
Detention time, hr	9.4	6.2	5.4	4.8	4.2	5.7
Temperature, °C	15	21	10	14	14	16
Est. NPDOC removal at 15°C,% (a)	16.1	23.8	19.8	30.7	36.4	40.9
Reaction coeff. per unit-	0.30	0.51	0.55	0.71	0.86	0.65
Volatile solids	0.16	0.16	0.39	0.13	0.091	0.075
FRM	0.29	0.18	0.51	0.77	0.53	0.43
Carbohydrates	108	112	4.7	4.9	6.8	3.4
10^6 AFDC	1.3^-6	2.1^-6	5.0^-6	1.5^-5	9.7^-6	6.6^-6
Est. UV absorbance removal at 15°C, % (a)	8.1	21.9	16.0	32.9	44.4	40.0
Reaction coeff. per unit-	0.22	0.50	0.51	0.73	0.90	0.65
Volatile solids	0.12	0.15	.036	0.13	0.096	0.074
FRM	0.22	0.18	0.47	0.78	0.55	0.43
Carbohydrates	81	110	4.3	4.8	7.2	3.4
AFDC	9.8^-7	2.0^-6	4.6^-6	1.6^-5	1.0^-5	6.6^-6

(a) Removal at 15°C calculated using regression factors in Table 90.

Comparisons were made between the data for the three filters which had not been harrowed before or during the study period against the three at West Hartford which had been harrowed. The results are summarized in Table 103. The comparisons between the two sets of filters, differentiated by having been cleaned by harrowing or not, is presented to raise the issue of possible significance. The three filter plants which had not been harrowed filtered raw waters from significantly different sources, with sand of different chemical characteristics, and had been in operation for different lengths of time. One plant had never been cleaned, another cleaned only a

TABLE 103: MEAN FIRST ORDER REACTION COEFFICIENTS (HR^{-1}) FOR REMOVAL OF NPDOC AND UVA BETWEEN PLANTS WHICH HAD CLEANED WITH HARROWING VS PLANTS WHICH HAD NOT.

	Filters which had not been harrowed			Filters which had been harrowed			Is difference significant
	Gorham NH	Newport NH	Newark NY	West Hartford, CT			
				Filter 21	Filter 18	Filter 1	
Loading rate,m/hr	0.072	0.11	0.07	0.14	0.16	0.1	
Filter depth, m	0.68	0.68	0.75	0.68	0.68	0.7	
Detention time, hr	9.4	6.2	5.4	4.8	4.2	5.7	
Temperature, °C	15	21	10	14	14	16	
Est. NPDOC removal at 15°C, %	16.1	23.8	19.8	30.7	36.4	41	
Reaction coeff.	0.45±0.14			0.74±0.11			>90%
per unit-							
Volatile solids	0.12±0.22			0.098±0.028			No
FRM	0.32±0.16			0.57±0.17			No
Carbohydrates	75±61			5.1±1.7			No
10^6 AFDC	2.8±1.9			10.6±4.4			No
Est. UV A removal at 15°C, %	8.1	21.9	16	32.9	44.4	40	
Reaction coeff.	0.41±0.16			0.76±0.13			>90%
per unit-							
Volatile solids	0.10±0.06			0.10±0.03			No
FRM	0.29±0.16			0.59±0.18			No
Carbohydrates	65±55			5.1±1.9			No
10^6 AFDC	2.5±1.8			10.8±4.6			No

(a) Removal at 15°C calculated using regression factors in Table 90.
No = no significant difference using two-tailed t-test at 90 percent confidence limit.

few times, and the third had been cleaned repeatedly by scraping. The harrowed filters had been in service for periods ranging from 19 years down to less than one year. The concentrations of volatile solids, FRM, carbohydrates, and AFDC in the lower 60 cm of filter were presumed to be equal to those concentrations at a depth of 30 cm. The filtration rates, EBCT's, and operating temperatures were normalized using simple equations for biological reaction models. With these substantial qualifications in mind, it is appears the performance of the two sets of filters were significantly different, at over 90 percent confidence, in removal of both NPDOC and UV absorbance. The major differences were, however, between the filters at the Gorham and Newport plants which had not been cleaned (or cleaned only by surface raking at the time of media sampling) and the harrowed filters at West Hartford, CT. The characteristics of the scraped filters at Newark, NY were intermediate between those of the abovementioned sets. The NPDOC removals, when expressed as removal per unit mass of volatile solids, FRM, carbohydrates, and AFDC, show the removals of NPDOC per unit of volatile solids, FRM, carbohydrates, and AFDC not to be statistically different at the 90 percent confidence level. This conclusion was consistent with the results from the laboratory columns reported in Section 4.2.3 on the influence of natural coating material on filter media where the removal of NOM varied with the relative natural coating on the sand media. The major differences in performance were between the filters which had not been cleaned by either method and those which had been in service longer and cleaned repeatedly by either method. The unusually high concentration of volatile solids at the Newark, NY plant make comparisons relating to that paramater unreliable. The Newark, NY plant takes its supply from a lake with periodic algal blooms and also continuously prechlorinates the flow to the plant for algal control in intake line. These factors may result in the accumulation of higher concentrations of inactive volatile solids than at the other plants included in the study.

The UV absorbance removals, when expressed as removal per unit of volatile solids, FRM, carbohydrates, and AFDC, show the removals of UV absorbance per unit mass of volatile solids, FRM, carbohydrates, and AFDC also not to be statistically different at the 90 percent confidence level. This difference may have been a result of the relative activity of the biomass within the volatile solids at the respective plants. Analyses for the microbial activity or rates of mineralization (Spanos, 1989) might clarify this difference.

Summary: The removal information for the two sets of filters, unharrowed vs harrowed, have similar rates of NPDOC and UV absorbance removal, and it is possible that the unit rates of removal are the same for volatile solids, FRM, carbohydrates, and AFDC for both NPDOC and UV absorbance. These similarities, though based on supposition, should be explored by further study. In particular, filters having longer history of operation and more sampling records. Media characterization throughout the media depth should be used to test these relationships.

5.7 CLEANING FREQUENCY

It had been planned to compare cleaning methods at either the Gorham or Newport plants over consecutive cleaning operations. The time required to develop sufficient headloss and associated filter deposits for cleaning was so long, however, that sampling at that plant was moved to the Newport plant. Cleaning operations were more frequent at that plant, but the field studies had to be terminated in early 1994 due to personal commitment elsewhere. Consequently, data could not be obtained directly to compare the frequency that would result from the different cleaning methods.

The pilot plant operation at Portsmouth, NH, provided a means of estimating the comparative rates that filter headloss would develop. Three filters were ripened over the period of February to June 1993 while using the scraping method for cleaning, and then operated in parallel for five filter cycles between June and September 1993 while using different cleaning methods on each filter. One filter was cleaned by scraping to the bottom of the darkly colored sand. The other two filters were cleaned by harrowing, one to a depth of 5 cm (2 in) and the other to a depth of 15 cm (6 in). The development of headlosses were shown in Figure 17. The three filters developed headloss at similar rates through the first three cycles, and the scraped filter continued to develop losses at a similar rate through the remaining two cycles of the comparison. The harrowed filters, however, developed losses at accelerated rates after the third cycle. The media was sampled between the surface and 2.5 cm and between 25 and 30 cm. The results have been presented earlier in Table 74 and reviewed on the following page. Media characteristics appeared to have begun to develop but not sufficiently to differentiate for all parameters. Additional evidence is needed to support the differences between filters cleaned by the different methods.

The comparative performances of the full-scale plants at Newark, NY and West Hartford also provide evidence of the greater rate of headloss development in filters cleaned with the harrowing method. The raw water supplies of the two plants have been discussed earlier, with the evidence that both are generally high quality and approximately the same particle count, NPDOC, and UV absorbance, but with higher turbidity and summer algae (Canandaigua Lake Watershed Task Force, 1994) in the raw water at the Newark plant. The length of filter runs over the three year period of 1991 to 1993, the total volumes of water filtered per run during the evaluation period in the summer and fall of 1993, and the turbidity and NPDOC loads for the filters are indicated in Table 104.

The length of the filter cycles at the Newark plant were longer that those at West Hartford, except for Filter 21 which had been resanded less than one year before the evaluation period. This data was compared with the records for Filter 19 which had been in service 20 years since it had been last resanded, and which had averaged 17.0 ML/100 sq. meters (4.17 MG/1000 sf) during its last two filter runs before reconditioning. The production from Filter 19 was lower than for either Filter 3 or 4 at Newark and Filter 21 at West Hartford, but still significantly higher than for Filters 1 and 18 at West Hartford. If the length of the filter cycles at the plants were normalized to the same final headloss, the filter runs of the scraped filters at Newark, NY would have been about three times those for Filter 21 at West Hartford. The volumes filtered per filter run for all filters was above the range of "40 to 80 MG/acre", or 3.0 to 6.1 ML/100 sq meters (0.75 to 1.5 MG/1,000 sf) reported by Turneaure and Russell (1924).

The turbidity loads on the filters during the cycle were much heavier at the Newark plant than at West Hartford. Algal development in the supply to the Newark plant causes the summer filter cycles to be one-third shorter that in the winter. The length of filter cycles at West

TABLE 104: COMPARISONS OF FILTER RUN, VOLUME OF WATER FILTERED, AND TURBIDITY LOADS FOR NEWARK, NY AND WEST HARTFORD, CT.

Parameter	Newark, NY		West Hartford, CT		
	Filter 3	Filter 4	Filter 1	Filter 18	Filter 21
Years since resanding	1.5	3	19	13	<1
Filter run (a), days -June-Nov. -Nov.-June	 93±36,n=3 147±32,n=3	 98±76,n=6 145±35,n=4	 33±6,n=14 42±25,n=7	 35±8,n=13 55±30,n=8	After resanding: 36±8,n=4 -
Headloss change over run, m (ft)	0.52±.15 (1.7±.5)	0.73±.03 (2.4±.1)	Meter inoperative	Meter inoperative	1.8±.01 (5.8±.0)
Volume filtered, ML/100 sq. meters (MG/1000 sf	25.6 (6.29)	19.8 (4.85)	6.88 (1.69)	10.7 (2.62)	24.2 (5.95)
Turbidity load (b), NTU•ML/100 sq. meters (NTU•MG/ 1000 sf)	77.4 (19.0)	60.7 (14.9)	6.19 (1.52)	9.62 (2.36)	21.9 (5.37)
NPDOC removed (c) kg/100 sq. meters (lb/1000 sf)	50 (22)	9.3 (19)	3.4 (7)	5.3 (11)	10 (20)

(a) The filter cycles at the respective plants are ended when the headlosses increase and filter flows decrease to levels the operators decide will not supply the expected water supply requirements of the coming several weeks. There is no precise rule used at either plant.

(b) The turbidity load was defined as the product of flow and the daily turbidity of the raw water to the plant, over the September to November period.

(c) The estimates of NPDOC removal were made from the volumes of water filtered, the mean NPDOC of the raw and filtered over the September to November period.

Hartford were also shorter during the summer and fall than in the winter, by about one-fifth, although there is no record of algal growths in their supply. The NPDOC mass removed by the filters was in the range of 3 to 10 kg/100 sq. meters (7 to 22 lb/1000 sf). These are below the range of 10 to 30 kg "carbon trapped" /100 sq. meter reported (Renton et al.,1991) at Thames

Water Authority. The basis of their figures was not reported and may have included particulate carbon as well as the NPDOC monitored in this study. The volume of water filtered per filter cycle also was not reported (Renton et al., 1991).

Summary: The harrowed filters developed headlosses more quickly than the scraped filter before the end of the fifth cleaning cycle. Harrowing resulted in greater filter resistance in the upper layer of the filter bed than scraping but harrowing to the depth of 30 cm, instead of 5 cm, can reduce the impact of harrowing-induced filter resistance.

5.8 EFFECTIVENESS OF CLEANING METHODS

The effectiveness of the cleaning methods is usually measured by the rate at which a filter builds up "headloss", or the resistance of the filter and its contents to the passage of applied water. As discussed earlier in this section, the scraped filters at the Newark, NY plant developed headlosses more slowly than the filters at West Hartford. The headloss of the scraped pilot-scale filter at Portsmouth, NH also developed more slowly than in either of the harrowed pilot-scale filters.

The mass of materials removed from a filter by each of the cleaning methods also was estimated by comparing the mass of volatile solids, biomass, and metals in the filter sand cores taken before and after several cleaning events. A summary of that information is presented in Table 105 for the volatile solids component, with the amounts removed by the respective cleaning methods.

The calculated mass of volatile solids removed from the upper 30 cm of Filters 18 and 21 at West Hartford did not correlate with the loads based on the samples from the washwater and its estimated flow volumes. The calculated mass values were based on the difference between the mean volatile solids concentrations in the upper 30 cm before and after harrowing. The

TABLE 105: VOLATILE SOLIDS REMOVED BY CLEANING FILTERS.

Plant & Filter	Date of cleaning	Volatile solids in upper 30 cm of filter (a) kg/100 sm (lb/1000 sf)	Volatile solids removed by cleaning kg/100 sm (lb/1000 sf)	
			Scraping (b)	Harrowing
Newport, #3	May 18,'93	120±16 (240±34)	-	0.24 (0.50)$^{(c)}$
Newport, #3	July 26,'93	130±18 (270±37)	-	0.70 (1.4)$^{(c)}$
Newport, #1	Nov.9,'93	140±35 (280±71)	5.9±1.6 (12±3)	-
Newport, #2	Jan.9,'94	66±18 (130±37)	-	3.6(7.4)$^{(c)}$
Newark, #3	Aug.17,'93	480±84 (980±170)	43±8 (88±17)	-
Newark, #4	Aug.17,'93	520±60 (1050±120)	49±5 (100±10)	-
Newark, #4	Oct.26,'93	570±79 (1160±160)	54±5 (110±11)	-
West Hartford #21	Sept.15,'93	220±43 (460±88)	-	-
West Hartford #21	Oct.12,'93	230±18 (470±38)	-	6.4 (13) $^{(c)}$ 45±20 (92±48)$^{(d)}$
West Hartford #18	Oct.13,'93	300±31 (600±63)	-	7.0 (14)$^{(c)}$
West Hartford #1	Jan.26,'93	220±15 (450±31)	-	-
West Hartford #1	Oct.5,'93	310±42 (630±86)	-	2.0 (4.0)$^{(c)}$
West Hartford #1	Nov.2,'93	270±36 (550±74)	-	-

(a) The material in the upper 30 cm of filter media was calculated as the mean concentration of the top 1.2 cm and the 25-30 cm samples over the mass of media in the upper 30 cm.

(b) The material removed by scraping was calculated as the material in the thickness of sand removed at the concentration in the upper 1.2 cm. 2.5 cm (1 in) was removed at Newark, NY and 1 cm (3/8 in) was removed at Newport, NH.

(c) The material removed by harrowing was calculated from the composite samples of wash water flow and its flow.

(d) The material removed by harrowing was calculated as the difference between the material in the upper 30 cm of media before cleaning and after cleaning.

calculations were:

$$\text{Mean volatile solids, \%} = \frac{(\text{Vol. Solids in Top 1.2cm}) + (\text{Vol. Solids in 25-30cm})}{2}, \text{ and} \qquad (10)$$

Mass volatile solids, kg/100 sq. meters

$$= \frac{\text{Mean volatile solids, \%}}{100} * 30 \text{ cubic metes} * \text{Unit weight of sand.} \qquad (11)$$

The unit weight of sand was taken as the product of the unit weight for dense dry sand with mixed grain size (Terzaghi & Peck, 1948) as 2083 kg/cubic meter (130 lb/cf) and the mean total dry solids for the depth of the sample in the filter bed. The mass in the wash water was based on the composite sampling reported in "Results and Discussion of Results in Individual Plants." The wash water sampling was carried out according to the methods presented in Methods and Materials and the results generally follow the estimated weights of volatile solids in the upper 1.2 cm of the filter media. The mean value of the percent volatile solids at the top 1.2 cm (1/2 in) and the lower 25-30 cm (10-12 in) layers of the filter, before and after the cleaning process, also appear consistent with the data on these and other filters in the study. Even though Filters 18 and 21 had not been cleaned thoroughly at the time of the September 15 cleaning, due to the power failure and water shortage, the solids that remained in the filters until the next cleaning should have been indicated in the results of analyses on both the washwater samples and the media cores. Errors from the washwater sampling would have been expected to have been equally divided between over and under representing the true mean, or below the mean if solids were settling in the channels and not collected by mid-depth sampling. Any errors in the sand core sampling might also have been expected to be equally divided around the mean, yet the samples taken from Filter 19 in March 1994 indicated that there were areas of the filters, adjacent to wall and roof columns, where the harrow does not reach and the media is not effectively cleaned. The total area represented by those portions of the filter within approximately 30 cm (12-in) of the walls and columns at West Hartford amount to only approximately 6.5 percent of the total filter area. That would not account for the differences, however, even with a liberal allowance for uncleaned areas in corners of the filter.

The mass of volatile solids removed at Newport by harrowing was approximately equal to that removed by scraping, but the mass removed by hand raking was only about one-tenth as much as by either scraping or harrowing. This may have been due to the media being less mature at the time of the hand raking operations, after only 13 and 15 months of operation as opposed to 18 and 21 months for scraping and harrowing, respectively. The most obvious difference between the cleaning methods was the extent to which the media was affected, as the surface of the filters were hand raked to a depth of less than 1.2 cm (1/2 in) only twice during a cleaning operation, while harrowing penetrated the filters to a depth of 15-20 cm (6-8 in) during repeated traverses and scraping entirely removed most or all of the media depth affected by raking. It is concluded that hand raking is not an effective means of removing volatile solids from the media. Hand raking was effective in reducing the head loss of the filters over the summer of 1993 and maintained water production while the filter media compacted to support the weight of the equipment for harrowing. The method could be used in the future to extend the time before scraping or harrowing is necessary, but would allow accumulations of organic matter in the filter.

The scraping method removed the greatest mass of volatile solids from the filters at Newport, but the harrowing method was used only after a prolonged period when the raw water temperature was low and at a time when the calculated volatile mass in the upper 30 cm (12 in) of the media was half that at the time of scraping. If the removal by cleaning method were normalized as a percentage of the original mass in the upper 30 cm, then the harrowing method would have removed slightly more volatile matter, removing 5.3 percent as compared with scraping to a depth of 1 cm (3/8 in) which removed 4.3 percent. It must be noted, however, that the measurements on both scraping and harrowing were not replicated and the conclusion needs to be supported by other evidence. The depth to which the sand was scraped at Newport was also less than practiced at most plant, 1 cm (3/8 in) as compared to 2.5 cm (1 in).

Only the scraping method has been used at Newark, NY and a direct comparison between cleaning operations at this plant with the results of harrowing these filters is not possible. The mass of volatile solids removed by scraping operations was complete for the depth of media scraped. The scraping at this plant was estimated at the time of cleaning to have been 1.9 cm (3/4 in) but the long term mean scraping depth appears to have been 2.5 cm (1 in) based on the changes in sand levels and the number of cleanings since resanding. If the scraping depth were 2.5 cm (1 in), then 9.0 ± 0.8 percent of the volatile mass in the upper 30 cm (12 in) of filter was being removed. If the depth were 1.9 cm (3/4 in), then the removal would have been reduced to about 7 percent. There were no measurements taken to further define changes in concentrations of volatile matter or other parameters with depth in the upper 1.2 cm (1/2 in) of the Newark filters.

Although the filters at West Hartford have been cleaned solely by harrowing for more than 40 years, it is possible to compare the results of harrowing with estimates of the materials would have been removed with a selected thickness of the upper layers of media. This thickness was selected to be 2.5 cm (1 in) based on the apparent long-term depth of scraping at Newark, NY and the wide-spread practice of scraping to this depth (Letterman and Cullen, 1985). The mass of materials that would have been removed with scraping to a depth of 2.5 cm (1 in) and that were removed by harrowing are presented in Table 106.

The effectiveness of the harrowing methods at West Hartford were low relative to the estimated load of volatile solids in the filters, if based only on the washwater sampling, but the volatile solids in the top 1.2 cm of sand media in the filters (x=11.5 kg, s=4.4, n=5) were maintained consistently lower, by 46 percent than found in the Newark, NY plant (x=21.2 kg, s=2.5, n=3)over the same season. The data on cores before and after cleaning West Hartford Filter 21 showed decreases in all filter media parameters after harrowing. Only the percent total dry solids of the media increased after harrowing. Relative standard deviations on the mean values generally decreased also, indicating greater uniformity of the media after harrowing. The data for Filter 18 cannot be used to prepare a similar estimate of the differences in materials in the media before and after harrowing because the September 15, 1993 cores were after an abbreviated cleaning session, and the October 13, 1993 cores were taken at the end of that filter run rather than before the cleaning of September 15. The harrowing method removed more material from the filter media than did the scraping method except in Filter 1. Filter 1 does not have inlet and outlet channels on opposite sides of the filter bed so that washwater can flow continuously across the filter during the harrowing process.

TABLE 106: MATERIAL IN UPPER 30 CM OF FILTERS AT WEST HARTFORD, CT, THAT WOULD HAVE BEEN REMOVED BY SCRAPING AND WERE REMOVED BY HARROWING.

Filter & Date	Cleaning Method	Volatile Solids kg/100 sm (lb/1000 sf)	FRM kg/100 sm (lb/1000 sf)	Carbohydrate kg/100 sm (lb/1000 sf)	AFDC Count/ 100 sm (= colonies/ 1000 sf)	Iron kg/100 sm (lb/1000 sf)	Manganese kg/100 sm (lb/1000 sf)	Calcium kg/100 sm (lb/1000 sf)	Aluminum kg/100 sm (lb/1000 sf)
No. 21, Sept. 15	Harrowing (a)	-	-	-	-	-	-	-	--
	If scraped (c)	23±5 (47±9)	72.1±23.9 (147±49)	8.44±4.71 (17.3±9.6)	1x10^10 ±2x10^9	-	-	-	--
No. 21, Oct. 12	Harrowing (a)	6.4 (13)	-	-	-	-	-	-	-
	Harrowing (b)	45±20 (92±48)	390±134 (797±270)	23.5±8.9 (48.0±18.3)	3x10^10 ±4x10^10	-	-	-	--
	If scraped (c)	26±2 (54±4)	78.5±16.5 (160±34)	9.25±0.86 (18.9±1.8)	3x10^9 ±3x10^8	147±3 (301±6)	31.5±0 (64.4±0.1)	16.8±1.3 (34.4±2.6)	58.5±3.5 (120±7)
No. 18, Oct. 13	Harrowing (a)	7.0 (14)	-	-	-	-	-	-	-
	If scraped (c)	23±3 (48±7)	50.6±5.5 (104±11)	9.62±1.97 (19.7±4.0)	7x10^9 ±6x10^9	155±15 (318±31)	21.0±1.2 (43.0±2.4)	11.5±1.9 (23.5±3.8)	60.4±8.0 (123±16)
No. 1, Oct. 5	Harrowing (a)	2.0 (4.0)	-	-	-	-	-	-	-
	If scraped (c)	26±3 (54±6)	76.3±24.3 (156±50)	7.55±1.10 (15.4±2.2)	1x10^10 ±6x10^9	165±9 (338±18)	22.0±1.6 (44.9±3.3)	15.4±4.2 (31.5±8.6)	74.3±7.8 (152±16)
No. 1, Nov. 2	Harrowing (a)	-	-	-	-	-	-	-	-
	If scraped (c)	18±4 (38±7)	38.7±12.8 (79.2±26.2)	6.61±1.42 (13.5±2.9)	-	168±6 (343±11)	19.4±0.4 (39.7±0.8)	10.6±0.9 (21.7±1.9)	64.5±8.0 (132±16)

(a) Materials as measured by composite sampling of wash water flow.
(b) Materials as calculated from difference between mean concentrations in upper 30 cm (12 in) of media before and after cleanin
(c) Materials as calculated for top 2.5 cm (1 in) of media from core samples of top 1.2 cm (1/2 in).

Summary: The harrowing method being practiced at West Hartford, except in Filter 1 which has not been properly equipped, removed more accumulated material than would the scraping method if only 2.5 cm of sand were removed.

5.9 CLEANING METHOD COSTS

The costs of the scraping and harrowing cleaning techniques at the respective plants are summarized in Table 107. The directly measured labor costs for the scraping method, in person-hours per unit of area cleaned, are twice those for harrowing method. The results at the Newport, NH plant which directly compared the costs of the two cleaning methods, on adjacent filters and by the same personnel, demonstrated the scraping method used twice the labor required for harrowing, although the length of time harrowing method at the Gorham plant (Bernier, 1994) are essentially the same as at Newport. The direct labor costs per unit of filter area cleaned at West Hartford were about one-half this (0.63 persons-hrs/100 sq. meters, vs 1.20 persons-hrs/100 sq. meters at Newport), but the costs at West Hartford would be about equal to the Newport costs if the additional time required for moving tractors and ventilation fans between buildings were included. The tractors and ventilation fans were already located or permanently installed at the other plants. The time to harrow filters at the Gorham and Newport plants had been based on the time per unit area used at West Hartford and no studies were made to determine if the time should be modified.

Larger crews were used for scraping, ranging from 3 to 5 persons at various times at the two plants monitored in this study. The direct labor used in the Newport, NH and Newark, NY plants, including the time for removing the sand from the filters and dumping it in storage piles, was almost identical on the basis of person-hours per unit of area cleaned, and considerably lower than reported for other plants (Letterman and Cullen, 1985). The labor required at these plants averaged 2.7 person-hours per 100 sq. meters (2.5 person-hrs/1,000 sf) as opposed to the average of 8.9 hrs per 100 sq. meters of filter (8.2 hrs/1,000 sf) from the 1983 data (Letterman and

TABLE 107: SUMMARY OF CLEANING COSTS.

Costs per 100 sq meters (1,000 sf)	Scraping		Harrowing		
	Newport, NH (n=1)	Newark, NY (n=3)	Gorham, NH (Bernier, 1994)	Newport, NH (n=1)	West Hartford, CT (n=3)
Labor, hrs					
Direct	2.70 (2.50)	2.71 (2.52)	1.20 (1.11)	1.20 (1.11)	0.63 (0.58)
Administrative	0.30 (0.28)	0.20 (0.18)	-	0.30 (0.28)	0.08 (0.07)
Equipment, operating hrs					
Truck	0.60 (0.56)	0.69 (0.61)	0 (0)	0.60 (0.56)	0 (0)
Tractor	0 (0)	0.10 (0.09)	1.20 (1.11)	0 (0)	0.31 (0.29)
Sand, cu.meters (cy)	0.96 (1.16)	1.82 (2.21)	0 (0)	0 (0)	0 (0)
Raw water drained, ML (gal)	0.16 (37,700)	0.03 (7,380)	0 (0)	0.15 (37,450)	0 (0)
Wastewater,					
Volume, ML (gal)	0 (0)	0 (0)	Information not available	0.058 (14,100)	0.22 (5,130)
Sett. Solids, L (gal)	0 (0)	0 (0)		540 (129)	690 (180)
Susp. Solids, kg (lb)	0 (0)	0 (0)		12.9 (26.4)	18 (38)
Susp. Solids, % Vol.	0 (0)	0 (0)		28	38
Filtered water, ML (gal)	0.30 (77,700)	0 (0)	Information not available	0.28 (68,500)	0 (0)
Approximate cost, 1996 dollars	$250 (230)	$220 (200)	Insufficient information	$150 (140)	$32 (29)
Time out of service, hrs					
Actual cleaning time[a]	0.60 (0.55)	0.71 (0.66)	1.21 (1.12)	0.60 (0.55)	0.32 (0.30)
Total time	24.5 hrs	13 hrs	4 days	25 hrs	34 hrs

(a) The actual time for cleaning shown is for the hours that labor is being performed and does not include time to drain supernatant water, drain filters between wet and dry harrowing, refilling the filter, or ripening before returning the filter to service.

(b) Costs are calculated using labor = $30/hr, administration = $40/hr, equipment = $15/hr, sand = $30/ton, raw water = $.10/1,000 gallons, wastewater disposal = $1.00/1,000 gallons, and filtered water = $1.00/1,000 gallons. All costs are site specific and should be calculated for any location being considered. Costs, fall 1996 (ENR Common Labor Index = 11,560, 1913 basis).

Cullen, 1985) if the Newark plant were excluded. Both the Newport, NH and Newark, NY plants had concrete access ramps for equipment and personnel which greatly facilitated work. Crew size for scraping was limited by the number of persons who could be served by the equipment used to carry the sand from the filter. In plants which cannot use heavy equipment, the crew size would be adjusted to the labor supply and the time the filter can be out of service.

The equipment used for the cleaning operations are different at the several plants studied. The equipment used is listed in Table 108 for reference but it must be emphasized that a specific plant might have used equipment of a variety of manufacturers, models, and sizes with equal or greater satisfaction. The costs of equipment at a particular plant will be determined by the local selections and methods of purchase.

TABLE 108: EQUIPMENT USED FOR CLEANING FILTERS.

Newport, NH		Newark, NY	West Hartford, CT
Scraping	Harrowing	Scraping	Harrowing
John Deere 855 Tractor, with front loader bucket. Shovels, one per person	John Deere, 25 HP lawn tractor.	Chevrolet S-10, with locally installed dump box (cap. approx. 1 cu.meter). Shovels, one per person	Ford 1720, 25 HP, 4 wheel drive, with spring harrow Case 350 crawler, with scarifier.

The volume of sand removed when scraping a filter has been estimated from the intended scraping depth of 1.2 to 2 cm (one-half to 3/4-in). The actual volume was measured after being removed from the filter at the Newport, NH plant and was equivalent to only 1 cm (3/8 in). The estimated thickness of the sand layer removed during cleaning at Newark, NY was reestimated from the change of sand level in the filters after the recorded number of cleaning events, giving an estimate of 2.5 cm (1 in.) removed per cleaning as compared to the 2 cm (3/4 inch) originally estimated. The time required to remove the sand would be in proportion to the depth of sand removed by scraping.

The cost of sand for a plant varies with the location of the plant and the specifications for the sand, but is a significant factor in the selection of the cleaning method where sand is more expensive. Costs of sand to the respective plants when last purchased was: Newport, NH, 1992, $23/cu. meter ($30/cy); Newark, NY, 1991, $7.30/cu. meter ($11/cy), plus 30 mile haul); and West Hartford, CT, 1993, $16.80/cu. meter ($22/cy). All the plants use the same basic specification, AWWA Standard for Filtering Material B100, except the Newark plant does not limit the acid solubility to less than 5 percent and uses a local "calcium sand" with more than 35 percent of the material acid soluble. The source of the AWWA limitation on acid solubility has not been researched although one early reference (Turneaure and Russell, 1924) stated "a sand containing a considerable amount of lime will increase the hardness of the water. It has also been found that the presence of aluminous and calcareous material increases very materially the resistance to the flow of water". This sand has presented no operating difficulties with the very hard raw water supply at the Newark plant.

The volumes of water drained from filters before cleaning depend upon the plant schedules. In the Gorham, Newark, and West Hartford plants, the inlet valve to the filter was closed the night before a filter is cleaned allowing the supernatant water to drain through the filter without being wasted. At the Newport, NH plant, however, the practice was to dump the entire supernatant volume to waste just before the cleaning which accounts for the large volume of raw water used. The practices adopted at a particular plant will depend on the staffing schedule and the value of the water, but a small volume will have to be wasted before a filter is scraped as the water drained from within the sand media.

Wash water production data showed Newport, NH used more water for cross-flow during harrowing than at any of the filters at the West Hartford plant. The rate of flow could be reduced but it was observed by the personnel that the suspended solids from wet harrowing would rapidly settle onto the filter surface after the tractor had passed. For this reason, it was not believed that the volume should be reduced. The cross-flow velocity in the Newport, NH filter was estimated at 0.91 meter/min (0.05 fps) and at 0.64 meter/min. (0.035 fps) in Filters 18 and 21 at West Hartford. The volumes of settleable solids and mass of suspended solids at the two different plants were similar even though the West Hartford filters had been in service longer since the sand had been washed.

Another significant factor determining the volume of water used in the cleaning cycle is the ripening period. The Newport, NH filter effluent displayed a noticeable improvement during the overnight period while filters were ripened before being returned to service. The Newark, NY filter operations in this study, as in the summer of 1983 (Letterman and Cullen, 1985), did not show the need to ripen the filters to produce filtered water having low turbidity and particle count, yet several other slow sand filter plants studied in the 1985 report did. The West Hartford filters in this study were not ripened before being returned to service but the filtered water, as was presented in Figure 16, showed total coliform bacteria were present in numbers that would ordinarily justify a period of ripening. The decision on whether to return a filter to service without a ripening period will have to be made on a plant-by-plant basis, using performance information collected after the filter is cleaned, and with consideration given for the duration of the time the filter has been out of service.

The time that filters monitored in this study were out of service for a cleaning event was found to be related as much to the scheduling requirements of the staff and whether the filter needed to ripen before being returned to service as it was to the cleaning method used. The very short time the Newark, NY filters were out of service was due to the efficiency of the scraping operation at this plant and the lack of a ripening period. The very long time the filters were out of service at West Hartford was for the convenience of scheduling separate crews for the two steps of harrowing, and the overnight period between them. At the time of the September 15, 1993 sampling, however, Filter 21 was wet and dry harrowed and returned to service in only about 12 hours which approached the time used at Newark. It has been previously reported that the shorter the time that the filters are out of service, the more quickly the bacteria will recover and the ripening period will be shortened (Huisman and Wood, 1974; Ellis, 1985; Bauer, 1994). For this reason cleaning operations should be scheduled so that the filters are returned to service as soon after being drained as possible.

Part of the sand is removed each time a filter is cleaned by scraping and eventually the thickness of the filter sand is reduced to an unacceptable level. The filter must then be taken out of service and resanded. The frequency depends on the amount of sand initially present, the amount removed per cleaning event, and the minimum thickness that is allowable. The Newark plant used an initial depth of 0.75 to 0.9 meters (30 to 36 in), removed about 2.5 cm (1 in) per cleaning, and resanded when the thickness is down to about 0.3 m (1 ft). Other factors were also considered when deciding to resand, such as scheduling, budget surpluses, and general filter performance which may lead to earlier resanding.

The history of the four filters at the Newark plant since 1986 was for filters to be resanded after an average of 5.8 years. The time out of service for resanding averaged 26 days, or 1.2 percent of the time, of which 9 days was spent resanding with 4 days for weekends and interruptions and an average of 11 days ripening the sand. The comparable information on the four most recent West Hartford filters reconditioned was for them to be reconditioned at about a twenty year interval, with the filters out of service for six months, or 2.5 percent of the time. Of that time, an average of 70 day was spent reconditioning with 30 days for weekends and interruptions and the balance of the time for ripening the sand. The actual time spent for the resanding or reconditioning was 1.8 days/100 sq. meters (1.7 day/1000 sf) at Newark and 3 days/100 sq. meters (2.8 days/1000 sf) at West Hartford. The ripening time at Newark averaged 11 days but about 2 months at West Hartford.

CHAPTER 6

CONCLUSIONS

This project focused on evaluating two slow sand filter cleaning methods, surface scraping and filter harrowing, for their impact on filter treatment performance and operational and maintenance requirements. The objective was to assess the effectiveness and limitations of each filter cleaning method with the goal of assisting small water systems to make an informed decision as to which cleaning method would be most advantageous to them. Several significant conclusions were made during the course of this investigation and are summarized as follow:

- Both surface scraping and filter harrowing were effective methods for cleaning slow sand filters. Each method has been utilized at separate locations in New York and New England with few complaints or concerns and with minimal disruptions to the filtration process.

- The choice of the most appropriate filter cleaning method depended on several factors but one that has been often overlooked is the capability and professionalism of the water utility personnel. The differences in organizational capability, adaptability, and overall knowledge of their own treatment process were significant between staff at the filtration facilities monitored. In many instances, whichever filter cleaning method is easiest to implement may be the most appropriate. Filters cleaned by either method can produce satisfactory quality drinking water.

- Assessment of filter cleaning methods involved evaluation of filter treatment performance, cleaning effectiveness and frequency, filter ripening requirements, and cleaning costs. Because of the diversity between the treatment facilities and the lack of full-scale side-by-side comparisons, no filter cleaning procedure emerged as clearly the most efficient based on the above criteria. In general, filter harrowing increased cleaning frequency but required fewer hours of labor per cleaning event. The actual filter downtime per cleaning event, based on procedural protocol rather than water quality data, was approximately the same for both methods.

- Some trends in the removal of NPDOC and UV absorbance suggested filter harrowing resulted in more efficient filter treatment performance but the conclusion must be tempered because the trend was not consistent and was dependent on other confounding factors , e.g. water source, temperature, sand age.

- Overall slow sand filter performance, on removal of turbidity, particles, NPDOC, and UV absorbance, was influenced by water temperature. Removal of NPDOC and UV absorbance was also influenced by sand media age, filter biomass content, source water quality, and filtration rate/empty bed contact time. Filter media size and sand filter depth were not evaluated individually in this study. In general, slow sand filter performance was enhanced with higher temperature, older sand media, higher filter biomass content, and source water with NOM conducive to adsorption/biodegradation. The influence of filtration rate depended on the biodegradability of the organic matter. Increasing hydraulic loading rate improved the kinetic removal of easily biodegradable organic compounds.

- Filter biomass was quantified by protein content (FRM), carbohydrate, bacterial counts, and volatile solids. Each of the testing methods had its advantages and disadvantages but the easiest and most consistent method was the volatile solids test followed by carbohydrates. None of these techniques could be correlated with bioactivity since bioactivity determinations were not directly performed in this study.

- Biomass distribution within a filter bed was dependent on filter cleaning method. Surface scraping resulted in the highest biomass located in the schmutzdecke/upper sand layers decreasing with depth below the filter surface. Filter harrowing resulted in a more heterogenous distribution of biomass throughout the filter bed with elevated accumulations just below the harrowed layers.

- The inorganic and biological composition of sand surface coatings varied with sand media age, filter bed depth, and cleaning method. Although confounding problems occurred, a direct relationship existed between inorganic accumulations, e.g.. iron and manganese, and the removal of NOM as measured by NPDOC and UV absorbance.

- Filters cleaned by the harrowing method will remain at or near full media depth until resanding is necessary. The depth of media in filters cleaned by scraping will be progressively reduced and resanding will be required earlier.

- The harrowing method of cleaning uses less labor and sand than the scraping method, but the water required during wet harrowing results in the use of more water and produces more wastewater. The use of water and production of wastewater if the filters are cleaned by scraping results only if the filters must be "ripened" after cleaning. The estimated total cost for labor, equipment, water, and replacement sand media is lower for filters cleaned with the harrowing method.

- In order to fully evaluate slow sand filter cleaning methods, the assessment period needs to encompass the handling of sand media from resanding operation to resanding operation, a period generally measured in 5 to 10 years increments. Filter cleaning methods may have a profound influence on resanding operations both in frequency of cleaning and in requirements for material handling.

CHAPTER 7

RECOMMENDATIONS

Several questions arose during the study which could not be resolved because critical facilities were not available or could not be used during the time the facilities were available. Other questions were suggested by this study.

7.1 COMPARATIVE STUDY OF THE TWO SLOW SAND FILTER CLEANING METHODS

The present study was unable to use the facilities at Gorham, NH for the full-scale comparisons of the scraping and harrowing methods. The filters at Gorham did not reach terminal headloss for cleaning until after it had been necessary to transfer the study to another plant. The Gorham filters operated for a total of 2.75 years before cleaning was required. The filters at the Newport plant ripened satisfactorily, yet the time remaining for the study did not allow for more than one cleaning operation with each method.

The high quality raw water supplies for which slow sand filtration is commonly used in upper New England resulted in prolonged a ripening period. Additionally, as reported during the evaluation periods at Newport and West Hartford, new or resanded filter may not be able to be harrowed when first used. During the initial cleaning operations, harrowing operations will have to be modified until the filter media will bear the weight of harrowing equipment. Finally, when the planned cleaning methods are used, they should be monitored over several seasons to separate the effects of temperature and seasonal water quality.

A full-scale comparison of the two cleaning methods should still be performed with side-by-side filters using the same sand source and with the same water source. Such a study should begin with a new plant and virgin sand, and operate over at least one resanding cycle (four or more years) for the filter cleaned with the scraping method and possibly over a resanding cycle for the filter cleaned with the harrowing method (ten to twenty years). A realistic budget will also be necessary to maintain the sampling, testing, and data analysis over the study period.

7.2 RIPENING

The initial ripening period for slow sand filters should be monitored to define the changes in both the chemical (organic and inorganic) and biological content of the sand coatings as a function of depth in the filter, filter run time, and treatment performance. The role of filter ripening and aging on the performance of the slow sand filters needs to be further defined. The need for re-ripening after a cleaning operation should also be further compared, side-by-side, for several cycles over a period of years to determine if either cleaning method may have an additional need to filter to waste before returning to service.

7.3 REMOVAL OF NATURAL ORGANIC MATTER (NOM)

The importance of filter biomass to performance has been shown previously yet biomass alone is not the reason for higher performance in the West Hartford filters. Emphasis should be given to developing a relationship between biomass and bioactivity, and distinguishing between surface removals of NOM and the removals occurring with depth in the media. Performance of the filter media in removing both particulate and dissolved NOM need to be considered.

7.4 INFLUENCE OF TEMPERATURE

Temperature is one of the most important parameters in performance of slow sand filters as measured by turbidity, particles, NPDOC, and UV absorbance. Earlier temperature studies have used the removal of turbidity, coliform, and Giardia cysts but there has been limited data on the removal of THM or surrogates relative to temperature and raw water characteristics. Information should be collected and used to estimate the relative seasonal effectiveness of the biofiltration process.

7.5 FILTER MEDIA SIZE

The rate of headloss development in filters which had been cleaned by harrowing was greater than for filters which were cleaned by scraping. The filter to be harrowed in the comparative study might use a larger size ($\geq$0.4 mm) or more uniform grain size to reduce headlosses and extend the length of filter runs.

More detailed studies are needed to relate the influence of media size on headloss development, before and after each cleaning method.

7.6 SAMPLING AND ANALYTICAL METHODS

Arrangements are needed to allow sampling to the full depth of the sand filter during filter operations so that draining is not necessary. The filters sampled during this study could have been grouped, roughly, into two types: "young" filters into which the sampler could be pressed by hand but the sand would not remain in the sampling tube while being withdrawn unless the filter had been drained to below the level of the sample, and "older" filters from which a sample could be taken but the tube could be driven to a depth of only about 30 cm (12 in). The Gorham and Newport filters were examples of the former, and the Newark and older West Hartford filters were of the latter type.

The plant selected for a comparative study should be located near the laboratory to allow frequent sample collection and analysis, improving the statistical significance of the removal performance data. The plant should also have instrumentation on the raw water supply to the filters, and on finished and wash water lines from each filter with flow indicators, recorders, and totalizers; permanent sampling connections should be installed on all raw, filtered, and wash water lines; and headloss indicators should be required on each filter. This instrumentation should be required on larger plants and would also be appropriate on all plants in order to monitor treatment performance, development of headlosses leading to the cleaning, and wash water discharges.

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APPENDIX A

SUMMARY OF EXPERIMENTAL DESIGN

A.1 GENERAL

This appendix summarizes the number of full-scale water treatment plants, laboratory-scale column tests, and pilot-plant tests. The summaries list the parameters analyzed and the individual process measurements at each scale of the investigation.

TABLE A.2: FULL SCALE WATER TREATMENT PLANTS.

Plant Location	Gorham, NH	Newport, NH	Newark, NY	West Hartford, CT
Filter cleaning method	Not cleaned over study period	Raking, scraping, harrowing	Scraping	Harrowing
Factors investigated	Performance, development of headloss with time, media ripening	Performance, media biomass, ripening after cleaning, costs of cleaning by raking, scraping, and harrowing	Performance, media biomass, ripening after cleaning, costs of cleaning by scraping	Performance, media biomass, ripening after cleaning, ripening after reconditioning, costs of cleaning by harrowing, costs of reconditioning
Process parameters monitored	Flow, headloss, temperature, pH, turbidity, NPDOC, BDOC, UV absorbance, total coliform	Flow, headloss, temperature, pH, turbidity, NPDOC, BDOC, UV absorbance, total coliform	Flow, headloss, temperature, pH, turbidity, NPDOC, BDOC, UV absorbance, total coliform	Flow, headloss, temperature, pH, turbidity, NPDOC, BDOC, UV absorbance, total coliform
Additional parameters monitored	Dissolved oxygen, color, fecal coliform	Particle counts	Particle counts	Particle counts
Parameters monitored on occasion	Dissolved oxygen, alkalinity, hardness	Iron, manganese, nitrate, phosphorus	Iron, manganese, nitrate, phosphorus	Iron, manganese, nitrate, phosphorus, ammonia
Media parameters monitored	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum
Cleaning waste parameters monitored	None	Flow, turbidity, settleable and suspended solids, UV absorbance, iron,manganese costs	Volume, costs	Flow, turbidity, settleable solids, total and volatile suspended solids, UV absorbance, iron, manganese, costs
Ripening period parameters monitored	None	Time, flow, turbidity, particle counts, total coliform, UV absorbance	Time, turbidity, particle counts	Time, flow, turbidity, particle counts, total coliform, UV absorbance, NPDOC

TABLE A.2: PILOT SCALE TESTS.

Filter column	No. 1	No. 2	No. 3
Filter cleaning method	Scraping	Harrowing to 5 cm	Harrowing to 15 cm
Factors investigated	Performance, development of headloss with time, media changes, ripening after cleaning	Performance, development of headloss with time, media changes, ripening after cleaning	Performance, development of headloss with time, media changes, ripening after cleaning
Process parameters monitored	Flow, headloss, temperature, turbidity, pH, dissolved oxygen, color, total coliform, NPDOC, UV absorbance	Flow, headloss, temperature, turbidity, pH, dissolved oxygen, color, total coliform, NPDOC, UV absorbance	Flow, headloss, temperature, turbidity, pH, dissolved oxygen, color, total coliform, NPDOC, UV absorbance
Parameters monitored on occasion	BDOC, raw water iron and manganese	BDOC, raw water iron and manganese	BDOC, raw water iron and manganese
Media parameters monitored	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum
Ripening period parameters monitored, 1 event	Flow, headloss, temperature, turbidity, particle counts, pH, dissolved oxygen, color, NPDOC, UV absorbance	Flow, headloss, temperature, turbidity, particle counts, pH, dissolved oxygen, color, NPDOC, UV absorbance	Flow, headloss, temperature, turbidity, particle counts, pH, dissolved oxygen, color, NPDOC, UV absorbance

TABLE A.3: LABORATORY SCALE COLUMN TESTS.

Column test	Series 1	Series 2	Series 3	Series 4
Factors investigated	Influence of sand media age and depth on removal of organic carbon from different water sources	Influence of sand media from different plants on removal of organic carbon from different water sources	Influence of proportion of natural media coating on removal of organic carbon from different water sources	Influence of EBCT and filter rate on removal of organic carbon from different water sources
Common experimental conditions	Temperature, application rate, water sources	Temperature, application rate	Temperature, application rate, water sources	Temperature, water sources
Process parameters monitored	TOC, UV absorbance	TOC, UV absorbance	TOC, UV absorbance	Flow, TOC, UV absorbance
Media parameters monitored	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum	Grain size, total and volatile solids, FRM, carbohydrates, AFDC, iron, manganese, calcium, aluminum

APPENDIX B

QUALITY ASSURANCE AND QUALITY CONTROL

B.1 METHOD DETECTION LIMITS

Data was reduced with standard statistical methods (Collins et all, 1992b). Method detection limits (MDL) were estimated for analytical procedures based on methods presented in Standard Methods (APHA, 1989). Blanks were used in all procedures except pH, alkalinity, temperature, and dissolved oxygen, to detect contamination from reagent, labware, and instrumental drift. Duplicate, triplicate, and standards were used as previously summarized in Table 19. The results for MDL, calculated at three times the standard deviation of analysis of seven blank samples, are summarized below in Table B1.

TABLE B1: METHOD DETECTION LIMITS.

Parameter	Method detection limit
Turbidity, NTU	0.09
Particles, 1-20 um, number per mL	77
NPDOC or TOC, mg/L	0.18
BDOC, mg/L	0.18
UV absorbance @ 254 um, cm^{-1}	0.0015
Total solids, percent	0.09
Volatile solids, percent	0.06
Folin reactive material, mg/gdw	0.18
Carbohydrates, mg/gdw	0.007

B2: SEPARATION OF VARIANCES IN EXPERIMENTAL DATA

The variance in various experimental analyses was analyzed. These analyses determined the relative significance of the analytical results between replicated analytical tests, between multiple samples (such as the three cores taken in each filter, or the separate filter depths in each core), and between filters. For example, if the variance between replicates exceeded that between samples or filters, then differences between samples would not likely be significant. The nested analyses of variance are presented for the data for the Newark, NY plant in the attached spreadsheet.

DISSERTATION		SEPARATION OF VARIANCES								
GENERAL FORMAT		3/3/96	Dowdy & Wearden (1991), p373.							
		Parameter, source, reference in lab book:								
		Total Solids, Newark 8/17/93, Top 1/2"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1		86.93	87.03							
		84.87	86.61							
Ti 1.		171.8	173.64	0	0	0	0			
Core # 2		86.06	85.52							
		86.53	85.16							
Ti 2.		172.59	170.68	0	0	0	0			
Core # 3		89.49	81.91							
		89.37	81.91							
Ti 3.		178.86	163.82	0	0	0	0			
Ti..		523.25	508.14	0	0	0	0	1031.39	= Total	
		273790.6	258206.3	0	0	0	0	531996.8	= Ti2	
		91293.45	86119.5	0	0	0	0	177413	Tij2	
SSy2ijk		45648.96	43059.91	0	0	0	0	88708.87		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		88708.87		B = SSTik2/n =		88706.48			
	A = STi2/bn =		88666.14		CF = T2/abn =		88647.11			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	19.02601	MSa = SSa/(a-1)		19.02601	MSa/MSb	1.88661
Among cores		a(b-1)	4	SSb = B-A	40.33903	MSb = SSb(a(b-1)		10.08476	MSb/MSe	25.29146
Among replicates		ab(n-1)	6	SSe = T-B	2.39245	MSe = SSe/ab(n-1)		0.398742		
		Parameter, source, reference in lab book:								
		Total Solids, Newark 8/17/93, 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1		92.11	92.06							
		91.78	91.76							
Ti 1.		183.89	183.82	0	0	0	0			
Core # 2		90.99	90.95							
		91.25	91.02							
Ti 2.		182.24	181.97	0	0	0	0			
Core # 3		89.9	90.51							
		90.28	89.92							
Ti 3.		180.18	180.43	0	0	0	0			
Ti..		546.31	546.22	0	0	0	0	1092.53	= Total	
		298454.6	298356.3	0	0	0	0	596810.9	= Ti2	
		99491.78	99457.86	0	0	0	0	198949.6	Tij2	
SSy2ijk		49746.05	49729.15	0	0	0	0	99475.2		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		99475.2		B = SSTik2/n =		99474.82			
	A = STi2/bn =		99468.48		CF = T2/abn =		99468.48			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.000675	MSa = SSa/(a-1)		0.000675	MSa/MSb	0.000426
Among cores		a(b-1)	4	SSb = B-A	6.336067	MSb = SSb(a(b-1)		1.584017	MSb/MSe	24.8831
Among replicates		ab(n-1)	6	SSe = T-B	0.38195	MSe = SSe/ab(n-1)		0.063658		
		Parameter, source, reference in lab book:								
		Volatile Solids, Newark 8/17/93, Top 1/2"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1		1.08	1.09							
		1.16	1.1							
Ti 1.		2.24	2.19	0	0	0	0			
Core # 2		1.23	1.21							
		1.18	1.35							
Ti 2.		2.41	2.56	0	0	0	0			
Core # 3		0.79	1.26							
		0.77	1.36							

Ti 3.		1.56	2.62	0	0	0	0			
Ti..		6.21	7.37	0	0	0	0	13.58	= Total	
		38.5641	54.3169	0	0	0	0	92.881	= Ti2	
		13.2593	18.2141	0	0	0	0	31.4734	Tij2	
SSy2ijk		6.6343	9.1219	0	0	0	0	15.7562		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		15.7562		B = SSTik2/n =		15.7367			
	A = STi2/bn =		15.48017		CF = T2/abn =		15.36803			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.112133	MSa = SSa/(a-1)		0.112133	MSa/MSb	1.748441
Among cores		a(b-1)	4	SSb = B-A	0.256533	MSb = SSb(a(b-1)		0.064133	MSb/MSe	19.73333
Among replicates		ab(n-1)	6	SSe = T-B	0.0195	MSe = SSe/ab(n-1)		0.00325		
		Parameter, source, reference in lab book:								
		Volatile Solids, Newark 8/17/93, 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1		0.85	0.68							
		0.97	0.76							
Ti 1.		1.82	1.44	0	0	0	0			
Core # 2		0.96	0.97							
		0.92	1							
Ti 2.		1.88	1.97	0	0	0	0			
Core # 3		0.71	0.83							
		0.7	0.79							
Ti 3.		1.41	1.62	0	0	0	0			
Ti..		5.11	5.03	0	0	0	0	10.14	= Total	
		26.1121	25.3009	0	0	0	0	51.413	= Ti2	
		8.8349	8.5789	0	0	0	0	17.4138	Tij2	
SSy2ijk		4.4255	4.2939	0	0	0	0	8.7194		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		8.7194		B = SSTik2/n =		8.7069			
	A = STi2/bn =		8.568833		CF = T2/abn =		8.5683			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.000533	MSa = SSa/(a-1)		0.000533	MSa/MSb	0.015451
Among cores		a(b-1)	4	SSb = B-A	0.138067	MSb = SSb(a(b-1)		0.034517	MSb/MSe	16.568
Among replicates		ab(n-1)	6	SSe = T-B	0.0125	MSe = SSe/ab(n-1)		0.002083		
		FRM, Newark 8/17/93, Top 1/2"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1		1.88	1.8							
		2.51	2.08							
Ti 1.		4.39	3.88	0	0	0	0			
Core # 2		0.603	1.66							
		0.98	1.71							
Ti 2.		1.583	3.37	0	0	0	0			
Core # 3		0.185	2.08							
		1.17	2							
Ti 3.		1.355	4.08	0	0	0	0			
Ti..		7.328	11.33	0	0	0	0	18.658	= Total	
		53.69958	128.3689	0	0	0	0	182.0685	= Ti2	
		23.61401	43.0577	0	0	0	0	66.67171	Tij2	
SSy2ijk		12.56163	21.5725	0	0	0	0	34.13413		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		34.13413		B = SSTik2/n =		33.33586			
	A = STi2/bn =		30.34475		CF = T2/abn =		29.01008			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	1.334667	MSa = SSa/(a-1)		1.334667	MSa/MSb	1.784845
Among cores		a(b-1)	4	SSb = B-A	2.99111	MSb = SSb(a(b-1)		0.747777	MSb/MSe	5.620436
Among replicates		ab(n-1)	6	SSe = T-B	0.798277	MSe = SSe/ab(n-1)		0.133046		

		Parameter, source, reference in lab book:								
		FRM, Newark 8/17/93, 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1	•••••••••	0.38	0.179							
		0.38	0.382							
Ti 1.		0.76	0.561	0	0	0	0			
Core # 2		0.332	0.731							
		0.403	0.322							
Ti 2.		0.735	1.053	0	0	0	0			
Core # 3		0.328	0.392							
		0.394	0.653							
Ti 3.		0.722	1.045	0	0	0	0			
Ti..		2.217	2.659	0	0	0	0	4.876	= Total	
		4.915089	7.070281	0	0	0	0	11.98537	= Ti2	
		1.639109	2.515555	0	0	0	0	4.154664	Tij2	
SSy2ijk		0.824253	1.396083	0	0	0	0	2.220336		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		2.220336		B = SSTik2/n =		2.077332			
	A = STi2/bn =		1.997562		CF = T2/abn =		1.981281			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.01628	MSa = SSa/(a-1)		0.01628	MSa/MSb	0.81636
Among cores		a(b-1)	4	SSb = B-A	0.07977	MSb = SSb(a(b-1)		0.019943	MSb/MSe	0.836728
Among replicates		ab(n-1)	6	SSe = T-B	0.143004	MSe = SSe/ab(n-1)		0.023834		
		Carbohydrates, Newark 8/17/93, Top 1/2"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1		0.3118	0.3025							
		0.2626	0.3265							
Ti 1.		0.5744	0.629	0	0	0	0			
Core # 2		0.2946	0.3314							
		0.3029	0.34							
Ti 2.		0.5975	0.6714	0	0	0	0			
Core # 3		0.3306	0.3211							
		0.3082	0.3322							
Ti 3.		0.6388	0.6533	0	0	0	0			
Ti..		1.8107	1.9537	0	0	0	0	3.7644	= Total	
		3.278634	3.816944	0	0	0	0	7.095578	= Ti2	
		1.095007	1.27322	0	0	0	0	2.368227	Tij2	
SSy2ijk		0.548999	0.636997	0	0	0	0	1.185996		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		1.185996		B = SSTik2/n =		1.184113			
	A = STi2/bn =		1.182596		CF = T2/abn =		1.180892			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.001704	MSa = SSa/(a-1)		0.001704	MSa/MSb	4.493041
Among cores		a(b-1)	4	SSb = B-A	0.001517	MSb = SSb(a(b-1)		0.000379	MSb/MSe	1.209007
Among replicates		ab(n-1)	6	SSe = T-B	0.001882	MSe = SSe/ab(n-1)		0.000314		
		Parameter, source, reference in lab book:								
		Carbohydrates, Newark 8/17/93, 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Core # 1		0.3731	0.3293							
		0.3261	0.3157							
Ti 1.		0.6992	0.645	0	0	0	0			
Core # 2		0.3141	0.301							
		0.324	0.3244							
Ti 2.		0.6381	0.6254	0	0	0	0			
Core # 3		0.3323	0.3016							
		0.3526	0.3018							
Ti 3.		0.6849	0.6034	0	0	0	0			

Ti..		2.0222	1.8738	0	0	0	0	3.896	= Total	
		4.089293	3.511126	0	0	0	0	7.600419	= Ti2	
		1.36514	1.171242	0	0	0	0	2.536382	Tij2	
SSy2ijk		0.68393	0.585987	0	0	0	0	1.269917		
	a =	2	b =	3	n =	2				
	T = SSSyijk2 =		1.269917		B = SSTik2/n =		1.268191			
	A = STi2/bn =		1.266737		CF = T2/abn =		1.264901			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.001835	MSa = SSa/(a-1)		0.001835	MSa/MSb	5.047191
Among cores		a(b-1)	4	SSb = B-A	0.001454	MSb = SSb(a(b-1)		0.000364	MSb/MSe	1.264125
Among replicates		ab(n-1)	6	SSe = T-B	0.001726	MSe = SSe/ab(n-1)		0.000288		
		Iron, Newark Filter 3, 8/17/93 & Filter 4, 10/26/93 Top 1/2" & 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Top 1/2"		9.83	11.4							
		8.37	10.6							
Ti 1.		18.2	22	0	0	0	0			
10-12"		8.76	9.27							
		10.1	9.15							
Ti 2.		18.86	18.42	0	0	0	0			
Core # 3										
Ti 3.		0	0	0	0	0	0			
Ti..		37.06	40.42	0	0	0	0	77.48	= Total	
		1373.444	1633.776	0	0	0	0	3007.22	= Ti2	
		686.9396	823.2964	0	0	0	0	1510.236	Tij2	
SSy2ijk		345.4334	411.9754	0	0	0	0	757.4088		
	a =	2	b =	2	n =	2				
	T = SSSyijk2 =		757.4088		B = SSTik2/n =		755.118			
	A = STi2/bn =		751.805		CF = T2/abn =		750.3938			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	1.4112	MSa = SSa/(a-1)		1.4112	MSa/MSb	0.851917
Between levels		a(b-1)	2	SSb = B-A	3.313	MSb = SSb(a(b-1)		1.6565	MSb/MSe	2.892439
Among replicates		ab(n-1)	4	SSe = T-B	2.2908	MSe = SSe/ab(n-1)		0.5727		
		Manganese, Newark Filter 3, 8/17/93 & Filter 4, 10/26/93 Top 1/2" & 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Top 1/2"		0.505	0.693							
		0.468	0.554							
Ti 1.		0.973	1.247	0	0	0	0			
10-12"		0.469	0.447							
		0.597	0.403							
Ti 2.		1.066	0.85	0	0	0	0			
Core # 3										
Ti 3.		0	0	0	0	0	0			
Ti..		2.039	2.097	0	0	0	0	4.136	= Total	
		4.157521	4.397409	0	0	0	0	8.55493	= Ti2	
		2.083085	2.277509	0	0	0	0	4.360594	Tij2	
SSy2ijk		1.050419	1.149383	0	0	0	0	2.199802		
	a =	2	b =	2	n =	2				
	T = SSSyijk2 =		2.199802		B = SSTik2/n =		2.180297			
	A = STi2/bn =		2.138733		CF = T2/abn =		2.138312			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.000421	MSa = SSa/(a-1)		0.000421	MSa/MSb	0.020234
Between levels		a(b-1)	2	SSb = B-A	0.041564	MSb = SSb(a(b-1)		0.020782	MSb/MSe	4.261933
Among replicates		ab(n-1)	4	SSe = T-B	0.019505	MSe = SSe/ab(n-1)		0.004876		

		Calcium, Newark Filter 3, 8/17/93 & Filter 4, 10/26/93 Top 1/2" & 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Top 1/2"		96.1	88							
		99.4	96.4							
Ti 1.		195.5	184.4	0	0	0	0			
10-12"		114	99.6							
		103	93.1							
Ti 2.		217	192.7	0	0	0	0			
Core # 3										
Ti 3.		0	0	0	0	0	0			
Ti..		412.5	377.1	0	0	0	0	789.6		
		170156.3	142204.4	0	0	0	0	312360.7		
		85309.25	71136.65	0	0	0	0	156445.9		
SSy2ijk		42720.57	35624.73	0	0	0	0	78345.3		
	a =	2	b =	2	n =	2				
	T = SSSyijk2 =		78345.3		B = SSTik2/n =		78222.95			
	A = STi2/bn =		78090.17		CF = T2/abn =		77933.52			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	156.645	MSa = SSa/(a-1)		156.645	MSa/MSb	2.359378
Between levels		a(b-1)	2	SSb = B-A	132.785	MSb = SSb(a(b-1)		66.3925	MSb/MSe	2.170576
Among replicates		ab(n-1)	4	SSe = T-B	122.35	MSe = SSe/ab(n-1)		30.5875		
		Aluminum, Newark Filter 3, 8/17/93 & Filter 4, 10/26/93 Top 1/2" & 10-12"								
		Filter 3	Filter 4	Filter	Filter	Filter	Filter	Total		
Top 1/2"		4.72	5.04							
		4.24	5.18							
Ti 1.		8.96	10.22	0	0	0	0			
10-12"		4.01	4.02							
		4.26	3.92							
Ti 2.		8.27	7.94	0	0	0	0			
Core # 3										
Ti 3.		0	0	0	0	0	0			
Ti..		17.23	18.16	0	0	0	0	35.39		
		296.8729	329.7856	0	0	0	0	626.6585		
		148.6745	167.492	0	0	0	0	316.1665		
SSy2ijk		74.4837	83.7608	0	0	0	0	158.2445		
	a =	2	b =	2	n =	2				
	T = SSSyijk2 =		158.2445		B = SSTik2/n =		158.0833			
	A = STi2/bn =		156.6646		CF = T2/abn =		156.5565			
Source		df		SS		MS			F	
Between filters		a-1	1	SSa = A-CF	0.108112	MSa = SSa/(a-1)		0.108112	MSa/MSb	0.152119
Between levels		a(b-1)	2	SSb = B-A	1.418625	MSb = SSb(a(b-1)		0.709313	MSb/MSe	17.59535
Among replicates		ab(n-1)	4	SSe = T-B	0.16125	MSe = SSe/ab(n-1)		0.040312		

APPENDIX C

SAMPLE CALCULATIONS

C.1 FIRST ORDER REACTION COEFFICIENTS IN TABLE 102.

This sample calculation is based on the data for the Newark, NY plant. The calculations for the other filters was similar, but used the data for the other filters.

Loading rate: Filter area = 42m x 12m (from field measurement)
Mean flow at time of sampling for NPDOC and UV absorbance = 0.445 mgd
(from plant records for each filter, each day)
Loading rate = Flow/Area
= (0.445 MGD x 3785 cubic metes/MD)/(504 sm x 24 hr/d)
= 0.14 m/hr

Detention time: Detention time = Filter depth/Loading rate
= 0.75 m/0.14 m/hr
= 5.4 hr

Temperature: Temperature on date filter media sampled.

Estimated NPDOC (or UVA) removal at 15°C:
Reference temperature adopted for comparison of data = 15°C.
Estimated removal, based on data in Table 90.
= e^(2.22+0.51x15) = 19.8 percent

Reaction coefficient:
Based on equation (9), = (ln Percent Removal)/Detention Time
= (ln 19.8)/5.4
= 0.554

Reaction coefficient per unit of ....:

Volatile solids-Mass of volatile solids in one square meter of filter area is estimated as:

(Mean of concentration in upper 1.2 cm {1.13 %}
and concentration between 25-30 cm {0.84%}) x .30 m =.2955
(Mean of concentration between 25-30 cm) x depth of filter below .30 m (0.45 m) =.3780
Sum = .6735
Sum/0.75 = mean concentration. in one square meter of filter area = 0.898
Mass of volatile solids in one square meter of filter area
= Mean concentration. x Filter depth x Filter mass
= 0.898 x 0.75 m x 2083 kg/cubic meter sand (Terzaghi and Peck,1948)
= 14.03 kg
Reaction coeff. per unit mass of volatile solids = Reaction coeff./Mass of volatile solids
= 0.554/14.03 = 0.0395

FRM, Carbohydrates- Similar calculations, based on mg/Kg dry weight instead of percent.
AFDC- Similar calculations, based on 10^6 AFDC/Kg dry weight.