Geotextiles as Biofilm Attachment Baffles for Wastewater Treatment

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Eyüp Nafiz Korkut
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To my father, Halit Korkut
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A bench scale pilot plant study was undertaken using geotextile baffles as biofilm attachment media for wastewater treatment. The herein named Geotextile Baffle Contact System (GBCS) removed suspended solids and hosted growth of microorganisms to absorb and decompose carbonaceous and nitrogenous pollutants. The test liquid was one sample of screened plant influent and twelve samplings of effluent from primary treatment at a Philadelphia Water Department (PWD) wastewater treatment plant that treats combined sanitary and storm sewage. The main goal was to meet secondary treatment standards, i.e., low concentrations of total suspended solids and biochemical oxygen demand in the effluent. The once-through hydraulic loading rate was similar to that used in conventional low rate trickling filters 20 gal/day-sq.ft. A second goal was reducing ammonia and nitrate to receiving water standards. It was also desired to digest excess sludge within the system.

Twenty gallon glass tanks were used as reactors for the bench scale pilot plant experiments. Geotextile coupons were hung as baffles transverse to the flow in a sinuous pattern to increase path length and contact area, using elements from lamella settlers, granular depth filters and trickling filters. The first phase screened candidate geotextiles with respect to biomass attraction by immersion in wastewater. Only nonwoven needle punched geotextiles were found to host a substantial biomass. A second phase was investigating biodegradation efficiency under continuous aerated flow through the GBCS tanks with a nonwoven needle punched geotextile. Over 90% TSS and BOD₅ removal occurred quickly, and over 90% conversion of NH₃ to NO₃ was detected after the third week. Denitrification increased steadily, producing effluent concentrations below 8 mg/l
after five weeks, corresponding to the increasing biofilm thickness. The third phase used nonwoven staple fiber baffles. There was a similar performance in removing and biodegrading suspended, colloidal and dissolved organic materials.

A parallel study of biomass distribution with photographs, dry solids retention, and scanning electron microscopy showed that TSS removal was a combination of sedimentation, filtration and baffle surface sorption. It was concluded that the high ratio of surface area to reactor volume supported efficient substrate and oxygen transfer.
Chapter 1. Introduction, Background and Summary of Results

1.1 Scope and Rationale

This study used geotextiles as the attachment media for microorganisms to remove biodegradable constituents from water pollution sources, resulting in development of the herein designated Geotextile Baffle Contact System (GBCS). The intent is a sustainable process that produces an effluent quality suitable for stream discharge. The test liquid used was twelve samplings or runs of primary treatment effluent from the Philadelphia Water Department (PWD) Southeast Water Pollution Control Facility (SEWPCF). This facility serves an area with combined (sanitary and storm) sewers, such that the plant influent varied with weather conditions. Primary clarifiers remove most settleable and suspended solids but not the colloidal or dissolved organic constituents. In these experiments, this organic substrate (colloidal and suspended part) was degraded in continuous once-through horizontal flow through a sinuous channel formed by closely spaced geotextile baffles, as shown on Figures 1.1a and 1.1b. The bench scale pilot plant not only satisfied secondary treatment (carbonaceous materials) standards, but also accomplished advanced treatment, mineralizing nitrogenous constituents. Most sludge captured or produced in the biochemical reactions was also aerobically decomposed within the reactor vessel.

This work is a combination of sanitary engineering and geosynthetics. Geotextiles are thin, durable porous polymeric products used in subsurface construction in primary functions of filters, drains, separators and reinforcement elements. To the author’s knowledge, their use in wastewater treatment has not been studied, although plastic media have been used in trickling filters and lamella settlers. The impetus for this present dissertation was a study of biological clogging of landfill leachate filters by George Koerner (1993). The biomass was sustained by
extracting substrate from leachate, which implied improvement in its quality. The degree of clogging stabilized in some types of geotextiles, representing a sustainable distribution of pore space between channels and biomass. The premise of the present study is that this behavior can be managed to provide treatment of dilute liquids by separating hydraulic and treatment functions and thus avoiding the clogging issue.

Figure 1.1a: Plan View of Geotextile Baffle Contact System (GBCS)

Figure 1.1b: Cross Section of Geotextile Baffle Contact System (GBCS)
Questions addressed in this dissertation include:

- Which types of geotextiles attract microorganisms and support their growth?
- What degree of Total Suspended Solids (TSS) removal can be obtained?
- What degree of conventional (carbonaceous) treatment can be obtained?
- What types of advanced treatment (nitrogenous) can be done?
- How can the volume of waste sludge be minimized?

1.2 Summary Description of Process

The first question was answered with batch tests for screening candidate geotextiles. As described in Chapter 4, the result was that only nonwoven needle punched geotextiles with interior porosity captured microorganisms from the influent and hosted their growth to a continuous treating biomass. The GBCS process has six stages:

- Colonizing from influent TSS microorganisms by filtration, sorption and settlement
- Growth of treating biomass from within the geotextile out to the baffle surfaces
- Sorption of dissolved substrate by the biofilm
- Aerobic biodegradation of organic material and conversion of ammonia to nitrate
- Partial denitrification in the anaerobic interior biomass
- Aerobic decomposition of sediment and excess biomass sloughing off the baffles

The baffles are inoculated by filtering TSS from influent short-circuiting between channels through the porous baffles. This allows colonization by the microorganisms attached to the organic particles. As biomass growth reduces baffle permeability, influent is deflected through the channels, tangential to the baffle surfaces, similar to attached growth trickling filters. The long, narrow channel and its quiescent conditions foster sedimentation of the finer
particles not removed in primary treatment, similar to lamella settlers. The TSS filtration process continues baffle-by-baffle (Fig 1.1a and 1.1b) until the sorption and sedimentation has progressed along the channels to a steady state that has removed the delivered suspended material. The high ratio of baffle surface area to reactor volume provides opportunity for substrate sorption on a large treating biomass. A low food/mass (F/M) ratio maintains the biomass in the endogenous (near starved) condition that limits sludge production. Finally, when denitrifying bacteria have matured in a thick biofilm with an anaerobic interior, the full sequence of biochemical reactions to mineralize the sorbed substrate can occur in place. This continuous process is analogous to the same processes occurring in the same tank in a series of stages in a sequential batch reactor (SBR). The biofilm thickness and mass per unit area of baffle surface is limited only by the properties of the porous fabric and the capability of the slime layer to adhere to the surface of the baffles and thus directly contact the aerated flow through the channels.

1.3 Measures of Success

The function of the geotextile leachate filter that inspired this project was to protect the downstream drainage system in a landfill leachate collection system from clogging, while the goal in conventional use of geotextiles as soil filters is to retain particles in place while allowing passage of water from one medium to another. In an initial study of using geotextiles for biological treatment to improve water quality to allow effluent discharge, this work involves “proof-of-concept”. However, to have engineering value, results must be related to the performance standards required for effluent quality as written in discharge permits for conventional biological wastewater treatment. Hence, two goals are relevant:
1. Most discharge permits use a secondary treatment standard. There are two lumped indicators used to characterize wastewater: Total Suspended Solids (TSS) and 5-day Biochemical Oxygen Demand (BOD$_5$). Either at least 85% reduction in TSS and BOD$_5$ from the influent values, or effluent with less than 30 mg/l for each parameter is generally required (Federal Register, 1988).

2. Some permits limit discharge of nitrogenous compounds. The maximum effluent concentrations often applied are 2 mg/l for ammonia (NH$_4$) and 10 mg/l for nitrate (NO$_3$).

Secondary treatment appears feasible, as it is dominated by degradation of carbonaceous materials. The issues are the amount of baffle surface area and oxygen supply required to treat a given organic loading rate. Nitrogen transformation processes occur at later stages in a sequence of biochemical reactions, but all applications do not require such advanced treatment, so in some cases, this could be sacrificed for higher hydraulic loading rates.

1.4 Outline of Dissertation

As noted above, this dissertation is a combination of sanitary engineering and geosynthetics. Thus, it is necessary to document how this work borrows from, and fits into each discipline. To set the stage, the balance of Chapter 1 is a series of summaries on the literature of geotextile biological clogging, features of suspended and attached growth methods, and documentation of the test liquid effluent. Following this is a presentation summary of the results in terms of both the effluent quality obtained and a study of interaction between the geotextile structure and the biomass to explain why the observed results occurred quickly and efficiently. The last part of Chapter 1 includes the discussion of applications to problems other than the central one, wastewater treatment.
Chapter 2 is a more detailed description of geotextile filters, and the general classes of filters. Chapter 3 describes receiving water impacts, and then summarizes the principles and practices of biological wastewater treatment. The intent is not only to demonstrate how the GBCS relates to conventional wastewater theory, but also how the pilot plant design adapted several specific techniques of wastewater treatment.

The complete experimental program is described in Chapters 4 and 5. Chapter 4 presents the experimental design rationale, describes the apparatus and procedures, and presents the results of Phase I screening of candidate geotextiles. Chapter 5 expands on the summary results presented in Chapter 1 for the two phases of “production” experiments, Phase II and Phase III. Chapter 6 presents the conceptual design of a prototype scale-up study proposed to refine the bench scale test results to useable design parameters and future research. Chapter 7 includes an example design for wastewater treatment in a small community, and Chapter 8 presents a summary and conclusions from the total efforts.

1.5 Literature Review: Geotextile Clogging

Geotextiles are manufactured from polypropylene (PP) or polyester (PET) resin in a variety of fabrications:
- woven monofilament
- woven multifilament
- woven slit-film monofilament
- woven slit-film multifilament
- nonwovens continue filament heat-bonded,
- nonwoven continues filament needle-punched
- nonwoven staple needle-punched,
- nonwoven resin-bonded,
- other woven and nonwoven combinations

They serve separation, reinforcement, filtration, drainage and containment functions in infrastructure projects (Koerner, R.M., 1994). Designing with geosynthetics involves determining the product characteristics required for the function. In addition to having measurable hydraulic and mechanical properties that are used in analytical expressions, available products have internal structures and surface textures that have been empirically correlated with behavior in service for particular conditions.

Soil filter design illustrates the sequence of analysis and product specification, and also the starting point for this research. The practice of using geotextiles in place of soil filters developed in the 1970’s and 1980’s. Soil filters are a separation layer to protect the physical integrity of the soil mass being drained (upstream) and the hydraulic integrity of the drain removing water from the area (downstream). The intent is to maintain adequate seepage from the soil mass while preventing particle mobilization from within it. Unlike conventional filters that eventually clog and are replaced, a geotextile filter must not only remain permeable, but must keep particles in their original location. This filter retention criterion is satisfied first by selecting an appropriate apparent opening size (AOS) based on the soil gradation. The hydraulic function is then satisfied by selecting a filter with a permeability or permittivity providing the required hydraulic capacity.

Migration of particles into the filter represents failure in both criteria, as both substantial soil particle movement and water pressure buildup destabilize the soil mass. Marks (1975) showed that the clogging of nonwoven geotextiles depends on fiber density, and Gourc (1990) showed that clogging will occur when the geotextile void and the soil particle sizes are
similar. Clogging can also result from deposition and/or growth of organic material. Hoogerdendorn and Van der Meulen (1977) showed that algae and organic matter in natural waters can clog geotextiles. The issue of biological clogging came to the fore in adapting the practice of geotextile filter design to protect the drains in leachate collection systems in the 1980's. Leachate has a high concentration of inorganics and organics, as fine slurry and solutes (Williams; 1989; Legge 1990 and Sansone, 1991). BOD$_5$ concentrations have been detected up to 20,000 mg/L (Lu et al., 1985). There is a well founded concern for solids, chemical precipitation, and biological clogging. Canelli and Cazzuffi (1987) and Gribb (1988) studied the decrease in permeability from deposition of suspended solids. It was also evident that the geotextile filters also attracted microbial growth. Lu et al., 1985 found that bacteria in leachate grow within the fibers. Koerner and Koerner (1990) detected up to 75% or 100 % loss in filter permeability due to clogging from biological growth. Mlynarek et al. (1990) developed a method to identify biomass within a geotextile filter by microscopic examination.

As noted above, G.R. Koerner (1993) systematically investigated clogging of geotextile landfill filter clogging using several leachate sources, geotextile types, and test conditions. Leachate was permeated through columns packed with alternating layers of gravel, geotextile, and sand. It was concluded that:

- Geotextiles can excessively clog even over a brief period of permeation with leachate
- Filter porosity, pore size and thickness each affect performance
- Both flow rate and leachate strength (sum of the mass loading rate) affect clogging
- Heatbonded NW geotextiles had the lowest residual permittivity, needle punched NWs had the highest, and wovens were intermediate
- Leachate recirculation aggravates clogging
The question of whether geotextiles attract microorganisms was implicitly resolved by Corcoran and Bhatia (1996). In 1993, they exhumed samples of one of the first geotextiles used as leachate collection system filters, installed in 1988 at the Fresh Kills landfill in New York City. The NW geotextiles protected aggregate drains in trenches excavated in a fine-grained subgrade. Only on the top did the geotextile filter material directly contact the liquid waste. On the other three sides, the geotextiles were conventional filters, retaining the fine-grained soil in place while allowing inflow of the limited flow of leachate that was filtered in seepage through the subgrade. Hence, most contact between the filter and leachate was tangential rather than transverse, i.e., along the drain path where the geotextile was effectively the boundary of the subsurface channel. Even so, bacteria grew within the fibers of the nonwoven geotextile and formed a biofilm that decreased sidewall permittivity.

These findings must be put into perspective by using the geosynthetic practice of “designing-by-function”. The emphasis on solids retention in draining soil masses is less important in landfill drainage. There, the criterion is to allow passage only of material that will stay in solution or suspension to prevent drain clogging. Mobilizing fine particles from a waste deposit is not a problem in itself. Settlement prior to capping is desirable, and leachate recirculation systems rely on conveying suspended and dissolved solids as described further below. Finally, leachate quantities are low, generated from direct rain infiltration only, rather than regional flow. The hydraulic capacity required of a leachate filter (gal/ft$^2$/yr) is generally lower than of soil filters (gal/ft$^2$/day). Hence, there is more tolerance for partial clogging in landfill filters. Koerner (1993) showed that even with a loss of several orders of magnitude in permeability due to biological clogging, if it reached a steady state, as observed with some fabrications, many geosynthetic filters could still function as needed. The final, but not the initial, permeability matters. In order to determine the level of clogging, long-term flow
(clogging) test, gradient ratio (clogging) test and hydraulic conductivity ratio (clogging) test can be carried out (R.M. Koerner, 1998).

Leachate recirculation accelerates biodegradation and dimensionally stabilizes waste deposits before final capping. After percolating through heterogeneous waste, blended liquid is reapplied at the surface to seep through again. Biodegradation is assisted by the increased moisture content and the distribution of microbial inoculant and nutrients through a deposit. Recirculation continues until readily decomposed, dissolved or erodible constituents are depleted. The result is decreased waste thickness, higher density, and less threat of mobile pollutant release. As a plane of intimate contact between a biofilm formed by filtration and expanded with a continuous substrate supply, some biological clogging is not a surprise. The leachate collection system filter is the preferred place for biomass growth in the entire facility, limited by its anaerobic condition.

The intent in the present study is to take advantage of microorganism attraction to geotextiles that is a problem in soil and landfill drainage is as an opportunity to protect receiving waters from pollution discharges. However, the feasibility of using geotextile filters to treat wastewater or weather generated flows requires high hydraulic capacity. Perhaps, only dilute concentrations of biodegradable materials can be handled, but the suspended and dissolved organic concentrations in wastewater and urban runoff are typically an order of magnitude lower than fresh leachate.

Filtration in general, and biological fouling in particular, are common concerns. Research is ongoing in many engineering specialties. Of course, there is much literature on biological clogging of sand filters and septic system leaching beds. Study of biological processes was adapted from agricultural practice in the 1960’s and 1970’s. Neva et al., (1964) found a
relationship between accumulation of microbial polysaccharides and biological clogging of sand. Wood and Bassett (1975) demonstrated that growth of anaerobic bacteria in recharge basins changed both soil permeability and the quality of the percolating water. Matsumoto and Okubo (1979) used sand columns to investigate the effect of infiltration rate, the most critical engineering parameter, on biological clogging and water quality changes. Findings were:

- Lower initial infiltration rates removed more soluble organics than higher rates
- The infiltration rate affected the production of volatile fatty acids
- The lower the infiltration rate, the higher the ammonia removal rate
- Hydraulic conductivity in the bottom layers decreased at the higher infiltration rates

Filter processes are studied in several disciplines. Schedegger (1957) divided filtration into three classes: medium, cake, and depth filtration. Chapter 2, in addition to expanded discussion of geotextile materials and types, relates their behavior to these broad filtration classifications.

1.6 Attached or Fixed-Film Biomass

There are two basic methods to use microorganisms in biological treatment: suspended and attached growth. Suspended growth is used in high flow applications such as the activated sludge method. A reactor containing wastewater and activated sludge is aerated to transfer oxygen and keep the mixture turbulent to foster contact between substrate (carbon and energy sources) and microorganisms. The actual decomposition and mineralization may occur in this process, as in extended aeration methods, or occur in sludge digesters where the microorganisms that sorbed the waste are detained. The importance of suspended growth to
this study is that most of the theory and practice of biological wastewater treatment, such as F/M (food/mass) ratio and other engineering indices have been developed with suspended growth. Attached growth is less mechanically complex and often more robust when subjected to varying hydraulic and organic loadings. Substrate is sorbed from influent onto a fixed biofilm by various methods that bring the active treating biomass and the substrate into contact. The two most common methods are filtration or tangential contact, typically used in sand filters and trickling filters, respectively. Permeating influent through a filter assures intimate contact, but accumulation of inert material and decomposition products will eventually clog a filter. Backwashing, filter replacement, or rest intervals for degradation of excess organic material to restore the hydraulic capacity of granular filters. Another approach is tangential contact, as is used in trickling filters. Influent flows over coarse media coated with a biofilm. To optimize substrate transfer, the water film thickness is controlled by the hydraulic loading rate (HLR), and air circulates between the media oxygen diffusion into the water film. Excess biomass sloughs off the media for sedimentation and digestion elsewhere. More detailed discussion is included in Chapter 3.

The present project involves investigation of both types (filter and tangential) of contact between source liquid and geotextile media. As implied earlier, deliberate clogging is used in the early stages of GBCS start-up to form the active biomass. This dissertation studied the feasibility of using the tangential contact approach with geotextile baffles arranged as shown in Figure 1.1a and 1.1b. A companion dissertation, referred to where appropriate, studied treatment of the same influent in continuous permeation through columns with multiple geotextile filters in succession. Due to the differing requirements for hydraulic head, it appears likely that the effluent from the baffle treatment would be discharged to surface water, while effluent from geotextile filter permeation would probably be recharged to groundwater. To compensate for the less intimate contact between substrate and biofilm, the
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pilot plant GBCS apparatus was designed had a very large contact surface area (Figure 1.1a and 1.1b).

1.7 Test Liquid

This study required a realistic, continuously generated and well documented test liquid from the (PWD) Southeast Water Pollution Control Facility (SEWPCF) was used. Primary effluent is an intermediate treatment product that has been processed by screening and sedimentation of settleable solids, but not biochemical processes that remove suspended and dissolved organics. Following primary treatment, the SEWPCF uses an activated sludge biological treatment process, such that the GBCS is an alternative biological treatment technique. Depending on weather conditions, the SEWPCF also treats combined (sanitary and urban runoff) sewage, as shown by the average 75 mgd dry weather flow and 200 mgd wet-weather flow. The service area includes Center City Philadelphia, dense residential areas and industrial districts. Hence, the study also indicates feasibility of using geotextiles to treat weather related pollution sources such as urban runoff and combined sewer overflow (CSO).

The first sample, used in the Phase 1 geotextile screening (“Pilot Run”) is shown on Table 1.1 was dilute in TSS (21 mg/l) and BOD$_5$ (33 mg/l) terms, representing a dry weather (sanitary) influent that had a long primary clarifier detention time. However, characterization as “dilute” can be deceptive, as illustrated by the detailed analysis on Table 1.1.
### Table 1.1: Sample Wastewater Analysis Used in Phase I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological Oxygen Demand (BOD₅)</td>
<td>33</td>
</tr>
<tr>
<td>Total Suspended Solids (TSS)</td>
<td>21</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (COD)</td>
<td>151</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>13.5</td>
</tr>
<tr>
<td>Nitrate (NO₃)</td>
<td>1.82</td>
</tr>
<tr>
<td>Dissolved Oxygen (DO)</td>
<td>1.7</td>
</tr>
<tr>
<td>Phenol</td>
<td>0.04</td>
</tr>
<tr>
<td>Iron</td>
<td>0.95</td>
</tr>
<tr>
<td>Phosphate (as PO₄⁻²)</td>
<td>0.22</td>
</tr>
<tr>
<td>Sulfates (as SO₄⁻²)</td>
<td>40</td>
</tr>
<tr>
<td>pH</td>
<td>7</td>
</tr>
</tbody>
</table>

BOD₅ is measured using a sludge “seed” to predict oxygen demand by microorganisms. Another index, Chemical Oxygen Demand (COD), measures the amount of an oxidizing agent consumed when the organic matter in water sample is completely oxidized to CO₂. The COD of this sample was much higher than the BOD₅, probably reflecting the organic and inorganic constituents that resist rapid biodegradation. Nevertheless, this indicates a complex source liquid which may contain traces of materials that could inhibit biological treatment. The low value of phenol implies that much of the hydrocarbons often found in urban runoff were removed in the primary tanks. An NTIS report (1982) characterizing runoff quality at the Honolulu Airport indicated a median phenol concentration of 0.17 mg/L, an order of magnitude higher than the SEWPCF Pilot Sample.
1.8 Summary of Results

This section summarizes Chapters 4 and 5. The work was conducted in three phases:

Phase I. Geotextile selection for relative biomass retention (Pilot Sample)

Phase II. Two tank pilot plant process investigations (Runs 1-11)

Phase III. Single tank pilot plant geotextile type investigation (Runs 12-13)

Phase I studied which geotextiles attracted microorganisms. Forty eight 10 in. x 10 in. coupons were cut from eight different geotextiles, distributed among four tanks, and immersed for a week in the pilot sample (Table 1.1) with continuous aeration. The geotextiles used in this study are listed on Table 1.2 Selected properties as reported by the manufacturer are listed in the second through forth columns.

In the equivalent of extended aeration treatment with a week of retention, all four tanks displayed nearly 100% removal of TSS and BOD₅ from the liquid. At the end of this incubation, the coupons were extracted, air dried and weighed to indicate the retained organic material. This was assumed to be the residue of microorganisms that had attached to the geotextile, grown until the dissolved substrate was depleted, and then went through endogenous degradation of the cell mass. The average dry biomass retained per coupon is shown on the last column of Table 1.2. Substantial organic material retention was found only with the needle punched nonwoven geotextiles, but not the two types of woven geotextiles, fiber (W/F) and slit-film (W/SF).
Table 1.2: Phase I Geotextile Properties and Dry Biomass Retained After Immersion

<table>
<thead>
<tr>
<th>Product (Type &amp; Polymer)</th>
<th>Apparent Opening Size (AOS), mm</th>
<th>Permittivity sec(^{-1})</th>
<th>Puncture Resistance lbs</th>
<th>Avg. Dry Biomass Retained/Coupon Grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amoco 2130 W/F/PP</td>
<td>0.6</td>
<td>0.05</td>
<td>65</td>
<td>0.026</td>
</tr>
<tr>
<td>Amoco 1199 W/F/PP</td>
<td>0.212</td>
<td>0.28</td>
<td>135</td>
<td>0.015</td>
</tr>
<tr>
<td>Amoco 2002 W/F/PP</td>
<td>0.425</td>
<td>0.05</td>
<td>90</td>
<td>0.013</td>
</tr>
<tr>
<td>Geotex 315 ST W/SF/PP</td>
<td>0.212</td>
<td>0.06</td>
<td>125</td>
<td>0.003</td>
</tr>
<tr>
<td>Trevira 1125 NW/CF/PET</td>
<td>0.210-0.149</td>
<td>2.01</td>
<td>115</td>
<td>0.078</td>
</tr>
<tr>
<td>Amoco 4545 NW/ST/PP</td>
<td>0.212</td>
<td>2.1</td>
<td>55</td>
<td>0.0017</td>
</tr>
<tr>
<td>Polyfelt TS700 NW/CF/PP</td>
<td>0.12-0.18</td>
<td>1.6</td>
<td>120</td>
<td>0.135</td>
</tr>
<tr>
<td>Amoco 4551 NW/ST/PP</td>
<td>0.212</td>
<td>1.5</td>
<td>90</td>
<td>0.055</td>
</tr>
</tbody>
</table>

W = Woven, NW = Nonwoven, F= Fiber, SF = Slit Film, ST=Stapled, CF = Continuous Filament, PP = Polypropylene, PET = Polyester

Phases II and III were bench scale pilot plant studies, using needle punched geotextiles only of both types of fabrication, staple fiber and continuous filament. The companion study using geotextiles as filters also showed that biodegradation was accomplished only with nonwovens, although clogging remained an issue. In the present study, while influent flow tangential eliminated clogging as a concern, the efficiency of contact between colonizing microorganisms and the media, and then between substrate and the developed biofilm, was unknown. To enhance interaction, the sinuous layout shown on Figures 1.1a and 1.1b was
used. In Phase II, two tanks were used sequence, in part to provide an intermediate measurement point, but the second tank was shown to be redundant. Thus, only one tank was used per test in Phase III, which varied the geotextile as well as operational parameters.

Each twenty gallon (12 in. x12 in. x30 in.) tank had fifteen 10 in. x 10 in. geotextile baffles suspended at 2” centers to providing 2” clearance from one tank wall and the bottom. This provided a uniform channel width, clearance from the diffuser and a sludge accumulation zone. Placing the baffles 83% across the nominal pathway providing the initial encouragement of filtration capture of TSS in the porous geotextiles, but when they became “clogged” and forced flow through the channels, the total path length was 15 ft. Other indices can be derived from this arrangement. Considering both sides of the baffles, the potential biofilm surface area/reactor volume ratio was almost 8 ft$^2$/ft$^3$. The hydraulic loading rate of 20 gallons/day was selected to provide a conservative 1.0 gal/day/ft$^2$ of baffle surface. This also provided 22.5 hours of tank hydraulic retention time, a horizontal channel velocity of 3.4x10$^{-5}$ ft/sec and a surface settling rate of 10 gpd/ ft$^2$.

To test the limits of the GBCS in the first run of Phase II with the bench apparatus (Figures 1.1a and 1.1b), Sample No. 1 was plant influent upstream of the primary tanks, processed only by screening and grit removal. This was a wet weather flow, with TSS = 318 mg/l and BOD$_5$ = 114 mg/l, reflecting scour of material deposited in combined sewers. The balance of the work used 7 samplings of primary effluent obtained at intervals over a three month period. Figure 1.2 represents the samples used in the Phase II biodegradation studies. TSS varied from 31 mg/l to 52 mg/l.
Figure 1.2: Phase II Influent and Effluent TSS Concentrations

SEWPCF primary effluent BOD$_5$ varied over a similar range, as shown on Figure 1.3. The primary effluent samples used in the last phase also fall within these limits. TSS and BOD$_5$ sample analysis was done by the PWD Bureau of Laboratory Services.

Figure 1.3: Phase II Influent and Effluent BOD$_5$ Concentrations
The clear glass tank bottom allowed visual monitoring of sedimentation patterns. This started with influent TSS capture, perhaps because the settling rate is an order of magnitude below that of conventional clarifiers, which allowed fine organic particle sedimentation. The geotextile with the highest biomass retention from Phase I (Table 1.2) was used in Phase II. Its light-colored material allowed observation of the surface biomass growth. With continued biomass growth, sloughing of excess surface slime from the baffles also occurred.

In Phase II, one dose of raw wastewater and seven of primary effluent were pumped through two tanks in Sequence II. A 20 gallon dose was applied on each of five days in succession, for a total of 100 gallons/run. With the second tank shown as unnecessary, as discussed below, the Phase III set with a different geotextile used two more runs.

It was quickly shown that the geotextile baffle system could provide secondary treatment. Figure 1.2 indicates that even with the raw wastewater TSS of 300 mg/l, TSS was reduced to 5 mg/l in the first tank. Similar results were measured with the more dilute primary effluent. Fine sediment accumulation on the bottom of the first four or five channels was evident. This deposition around the bubble diffuser appeared to reach a steady state after three runs, indicating that the sludge was being degraded. At about the sixth run, the sediment thickness increased. Local tears in the slime layer on the first two or three baffles appeared and were then obscured. This indicated that the slime layer projecting from the baffle surface had commenced to slough off, but was replaced by fresh biomass. Decomposition of dissolved organics also commenced rapidly. Figure 1.3 shows that the raw wastewater BOD₅ was reduced from 110 mg/l to 10 mg/l. The following runs with primary effluent showed reduction to 5 mg/l or less. The effect of limited aeration was studied at the end of Run 8, oxygen stopped in the second tank. With success in secondary treatment, nitrogenous compound concentrations were also monitored. Figure 1.4 and 1.5 show the concentrations of ammonia and nitrate in the influent and effluent for Runs 2-8. The influent NH₃ delivered to
the GBCS varied from 10 to 25 mg/l. The source primary effluent had not decomposed sufficiently to transform ammonia to nitrate, so the influent nitrate was below 2 mg/l.

Figure 1.4: Phase II Influent and Effluent NH$_3$-N Concentrations

Figure 1.5: Phase II Influent and Effluent NO$_3$-N Concentrations
Figure 1.4 shows that with full aeration, influent ammonia was reduced to the desired 2 mg/l. Ammonia reduction decreased with the limited aeration in Run No. 9, indicating that continued aeration is required if ammonia removal is required for effluent discharge. Figure 1.5 shows that some denitrification occurred, increasing with either biofilm age or thickness. Effluent concentration below 10 mg/l was achieved after a month of throughput. This reaction requires an anaerobic condition. Since the tank liquid was aerated all the time, it is concluded that denitrification commenced when biofilms grew thick enough to form an internal anaerobic zone.

Analysis of aqueous samples indicated negligible additional treatment in the second tank, as the first tank already met treatment goals. Nevertheless, a brown biofilm was visible on the second tank baffles. At the end of Phase II, all were exhumed, air dried, and weighed, with the results shown on Figure 1.6 (first tank) and Figure 1.7 (second tank). It can be seen that the dry organic weight varied from about 3.5 g/baffle (about 2.2 g/ft$^2$, double side) at the head of the first tank, with a brown coating obscuring the geotextile fibers, to 1.25 g/baffle at the end of the tank, where the geotextile fibers were visible, and the biomass was contained within the fabric porosity. These observations indicated that the biomass did indeed grow outward from microorganisms captured within the porous interior structure. This continued until the surface slime layer covered and clogged the pores. The baffle fibers were partially obscured by surface slime up to about the tenth baffle, but with no visible sediment deposition on the reactor bottom, it appeared that the biomass beyond this and into the second tank was colonized by microorganisms in colloidal form. The biofilm densities shown on Figure 1.6 are more than thirty times higher that shown for the same geotextile in Table 1.2, but the accumulated organic exposure on a per square foot basis was higher by almost two orders of magnitude.
Figure 1.6: Net Dry Biomass Change on Geotextile Samples for Tank 1

Figure 1.7: Net Dry Biomass Change on Geotextile Samples for Tank 2
While a trend of decreasing biomass with distance substrate availability is evident in the first tank, there is not a linear relationship with biofilm density and treatment, as biofilm also grew on the baffles in the second tank. Figure 1.7 shows that retained biofilm in that vessel varied from 2.0 g/baffle to 1.0 g/baffle.

1.9 Biofilm Morphology in Geotextile Media

This empirical study used products that were manufactured for other uses. It was found that some geotextiles support biofilm, and others do not. The needle punched products are different from the other types in having a thick interior porosity with a complex structure. Physical observations that the biomass grew from internal filtering also indicated that the behavior was also different from other uses of plastic media as biofilm attachment, e.g. trickling filters. The most surprising result was the substantial denitrification while the liquid in the tank was continuously aerated. This implies a thick biofilm that contained an anaerobic zone within it. Projection of the biofilm thickness as a slime layer beyond the fabric surface into the channels was limited, probably based on mechanical cohesion as is also seen with trickling filters. A model of biomass growth and morphology in porous geotextiles would guide fabrication of new products for the biological degradation function.

Figure 1.8 and 1.9 illustrate two models of biofilm morphology in an idealized two-dimensional matrix, each with different hydraulic and contact surface area characteristics. Figure 1.8 shows biofilm coating the fibers of the media, consistent with trickling filter experience. The plastics used in such applications are hydrophobic, but microorganisms bind to surface imperfections and secure substrate from passing flow with their cilia and flagella. Biofilms are an assemblage of microorganisms and other particulate material bound together by a matrix of extracellular polymers (Perry & Stanley, 1997). Biofilms thicken by growth,
but more organisms are attracted, adhering to the gelatinous coating. Figure 1.8 extends this one-dimensional model to the idealized pattern of fibers surrounding a pore. It can be seen that biomass growth would not only intrude into the pore channel, but the surface area available to absorb substrate decreases. The problem is that, in this model, if the biofilm growing from enclosing fibers coalesce, the interior biomass is cut off from substrate.

Figure 1.9 shows an alternate model derived from conventional filter behavior, i.e., entrapment of particles within the matrix. This would produce a more discontinuous biomass, a floc rather than a biofilm. The trapped microorganisms grow inside a pore, “rattling” within the fibers, but not necessarily adhering to them. Influent conveying substrate flows around, rather than through the discontinuous floc morphology. The surface area for substrate sorption would not change radically as the biomass grows according to this model. A finite permeability remains if the biomass avoids contact with the hydrophobic polymer fibers.

Figure 1.8: Two-Dimensional View of Attached Biofilm Model
Figure 1.9: Two-Dimensional View of Internally Suspended Biofilm Model

Figure 1.10 is a Scanning Electron Micrograph (SEM) picture of a baffle extracted after Run 9 and then air-dried. It shows a complex pore structure between widely spaced fibers. The biomass floc is plate-shaped, growing in layers as a combination of the two models described above. Some attachment to the fibers is evident.
This biomass morphology explains both the eventual steady-state permeability observed by G. Koerner (1993) and the nitrification-denitrification found in this present study, as it is evident that a finite permeability still exists even with a certain amount of “clogging”. Hence, an equilibrium permeability would evolve that allowed a finite rate of substrate supply to maintain an endogenous (near starved) condition. In the GBCS, a hydraulic gradient still exists across the baffles between channels, and so does a finite permeability in the biomass morphology shown on Figure 1.10. Hence, products of decomposition in the well aerated surface, such as ammonia, and then nitrate are conveyed into the interior of the biomass, rather than out of it, as in trickling filters with a biomass attached to an impermeable media. With successively lower oxygen availability along the interior pathway across the baffle to the next channel, the conditions for nitrification (low oxygen demand) and denitrification
(anaerobic) are provided. Consequently, nitrogen gas and at least partially denitrified water emerge into the down gradient channel.

With the basic morphology of the interior biomass established, i.e., plate-like sheets both attached to and trapped between the fibers, the sloughing of slime layers projecting beyond the fibers can be explained. With a low affinity for the fibers, it is reasonable to expect that projecting cells are anchored mostly to the interior biomass. However, with outward growth, the interior cells that had developed to degrade carbonaceous substrate are isolated from it and oxygen. As described in Chapter 3, there is a well established cycle of bacterial growth and decay, accompanied by scavenging by protozoa. As the interior biomass declines in vitality and specializes in nitrogen conversions, the cell mass shrinks, and the anchorage for the projecting biofilm weakens and fails. This is illustrated on Figure 1.11. An important result is that the sloughed or peeling sheet would be a combination of actively growing and dead cells. On the tank bottom, with plenty of oxygen, the protoplasm of the latter is food for the former, perhaps explaining the rapid sludge decomposition observed.

![Figure 1.11: One-Dimensional Sequence Model of Biofilm Growth and Eventual Sloughing](image-url)
1.10 Potential Applications to Wastewater Treatment

In engineering research, it is necessary to show that there is a problem to be solved, that the work contributes to a solution, and, with design parameters developed from prototype scale studies (Chapter 6), an improved solution will be developed. There are 3 potential applications to wastewater treatment: small, community scale and onsite systems.

The geotextile baffle method may be appropriate for small wastewater treatment plants having difficulty in consistently meeting discharge standards. Such facilities generally have limited surface space, available hydraulic head, operator effort and sludge handling capacity. The GBCS could be retrofitted in an existing facility as a solution to the following issues:

- To complete treatment at plants not producing effluent meeting discharge standards
- Seasonal low flow period “polishing” of secondary effluent to reduce BOD$_{ult}$ and ammonia and/or remove nutrients by denitrification
- Secondary treatment in rural areas after primary clarification in lagoons
- Pretreatment for a septic system or a rapid infiltration system.

Figure 1.12 shows schematic layouts of supplementary treatment units inserted between an existing facility and the discharge. The baffle units can be oriented as desired, and be as deep as needed to fit the site constraints, perhaps built as an inverted siphon. It is reasonable to expect that the first two applications cited above can be run at high loading rates, expressed in terms of gal/day/ft$^2$ of baffle. The last two applications may require lower loading rates. A persistent issue in biological treatment of continuous flows is handling excess biomass, an organic sludge. It was observed in the experiments that much of this was aerobically
degraded within the tank along with the settled TSS. If the GBCS is used in a supplemental mode as shown on Figure 1.12, some form of sludge handling would already be in place.

![Diagram of wastewater treatment system]

Figure 1.12: Schematics of Retrofit Installations at an Existing Wastewater Treatment Facility

Onsite wastewater treatment and effluent disposal by infiltration is often the only option at sites remote from sewer systems or surface water. The wastewater receives primary treatment in a septic tank, which releases liquid containing suspended and dissolved organic material to an infiltration surface (called a leaching or absorption bed, field or trench). A biomat or “schmutzdecke” accumulates on the infiltration surface, limiting its hydraulic capacity. Clogging is a frequent problem. Overflow of decomposition products, solids or grease from a septic tank exacerbates this condition.

A passive GBCS may improve performance with little additional cost, especially when pumping is required to lift septic tank effluent up to the infiltration surface. A wetwell to accumulate tank overflow between doses is required anyway. Reducing organic loading on
the infiltration surface will extend its service life. Baffles can be inserted in the wetwell to function as a “roughing filter”, a common use of trickling filters to reduce BOD₅ to a strength compatible with treatment in a public facility. In the onsite application, the baffles would capture suspended solids by contact and absorb dissolved organics as the wetwell water level rises between pump cycles. The attached biomass re-aerates as the pump displaces the stored water.

1.11 Potential Applications to Weather Related Discharges

Using geotextiles to improve water quality by supporting biodegradation also shows promise in application to intermittent, weather-generated water pollution. Since the Clean Water Act of 1972, billions of dollars have been invested in treatment facilities to reduce the impacts of continuous wastewater effluent point discharges. However, while water quality has generally improved, many streams still do not meet standards established to protect drinking water sources, aquatic habitat and recreation. Many treatment plants, such as the PWD facilities, actually discharge effluent of better quality better than that of the receiving stream.

Attention has thus shifted to weather related stream pollution sources such as urban runoff and, in older cities in the Northeast, Midwest and Northwest, combined sewer overflows (CSO). These are not “non-point” in that their locations are known, but they are dispersed and discharge intermittently. Both water quantity and quality vary during an event. This has generated the need to develop “Best Management Practices” (BMPs) to comply with the Total Maximum Daily Load (TMDL) allocation distributed among dischargers to a receiving stream to limit releases to that which natural processes can assimilate to maintain the stream classification.
BMPs are particularly difficult to implement in urban areas due to space and available hydraulic head constraints. Nevertheless, the streams and the parks through which they often flow are among the remnants of a natural environment in metropolitan areas. The public increasingly demands that they not just function as drains and aesthetic backdrops, but also be thriving aquatic habitats. Storm drainage systems usually discharge without treatment, which can adversely impact the quality of receiving waters, sediments and biota (Pitt et al., 1995). Bannerman et al. (1993), studied runoff from various sources such as streets, parking lots, roofs, driveways, and lawns in residential, commercial, and industrial areas. Solids, phosphorous, and heavy metals loads were determined for each source area type from the measured concentrations and runoff volumes. Streets were critical for most pollutants in all land uses. Parking lots were critical in commercial and industrial land areas, while lawns and driveways contributed large phosphorous washoff in residential neighborhoods.

It has been found that the first \( \frac{1}{4} \) in. -\( \frac{1}{2} \) in. of a storm, the “first flush”, includes most of the mobilized pollutants that accumulated on the surface since the preceding storm. Thus, it may be necessary to treat only this first flush. Lee and Bang (2000) investigated runoff pollutant types, relationships between pollutant load and runoff hydrology, and the first flush effect in urban areas. Nine watersheds with varying land use and topographic characteristics were studied. By comparing runoff hydrographs and pollutographs of each watershed, it was concluded that the peak pollutant concentration occurred before the peak flow in watersheds smaller than 100 ha. However, the peak pollutant concentration occurred after the peak discharge rates in larger watersheds with less than 50% impervious area. Thus treatment of the first flush appears to be most effective in small, highly disturbed catchments, concentrating on traveled surfaces such as streets and parking lots.
Many of the materials entrained in runoff can be separated by physical means such as screening, sedimentation and floatation. However, suspended and dissolved organic constituents may also be of concern, especially pathogens derived from animal waste and attached to the TSS. Contact with a surface texture that sorbs organic material will improve runoff quality. Since it is captured in a transient event, the intercepted material would be decomposed up to the next event. Keeping an active residual biomass viable for treatment is a concern, so the capability of the GBCS to develop an active biomass from each fresh batch of runoff is desired.

Nevertheless, it has not been shown in this study that stormwater, by itself, can be improved by the method developed. This will be the case only if a substantial proportion of the pollutants are biodegradable. The more appropriate weather-related pollution application for the geotextile baffles is combined sewer overflows (CSO). They have been found to present a threat to water quality in terms of TSS, $\text{BOD}_5$, and total coliform (Palmer, 1950, 1963). With a higher $\text{BOD}_5$, the adverse effects of CSO discharges into surface waters in terms of oxygen depletion and eutrophication are stronger than urban runoff (Marsalek et al., 1993). However, it has been shown in the baffle tests of this dissertation that combining wastewater with the first flush of urban runoff does not retard the treatment process.

Hence, the logical first step in applying the geotextile baffle treatment to weather related pollution discharges is to CSOs. There are between 15,000 and 20,000 CSOs currently in operation (Association of Metropolitan Sewerage Agencies, 1988), serve a population of about 40 million in almost 800 communities. Overflow frequency and quality differ from street runoff. The interceptor that transmits dry weather sanitary flow from local sewers to a treatment plant conveys the first flush of the runoff as in light storms with the sanitary flow. In severe storms, the hydraulic load exceeds interceptor capacity. Diversions placed at
intervals direct excess flow to a local waterway, often at points where storm drains would discharge anyway. CSO is more than a blend of the ongoing sanitary flow and runoff from streets that have been flushed, also including organic material deposited in dry weather in the oversized (for sanitary flow) sewers. A range of CSO concentrations (mg/l) were reported by P. Moffa, (1997) of 270 <TSS<550 and 60<BOD<220, and 200 x 10³ < fecal coliforms/100 ml <1140 x 10³, but low in nutrients. The high TSS represents the flushing of sewers, not the street. Regardless, this indicates that a large proportion of the pollutants in CSO are degradable organics, amenable to sorption and biological treatment by attached growth.

Figure 1.13 illustrates a possible CSO retrofit layout, adapted from Metcalf & Eddy (1991). The geotextile baffle tank could be installed either along the outfall as shown, or in an off-line chamber, depending upon space constraints. A screen/sedimentation chamber is necessary, and shown. The most critical goal is removing TSS, with pathogens being among the microorganisms attached to the organic particles.
Chapter 2. Geotextiles, Their Filter Behavior and Clogging Mechanism

2.1 Introduction

Geotextiles are pervious textiles, a subset of geosynthetics, manufactured polymeric materials (geogrids, geomembranes, geocomposites, etc.) used in subsurface projects. The use of geosynthetics in infrastructure construction and repair is increasing as an alternative to natural materials due to controlled fabrication quality, rapid installation, and volumetric economy (Koerner and Soong, 1995). Geotextiles thus have dozens of applications. In any one, they generally serve at least one primary function such as layer or strata separation, reinforcement, filtration or drainage as a component of the total design (R.M. Koerner, 1998). Geotextiles were first used for filters as alternatives to granular soil filters (Barrett, 1966). The earliest application was draining retaining wall backfill. This use reflects the usual focus in designing a geotextile filter as managing a trade off between assuring permeability, also expressed in terms of permittivity, and soil retention. The key material property for the latter concern has been found to be the apparent opening size (AOS). A designer selects from the available products for those having the desired engineering properties. Manufacturers are aware of these needs.

Special consideration is required when the permeating liquid is not clean water, such that excessive clogging may result from causes other than failure to keep the inert retained soil particles in place. The susceptibility to clogging by biological growth or chemical precipitation has been identified (Koerner G., 1993) and laboratory methods to evaluate its extent have been developed for ASTM. However, this is a rather “defensive” approach to biochemical activity i.e. empirical effect on permittivity. The use of geotextiles to encourage biofilms and provide optimum conditions for wastewater treatment is a new application, so
products made for this purpose are not yet developed or marketed. However, geotextile filters are the most closely related standard application to biological treatment of dissolved organics during permeation of effluent across the plane of the geotextile. Clean water permeability is the logical baseline for investigating clogging effects. It would also appear that there is some correspondence between retaining soil particles and arresting movement of suspended solids without blocking the entrances to pore channels. These organic particles are not only a clogging threat, but are the source of the treating microorganisms and part of the substrate as well.

The ability to support an internal biofilm to remove solutes has not been addressed to the author’s knowledge. The major unknowns are the geotextile characteristics that influence the amount, morphology and treatment effectiveness of the biofilm, especially in the interior of the fabric. Optimization of biodegradation may involve the AOS, the porosity (related to another index, fabric density), the pore size distribution (PSD) and the tortuosity of channels through the fabric. Geotextile materials are hydrophobic, so it would appear at first glance that the biofilm forms primarily by entanglement in the pore structure, looping filaments around the geotextile fibers. However, in other wastewater treatment methods such as trickling filters and RBCs, biofilms grow on smooth plastic media (Rittmann and McCarty, 2001). Hence, it is useful to concentrate, for the moment, on:

- Filter theory
- Textural indices from current manufacturing processes
- The observed behavior of geotextiles embedded in soil as filter-separator

The geotextiles used in this study were selected as candidates for experiments based on their texture and suitability for use as a filter for a soil with a wide distribution of opening sizes.
Evaluation of the water quality and permeability results from the experiments may indicate measures to optimize manufacturing to produce the desired hydraulic and treatment performance, as has been done for other geotextile applications.

2.2 Geotextile Types

Synthetic fibers are the basic elements of a geotextile, described by composition (polypropylene -PP, polyethylene -PE or polyester -PET), thickness (denier) and length (continuous filaments or short staples). The manufactured product is classified by the fabrication method, with the basic division being woven or nonwoven.

Woven geotextiles are composed of two sets of yarns systematically interfaced to form a planar structure. The result is a pattern of fully penetrating, uniformly sized parallel channels that are isolated from each other, as shown on the attached scanning electron microscope Figure 1.1. While the weave tightness can be varied to adjust pore size and unit fiber surface area per, the thickness of the product and the pore size are dominated by the thickness of the fibers used. Having distinct channels passing through the geotextile thickness would appear to assure permeability, but there is a risk of complete blockage by particles of a corresponding or larger size. This is remedied by selecting the proper AOS for a soil filter application. However, blockage by a coating of suspended organic particles on the relatively smooth surface of a woven geotextile would be a major concern in a wastewater treatment application.
Nonwoven geotextiles are formed of fibers arranged in a random pattern into a planar structure. There are two basic types: heat set filament, and needle punched. The latter is subdivided into continuous filament (long fibers) or staple (short fibers). The thickness of heat set geotextiles can be varied by laying down more filament layers, which also gives more fiber surface area in contact with the flow. However, heat set geotextiles are inherently low AOS, and susceptible to clogging by suspended solids. The needle punched process allows more flexibility in both fiber density and unit fiber surface area, both of which can be adjusted independently of the thickness of the fibers used. Needle punched fabrication can vary indices that may affect both biological clogging and treatment such as pore size, permittivity, channel continuity and internal attachment surface area. Figure 2.2 is an SEM image of continuous filament needle punched structure. Finally, the surface texture of needle
punched geotextiles can be more readily modified than either woven or heat set geotextiles. This may allow interception of suspended solids as a filter cake away from the main body of the geotextiles. This would produce a synergistic relationship with transmissivity, the capability of conveying flow in the plane of the fabric, which could redistribute flow around blocked surface openings and through the fabric.

Figure 2.2: SEM Image of a Nonwoven Geotextile

An abridged manufacturer’s list of the properties of the geotextiles used in this study, converted to common units, is listed in Table 2.1.
Table 2.1: Published Properties of the Geotextiles Used in Phase I, Phase II & Phase III

<table>
<thead>
<tr>
<th>Product Name/ Structure/ Polymer Type</th>
<th>Apparent Opening Size (AOS), mm</th>
<th>Permittivity, sec(^{-1}) (Flow rate, gpm/ft(^2))</th>
<th>Puncture Resistance, lbs</th>
<th>Trapezoidal Tearing Strength, lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amoco 2130 (W/F/PP)</td>
<td>0.6</td>
<td>0.05</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Amoco 1199 (W/F/PP)</td>
<td>0.212</td>
<td>0.28</td>
<td>135</td>
<td>100 (MD) 60 (XD)</td>
</tr>
<tr>
<td>Amoco 2002 (W/F/PP)</td>
<td>0.425</td>
<td>0.05</td>
<td>90</td>
<td>75</td>
</tr>
<tr>
<td>Geotex 315 ST (W/SF/PP)</td>
<td>0.212</td>
<td>0.06</td>
<td>125</td>
<td>120</td>
</tr>
<tr>
<td>Trevira 1125 (NW/CF/PET)</td>
<td>0.210-0.149</td>
<td>2.01</td>
<td>115</td>
<td>105 (MD) 95 (XD)</td>
</tr>
<tr>
<td>Amoco 4545 (NW/ST/PP)</td>
<td>0.212</td>
<td>2.1</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Polyfelt TS700 (NW/CF/PP)</td>
<td>0.12-0.18</td>
<td>1.6</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Amoco 4551 (NW/ST/PP)</td>
<td>0.212</td>
<td>1.5</td>
<td>90</td>
<td>65</td>
</tr>
</tbody>
</table>

2.3 Filter Functions, Modes and Types

The uses of geotextiles are so varied that it is necessary to focus the discussion to their use relevant to this study, soil filters to allowing water passage while preventing solid convection, which is actually an effluent quality standard: low turbidity. However, rather than assume that solution to the wastewater treatment problem is a direct extension of soil filters, it is wise to review filter practice across engineering disciplines. Even limiting discussion to cases where
fluids permeate a thin, permeable physical unit still encompasses dozens of applications. Filtration is a process where suspended or dissolved solids are separated from a fluid (water, air, wastewater) as it flows through a porous media. The intention is not only a set level of solids removal, but also minimal energy (head) loss. Filter design is based on parameters such as its channel morphology, the size and shape distribution and concentration of suspended solids or dissolved solids characteristics, and fluid properties such as viscosity and density. Another important factor when designing a filter is the source of the driving force, which may be gravity, suction or positive pressure.

Schedegger (1957) divided the filtration processes into three classes:
- medium filtration
- depth filtration
- cake filtration.

In medium filtration, particles, which are larger than the holes in the filter, are retained, generally at the surface openings or shortly inside the upgradient face of the unit. The filter behaves like a sieve. Failure, defined as excessive head loss to provide the desired fluid flow, tends to occur by surface blinding or blockage. In depth filtration, particles smaller than the filter pores are retained within the filter due to impact on or attraction to the walls of the pore channels. This mechanism eventually may result in excessive internal clogging of the filter pore channels. Depth filtration also applies to biochemical reactions that remove solutes by sorption, electrostatic attraction, etc. In cake filtration the solids accumulate on or in front of the surface of the filter, to a large extent within the solids of interest that were retained before direct contact with the filter.
Soil and GT filters are intended to be a variation of cake filtration in that it is desired to keep soil particles in their original position, i.e., minimize mobilization into the “influent” in the first place. As described in more detail below, this is often done after localized particle movements have formed a filter cake layer. The filter is specified to be more permeable than the upgradient soil to allow minimization of head loss across the composite filter cake-geotextile filter, as indicated by the gradient ratio test.

The present case, geotextile biofilters for wastewater treatment, is intermediate in the range of filtration modes. Two types of solid are conveyed in the influent: suspended and colloidal. The biofilter must physically intercept the former and digest both by biochemical reactions. As noted in the introduction, the issue in onsite treatment systems is physical clogging of the infiltration surface of the absorption or leaching field, a type of medium filtration. The premise is that this is particularly restrictive when the subgrade is permeable, i.e., the filter has excess influence on hydraulic design of the system compared to customary expectations (above). The improved performance and dimensional efficiency of geotextile filters compared to the graded soil filters that they have largely replaced is sought with wastewater biofilters formed with a geotextile matrix. It is probably desirable to maintain a pervious, acclimated biofilm at or above the filter surface, similar to the filter cake that forms just above soil filters.

With the usual filter purpose being solids removal, the question arises on the fate of the materials removed from the flow. Basic filter classifications are sacrificial, cleanable or self-regulating. In sacrificial filters, either the suspended particles are captured and accumulate in the filter pores (e.g., air filters), or the dissolved materials are sorbed or exchanged on surfaces within the filter up to a capacity limit (e.g. carbon filters or water softeners). When the filter becomes clogged, as indicated by excessive head loss or decreased flow rate, or
becomes depleted, as indicated by minimal decrease in solute concentrations between influent and effluent, the filter is replaced. It may be recycled, but removed from the system nonetheless, implying a need for accessibility. In cleanable filters, solids are similarly entrapped or sorbed, but the filter unit stays in place while a mechanical, hydraulic or chemical process removes entrained materials. Baghouse air filters at power plants are shaken to release fly ash, potable water treatment filters are backwashed, and chemical filters are regenerated by an acid or solvent wash.

However, providing access for replacement or other service is impossible in most infrastructure applications. Embedded soil filters must be self-sustaining with varying flow rates for an indefinite period with no maintenance. Consequently, it is expected that the local particle movements that establish the filter cake occur quickly, and remain stable thereafter. Similarly, it is desired that biofilters for onsite wastewater and dispersed stormwater treatment be self-sustaining, although occasional service is not difficult as with highway edge drains or leachate collection systems. In the geotextile biofilters, there would be an initial establishment of a biofilm that reduces permeability only to an acceptable level. Thereafter, the ideal is mineralization of suspended and dissolved organic materials. This would convert them to harmless, mobile byproducts such as water, carbon dioxide, and nitrogen gas. To the extent that mineralization does not occur, the goal is continued seepage convection of dissolved materials only. The biofilter would have the same goal as almost any other filter: prevent downstream movement of suspended solids. The accumulation of partly decomposed and non-biodegradable byproducts must not further affect hydraulic capacity, or else do so slowly such that maintenance at extended intervals can be done economically. If there is diurnal, seasonal, or meteorological variation in the flow, unclogging by endogenous respiration may occur during periods without fresh substrate supply induces, i.e. the biofilm digests itself, a form of filter self-cleaning. In any practical application, the critical parameter
in wastewater treatment filters is the hydraulic loading rate. It determines the required filter “footprint”, which is the main cost and physical constraint. In soil filters for edge drains, seeping cut slopes, and landfill leachate collection systems, the filter “footprint” is a given: the question is whether the permeability is sufficient to convey the incident seepage without surcharge pressure.

Experience with soil filters sheds little light on some aspects of bioactive geotextiles, notably treating the dissolved materials. This has more in common with carbon and sand filters in that biochemical reactions take time, and many reactions occur in sequence, as described in the following chapter. Hence, issues such as intimacy of contact between substrate and biofilm, detention time, and reactor dimensions are not important in soil filters, but are critical in the present study. The internal structure and thickness of the candidate geotextiles are important, as some reactions are expected to occur within the filter. It is in this context that review of the types of geotextile products can be reviewed.

2.4 Geotextile Soil Filters

Geotextiles are used to replace soil filters in various civil and environmental applications. Adequate permittivity, proper soil retention and avoidance of excessive long term clogging are the three fundamental criteria required for a properly functioning soil filter or geotextile filter.

2.4.1 General Principles

With the features sought in the wastewater treatment application identified, more value can be extracted from a review of research and practice in geotextile soil filters, especially the
internal structure. The essential concept is that the filter opening size must be small enough to prevent soil erosion, while the permeability must be high enough to allow free drainage of water (Cazzuffi et al., 1999). The filter opening size selection must be based on the soil grain size distribution, a fundamental parameter in designing a filter. Unlike a sacrificial filter whose pore size is set smaller than the smallest particle whose passage must be prevented, soil filters use the larger particles in the soil being protected to restrain the rest of the soil body. Under steady state flow conditions for uniformly graded soils, standard practice is that the geotextile opening size must be smaller than $d_{85}$, on the larger end of the gradation of the selected base soil. The model assumes that the coarser particles accumulate next to the interface and form an arching network that traps smaller particles (Moraci, 1992; Fluet 1993).

AOS (apparent opening size) is the basic indicator of the pore size of a geotextile. The AOS test involves dry sieving of glass beads and ASTM D 4751 describes the standard methodology. The AOS actually measures the near-largest pore diameter in the geotextile. Using similar terminology as soil gradation, AOS is commonly expressed as $O_{95}$ (based on retaining 95% of a given size glass bead). There are other indicators opening sizes that design methods have used such as $O_{90}$, $O_{98}$, $O_{f}$ or filtration opening size (FOS). When two different geotextiles (same $O_{95}$ value) were compared, each geotextile might have different hydraulic behaviors. Bhatia et al. (1991) found that geotextiles with similar FOS values may experience different degrees of clogging and quantities of soil piping. To obtain the smaller pore sizes of a geotextile the complete pore size distribution (PSD) must be measured. The pore size determination methods described in the literature are: dry sieving with soil (Belgium and UK) or glass beads (USA, ASTM D 4751), wet sieving (The Swiss and German standard), hydrodynamic sieving (Canada, France and Italy), the suction method (Dennis and Davies, 1984), mercury intrusion porosimetry (MIP) (Elsharief, 1992, and Prapaharan et al., 1989), capillary liquid extrusion porosimetry (Miller and Tyomkin, 1994), the bubble point method
(Bhatia and Smith et al., 1994, and Fisher, 1994), the minimum bubble pressure technique (Miller et al., 1986), and image analysis (Wates, 1980; Rollin et al., 1982; Prapaharan et al., 1989; and Elsharief, 1992). Many designers identify the PSD of a geotextile as being an equally important property as the grain size distribution of a soil (Bhatia, 1991). It was recognized in practice with the soil filters that geotextiles have replaced that the grain size distribution, and thus, the pore size distribution of both the soil being filtered and the filter should be parallel.

### 2.4.2 Detailed Pore Size Measurements

Pore size has been used generically to represent the void space between geotextile fibers. However, each pore size determination method measures different parts of a void. A void is an opening between fibers or soil particles, and a pore channel is a continuous void through the geotextile or soil, in which water or conveyed material would flow across the layer. In soils, a channel follows a sequence of wider spaces between generally spherical particles, and the throats between them. As described earlier, the channels through a woven geotextile are also expected to have a regular internal structure. However, nonwoven geotextiles, a very complex pore structure is envisioned, as conceptually illustrated in Figure 2.3 (Fisher, 1994). Therefore, a numerical description of pore size would mean the size of the void at any location along this channel.
Depending on the test method, at least four different types of pore size distribution (PSD) can be found in the literature for geotextiles (Fisher et al., 1993). These methods are:

1. Sieving pore size distribution (SPSD) based on the probability of a particle of a certain diameter (i.e. glass beads) passing through a geotextile opening during certain time of shaking or cycles of immersion.
2. Theoretical pore size distribution (TPSD), consisting of geometrically determined pore openings based on specific properties of the geotextile.
3. Numerical pore size distribution (NPSD), based on counting number of the pores in the geotextile.
4. Volumetric pore size distribution (VPSD), based on the percentage of total pore volume occupied by each pore size.
There are differences in these four methods, so each method would not necessarily provide same PSD (Fisher et al., 1996). These methods are described below:

Method-1, SPSD: This uses either dry and wet or hydrodynamic sieving methods. These methods usually provide a single representative pore size (the largest one) not the complete PSD of a geotextile. One of the disadvantages of these methods is that if there is a constriction in the geotextile pore channel the particle or glass bead will not pass through. During sieving large particles will get trapped in small constrictions and small particles will pass through the large constrictions. Additionally, because the weight of the soil or glass beads passing through the geotextile determines the pore sizes, the larger particles, which weigh more, will change the results and suggest more large pores. Also, large trapped beads will block the small particles from passing. Another disadvantage of sieving method is; if the glass beads or the soil were vibrated for long time or immersed repeatedly for enough cycles, almost all of the beads/soil particles could pass through a single large hole in a geotextile. As a result, sieving method may provide the largest pore constriction size in the geotextile, but it can not provide the geotextile PSD (Fisher et al., 1996).

Method-2, TPSD: The pore size distribution is determined by using a mathematical model based on idea of mass per unit area and thickness of the geotextile, as well as the density and the diameter of the fibers (Fisher et al., 1996).

Method-3, NPSD: Numerical pore size determination is not commonly used in geotechnical designs today because these two methods (image analysis and minimum bubble pressure technique) are expensive, difficult and have some disadvantages (Fisher 1994). These methods are also not very useful when designing geotextiles for drainage purposes because
they don’t provide porosity and the shape of the pore channel. They only measure a pore size at a particular location within the pore channel (Fisher et al., 1996).

Method-4, VPSD: These methods are used to determine the pore sizes of geotextile that make the most contribution to measuring the free volume within the geotextile (Miller and Tyomkin, 1986), but don’t indicate the number of the pores and the pore constrictions. The extrusion and intrusion methods are similar in this type of volumetric distribution. The suction method and the liquid extrusion porosimetry, however, are different from mercury intrusion porosimetry (MIP). The suction method measures the pore volume at specific limiting sizes for one-way flow through the geotextile. In MIP method, mercury is intruded into the geotextile from all sides, and all free volume is measured. However, this is not necessarily the volume available for flow or storage. By measuring the voids, the true porosity is obtained. However, the true porosity includes volume-related pore space that does not influence filtration behavior. The extrusion test provides a modified porosity because of the one-way flow of the liquid out of the geotextile during the test. The porosity measured by this method will be more representative because it includes only those voids associated with flow through the geotextile as shown on Figure 2.4.
2.4.3 Selection of Geotextile PSD for Filtration Design

The MIP method provides the best representative PSD because of its multidirectional intrusion procedure, and the bubble point method should provide the smallest PSD because it measures constriction size, as illustrated in Figure 2.5.

Figure 2.4: Probable PSD in a Pore Channel as Measured by MIP, Liquid Extrusion Porosimetry and the Suction Method (Fisher, 1994)

Figure 2.5: PSDs for Various Testing Methods (after Bhatia and Smith, 1994)
However, sieving tests are the only test currently accepted by designers. As mentioned earlier the sieving methods do not represent the complete geotextile pore structure. Similarly, a TPSD is not recommended for design because pore sizes are determined from such parameters that are not easy to measure like fiber diameter and fiber density. The TPS method is useful only for comparison and analysis purposes. NPSD pore size method is useful for probabilistic and theoretical purposes, where the number of the pore channels needs to be known. However, this method won’t provide information on the flow capacity of the geotextile (Fisher et al., 1996).

It might seem that VPSD is the best method, because weight is directly related to volume. This method might also be a better indication of the flow in the geotextile, because VPSD determines the pore diameters that contribute the most pore volume. It may be these pores that govern the filtration behavior, especially regarding the drainage. One should consider the interconnections between the pores, especially in nonwoven geotextiles, and the ability of soil and water to flow out of one pore channel into another if the former channels become clogged. NPSD can’t take this issue into consideration. As seen in Figure 2.6 the VPSD measured by MIP is not significant terms of filtration behavior because it assigns too much volume to the larger pores. The maximum pore size is measured four times larger than the constriction size. This has no meaning because during filtration a soil particle might encounter the constriction first and never pass through the geotextile. So constriction size governs whether the soil particle passes or retains in the geotextile (Fisher et al., 1996). However, the space occupied by internal biofilm need not be that otherwise used by flowing liquid.
Recently, the bubble point method has been used to determine the pore size of geotextiles (Bhatia and Smith, 1994; and Fisher, 1994). This method is a current ASTM test (F 316) and is used for membrane filters, however, it has not been standardized for geotextiles. The flow rate of gas (instead of liquid) is measured in this test. The flow rate of gas is measured through a dry geotextile over a range of pressure. Then this same geotextile is saturated with a non-wetting liquid and the process is repeated. As the pressure is increased, fluid is forced from the initially saturated geotextile, beginning with the largest pores first. As the more liquid is extracted, the flow rate of gas increases, becoming closer to that measured with the dry geotextile under the same pressures. To calculate the percent pore area of a particular size, the flow rate through the wet geotextile is divided by the flow rate through dry geotextile at the same pressure. Finally, the pressure is related to the pore size (Bhatia and Smith, 1994; Fisher, 1994).
The bubble point method is probably the best PSD to represent filtration behavior of geotextiles, because it is the size of the pore constriction that determines whether a soil particle or suspended organic floc will pass (de Mello, 1977; Wates, 1980; and Kenny et al., 1985). Only the bubble point method can measure a complete, true pore constriction size distribution. For these reasons bubble point method is recommended for geotextile pore structure characterization, Figure 2.7.

Figure 2.7: Typical PSDs Obtained from Bubble Point Tests (after Fisher, 1994)

In conclusion, there are many methods available to determine the pore sizes of geotextiles. It is agreed by most designers that the PSD of a geotextile is a unique property of that geotextile, similar to the grain size distribution of a soil. Therefore, the bubble point test
method is considered advantageous because it can be performed quickly and efficiently, the results are repeatable, and the results provide an accurate estimate of geotextile permeability (Fisher et al., 1996).

2.5 Hydraulic Performance of Geotextiles

One of the main issues in using geotextiles is their performance once in contact with soil. Opening size, hydraulic conductivity, and soil diameter are very important criteria in selection of geotextiles. Geotextiles with very fine openings may clog the geotextile openings or active soil pores causing cake formation. Research shows that upward flow is more critical than the downward flow (Dierickx & Yuncuoglu, 1982, 1993).

2.5.1 Gradient Ratio Test

The gradient ratio test (ASTM D5101) is intended as a performance test for evaluation of soil/geotextile compatibility in filtration applications. The test involves permeation of water through a soil sample that is placed upstream of, and contact with, the candidate geotextile. The gradient ratio (GR) is defined by the ratio of hydraulic gradient in the soil/geotextile composite to that in the soil itself. Under ideal conditions the head loss is the same in each, GR=1. Any movement of soil particles out of the system will develop a more permeable zone upstream of the geotextile, and relatively smaller head loss in the soil/geotextile zone. If the GR is less than 1, the loss of fine particles could cause a piping failure. If the GR is greater than 1, then clogging by accumulation of fines on the geotextile is a problem, such that the intent to have the larger particles restrain the smaller one in their original location has not been successful, but they did not pass out of the system, and thus threaten the stability of the upstream soil body. A limit of GR=3 has been proposed as a performance-related design
criterion, Figure 2.8 (Haliburton and Wood, 1982). The gradient ratio test provides an attractive method for assessing soil/geotextile compatibility because the candidate geotextile is tested against the soil to be protected, water is permeated through the system, and any potential for piping or clogging can be observed by inspection (Fannin et al., 1996).

![Gradient Ratio Test Data](image)

**Figure 2.8: Gradient Ratio Test Data Used to Illustrate Geotextile Clogging Potential**

### 2.5.2 Soil and Geotextile Modifications

Several types of stable soil structures have been proposed in the soil just upgradient of the geotextile as illustrated on Figure 2.9 (Rollin and Lombard, 1988), and two impacts of particle impacts on the geotextile structure are shown on Figure 2.10 (Mylnarek et al., 1990). Soil particle retention at the soil/geotextile interface can be observed in well-graded soils forming a bridge network (Figure 2.9a). The silty soils or sandy soils with some clay content can cause the vault network at the geotextile/soil interface (Figure 2.9b). This could be a
desirable situation for the capture of suspended solids in the bioactive filter application. Finally, the term blinding is used to describe the mechanism occurring in a soil when the coarse particles retained by a geotextile are intercepting fines migrating from a soil. A layer of low permeable, clogged soil is established upstream of the coarse layer (Figure 2.9c). Another set of filtration mechanisms occur at or in the geotextile itself, as blocking and clogging, as shown on Figure 10 (Mlynarek et al., 1990). Blocking mechanism usually occurs in woven geotextiles that are not very thick or in heat-bonded nonwoven geotextiles. The soil particles block the water flow either within or above the openings.

Figure 2.9: Soil Stabilization Mechanisms in Geotextile Filtration: a) Bridge Network Formation b) Vault Network Formation c) Blinding Mechanism (Mlynarek et al., 1990)
Therefore, clogging occurs within the thicker structure of needle-punched nonwoven geotextiles. Clogging sites within the geotextile structure can be classified as cavern or funnel types (Rollins et al., 1977). The clogging level depends on the quantity of the clogging sites and the quantity of the fines carried into the fabric (Chang et al., 1996).

In the early work of Calhoun (1972) and Haliburton and Wood (1982), the gradient ratio (GR) test was used to carry out extensive investigations into clogging. The GR test has been developed to evaluate the potential fouling of a geotextile.

### 2.5.3 Criteria for Geotextile Filter Design

The permeability of the filter should be higher than the upstream soil’s permeability. On the other hand, the filter voids should be small enough to retain the upstream soil materials. However, it should be taken into account that the fine particles might get into the filter voids.
and result in excessive clogging of the filter with time and hence a large reduction in permeability (Wilson-Fahmy, Koerner and Koerner, 1996).

Table 2.2: Existing Geotextile Permeability Criteria (Christopher and Fisher, 1992)

<table>
<thead>
<tr>
<th>Source</th>
<th>Criterion</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giroud (1982)</td>
<td>$k_e = 0.1k_s$</td>
<td>No factor of safety is applied</td>
</tr>
<tr>
<td>FHwA (Federal Highway Administration)-NC/NS, e.g. Calhoun (1972); Haliburton et al. (1982); and numerous others</td>
<td>$k_e = k_s$</td>
<td>For use with noncritical applications, nonsevere soil conditions and steady state soil.</td>
</tr>
<tr>
<td>FHwA-C/S, e.g. Carroll (1983); Christopher and Holtz (1989)</td>
<td>$k_e = 10k_s$</td>
<td>For use with critical and severe soil or dynamic hydraulic conditions.</td>
</tr>
<tr>
<td>French Committee on Geotextiles and Geomembranes (1986)</td>
<td>Based on permittivity ($\Delta\phi$) with $\Delta\phi = 10^{3.5} k_s$</td>
<td>For following conditions: -critical use $10^5 k_s$ -less critical use $10^4 k_s$ -clean sand use $10^3 k_s$</td>
</tr>
</tbody>
</table>

where;

NC/NS = noncritical/nonsevere, C/S = critical/severe,

$k_e =$ geotextile permeability, $k_s =$ upstream soil permeability,

$\Delta\phi =$ geotextile permittivity (kg / t), $t =$ thickness of the geotextile

The design of a geotextile filter addresses three requirements: adequate permeability, proper soil retention and long-term performance over the service lifetime. Existing geotextile permeability criteria are given in Table 2.2.
A summary of soil retention criteria is available from Christopher and Fisher (1992) and is given in Table 2. Gradient ratio tests, long-term flow tests, or hydraulic conductivity ratio tests are required for critical/severe applications. For critical/severe applications, soil/geotextile filtration tests should be carried out (Calhoun (1972); Haliburton and Wood (1982); Giroud (1982); Carroll (1983); Christopher and Holtz (1989); Koerner (1994)). The most recent FHWA (Federal Highway Administration) criterion via Christopher and Holtz (1992) are as follows:

1-Permeability criteria (Christopher and Holtz (1992))

1a-Critical/severe applications: \( k_g = 10 k_s \)

1b-Less critical/less severe (with clean m-c sands and gravel) : \( k_g = k_s \)

2-Soil retention criteria (Christopher and Holtz (1992)) Table 2.3.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Steady State Flow</th>
<th>Dynamic, pulsating and cyclic flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50 % passing #200 sieve</td>
<td>( O_{95} = (0.5-8)d_{85} )</td>
<td>( O_{95} = 0.5d_{85} )</td>
</tr>
<tr>
<td>= 50% passing #200 sieve</td>
<td>( O_{95} = 0.3 \text{ mm} ) (For wovens &amp; nonwovens)</td>
<td>( O_{95} = 0.5d_{85} )</td>
</tr>
</tbody>
</table>

3-Excessive clogging criteria (Christopher and Holtz (1992))

3a-critical/severe

Perform soil/geotextile filtration tests with selected geotextile.

Do performance test; GR = 3
3b-less critical/nonsevere

\[ O_{95} > 3d_{15} \text{ for } C_u > 3 \]

If \( C_u = 3 \) select a geotextile with maximum opening size possible

Percent open area = 4 % for wovens

Porosity = 30 % for nonwovens

2.6 Geotextile Filters with Reactive Liquids

It has been found that geotextiles colonize microorganisms, and the result of their occupancy of pore space is that the biofilm affects the permeability or its alternate expression, permittivity. In laboratory studies with high-strength landfill leachates under anaerobic conditions, Koerner et al. (1990) reported major to severe clogging (75% to 100% flow reduction) for geotextiles due to biological activity. A limit on the decrease in permeability due to the biofilm was often found, however. Apparently, as pores clogged and the cross-plane flow rate decreased, so did the supply of the substrate necessary for required for the biofilm to grow. Hence, a steady state flow condition was eventually reached. It must be noted that clogging is a relative term, as the clean water geotextile filter permeability is often much larger than needed. The tolerance for loss in permeability in a particular design depends upon the hydraulic capacity required. However, the flow of fine waste and solid particles through the geotextile filter could clog the gravel and pipe portions of the collection trench system.

It is reasonable to expect that the extent of clogging depends upon the strength of the influent. Koerner and Koerner (1990) also state TSS and BOD\(_5\) values are generally considered to be the best indicators of the available biological activity. Typical landfill leachate values for BOD\(_5\) have been reported to be in the range of 3,000 to 20,000 mg/l. Lu et al. (1985) also
report values for NH$_3$ (ammonia) concentration at landfills as measured by ammonia nitrogen (NH$_3$-N) is in the range of 0 to 250 mg/l. Low values of leachate BOD$_5$ indicate that the leachate is generated from aged landfill wastes that have passed through the aerobic stage of decomposition and are undergoing anaerobic activity. In such a case, a decrease in permittivity would be attributed to soil particle intrusion into the geotextile filter by fine grained material rather than biofilm expansion into the pores.

Mlynarek et al. (1990) has reported a method of identifying biological growth within a geotextile filter through microscopic examination of the material using select epoxies which don’t harm the biological growth (Corcoran et al., 1996). The outside of exhumed landfill filters usually appears to have a filter cake formed on it. It is usually recommended that non-woven geotextile filters be selected for the construction of leachate collection systems.

### 2.7 Review of Darcy’s Law and Permeability

Koerner, Martin and DeGroot, (1987) showed that permeability has a linear relationship with density of the granular media. Porous media are constructed by particles with interconnected voids. The fluid flows in this structure when a driving force is available. The driving force is expressed by Bernoulli’s equation (Eq-1);

\[ h = \frac{p}{u} + \frac{v^2}{2g} + z \]  

(1)

where;

- $h = \text{total head or driving force}$
- $p = \text{pressure}$
- $u = \text{unit weight of the fluid}$
v = velocity

g = acceleration due to gravity

z = height above a given datum

The head loss due to the velocity is usually neglected in most uniform gravels because the velocities are very small. The head loss over a certain depth is called “gradient”. Once the relationship between the hydraulic gradient and the fluid velocity is established the actual value of permeability can be established. The slope of a linear relation between gradient and velocity gives the permeability value. Darcy, in 1856, developed the empirical relationship for sand filters as follows:

\[ v = ki \]  \hspace{1cm} (2)

\[ Q = kia \]  \hspace{1cm} (3)

where;

v = velocity, cm/sec

Q = flow rate, cm\(^3\)/sec

k = permeability, cm/sec

i = gradient = \( \frac{dh}{dl} \) = change in head, cm / length of specimen, cm

a = area of the specimen, cm\(^2\)

The Reynolds number governs the validity of the Darcy’s Law in soil filters. The Reynolds number is defined in eq-4:

\[ R_e = \frac{\nu d}{\mu} \]  \hspace{1cm} (4)
where;
\( R_e \) = Reynolds number
\( \rho \) = density of the fluid
\( v \) = mean velocity
\( d \) = diameter of average pore channel
\( \mu \) = absolute viscosity coefficient

Terzaghi and Peck showed that Darcy’s law is valid only for \( R_e < 1 \), which indicates a laminar flow.

Some empirical methods can provide the permeability merely from soil characteristics (eq-5).

Hazen hypothesized that;

\[
k = C (d_{10})^2
\]

where;
\( k \) = permeability, cm/sec
\( C \) = a coefficient between 100 to 150
\( d_{10} \) = the apparent opening size, cm

As with natural soil filters, geotextiles allow seepage perpendicular to the plane of the fabric. Geotextiles must have adequate permeability as well as soil retention. Fluid movement through geotextiles is defined by the term “permittivity”. In geosynthetic engineering permittivity is used instead of permeability. Therefore, the term “geotextile thickness” is eliminated. Permittivity is defined as follows (eq-6);
\[ \varepsilon = \frac{k}{t} \quad (6) \]

where;

\( \varepsilon \) = permittivity, \( \text{1/sec} \)

\( k \) = permeability, \( \text{cm/sec} \)

\( t \) = geotextile thickness, \( \text{cm} \)

There is an upper limit for the apparent opening size of nonwoven geotextiles and the percent open area of woven geotextiles. If the open area of the filter is larger than it is supposed to be then excessive soil particles pass through the geotextile. This phenomenon is called “soil piping”.

2.8 Clogging Mechanisms

The discussions in this chapter indicate that treatment of clarified wastewater that nonetheless has significant suspended organics at practical flow rates is probably done best with thick needled punched nonwoven geotextiles (NPNW). However, the mechanism of clogging by fine particles, bacteria and chemical precipitates in such materials is not well understood due to their complex structure and the wide pore size distribution of these geotextiles. Clogging may reduce the permeability below the required value for design. Marks (1975) showed that nonwoven geotextile clogging depends on the fiber density. Geotextiles with the greatest fiber density clogged faster than geotextiles with less fiber density. Increases in fiber density were related to decreases in geotextile pore sizes and permeabilities. Gourc (1990) arrived at the following conclusions; 1) clogging and blinding depends on the particles arriving at the pore space at a given time, 2) maximum clogging occurs when void sizes and particle sizes are the same, 3) hydraulic gradient inversely affect clogging, 4) turbulent flow increases the
level of clogging, and 5) the application of normal pressure decreases the pore size geotextiles that are compressible which then increases clogging and blinding. Williams (1989), Legge (1990) and Sansone (1991) indicated that slurry of fine particle suspended solids in water passing through a geotextile is the worst case condition.

Hoogerdendorn and Van der Meulen (1977) showed that algae and organic matter in natural waters was enough to clog geotextiles. Koerner and Ko (1982) performed a long-term filtration tests and showed that algae grew in their column and bleach was introduced to the columns to inhibit the algae growth. Canelli and Cazzuffi (1987), Gribb (1988) and Koerner and Koerner (1990) performed studies on landfill leachate filtration and showed that decreases in permeability was attributed to the deposition of suspended solids.
Chapter 3. Receiving Waters and Wastewater Treatment Processes

3.1 Introduction

This chapter summarizes the principles and practices of wastewater treatment to illustrate where the geotextile baffle contact system (GBCS) fits into the “engineer’s toolbox”, and to explain why the observed treatment occurred. Most wastewater originates with a local water supply, but its quality is degraded by residential, industrial, commercial or institutional use. Treatment is required before the water is returned to the natural environment. The origin, composition, pathway and quantities of wastewater streams are known, such that an effluent discharge is called a “point source” of measurable and predictable potential impact on natural receiving waters. Impacts on stream hydrology and morphology are generally limited, as the water supply is often from the same watershed, and usually a fraction of the natural flow. The continuous effluent discharge may actually limit low flow extremes, but in such cases, its constituents dominate the water quality. Thus, the issue with point sources is rarely with the discharged volume, but the pollutants suspended or dissolved in it. However, in engineering design scale, the volume treated is the major concern. A combination of processes are selected as appropriate to the flow magnitude, site constraints and receiving water standards, with solutions ranging from septic systems to large activated sludge plants.

Conventional wastewater treatment is basically controlled acceleration of physical and biological processes that can occur in streams, but would adversely effects the recreational, water supply and aquatic ecology value if they occurred in the natural waterways. For centuries, dilution was the only form of pollution “control”. In the early and mid 20th Century, primary treatment to remove denser and larger particles by screening, sedimentation and floatation was introduced. In the latter part of the 20th Century, especially after the Clean
Water Act, secondary treatment with biological methods to remove dissolved carbonaceous material became the standard. Advanced treatment to remove nitrogenous constituents and other nutrients may also be required, depending upon the receiving stream conditions, such as low flows or long detention times. Billions of dollars have also been invested to pre-treat industrial wastewaters before their discharge to a public collection and treatment system, to protect the integrity of the collection system and the wastewater treatment plant processes. However, receiving waters often still do not meet designated quality levels. As described in Chapter 1, treatment of point sources only is often insufficient. Meteorologically induced “non-point” pollution discharges can degrade receiving water quality and alter the aquatic habitat, especially in urban streams. Suburban detention basins modify runoff discharge rates, and inert solids may settle out, but most non-point discharge facilities are designed for hydraulic capacity only. Older drainage systems discharge directly to waterways with no modification of runoff rate or quality. Combined sewers are often controlled to direct as much flow as possible through interceptors to treatment, but the wet weather overflows to streams are rarely treated. With improvements in point source effluent reaching maturity, the impact of non-point discharges has been recognized. The focus is now on best management practices (BMPs) to reduce degradation of water resources from them. BMPs are less costly and more efficient than the use of unit processes to reduce pollutant loads. They include the flood control, soil erosion control, less organic loadings to natural streams. The EPA has delineated the following preventative measures, construction controls, and corrective maintenance and operation practices as suggestions for BMPs:

Preventative measures

1. Utilization of greenways and detention ponds
2. Utilization of pervious areas for recharge
3. Avoidance of steep slopes for development
4. Maintenance of maximum land area in a natural, undisturbed state

5. Prohibiting developments on floodplains

6. Utilization of porous pavements where applicable

7. Utilization of natural drainage features

Soil Erosion Controls at Construction Sites

1. Minimizing area and duration of soil exposure

2. Protecting soil with mulch and vegetative cover and erosion control material

3. Increasing infiltration rates

4. Construction of temporary storage basins or protective dikes to limit storm runoff

Corrective Maintenance and Operation Practices

1. Control of litter, debris and agricultural chemicals

2. Regular street sweeping and repair

3. Improved roadway deicing and materials storage practices

4. Proper use and maintenance of catch basins and drainage collection systems

5. On-site retention or detention of stormwater runoff

Advances in modeling biochemical reactions in streams support development of a Total Maximum Daily Load (TMDL) system that allocates pollution discharges consistent with a stream’s assimilative capacity.

The goal of this dissertation was to develop a BMP that produces a predictable effluent quality and applicable as appropriate to both point and non-point discharges. The discussion is limited to conventional biodegradable pollutants described by lumped indicators.
3.2 Wastewater Characterization, Quality Parameters, and Composition

3.2.1 Wastewater Characterization

Wastewater has physical, chemical, and biological characteristics. Physical indices in common use include total suspended solids (TSS), odor, temperature, density, color and turbidity. In typical domestic wastewater, about 75% of the suspended solids and 40% of filterable solids are organic material, a combination of carbon, hydrogen, oxygen and nitrogen. Sulfur, phosphorus and iron may also be present. The principal organic substances in wastewater are proteins (40-60%), carbohydrates (25-50%) and fats and oil (10%). Urea is an important compound in wastewater, but it decomposes rapidly such that its decomposition products such as ammonia are detected at the end of a collection system. Along with proteins, carbohydrates, fats and oils, and urea, wastewater may also contain small quantities of synthetic organics such as surfactants, detergents, volatile organic compounds, and pesticides. However, most organic constituents in wastewater are biodegradable, described by several indices: biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), and total organic carbon (TOC), as described in more detail in section 3.2.2.

Several inorganic indicators also describe water quality as a host for biological activity, including pH, chlorides, alkalinity, nitrogen compounds, sulfur, phosphorus and heavy metals. Gases often found dissolved in wastewater include oxygen, hydrogen sulfide (H$_2$S), and methane (CH$_4$).

Most organisms found in wastewater are classified as eukaryotes, eubacteria or archaeabacteria. Multicellular plants and animals, and protists such as algae, fungi, protozoa (unicellular) are eukaryotes. Most bacteria are classified as eubacteri, but methanogens, halophiles, and thermaacidophiles have distinctive cell chemistry and are termed
archaeobacterians. Further description of biological constituents of wastewater is given in section 3.7.1.

### 3.2.2 Critical Wastewater Quality Parameters

With many constituents in domestic wastewater and urban runoff, a set of lumped parameters to describe water quality has been developed. Five indices of universal use in wastewater treatment are as follows (Corbitt, Robert A., 1989):

**Suspended Solids:** Table 3.1 classifies the solids commonly found in wastewaters by size. Total suspended solids (TSS) consist primarily of organic particles with a specific gravity near or below unity that are not easily removed by sedimentation, but can be filtered. TSS is measured by forcing wastewater through a 0.45-µm pore filter after removing dense inert particulate solids. Material remaining on the filter after drying at 103°C is the TSS. TSS affects aesthetic quality, but also hosts microorganisms and exerts an oxygen demand.

Table 3.1: Size Classification of Wastewater Solids (Metcalf & Eddy, 1991)

<table>
<thead>
<tr>
<th>Particle classification</th>
<th><strong>Particle size, mm</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved solids</td>
<td>less than $10^{-6}$</td>
</tr>
<tr>
<td>Colloidal solids</td>
<td>$10^{-6}$ to $10^{-4}$</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>greater than $10^{-3}$</td>
</tr>
<tr>
<td>Settleable solids</td>
<td>greater than $10^{-2}$</td>
</tr>
</tbody>
</table>

**Biodegradable Concentration:** The basic index of a stream’s capability to support aquatic life is dissolved oxygen (D.O.). Biodegradation of organic material reduces D.O. However, all carbonaceous wastewater material does not have the same impact, nor are all components
carbonaceous. Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) characterize the potential of a discharge to affect the D.O.

BOD is measured in a batch process where a microorganism seed is allowed to degrade organics in a vessel incubated at 20°C. The rate of oxygen use is plotted as shown on Figure 3.1. The two indices extracted from such a record are the five-day BOD$_5$ and the ultimate BOD$_{ult}$. BOD$_5$ represents rapidly decomposed substrate such as proteins, carbohydrates and fats. BOD$_{ult}$ also incorporates oxygen used in degrading more resistant carbonaceous material and conversion of ammonia released by decomposition of organic material to nitrate.

![Figure 3.1: Typical Biochemical Oxygen Demand Curve (Vesilind, 1994)](image)

BOD$_5$ is the most widely used indicator of pollution potential, employed in several ways:

1. To determined the amount of oxygen required to stabilize the organic matter
2. To design the dimensions and operational parameters of treatment facilities.
3. To assess compliance with wastewater discharge permits.
COD is measured by placing a wastewater sample in a flask containing chromic acid, a strong oxidizing solution. After refluxing the mixture on a burner for two hours, the amount of chromic acid remaining in the flask is determined by titration. The amount of dichromate depleted during the test is proportional to the sample COD. This value, expressed in mg/l, is always larger than the BOD. It is often also useful to measure Total Organic Carbon (TOC) for mass balance analyses. One technique is to inject an aqueous sample into a high temperature oven under aerobic conditions, and use infrared spectroscopy to measure the amount of carbon dioxide (CO$_2$) produced.

**Pathogens:** Wastewater contains enteric (digestive tract) disease-causing organisms such as bacteria, virus, and protozoa, such as *Shigella dysenteriae*, *vibrio cholerae*, *salmonella spp.* and *salmonella typhi* bacteria and poliovirus. The most common indicator of pathogen content is fecal coliform, expressed as colonies/100 ml. Wastewater treatment effluent that is not disinfected (e.g., septic systems) and non-point discharges (rarely disinfected), carry pathogens among the microorganisms attached to organic particles comprising the TSS. The microorganisms employed in biological treatment are described in detail in section 3.7.1.

**Nutrients:** Nutrients used in the formation of biomass include carbon, nitrogen, phosphorous and sulfur. Domestic wastewater contains more carbon than nitrogen, and more nitrogen than phosphorous. Often, just the latter two are meant by the term “nutrients”. There are several measures of nitrogen content, including Total Kjeldahl Nitrogen (TKN). Because ammonia and nitrate are separately addressed in regulations, the concentrations of these compounds are measured individually. Nitrogen and phosphorus are essential to the growth of protista and plants and are thus also called biostimulants. Other elements such as iron are also required in trace amounts for biological growth. Because nitrogen is an essential building block in the synthesis of protein, the nitrogen content must be known to evaluate wastewater treatability.
However, where control of algal growths in the receiving water to prevent eutrophication is required, removal or reduction of nitrogen prior to discharge is often desirable. This process is highly dependent on the pH.

\[ \text{NH}_3 + \text{H}_2\text{O} \quad \xrightarrow{\text{NH}_4^+ \text{OH}^-} \quad \text{pH} > 7 \quad \text{equilibrium is displaced to the left, pH< 7 ammonia ion is predominant.} \]

**Dissolved Inorganic Solids:** Most inorganic salts dissolve in water. The Total Dissolved Solids (TDS) in an aqueous sample is measured by first filtering it through a 0.45 µm filter, which is then heated, first obtaining the water content at 103°C and the organic fraction at 550°C. The amount of material left after combustion at 550°C is the TDS.

### 3.2.3 Wastewater Composition

Lumped parameter values typically present in untreated domestic wastewater are shown on Table 3.2. Typical concentrations are given as mg/l in the table. Nitrate, a nutrient in producing eutrophication, is rarely present as a free compound in raw wastewater. It is a product of biological degradation or transformation of ammonia, itself the product of urea decomposition.
Table 3.2: Typical Untreated Domestic Wastewater Composition (Metcalf and Eddy, 1991)

<table>
<thead>
<tr>
<th>Contaminants</th>
<th>Concentrations (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weak</td>
</tr>
<tr>
<td>TDS</td>
<td>250</td>
</tr>
<tr>
<td>TSS</td>
<td>100</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>110</td>
</tr>
<tr>
<td>TOC</td>
<td>80</td>
</tr>
<tr>
<td>COD</td>
<td>250</td>
</tr>
<tr>
<td>Organic Nitrogen</td>
<td>8</td>
</tr>
<tr>
<td>Free NH$_3$</td>
<td>12</td>
</tr>
<tr>
<td>Nitrites</td>
<td>0</td>
</tr>
<tr>
<td>Nitrates</td>
<td>0</td>
</tr>
<tr>
<td>Organic Phosphorus</td>
<td>1</td>
</tr>
<tr>
<td>Inorganic Phosphorus</td>
<td>3</td>
</tr>
<tr>
<td>Chlorides</td>
<td>30</td>
</tr>
<tr>
<td>Sulfate</td>
<td>20</td>
</tr>
<tr>
<td>Alkalinity (CaCO$_3$)</td>
<td>50</td>
</tr>
<tr>
<td>Grease</td>
<td>50</td>
</tr>
<tr>
<td>Total Coliform (mpn/100ml)</td>
<td>$10^6$-$10^7$</td>
</tr>
</tbody>
</table>

3.3 Unit Wastewater Loadings

As noted earlier, the volume to be handled is a key parameter in selecting a wastewater treatment method. Tables 3.3 to 3.6 show typical unit generation rates for residences, commercial facilities, recreational facilities and institutions, respectively.
Table 3.3: Daily Wastewater Flow Rates from Residential Sources (Metcalf & Eddy, 1991)

<table>
<thead>
<tr>
<th>Sources</th>
<th>Unit</th>
<th>Flow range, gal/unit/ day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartment</td>
<td>Person</td>
<td>35-80</td>
</tr>
<tr>
<td>Hotel</td>
<td>Guest</td>
<td>30-55</td>
</tr>
<tr>
<td>Typical home</td>
<td>Person</td>
<td>45-90</td>
</tr>
<tr>
<td>Better home</td>
<td>Person</td>
<td>60-100</td>
</tr>
<tr>
<td>Summer cottage</td>
<td>Person</td>
<td>25-50</td>
</tr>
<tr>
<td>Motel, without kitchen</td>
<td>Unit</td>
<td>75-150</td>
</tr>
<tr>
<td>Trailer park</td>
<td>Person</td>
<td>30-50</td>
</tr>
</tbody>
</table>

Table 3.4: Daily Wastewater Flow Rates from Commercial Sources (Metcalf & Eddy, 1991)

<table>
<thead>
<tr>
<th>Source</th>
<th>Unit</th>
<th>Flow range, gal/unit/ day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport</td>
<td>Passenger</td>
<td>2-4</td>
</tr>
<tr>
<td>Auto service station</td>
<td>Vehicle served</td>
<td>8-15</td>
</tr>
<tr>
<td>Bar</td>
<td>Customer</td>
<td>1-5</td>
</tr>
<tr>
<td>Bar</td>
<td>Employee</td>
<td>10-16</td>
</tr>
<tr>
<td>Department store</td>
<td>Employee</td>
<td>8-12</td>
</tr>
<tr>
<td>Hotel</td>
<td>Guest</td>
<td>40-60</td>
</tr>
<tr>
<td>Hotel</td>
<td>Employee</td>
<td>8-13</td>
</tr>
<tr>
<td>Industrial building</td>
<td>Employee</td>
<td>7-16</td>
</tr>
<tr>
<td>Laundry (self service)</td>
<td>Machine</td>
<td>450-650</td>
</tr>
<tr>
<td>Office</td>
<td>Employee</td>
<td>7-16</td>
</tr>
<tr>
<td>Restaurant</td>
<td>Meal</td>
<td>2-4</td>
</tr>
<tr>
<td>Shopping center</td>
<td>Employee</td>
<td>7-13</td>
</tr>
<tr>
<td>Shopping center</td>
<td>Parking space</td>
<td>1-2</td>
</tr>
</tbody>
</table>
Table 3.5: Daily Wastewater Flow Rates from Recreational Facilities (Metcalf & Eddy, 1991)

<table>
<thead>
<tr>
<th>Source</th>
<th>Unit</th>
<th>Flow range, gal/unit/ day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartment, resort</td>
<td>Person</td>
<td>50-70</td>
</tr>
<tr>
<td>Cabin, resort</td>
<td>Person</td>
<td>8-50</td>
</tr>
<tr>
<td>Cafeteria</td>
<td>Customer</td>
<td>1-3</td>
</tr>
<tr>
<td>Cafeteria</td>
<td>Employee</td>
<td>8-12</td>
</tr>
<tr>
<td>Campground</td>
<td>Person</td>
<td>20-40</td>
</tr>
<tr>
<td>Country club</td>
<td>Member present</td>
<td>60-130</td>
</tr>
<tr>
<td>Country club</td>
<td>Employee</td>
<td>10-15</td>
</tr>
<tr>
<td>Dining hall</td>
<td>Meal served</td>
<td>4-10</td>
</tr>
<tr>
<td>Hotel, resort</td>
<td>Person</td>
<td>40-60</td>
</tr>
<tr>
<td>Theatre</td>
<td>Seat</td>
<td>2-4</td>
</tr>
<tr>
<td>Visitor center</td>
<td>Visitor</td>
<td>4-8</td>
</tr>
</tbody>
</table>

Table 3.6: Daily Wastewater Flow Rates from Institutional Facilities (Metcalf & Eddy, 1991)

<table>
<thead>
<tr>
<th>Source</th>
<th>Unit</th>
<th>Flow range, gal/unit/ day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospital, medical</td>
<td>Bed</td>
<td>125-240</td>
</tr>
<tr>
<td>Hospital, medical</td>
<td>Employee</td>
<td>5-15</td>
</tr>
<tr>
<td>Rest home</td>
<td>Resident</td>
<td>50-120</td>
</tr>
<tr>
<td>School</td>
<td>Student</td>
<td>15-30</td>
</tr>
<tr>
<td>Dormitory</td>
<td>Student</td>
<td>50-100</td>
</tr>
</tbody>
</table>

Some wastewater flow generators are seasonal, but all show a diurnal variation. Small treatment systems display the most severe fluctuations in flow rate around these mean values. The peaking factor is the ratio of the peak flow rate to the average day derived from the preceding tables. Table 3.7 shows typical peaking factor values for small generators. Typical per capita residential pollutant unit loadings are shown on Table 3.8. BOD$_3$ and TSS values
are typically increased by 20% for households with kitchen garbage grinders, but the nutrient loadings are not significantly affected.

Table 3.7: Small Generator Wastewater Flow Peaking Factors (Metcalf & Eddy 1991)

<table>
<thead>
<tr>
<th>Peaking factor*</th>
<th>Individual residence</th>
<th>Small commercial establishments</th>
<th>Small community</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak hour</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Peak day</td>
<td>2.5</td>
<td>3</td>
<td>2.5</td>
</tr>
<tr>
<td>Peak week</td>
<td>2</td>
<td>2.5</td>
<td>1.75</td>
</tr>
<tr>
<td>Peak month</td>
<td>1.5</td>
<td>1.5</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Table 3.8: Typical Per Capita Wastewater Constituents (WPCF “Nutrient Control” FD-7, 1983)

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD₅</td>
<td>0.18 lb/day</td>
</tr>
<tr>
<td>TSS</td>
<td>0.2</td>
</tr>
<tr>
<td>NH₄</td>
<td>0.007</td>
</tr>
<tr>
<td>Organic Nitrogen</td>
<td>0.02</td>
</tr>
<tr>
<td>TKN</td>
<td>0.027</td>
</tr>
<tr>
<td>Total P</td>
<td>0.008</td>
</tr>
</tbody>
</table>

### 3.4 Receiving Water Concerns

Natural waters are living ecosystems, containing material and hosting biological activity. Groundwater discharged to streams as base flow conveys materials leached from geological weathering processes. Surface water ecosystems are also sustained by material conveyed by runoff from uplands and wetlands. The C-N-S recirculation cycle is shown on Figure 3.2. A hierarchy of energy extraction by organisms is illustrated on Figure 3.3. One organism’s waste is another’s substrate. Degradation rates vary, but correspond to oxygen usage, as
implied by Figure 3.1. Often, the most immediate effect of effluent discharge is disturbance of both the density and diversity of aquatic organisms, as illustrated in Figure 3-4.

Figure 3.2: Aerobic C, N and S Cycles (After McGaueny, 1968)

Figure 3.3: Energy Loss in Biodegradation (After McGaueny, 1968)

The types and amounts of microorganisms vary with the source. The TSS in secondary treatment effluent is activated sludge biomass not captured in clarifiers. The microorganisms in primary or septic tank effluent include fecal coliforms of human origin. Urban runoff
includes similar organisms from animal waste. In any case, the sudden introduction of competing microorganisms upsets the local balance, and the net increase in active biomass accelerates biodegradation and oxygen depletion. The discharged effluent may have different water quality indices than the receiving water, including dissolved oxygen (DO), temperature, turbidity, pH and TDS. The substrate released favors some species, and not others. Native species that are not comfortable with these conditions die or migrate elsewhere. The phenomenon shown on Figure 3.4 thus depends upon the characteristics of the effluent, the degree of dilution in the natural flow, and mixing conditions. The species diversity can be restored downstream, but this is difficult in urban areas when there is often a series of discharges along a stream.

Figure 3.4: Effluent Discharge Effects on Microorganism Diversity and Density (Vesilind, 1994)

Water quality indices change rapidly in a stream, such that it is difficult to recover representative samples of the aquatic habitat condition. Alternatively, the degree of stream impairment, if any, can be characterized by monitoring the density and diversity of benthic (bottom-dwelling) macro invertebrates, such as mayflies, other larvae, crayfish and worms. Their seasonally varying diversity (“taxa richness”) reflects habitat quality better than does a water quality grab sample. Indices such as the Hilsenhoff Biotic Index (HBI) compare the
populations of species tolerant and intolerant of organic pollution. Designation of stream sections on an “unimpaired” to “impaired” scale is also correlated with erosive concentrated runoff or CSO discharges which affect the physical habitat (stream morphology) as well as the water quality. Hence, the diversity or density of aquatic life may not be as appropriate an indicator of the impact of treated wastewater effluent as for weather related discharges.

As also noted earlier, the basic indicator of stream health for aquatic organisms is DO. As it decreases from the saturated value (about 9.2 mg/l at 20°C), aquatic life diversity decreases. Thus, stream classifications and standards are often based on DO depletion. Organic material in dissolved and suspended (particulate) form is a substrate or food source for organisms present in wastewater or non-point sources, and naturally occurring in streams. Depending upon the initial wastewater quality and the treatment that is done, the rate of biodegradation varies, as shown on Figure 3.3. The corresponding variation in the oxygen demand rate is shown on Figure 3.5. L is the ultimate oxygen demand, Since the long term need for oxygen is L and the amount of oxygen still needed at any time t is z, the amount of oxygen used at any time t is y=L-z.
The classical Streeter-Phelps analysis is used to predict the oxygen sag curve downstream of the discharge shown on Figure 3.6, which indicates the value and location of the lowest DO. Both curves shown could represent the same effluent discharged either into different streams or to a particular stream at different stages. The upper curve would represent a fast flowing stream, while the lower one represents a sluggish, deep stream. In either case, the rate of BOD exertion initially exceeds the reoxygenation rate, as the readily decomposed materials are consumed, causing decrease in the DO. Eventually, re-oxygenation overtakes the rate of depletion, and DO recovers.
The rate of deoxygenation is expressed as \(-k_1 z\), where \(z\) is the amount of oxygen still required at any time, i.e., the BOD remaining in the water. The term \(k_1\) is the deoxygenation constant, which depends on the waste type, temperature and stream velocity, in days\(^{-1}\) units.

The rate of stream reoxygenation is expressed as \(k_2 D\). The term \(D\) represents the current deficit from the saturation DO level, and \(k_2\) is the reoxygenation constant, with units of days\(^{-1}\). The value of \(k_2\) depends upon stream velocity and depth, as shown on Table 3.9.

Table 3.9: Typical Values of Reoxygenation Constant (Vesilind, 1994)

<table>
<thead>
<tr>
<th>Type of waterway</th>
<th>(k_2) at 20(^\circ)C (days(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small ponds or backwaters</td>
<td>0.1-0.23</td>
</tr>
<tr>
<td>Sluggish streams</td>
<td>0.23-0.35</td>
</tr>
<tr>
<td>Large streams, low velocity</td>
<td>0.35-0.46</td>
</tr>
<tr>
<td>Large streams, normal velocity</td>
<td>0.46-0.69</td>
</tr>
<tr>
<td>Swift streams</td>
<td>0.69-1.15</td>
</tr>
<tr>
<td>Rapids</td>
<td>&gt;1.15</td>
</tr>
</tbody>
</table>
High turbidity, settled solids and low DO adversely affect aquatic life. Incompletely treated effluent discharge may result in an oxygen level below that needed to support some types. The end products of complete aerobic degradation (mineralization) of organics are CO\(_2\) and H\(_2\)O, but in an anaerobic condition, methane (CH\(_4\)), noxious hydrogen sulfide (H\(_2\)S) and other gases are produced. For wastewater discharges, the oxygen sag curve is usually computed for the seven-day low flow for a ten-year return period. The maximum effluent BOD is determined to avoid violating the minimum acceptable DO level for the stream use classification. When analysis or monitoring demonstrate that conventional secondary treatment will not produce compliance with the minimum DO, more stringent treatment is required, perhaps seasonally. At higher flows, the oxygen deficit is not as severe, because the higher stream flow provides more dilution and the higher velocity supports faster reoxygenation. Consequently, the same quantity and quality of runoff or CSO discharge would not have the same effect on stream oxygen levels as would wastewater effluent discharged continuously, rain or shine, drought or flood. As noted earlier, wastewater also contains nutrients that can cause eutrophication, the excessive growth of algae. This condition reduces light penetration and oxygen transfer into the underlying water. Decomposition of sinking vegetative mass further depletes oxygen at depth. Nitrate and phosphorus support the algae growth as nutrients, either, which can be the limiting parameter. Since phosphorus is a non-volatile element, controlling eutrophication usually requires limiting the nitrate concentration in the effluent. Figure 3.7 shows the various forms of nitrogen in biodegradation sequence downstream from a discharge, or in a treatment plant, commencing with ammonia release from organic compounds and ending with mineralization to nitrogen gas. The last step requires anaerobic conditions.
Nitrate sources include onsite wastewater disposal, over-fertilized surfaces, and atmospheric washout (Riley, 2002). Ammonia, an intermediate product of organic nitrogen decomposition, is toxic to aquatic life above certain concentrations, and its conversion to nitrate requires dissolved oxygen. Groundwater is a source of potable water that is often untreated. Drinking Water Standards are ammonia (<2 mg/l) and nitrate (< 10 mg/l).

**3.5 Wastewater Treatment**

Wastewater treatment units and processes include three types of procedures to meet secondary standards;

1. Preliminary treatment to remove grit and large objects
2. Primary sedimentation to remove settleable and floatable solids and equalize flow
3. Secondary biological treatment to remove soluble BOD₃ and the balance of the TSS

Typical removal rates are shown on Table 3.10, lumping preliminary and primary together, and illustrating the typical results of two common methods of biological treatment of carbonaceous material. Removing nutrients is advanced treatment.
### Table 3.10: Typical Treatments with Common Unit Operations & Processes

<table>
<thead>
<tr>
<th>Unit Operation</th>
<th>BOD₃ Removal, %</th>
<th>TSS Removal, %</th>
<th>Organic N Removal, %</th>
<th>Ammonia Removal, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Treatment</td>
<td>30-40</td>
<td>50-65</td>
<td>10-20</td>
<td>0</td>
</tr>
<tr>
<td>Activated Sludge (suspended growth)</td>
<td>80-95</td>
<td>80-90</td>
<td>15-50</td>
<td>8-15</td>
</tr>
<tr>
<td>Trickling Filters (attached growth)</td>
<td>65-85</td>
<td>60-85</td>
<td>15-50</td>
<td>8-15</td>
</tr>
</tbody>
</table>

### 3.6 Physical Treatment and Physical Treatment Operations

#### 3.6.1 Preliminary Treatment

Preliminary treatment protects equipment from large or abrasive objects in the influent stream (screening and grit removal) and, in some cases, conditions wastewater (comminution) to ease subsequent operations. The most objectionable aspect of raw sewage discharge into watercourses is floating material. Thus, screens are the oldest treatment technique. Bar screens with 1 in. to 2 in. slots are placed at the head of a facility to intercept large objects and floating debris. Stainless steel or fabric microscreens with 0.01 to 0.06 mm openings may also be used at the downstream end of a plant to intercept residual suspended solids from biological treatment processes. Grit chambers remove sand and other inert material from the influent. Gravity grit chambers are shallow and rectangular. A uniform velocity; typically about 1 ft/s, allows denser particles settle while the lighter organic materials remain in suspension. In many plants, especially those without a separate primary treatment unit, comminutors grind the organic solids into particles of 0.3 cm or less in diameter.
3.6.2 Primary Sedimentation

Most wastewater treatment plants use a settling tank (also called sedimentation tanks or primary clarifiers) to remove as much organic material (See Table 3.2) as possible. As the solids settle the bottom of the tank, clarified liquid flows out over a weir. Primary treatment units also provide detention time for lighter materials, such as non-aqueous fluids, to coalesce and float to the surface for removal by skimming. As indicated on Table 3.9, conventional primary wastewater treatment removes about one half of the solids and one third of the BOD$_5$ from raw wastewater. Primary treatment also provides flow equalization to reduce fluctuation in wastewater quality and quantity feed to biological treatment units that follow. Secondary clarifiers, using the same principles, collect active biomass produced by biological processes. Major parameters in sedimentation design are the cross-sectional and footprint area, detention time, depth and overflow rate. Figure 3.8 shows a typical rectangular clarifier.

![Figure 3.8: Longitudinal Cross-Section of a Rectangular Sedimentation Tank](image)

Sedimentation tanks are generally divided into four zones: inlet, outlet, sludge accumulation, and settling. The first two zones dampen the currents caused by liquid entering or leaving the vessel as influent or effluent, respectively. The sludge accumulation zone stores the settled solids. Sedimentation considered to happen only in the fourth (settling) zone.
Ideal gravity sedimentation depends upon the settling velocity \( V_s \) of an individual spherical particle. In the rectangular tank shown, the horizontal velocity component, \( V_x \), is equal to the flow rate, \( Q \) (in \( \text{ft}^3/\text{sec} \) units) divided by the cross-sectional area “A” normal to the flow. The vertical component of the settling velocity, \( V_y \), is expressed by Stokes law:

\[
V_y = \frac{D^2 (G_s - 1)}{18\mu}
\]  

(1)

Where:

- \( D \) = particle diameter (see Table 3.1)
- \( G_s \) = specific gravity of solid
- \( \mu \) = dynamic viscosity of fluid

The net particle velocity derived from the vector algebra is \( V_s \), and it follows the trajectory shown. A particle with settling velocity \( V_s \), entering the settling zone at the surface will stay in suspension and be conveyed in the effluent flowing over the discharge weir. If this same particle entered just below the surface it would have just been removed, as shown on Figure 3.8. As rectangular tanks are wider, the horizontal \( V_x \) decreases. However, the tank size or detention time \( (Q/\text{volume}) \), or “footprint” is limited, for economy and space constraints. Hence, widening also shortens the path length, and in that regard, reduces the likelihood of interception of smaller particles. The basic index of sedimentation that is used in practice is the surface settling rate, which is expressed in terms such as gallons/day/\( \text{ft}^2 \). This term can be simplified to a velocity term analogous to \( V_s \). As the surface settling rate decreases, the tank size, detention time and capture increase, but so does the cost. Typical primary sedimentation tanks have surface settling rates in the range of 300 to 500 gpd/\( \text{ft}^2 \).
Direct use of Stokes’ law not only depends upon the idealization of spherical particles, but on an assumption that each particle falls individually. Sedimentation behavior is actually grouped into four classes depending on the characteristics and solids concentration: Class I sedimentation applies to dilute solutions containing discrete particles that do not tend to flocculate, and thus settle individually, as described above. Class II sedimentation describes a mixture of inert particles; suspended solids and flocculated suspensions with a broad range of sizes and surface characteristics, which thus settle at different rates. Class II is generally used to model primary wastewater settlement and water treatment sedimentation. The suspended solids concentration is assumed to be high enough that sedimentation is “hindered”, with particles interacting with each other to some extent. Class III refers to a still higher concentration of suspended solids, as in activated sludge and flocculated suspensions. This tends to produce zone settling, subdivided into hindered settling, transition, and compression zones. Class IV sedimentation describe thickening of sludges that derived from the other sedimentation methods. In this case, particles are in frequent, perhaps continuous physical contact with each other.

The very high efficiency in further clarification of the primary treatment effluent in the baffles (described in detail in Chapter 5) is, in part, attributable to the low influent TSS. Because it was less than 100 mg/l, the Class I sedimentation model tended to prevail, whereas the SEWPCF tanks, handling a heterogeneous raw wastewater, was Class III and thus, did not remove the smaller particles that it would if Stoke’s law prevailed. The high removal of the raw wastewater sample (TSS> 300 mg/l) also described in Chapter 5 is definitely Class III, and due in part to the larger particle sizes. However the removal of smaller particles as well within a few channels requires further explanation.
3.6.3 Other Particle Removal Systems

Conventional sedimentation basins need large areas and do not remove all small particles. Table 3.9 indicates typical removal of 50%-65% of the TSS, but a range from 30% to 90% has been reported (EPA, 1975). Bergheim et al. (1996) showed that the raw wastewater TSS concentration must be above 200-300 mg/l to provide removal rates greater than 80%. They also showed that removal rates fell with decreasing particle size (<70 micron), as would be expected from the labels of Table 3.2. These authors concluded that to remove smaller particles by gravity, a coagulant as is used in potable water treatment would be necessary. It is noted that, in the geotextile baffle system, other mechanisms such as filtration are in use.

However, centrifugal swirl separators and other methods have been developed to improve removal rates and use less surface area. (Makinen et.al. 1998). Plate or tube settlers, also called lamella settlers, increase sedimentation effectiveness by using a sequence of inclined tubes or plates several inches apart. This increases the settling area per unit volume. However, Summerfeldt (1999) found that these units require a constant flow to attain good removal rates. A variation called biological lamella sedimentation uses blocks of settlers installed in a sedimentation basin below the water surface. TSS removal is assisted by growth of biofilm on the block surfaces that attracts small particles (Characklis, 1990). The geotextile baffle coupons whose attachment surfaces are two inches apart is a similar geometry, with an added feature that the flexible geotextiles dampen local cross-currents.

Odd-Ivar Lekang et. al. (2000) evaluated the use of biological lamella sedimentation to treat effluent from fish tanks. A sedimentation basin with an inclined bottom had a wall of bioblocks consisting of spun polyethylene (PE) pipes with an open pore structure and a large surface area, nested together to form blocks. TSS removal was reported up to 40%, and up to 37% of the COD was removed. In other types of biologically active filters with low water
velocity, electrical interactions between the organic particles and the charged media surface also encourage particle attachment (Mc Dowell-Boyer et. al. 1986).

While regarded in wastewater treatment more as biological treatment rather than a solid separation method, filters are used in many fields to separate particles from fluids flowing through a porous medium, including colloidal particles. The most common type used in wastewater treatment is gravity filtration through a granular media bed, producing a combination of “medium” and “depth filtration” as described in Chapter 2 and illustrated on Figure 2.3. The latter is reproduced as Figure 3.9 for convenience. Removal mechanisms include interception, straining, flocculation, and sedimentation. Initially, surface straining takes place, which results in accumulation of deposits in the upper portion of the filter. With reduced exposed pore area, the velocities in the remaining surface pores increase and carry the particles into the filter. The particle removal zone progressively penetrates deeper into the bed. The localized turbulence also increases contact between particles and the pore walls. The former process promotes flocculation, resulting in trapping of larger flocs.

As described in Chapter 1, short-circuiting of influent through the porous, pervious baffles defining the sinuous channels reduced the TSS by filtration. As the fabrics clogged, the particle removal mechanism shifted to surface contact attraction.
Figure 3.9: Particle Removal Mechanisms in a Granular Filter (Metcalf & Eddy, 1991)
3.7 Secondary (Biological) Wastewater Treatment

Biological treatment reduces wastewater organic content and often, nutrients as well. Microorganisms in raw wastewater continuously provide innoculant for a culture that uses suspended and dissolved biodegradable materials as substrate, mineralizing them or generating byproducts and cell tissue. Aerobic treatment is preferred as it produces few intermediate byproducts, and thus allows direct effluent disposal.

As noted earlier, the basic classifications of biological treatment are fixed-film and suspended-solids growth. Table 3.11 illustrates key indices of suspended growth methods. Aeration time, a hydraulic detention time, is a major cost. Two related operational parameters are used to control the processes, the F/M ratio, the ratio of the mass of substrate or food (F) to active biomass (M), and the Mean Cell Residence Time (MCRT). The latter is also called the solids retention time (SRT) and is often labeled \( \tau_c \). Both parameters are used to adjust the amount of active biomass to the organic loading rate. The intent is to maintain the biomass in a stressed (endogenous) condition, forcing it to mineralize substrate rather than grow excess cell mass. Microorganisms also need nutrients and oxygen. Nutrients are rarely a restriction with domestic wastewater; their removal is often the problem. The rate of substrate utilization is proportional to the rate that oxygen must be supplied. While the geotextile baffle system is an attached growth method, it is similar to extended aeration in having continuous low rate air bubbling to enhance sludge digestion with a 22.5 hour aeration period.
Table 3.11: Loading and Efficiencies of Activated Sludge Systems (Vesilind, 1994)

<table>
<thead>
<tr>
<th>Process</th>
<th>Loading; F/M (lb BOD/d/lb MLSS)</th>
<th>Aeration Period (Hour)</th>
<th>BOD Removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended Aeration</td>
<td>0.05-0.2</td>
<td>30</td>
<td>95</td>
</tr>
<tr>
<td>Conventional Activ. Sludge</td>
<td>0.2-0.5</td>
<td>6</td>
<td>90</td>
</tr>
<tr>
<td>High Rate Activated Sludge</td>
<td>1-2</td>
<td>4</td>
<td>85</td>
</tr>
</tbody>
</table>

3.7.1 Organisms in Wastewater

Many naturally occurring microorganism types extract substrate from wastewater. These are;

**Bacteria**

Bacteria are the simplest forms of prokaryotic protista that use soluble food, including organic wastes, and are capable of self-reproduction. Bacterial cells have rod, sphere, and spiral shapes, and range in size from 0.5 to 5 µm. They reproduce by binary fission, where a mature cell divides into two new ones. In many species associated with water and wastewater treatment, the process of reproduction, growth, maturation, and fission occurs in 20-30 min under ideal environmental conditions. Some bacterial species form spores in adverse condition, with the tough coating providing resistance to heat, lack of moisture, and lack of food supply. Fortunately, only one spore forming bacterium, *Bacillus anthracis*, is pathogenic to human. Based on their energy source, bacteria are divided in to two groups: heterotrophic and autotrophic, although some types of bacteria function in both groups.

*Heterotrophic bacteria* use decaying organic material as both their energy and carbon sources for synthesis. Heterotrophic bacteria are classified by oxygen need. *Aerobes* require free dissolved oxygen. *Anaerobes* oxidize organics in the absence of dissolved oxygen.
Facultative bacteria use dissolved oxygen when it is available, but can also respire and multiply in its absence. *Escherichia coli*, a fecal coliform, is facultative. Autotrophic bacteria use carbon dioxide as their carbon source and oxidize inorganic compounds as an energy source. The most important autotrophs in wastewater treatment are nitrifying, sulfur, and iron bacteria. Nitrifying bacteria perform the following reactions:

\[
\text{NH}_3 \text{ (ammonia)} + \text{Oxygen} \rightarrow \text{NO}_2^- \text{ (nitrite)} + \text{energy} \\
\text{NO}_2^- \text{ (nitrite)} + \text{Oxygen} \rightarrow \text{NO}_3^- \text{ (nitrate)} + \text{energy}
\]

Autotrophic sulfur bacteria, *Thiobacillus*, convert hydrogen sulfide (H$_2$S) to sulfuric acid:

\[
\text{H}_2\text{S} + \text{Oxygen} \rightarrow \text{H}_2\text{SO}_4 + \text{energy}
\]

Sulfur bacteria grow in moisture condensed on the crowns of sewers carrying septic wastewater. Because they can live at low pH, sewers must be corrosion-resistant. Iron bacteria oxidize inorganic ferrous iron (Fe$^{+2}$) to ferric iron (Fe$^{+3}$) as an energy source

\[
\text{Fe}^{+2} + \text{Oxygen} \rightarrow \text{Fe}^{+3} + \text{energy}
\]

The filamentous bacteria thrive in pipes carrying water with dissolved iron, and deposit oxidized iron, Fe(OH)$_3$ as yellow or reddish slimes.

**Fungi**

The term “fungi” is commonly used to refer to microscopic nonphotosynthetic plants, including yeast and molds. The most common type of yeast used in industrial fermentation is the genus *Saccharomyces*. *Saccharomyces cerevisiae* is used by bakers, distillers, and
It is a facultative single celled fungus, 5-10 µm in size, and reproduces by budding. The aerobic reaction yields more energy than the anaerobic process. Under anaerobic conditions, the yeast produces alcohol as an end product through the following reactions:

**Anaerobic:**  Sugar $\rightarrow$ alcohol + CO$_2$ + energy

**Aerobic:**  Sugar + Oxygen $\rightarrow$ CO$_2$ + energy

Molds are parasitic filamentous fungi whose structure resembles higher plants, composed of branched, filamentous, threadlike growths called hyphae. Molds are nonphotosynthetic, multicellular, heterotrophic and aerobic, and reproduce by forming spores. They grow best in low pH solutions (pH 2-5) that are high in sugar content. A large growth of molds, induced by low pH, produces a filamentous activated sludge that does not settle easily.

**Algae**

Algae are microscopic photosynthetic plants. They perform the following reaction:

sunlight

\[
\text{CO}_2 + 2\text{H}_2\text{O} \quad \xrightarrow{\text{dark reaction}} \quad \text{new cell tissue} + \text{O}_2 + \text{H}_2\text{O}
\]

In photosynthesis, pigments, usually green chlorophyll, biochemically convert the energy in sun’s rays to a form usable for plant synthesis, increasing the number of algae. Autotrophic algae use CO$_2$ or bicarbonates in solution as their carbon source, and phosphorous (as phosphate) and nitrogen (as ammonia, nitrite, or nitrate) are nutrients necessary for growth. Some blue-green algae species can fix atmospheric nitrogen. Oxygen is released as a byproduct of the biochemical conversion of water. When sunlight is absent, algae perform the dark reaction, degrading stored food or their own protoplasm to provide energy for survival.
Algae grow most rapidly in stabilization ponds that are rich in inorganic nutrients and carbon
dioxide released from bacterial decomposition of waste organics. Green algae *chlorella* are
commonly found in oxidation ponds.

**Protozoans and Higher Animals**

Protozoans are aerobic single-celled animals that also reproduce by binary fission. They have
a complex digestive system to handle solid organic substrate as their carbon and energy
sources. Protozoans feed on bacteria and algae, and thus play a vital role in aquatic
ecosystems, activated sludge, trickling filters, and oxidation ponds. Free-swimming
protozoans move through water, ingesting organic matter at a very high rate. Stalked
protozoans attach by a stalk to organic particles and use cilia to propel their head through the
water to bring in food. Other protozoans have long hairlike flagella that move with a whiplike
action. *Amoeba* move and ingest organics through the action of their mobile protoplasm.
Rotifers are the simplest form of multicellular animals. They are also aerobes that feed on
solid organics. They use the cilia around their head to catch food. Rotifers are used as
indicators of unpolluted waters, being found in streams and lakes.

3.7.2 Metabolism, Energy, and Synthesis

Metabolism incorporates a series of oxidation and reduction biochemical processes
performed by organisms to yield energy for tissue synthesis, motility, and respiration. In
general use, metabolism indicates both catabolism and anabolism, both degradation and
assimilative reactions. *Oxidation* is the addition of oxygen, removal of hydrogen, or removal
of electrons. *Reduction* is the removal of oxygen, addition of hydrogen, or addition of
electrons. In autotrophic metabolism, reduced inorganic materials are oxidized, yielding
energy to extract carbon from carbon dioxide. In heterotrophic metabolism energy-yielding
reactions use reduced organic compounds as hydrogen donors, and oxidized organic or inorganic materials are the hydrogen acceptors. Organic matter releases energy during biological oxidation by dehydrogenation of the substrate followed by transfer of hydrogen, or electrons, to an ultimate acceptor. The higher the ultimate acceptor on the energy scale, the greater the energy yields from oxidation of 1 mole of a given substrate. In aerobic metabolism, oxygen is the ultimate hydrogen acceptor, yielding the greatest amount of energy. In facultative respiration, both aerobic and anaerobic, using oxygen bound in nitrates and sulfates yields less energy than the aerobic processes. Strictly anaerobic respiration provides the lowest yield of energy.

Relationships between metabolism, energy, and synthesis are critical in biological treatment. Energy for cell synthesis is the product of metabolism. The highest synthesis rate occurs when energy yield is a maximum value, with organic material providing both energy (Fig 3.3) and material for cell synthesis in heterotrophic metabolism. An aerobic process results in complete metabolism and synthesis of substrate, producing a large biomass, but also a high degree of mineralization. Anaerobic processes are incomplete metabolism, with a smaller biological growth rate and high-energy byproducts such as acetic acid and methane.

The two common sources of carbon for bacterial cell tissue synthesis are organic matter and CO$_2$. Heterotrophs use organic carbon to form cell tissue, while autotrophs use CO$_2$. Phototrophs use light as the energy source, and chemotrophs (nitrifying bacteria) use chemical oxidation. Chemoheterotrophic organisms are of primary importance in wastewater treatment due to their need for organic compounds as both carbon and energy source. However, when the goal is to convert ammonia to nitrate, chemoautotrophic nitrifying bacteria are also significant. Microorganisms also require inorganic nutrients such as N, S, P, K, Mg, Ca, Fe, Na and Cl.
Chemoheterotrophic organisms may be further grouped by their metabolic type and oxygen needs. Organisms generating energy by enzyme-mediated electron transport from an electron donor to an external electron acceptor have a respiratory metabolism. The process is aerobic respiration when oxygen is the electron acceptor. Fermentative metabolism does not involve an external electron acceptor, and is less efficient in yielding energy than respiration.

Inorganic compounds such as nitrate and nitrite function as electron acceptors for some respiratory organisms in the absence of oxygen (these organisms are referred to as anoxic). Organisms that generate energy by fermentation and can exist only in an environment that is devoid of oxygen are obligatory anaerobic. Facultative anaerobes have the ability to grow in either the presence or absence of molecular oxygen.

Much of the organic material in wastewater is large molecules that cannot penetrate bacterial cell walls. Bacteria hydrolyze larger molecules to smaller, less complex fractions to allow cell assimilation. Biochemical reactions also hydrolyze complex carbohydrates to soluble sugar compounds, protein into amino acids, and insoluble fats into fatty acids. If oxygen is provided, the reduced soluble organics are oxidized to carbon dioxide and water. If oxygen is not present or is limited, soluble organics are decomposed to intermediate products such as organic acids and alcohols that yield carbon dioxide and water.

Aerobic: \[ \text{Organics} + \text{Oxygen} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy} \]

Anaerobic: \[ \text{Organics} \rightarrow \text{Intermediates} + \text{CO}_2 + \text{H}_2\text{O} + \text{energy} \]

\[ \text{Organic acid intermediates} \rightarrow \text{CH}_4 + \text{CO}_2 + \text{energy} \]

Under anaerobic conditions, the pH of the solution decreases as organic acids are produced. However, high alkalinity minimizes acid interference with organic intermediate products and
methane-forming bacteria will use the organic acids as substrate. This anaerobic process is called digestion.

3.7.3 Enzyme Kinetics

The key components of biochemical reactions are enzymes, organic catalysts that perform biochemical reactions at certain temperatures and chemical conditions. Coenzymes, a component of the enzyme, determine what chemical reaction will occur. For example, the coenzymes nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) support hydrogen transfer. Cytochromes are respiratory pigments that can undergo oxidation and reduction, and serve as hydrogen carriers. Synthesis (anabolism) is the biochemical process of substrate utilization to produce new protoplasm for growth and reproduction. Cellular protoplasm is a mixture of hundreds of complex organic compounds, including proteins, carbohydrates, nucleic acids, and lipids. On a dry-weight basis, protoplasm is 10-12% nitrogen and 2.5% phosphorous; the balance is carbon, hydrogen, oxygen, and trace elements.

The reaction between an enzyme (E) and substrate (S) is as follows:

\[
E + S \xrightleftharpoons[k_2]{k_1} ES \xrightarrow{k_3} E + \text{products}
\]

The terms \(k_1\) and \(k_2\) are rate constants for dissociation of the ES intermediate to E and S. The modified substrate is converted to products, releasing the enzyme for other reactions. The rate of conversion of ES to final products is represented by \(k_3\). The Michaelis-Menten Equation describes the substrate decomposition rate:
$$r = r_m \left( \frac{S}{(K_m + S)} \right)$$  \hspace{1cm} (2)$$

In this expression, $r_m$ is the maximum rate of decomposition, $K_m$ is the saturation constant, and $S$ is the substrate concentration. Since $K_m$ and $r_m$ are constants, this relationship plots as a hyperbola, as shown in Figure 3.10. When $r_m / r = 2$, the measured “$r$” is half the value of the limiting rate $r_m$ and $K_m = S$. Thus, the substrate concentration at the half-maximum reaction rate is a characteristic constant $K_m$ of an enzyme-catalyzed reaction, the saturation constant.

![Figure 3.10: Reaction Rate versus Substrate in Enzyme-Catalyzed Reactions (Viessman, 1998)](image)

3.7.4 Growth Kinetics of Pure Bacterial Cultures

A pure culture can be created in a laboratory reactor by inoculating a medium with bacteria of a single species. Figure 3.11 illustrates the characteristic growth pattern.
After a short lag phase period during which bacteria adapt to the new environment, they reproduce by binary fission, exponentially increasing the number of viable cells and the total biomass in the culture medium. The maximum growth rate occurs when there is excess substrate. In this exponential growth phase, the metabolism rate is limited only by the organisms’ ability to process the substrate. The biomass growth rate can be expressed as:

\[ \mu = (\frac{dX}{dt})_g / X \]  

(3)

where:

\( \mu \) = specific growth rate, time\(^{-1}\)

\( (\frac{dX}{dt})_g \) = biomass growth rate, mass / unit volume-time

\( X \) = concentration of biomass, mass / unit volume

The population remains stable in a stationary phase, when cells have exhausted substrate or nutrients necessary for growth and the growth of new cells is offset by the death of old cells. A declining growth phase is induced by a shortage of substrate. The reproduction rate drops
until the number of viable bacteria again reaches a stationary level (reproduction equals death rate). Monod studied bacterial growth in batch reactors, finding it to be a function of microorganism and growth-limiting substrate concentrations. The Monod equation shows a relationship between the residual substrate and the specific growth rate of biomass:

\[
\mu = \mu_m \left( \frac{S}{K_s + S} \right) \quad (4)
\]

where:

\( \mu_m \) = maximum specific growth rate, time\(^{-1}\)

\( S \) = substrate concentration in solution, mass / unit volume

\( K_s \) = saturation constant, mass / unit volume

The Monod equation of Figure 3.12 is similar to Michaelis-Menten (Fig 3.10).

![Figure 3.12 Growth Rate versus Substrate in Growth Phases (Viessman, 1998)](image)

A generalized biomass growth rate equation is:

\[
\frac{dX}{dt}_g = (\mu_m XS/K_s + S). \quad (5)
\]

The term \((dX/dt)_g\) is the maximum specific growth rate, mass/unit volume/time. The growth yield “Y” is the incremental increase in biomass resulting from metabolism of an incremental
amount of substrate. In first two phases of the growth curve of a bacterial culture (exponential and declining growth phases), the growth yield ($Y$) is expressed:

$$X_m - X_o = Y(S_o - S_m)$$  \hspace{1cm} (6)

where:

$X_m - X_o$ = biomass increase;

$S_o - S_m$ = substrate used

$S_m$ = final substrate concentration at the end of declining growth phase, $\sim 0$

$X_m$ = maximum biomass concentration at the end of declining growth phase

Figure 3.13 shows a straight line or linear relationship between maximum biomass concentration, $X_m$ and the initial concentration of growth-limiting substrate, $S_o$.

![Figure 3.13: Growth Yield for a Series of Batch Cultures (Viessman, 1998)](image)

In the fourth phase of the growth curve, the *endogenous phase*, bacteria compete for a small amount of substrate. The metabolism rate decreases, causing rapid decrease in the number of viable cells, i.e, the death rate exceeds the reproduction rate. The total biomass also decreases as cells digest their own protoplasm as an energy source (lysis). The dying cells release
nutrients back into solution. The rate of biomass decrease in endogenous respiration is proportional to the biomass present:

\[
\frac{dX}{dt}_d = -k_d X
\]

(7)

where

\( \frac{dX}{dt}_d = \) biomass decay rate, mass /unit volume.time

\( k_d = \) microbial decay, time

Microbial growth is affected by several factors such as temperature, pH, nutrient availability, oxygen supply, presence of toxins, substrate type and sunlight for photosynthetic plants. Depending on the optimum temperature range for growth, bacteria are classified as psychrophilic, mesophilic, and thermophilic. Psychrophilic bacteria live slightly above freezing temperatures (4-10°C). Thermophilic bacteria thrive in the range of 50-55°C, limiting them to sludge digesting systems. Mesophilic bacteria prosper in the 20-40°C range, where most treatment systems operate. Trickling filters and aeration tanks operate in the range of 5-25°C. The rate of biological activity in the 5-35°C range doubles for every 10-15°C rise (Figure 3.14), expressed as follows:

\[
K = K_{20} e^{\gamma (T-20)}
\]

(8)

where

\( K = \) reaction-rate constant at temperature \( T \)

\( K_{20} = \) reaction-rate constant at 20°C

\( \gamma = \) temperature coefficient

\( T = \) temperature of biological reaction, °C
The value of ? is in between 1.047 and 1.072 depending on the temperature rise.

![Figure 3.14 General Effect of Temperature on Biological Activity (Viessman, 1998)](image)

The optimum pH in most biological wastewater treatment systems is between pH 6.5 and 8.5. Microbial activity is inhibited at high pH, and at pH below 6.5, fungi are favored over bacteria in the competition for food. Industrial facilities can produce metal ions, phenol and other materials toxic to microbial growth as well as humans. These and similar materials are removed before industrial effluent is discharged to a municipal sewer system, but may be present in urban runoff.

3.7.5 Population Dynamics

When organic material is released to a mixed population of microorganisms, there is competition for food between the various species. Under normal conditions, bacteria are the primary feeders, as shown on Figure 3.15. The dominating species depends on the type of organic waste and environmental conditions. Conditions that adversely affect bacteria include
acidic pH, low dissolved oxygen, and nutrient shortage, which can cause a rise in filamentous fungi and sludge bulking. As described above, bacteria are maintained in a declining or endogenous growth phases. Under these conditions, the bacteria die and lyse, releasing cell contents to solution. Thus, raw organic matter is synthesized and re-synthesized by various groups of bacteria.

Figure 3.15: Population Dynamics in Activated Sludge (Viessman, 1998)
Holozoic protozoans that feed on living organic matter such as bacteria are common in activated sludge. For a single reproduction, a protozoa consumes thousands of bacteria. There are two benefits of this prey-predator relationship: bacteria removal stimulates further growth, resulting in accelerated extraction of organic matter from solution. Second, the flocculation characteristics of the activated sludge are improved by reducing the number of free bacteria in solution, as a biological floc has improved settling characteristics. Competition also exists between the protozoan secondary feeders. Free-swimming protozoans are dominant when a solution contains high bacterial populations. Stalked-protozoans become dominant when its substrate is scarce, as they do not require as much energy as free-swimming protozoans, and thus compete more effectively with a low bacterial concentration.

### 3.7.6 Suspended Growth Wastewater Treatment

As noted earlier, biological treatment technology has been primarily developed with suspended growth, especially the activated sludge process used for most large scale wastewater treatment. Figure 3.16 shows a diagram of this process. The influent is a blend of primary treatment effluent, which supplies fresh substrate, and return activated sludge to form. By adjusting the sludge return, the “mixed liquor” has bioactive solids content (mixed liquor suspended solids-MLSS) of the desired F/M ratio (Table 3.10). This mixture is held in suspension by aeration for a short detention time to provide oxygen, contact between substrate and microorganisms, and synthesis of new cells. The liquid then flows to a secondary clarifier where the microorganisms settle (see Class III sedimentation, above) because the cells are denser than water. The effluent is discharged, some sludge is returned to the inflow, and the rest is “wasted”. Most substrate digestion occurs off-line, in sludge digesters.
As noted earlier, the flow rate dominates the range of feasible techniques and determines the sizes of treatment vessels and land area required. In general, the shortest feasible detention time is sought:

\[ \text{Volume} = \text{Detention Time} \times \text{Flow Rate} \]  

(9)

The systems shown on Table 3.10 trade off between hydraulic detention against sludge production and mechanical complexity. By limiting capital investment in a sequence of tanks and pipes, the activated sludge method is quite efficient for large flows. Sequential batch reactors and extended aeration are activated sludge process variations that combine or simplify unit operations for smaller flows. Extended aeration plants often dispense with primary sedimentation by comminuting settleable organic materials for combined treatment with suspended and dissolved organics. This method is often used in “package plants” for flows in the 10,000-50,000 gpd range. The tradeoff for using a simpler, less operator intense process that produces less sludge, with a low F/M ratio is detention times up to 24 hours, compared to 4-6 hrs for activated sludge.
When microorganisms are in exponential growth (phase II of Figure 3.11), F/M is high and $c_e$ is low, characterized by excess food and a maximum metabolism rate. As indicated earlier, the process of bacterial reproduction, growth, maturation, and fission can occur in less than an hour. Figure 3.17 shows the relationship between the rate of metabolism and F/M ratio.

Figure 3.17: Rate of Metabolism versus the F/M Ratio (Viessman, 1998)

High F/M and low $c_e$ are not favored per se in activated sludge plants, and are only used to accelerate uptake of substrate in a limited mixing and aeration period. While maintaining the biological culture in an exponential growth mode (Figure 3.11) efficiently removes organics from solution, it is undesirable for a continuous flow activated sludge system. The biomass does not readily settle out of solution by gravity in the secondary clarifier as expected, and a high F/M ratio will result in poor BOD removal from the final discharged effluent. A low F/M ratio, controlled by sludge recirculation, drives metabolic activity into endogenous phase. There may be an initial rapid growth when substrate and biomass are mixed, but competition for the limited available substrate will cause near-starvation conditions in a short
time. Under such low F/M ratio conditions, cell lysis (auto-oxidation of biomass) will occur. Prey activity also increases, with protozoa consuming bacteria. Even though the rate of cell growth is limited in endogenous phase, metabolism of organics is almost complete and the biomass rapidly flocculates and settles. This, the activated sludge process works best in the range of operation between the declining growth phase and the endogenous phase. Extended aeration plants use still lower F/M ratios to minimize sludge.

3.7.7 Attached Growth Wastewater Treatment- General

Aerobic attached growth biological treatment processes are usually used to remove organic matter, but are also used for nitrification (ammonia conversation to nitrate). Wastewater constituents are adsorbed by microorganisms attached to surface material as a biofilm. With growth, the thickness of the slime layer increases. Tricking filters remove organics from wastewater as it flows over a biofilm attached to media such as stones or plastic cylinders. Rotating biological contactors (RBCs) are large diameter plastic disks that attract biofilm and rotate slowly through tanks conveying the wastewater. Fixed-film treatment is also done with slow sand filters and septic system infiltration beds. Using geosynthetics as attached-growth media is a variation of this approach.

Since there is no biomass recirculation in attached growth, the use of an MCRT index is unclear. \( SRT \) treated as indefinite. Settleability is not an issue. F/M is indirectly used. The “M” of the active biomass is known from the reactor surface area and biofilm thickness. The F/M ratio thus is controlled by the organic loading rate, on a gal/day/unit surface area basis (HLR) for wastewater of a particular strength. In the same manner as in suspended growth, it is advisable to minimize sludge production. Thus, decomposition of substrate to complete mineralization within the biofilm to the extent
possible is encouraged by maintaining biomass in the endogenous phase. In the tangential flow mode, with a very high attachment surface area per unit of reactor volume, a very high biomass can be maintained.

3.7.8 Theory of Mass Transfer in Attached Growth

In some respects, attached growth is more complicated than suspended growth due to concerns about both mass transport and reaction. Substrate, oxygen and nutrients must be transported to microorganisms within the biofilm by diffusion and other mass transport processes. The solid media support is usually impermeable, although it need not be, as with the geotextiles, so individual constituent movements are generally in one direction only, as shown on Figure 3.18.

![Figure 3.18: Cross Section of Biological Slime](image)

The biofilm contains base film, surface film (biofilm), bulk liquid, and gas. Both the base film and surface film are an assemblage of microorganisms and other particulate material bound together by a matrix of extracellular polymers excreted by the microorganisms. The
base film is a structured accumulation, with well-defined boundaries. Transport of substrates (carbon and energy source), nutrients, electron acceptors (oxygen), and electron donors to and from the bacteria in the base film is considered a molecular diffusion process. The surface film is a transition zone between the base film and the liquid. Material transport within it is dominated by advection and turbulent diffusion. Biofilm thickness is a function of kind of microorganisms and hydrodynamic characteristics of system.

The biomass distribution is not uniform, nor is its physical characteristics such as porosity and density. Cell clusters are microbial aggregates, while voids are open structures relatively free of the polymers. It also appears that the cell clusters are pierced by small conduits, adding another level of transport path complexity. The effective diffusion coefficients thus vary with biofilm depth, influenced by changes in the biofilm structure. Bacteria types and biochemical reactions are similar to that of suspended growth as described above. Electron donors react with electron acceptors. With full aerobic mineralization, CO$_2$ and H$_2$O are end products;

Organic matter (H') = electron donor;  
$O_2$ = electron acceptor

$C_6H_{12}O_6 + O_2 + \text{Bacteria} \rightarrow CO_2 + H_2O$

There are, of course, intermediate steps. If two species do not complete for a particular nutrient, but only for space, their ultimate distribution will depend upon their relative specific growth rates at any point within the biofilm. Related reactions include:

$\text{COHNS} + O_2 + \text{Nutrients} + \text{bacteria} \rightarrow CO_2 + NH_3 + C_5H_7NO_2 + \text{other products} + \text{new cells}$

$C_5H_7NO_2 + 5O_2 + \text{bacteria (endogenous respiration)} \rightarrow 5CO_2 + 2H_2O + NH_3 + \text{energy}$
Active biomass dominates in the outer regions of the film, and biomass debris in the inner regions. The ultimate BOD of the cells is equal to 1.42 times their concentration.

Atkinson derived an expression describing the rate of organic flux into the slime layer, assuming diffusion into the slime layer controls the rate of reaction and not the concentration gradient across the liquid film.

\[ r_s = \frac{-(Eh_kS)}{(K_m+S)} \]  

(10)

where;

\( r_s \): rate of flux of organic material into the slime layer, ft/d

\( E \): effectiveness factor (0<\(E<1\))

\( h \): thickness of slime layer, ft

\( k_o \): maximum reaction rate, d\(^{-1}\)

\( S \): BOD concentration in the liquid in the volume element, mg/l

\( K_m \): Half velocity constant, mg/l

The effectiveness factor “\(E\)” is generally proportional to the liquid BOD. The substrate flux to and through the liquid-biofilm interface must equal the overall utilization rate per unit of biofilm planar area. Because the local substrate utilization rate depends on the concentration at a specific location, the utilization rates at various points in the biofilm will vary. The overall utilization rate by the biofilm must consider this by integrating the reaction rate over the biofilm depth.
3.7.9 Trickling Filter Operation

Trickling filters are the most commonly used attached growth method operating with tangential flow, as opposed to the permeation mode of substrate-biofilm contact in granular filters. Trickling filters are closed circular basins packed with large diameter crushed rock or plastic media, providing a high slime attachment area and also continuous large pores. Wastewater is distributed over the top of the bed by a rotary spray distributor. The wastewater trickles through the bed, flowing over the biofilm-coated media. This is often an intermittent operation. At intervals, the contact bed is drained and allowed to re-oxygenate and rest before the cycle is repeated, often using a six hour dose and drain alternating system. Trickling filters tend to clog in continuous flow, such that the need for long rest period and low applied loading rates are drawbacks. To further limit the clogging risk, very permeable media is used. Ideal media has the following characteristics:

1. A large surface area is provided for microbial film growth
2. The wastewater flows evenly in thin sheet over the microbial film
3. There is sufficient unsaturated void space for the free flow of air
4. There is sufficient void space to allow excess biomass to slough of the media and be carried away for digestion elsewhere
5. It is biologically inert, i.e it neither degrades nor inhibits microorganism
6. It is chemically and mechanically stable.

The recommended stone media size is generally two to four inches in diameter, as this range provides a compromise between sufficient surface area and large void space. For example, 2 inch rock will provide around 30ft$^2$ of surface area per cubic foot of reactor volume (98m$^2$/m$^3$) and will have around 50% voids. Plastic media can have both larger specific
surface area and larger void volume. Some certain plastic materials are available with specific surface areas between 30ft$^2$/ft$^3$ and 104ft$^2$/ft$^3$ an porosities of 93-95%. With larger void spaces in plastic media, wastewater and air can move simultaneously, thus allowing continuous wastewater treatment. They can thus be assumed to be used more and more in the future. Different internal configurations are possible. In one, PVC (polyvinyl chloride) media is manufactured as corrugated sheets bonded between flat sheets in modules or bundles, providing specific surfaces between 26 and 43ft$^2$/ft$^3$, and 95% porosity.

The basic description of the capacity of a packed tower, and thus, the size to serve a given flow rate, is the hydraulic loading rate (HLR) per unit of cross-sectional area, expressed as gal/day/ft$^2$ or ft$^3$/day/ft$^2$. The lower limit of HLR is that required to wet all of the media because otherwise, it is not being used effectively. Being more open, plastic media requires higher hydraulic loadings. One dumped plastic media manufacturer recommends a minimum about 100 ft$^3$/day-ft$^2$, while a commonly accepted value for coarse rock media is 135 ft$^3$/day-ft$^2$. The upper limit on modular plastic media is governed both by thin film flow and microbial film scouring. Flows as high as 1150 ft$^3$/day-ft$^2$ have been used with good results.

The performance of a trickling filter actually depends on the organic loading rate, expressed as the pounds of biodegradable BOD$_5$/day-1000ft$^3$, such that higher HLRs can be used with weaker strength influents, and lower HLRs are appropriate with stronger liquids.

Treated effluent is collected from the bottom of the filter by underdrains which have a porous structure through which air circulates. This effluent flows to a settling tank to separate solids. A portion of the liquid collected in the underdrain system or the clarifier is often recycled to dilute the incoming wastewater and maintain the moisture in the biological slime layer. The net daily ratio of recirculated flow to influent flow is generally kept less than 4. Trickling filter microorganisms remove soluble organic matter from the wastewater, converting soluble
organic matter into an insoluble form which can be removed by settlement. With continuous
detachment or sloughing of microorganisms from the film surface, the suspended solids
concentration in the reactor effluent exceeds that in the influent. A secondary clarifier is thus
required to remove these cells for off-line digestion as in the activated sludge method. The
need for primary sedimentation ahead of the trickling filter unit depends upon the type of
media employed. Rock media is susceptible to clogging, so primary sedimentation is used to
remove settleable solids which might clog the filter. The possibility of clogging modular
plastic is small and thus there is little need for primary sedimentation.

Although classified as aerobic treatment, the microbial film in a trickling filter is generally
considered to be aerobic to depth of only 0.1-0.2mm. The zone adjacent to the medium is
anaerobic. As wastewater flows over the microbial film, soluble and colloidal organic matter
is adsorbed on the film. Oxygen dissolved in the liquid layer that transfers into the biofilm is
replenished by reoxygenation from the surrounding air in unsaturated voids. Continuous air
flow through the bed is essential to prevent undesirable anaerobic conditions. Physical
characteristics, such as media configuration, bed depth, and hydraulic loading, strongly
influence the process.

As the slime layer thickness increases, the adsorbed organic matter is metabolized before it
can reach the bacteria near the media face. As a result of being starved for substrate the
microorganisms near the media face enter an endogenous phase of growth and lose their
ability to cling the media surface. The traction of the flowing liquid then washes the slime off
the media, and a new biofilm starts to grow. This phenomenon of is called “sloughing” and is
primarily a function of the organic and hydraulic loading on the filter. The hydraulic loading
accounts for shear velocities, and the organic loading accounts for the rate of metabolism in
the slime layer.
In most low-rate filters, only the top 2 to 4 ft (0.6 to 1.2m) of the filter medium will have biological slime. As a result, the lower portions of the filter may be populated by autotrophic nitrifying bacteria that oxidize ammonia nitrogen to nitrite and nitrate forms. If the nitrifying population is sufficiently well-established and if climatic conditions and wastewater characteristics are favorable, a well-operated low rate filter can provide both good BOD removal and a highly nitrified effluent.

Odors are a common problem, especially if the wastewater is stale or septic or if the weather is warm. Filters should not be located where occasional odor events would create a nuisance. Filter flies (psyshoda) may also breed in the filters unless control measures are used.

Factors that must be considered in the design of trickling filters include the dosing rate, the type and dosing characteristics of the distribution system, the type and physical characteristics of filter medium to be used, the configuration of underdrain system, provision for adequate ventilation and design of the required settling tanks. To optimize performance, there should be a continual and uniform growth of biomass and sloughing of excess biomass.

The biological community in the filter includes aerobic, anaerobic, and facultative bacteria, fungi, algae, and protozoans. Higher animals such as worms, insect larvae, and snails are also present. Facultative bacteria predominate. Along with the anaerobic bacteria, their role is to decompose the organic material in the wastewater. Achromobacter, Flavobacterium, Psedomonas, and Alcaligenes are among the common bacterial species commonly. Within the slime layer, where adverse growth conditions prevail, the filamentous forms Sphaerotilus natans and Beggiatoa are found. Nitrifying bacteria Nitrosomonas and Nitrobacter are found in the lower reaches of the filter.
In general, the microorganisms near the top of the bed where the food concentration is high are in a rapid growth phase, while microorganisms near the bottom are in a state of starvation. Algae can grow only in the upper reaches of the filter where sunlight is available. Generally, algae do not take a direct part in waste degradation, but during daylight hours, they add oxygen to the percolating wastewater.

### 3.7.10 Trickling Filter Applications

Trickling filters are used to treat both municipal and industrial wastewaters. While activated sludge is generally used with BOD$_5$ concentrations of organic matter is between 50-400 mg/l, BOD$_5$, trickling filters are economically applied to wastewaters stronger than that range, but limitations on oxygen transfer may cause odor and performance problems. However, because trickling filters can reduce organic matter, they are often used to pretreat high strength wastewaters prior to discharge to municipal sewers or treatment by activated sludge. Furthermore, because plastic media filters can be constructed as tall towers, they are particularly useful where land is limited. Finally, because they are simple to operate, trickling filters are often used by small communities that cannot afford the skilled operators required for activated sludge operation.

The advantages of trickling filters are simplicity, ease of operation, low operating cost, and production of waste sludge that is easily processed, thus making them valuable for remote sites or small communities. Because a large biomass is necessary to achieve effluents of high quality, they possess substantial reserve capacity which make them tolerant to changes in the influent. The dense nature of the microbial films that slough off the media produces sludge of relatively constant character that are readily removed by sedimentation. Another feature often claimed for trickling filters is the ability to survive shock loads of toxic wastes, due either to
the short retention time of the wastewater in the reactor, or because only surface organisms
may be killed.

Because the microorganisms grow attached to a fixed surface, the reactor biomass cannot be
adjusted in response to environment changes and therefore, there is no effective way to
control effluent quality. Consequently, if the influent concentration or flow rate increases, the
effluent quality will deteriorate. Likewise, if temperature drops, the rate of substrate removal
will also decrease. Changing seasons also affect filter performance. For example, rock media
filters may serve as a breeding ground for Psychoda flies in the summer, thereby creating a
nuisance condition in the immediate area. In the winter, icing can be a problem in northern
climates. The design characteristics of different trickling filters are given in Table 3.12.

Table 3.12: Comparison of Different Types of Trickling Filters (Davis and Cornwell, 1991)

<table>
<thead>
<tr>
<th>Type</th>
<th>Low. Rate</th>
<th>Intermediate Rate</th>
<th>High Rate Stone Media</th>
<th>Super Rate Plastic Media</th>
<th>Roughing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Loading</td>
<td>1 - 4</td>
<td>4 - 10</td>
<td>10 - 40</td>
<td>15 - 90</td>
<td>60 - 180</td>
</tr>
<tr>
<td>(M/d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Org. Load Rate</td>
<td>0.08 – 0.32</td>
<td>0.24 – 0.48</td>
<td>0.32 - 1</td>
<td>0.32 - 1</td>
<td>Above 1</td>
</tr>
<tr>
<td>(Kg BOD₅/d/m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recirculation</td>
<td>none</td>
<td>0 to 1:1</td>
<td>1:1 to 3:1</td>
<td>0 to 1:1</td>
<td>1:1 to 4:1</td>
</tr>
<tr>
<td>Filter Flies</td>
<td>Many</td>
<td>Various</td>
<td>Few</td>
<td>Few</td>
<td>Few</td>
</tr>
<tr>
<td>Sloughing</td>
<td>Intermittent</td>
<td>Various</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>Depth, (m)</td>
<td>1.5 - 3</td>
<td>1.5 – 2.5</td>
<td>1 - 2</td>
<td>Up to 12</td>
<td>1 to 6</td>
</tr>
<tr>
<td>BOD₅ removal, %</td>
<td>80 - 85</td>
<td>50 - 70</td>
<td>65 - 80</td>
<td>65 - 85</td>
<td>40 -65</td>
</tr>
<tr>
<td>Effluent Nitrification</td>
<td>Well</td>
<td>Some Nitrification</td>
<td>Nitrites</td>
<td>Limited Nitrification</td>
<td>None</td>
</tr>
</tbody>
</table>
3.7.11 Rotating Biological Contactors

Rotating biological contactors (RBCs) are a series of closely spaced circular polystyrene (PS) or polyvinyl chloride (PVC) disks mounted on a horizontal shaft and rotated through wastewater slowly flowing along a contoured bottom tank. The disks are typically 12 ft. in diameter, spaced along the shaft at 0.50-0.75 inch intervals, and are submerged 40% of their diameter. Biological growth attaches to the disk surfaces and eventually forms a slime layer over the entire wetted surface area. When rotated out of the tank, oxygen is dissolved from the air while the liquid trickles down over the biofilm. Disk rotation maintains the biomass in an aerobic condition. It also shears excess solids from the disks and maintains them in suspension to be carried to a clarifier. The alternating exposure to wastewater and air is similar to dosing a trickling filter with a rotating distributor, but at a much faster interval. RBCs are used for secondary treatment, and but they can also be operated in a continuous nitrification modes. They are usually designed on the basis of pilot plant and full-scale installations, although performance can be analyzed using an approach similar to that for trickling filters. Both hydraulic and organic loading rate criteria are used in sizing units for secondary treatment. Loading rates for warm weather and year round nitrification are considerably lower than for secondary treatment. The average organic loading based on total RBC surface area is 3.0lb BOD /1000ft²-day.

RBCs have a large amount of attached biological mass, and thus, a low-operating F/M. This also permits them to withstand hydraulic and organic surges effectively. 70% of the RBC systems installed are used for carbonaceous BOD removal only, 25 % for combined carbonaceous BOD removal and nitrification. In the design of an RBC system, consideration must be given to staging of the RBC unit, loading criteria, desired effluent characteristics, and settling tank requirements. RBCs have low power consumption and good process stability,
but they are not common due to the higher cost than trickling filters. Many of the RBC units had also operating problems such as shaft failures, media breakage, bearing failures, and odor problems.
Chapter 4. Experimental Procedures and Geotextile Selection

4.1 Introduction

This chapter describes the experimental approach, apparatus and procedures of performing the work. It also presents the results of Phase I work to select geotextiles for the pilot plant biodegradation studies of Phases II and III. The following Chapter 5 shows the experimental results using thirteen samplings of effluent from the PWD Southeast Water Pollution Control Plant (SEWPCP).

As noted in Chapter 1, it was found that geotextiles used as filters in leachate collection systems hosted a biomass sustained by extracting organic material from the flow, thus providing a degree of treatment. To bypass the excessive clogging problem that restricts hydraulic capacity, it was proposed that a biomass could be formed by filtration through geotextile specimens, but as the fabric pores filled, the high biofilm surface would extract organic material from flow tangential to specimens hung as baffles in the flow pathway. While avoiding the clogging problem in terms of hydraulic capacity, this produces a new concern of assuring contact between the biofilm and substrate conveyed parallel to it. To develop this premise, the work proceeded in three phases:

- Phase I batch screening of candidate geotextiles for relative biomass attraction
- Phase II pilot plant tests of the baffle system with pre- and post primary effluent
- Phase III confirmation tests with another geotextile
Experiments were done at the Woodring Laboratories of The Department of Civil, Architectural and Environmental Engineering at Drexel University between April 17 to November 20 of 2001.

4.2 Experimental Design Background

The questions listed in Chapter 1 were of three types: suitable geotextiles, treatment capability, and sludge decomposition. With demonstration by G.R. Koerner (1993) and others that some geotextiles host active microorganisms, and the sludge handling issue being simply to reduce the amount to be handled as much as possible, the key question is the treatment capability. From an engineering viewpoint, there are three practical issues: physical (space, head, etc.), mechanical simplicity (aeration, but once-through flow without recirculation) and decomposition extent and efficiency. It was thus desired that the experimental apparatus and test program model the wastewater, runoff and combined sewer overflow applications described in Chapter 1. The most demanding application is treatment of wastewater, as the flow is continuous and there are well developed standards for effluent quality. It was thought that if treatment of a realistic wastewater stream was successful, then extension to intermittent, weather-related flows would certainly be feasible, although the volumes are much higher.

4.3 Relationship to Established Methods

Wastewater treatment is a well developed technology. The experimental design for the Geotextile Baffle Contact System (GBCS) thus incorporated experience with the physical and biological treatment methods described in Chapter 3.
The first step in the treatment is further clarification of an influent that has already passed through Type II or III sedimentation in the SEWPCF primary tanks. The porous, pervious nature of the geotextiles was used to advantage to accelerate colonization by cross-plane filtration of TSS through baffles normal to the overall flow path as shown on Figure 4.1a. As it clogs, as shown on Figure 4.1b, the permeability of each baffle decreases, and biomass growth proceeds downgradient. However, the experimental design elements discussed herein apply to removing TSS and BOD$_5$ in the longer term when the baffles may be “clogged” and the filtration component is reduced.

Figure 4.1a: Short-Circuiting and TSS Capture to Form Biofilm

Figure 4.1b: Progression of Biofilm on Baffles in Sequence
The 20 gallon rectangular tank dimensions provided a cross-section area of 1.0 ft$^2$ normal to the flow, a surface area of 2.5 ft$^2$, and fifteen individual 10 in. x 10 in. baffles at 2 in. spacing and a constant 2 in. channel width through the zigzags. Among the influences on sedimentation of smaller particles are these channel dimensions and boundaries, the velocity and path length, and a lumped parameter, the surface settling rate. The baffles were arranged with narrow channels to foster contact of dissolved organic with the biofilm. In combination with the use of flexible baffle channel walls to dampen any turbulence, the narrow channels encouraged laminar flow as is formed the lamella settlers described in Section 3.6.3. With laminar flow, substrate would diffuse laterally (across the flow) to replace material sorbed from the streamlines along the baffles. It was thus seen as necessary to provide a very large baffle surface area and channel length, 15 ft., which was easily provided due to the thinness of the baffles. This also provided a long sedimentation path length (Figure 3.8). The selected flow rate of 20 gpd provided a channel velocity below $10^{-4}$ ft/sec, which would remove very fine organic particles (Section 3.6.2; Fig 3.8). The lumped index used in clarifier design is the surface settling rate. With the decisions made on dimensions and flow rate for the more fundamental process, the resulting surface settling rate, 10 gpd/ft$^2$, is an order of magnitude below that of conventional primary tanks.

For the biological treatment component, a two stage process was envisioned, a combination of granular and trickling filters in time sequence. Trickling filter media are generally impermeable, but with permeable baffles an active treating biomass is formed rapidly. Since the geotextiles are also very porous, it may take a long time for individual flocs to coalesce and form a continuous biomass with low permeability. It is reasonable, however, to assume that this condition exists when the biofilm projects as slime on the baffle surfaces. In the long term steady state, it is expected that the influent is treated primarily after being sorbed by flow past this biofilm. In this regard, the sinuous baffles are similar to a trickling filter, which
are described in terms of both flow rate normal to the footprint, and flow rate per unit of biofilm area. With the GBSC pilot plant operating at 20 gpd, the nominal flow rate of 20 gpd/ft$^2$ is similar to that of simple once-through trickling filters (Table 3.11). Since there is actually over 20 ft$^2$ of baffle surface “nested” within this “footprint” (actually horizontal in the GBCS), attached biomass is available for substrate sorption and decomposition at a rate of 1.0 gpd/ft$^2$ of baffle contact surface. The large amount of biomass accumulated on and in the fifteen baffles of the pilot plant and support a very low F/M ratio, and thus a near-starved endogenous condition (Figure 3.11). With a low F/M ratio and a 22 hour hydraulic detention time, a low sludge production rate (local mineralization) and high BOD$_5$ removal would be expected, as is the practice extended aeration method (Table 3.10). The excess biomass and captured sediment are readily decomposed on the tank bottom anyway.

This will be an advantage compared to trickling filters. As noted in Chapter 3, they extract dissolved material from the influent wastewater to produce biomass that then sloughs off for decomposition elsewhere. While the dissolved BOD$_5$ is reduced by absorbing dissolved and colloidal organic substrate, the suspended solids content of the effluent (before clarification) is actually higher than that of the influent from conversion of dissolved organics to cell material, requiring downstream clarifiers and a sludge digestion unit.

As described in Chapter 1, the GBCS process was also similar to another variation on activated sludge, sequencing batch reactor (SBR) used for nitrification/denitrification. The complete sequence of substrate carbonaceous and nitrogen degradation or conversion reactions appear to within the baffle in which it is sorbed when the biofilm becomes very thick.
4.4 Experimental Apparatus

The GBCS is shown in profile in Figure 4.2. Figure 4.3 is a photograph of the bench top two tanks Phase II arrangement, showing the tanks as coated to prevent light penetration. The age of the biofilm was indicated by its color. Figure 4.4 shows a light-colored fresh biofilm coating a baffle. Darker aged biofilm is shown in Figure 4.5.

Figure 4.2: Geotextile Baffle Experimental Apparatus
Figure 4.3: Geotextile Baffle Contact System (GBCS)

Figure 4.4: Fresh Biofilm Accumulation on Geotextile Coupons
4.4.1 Glass Tanks

In the Phase I and II of the experiments, 20 gallon glass fish tanks 12 in. wide, 12 in. high and 30 in. long were used. The sides of the glass tanks were covered with aluminum foil in order to prevent any light induced reactions, as shown on Figure 4.3. The top of the tanks was shielded by black HDPE plastic bags.

4.4.2 Peristaltic Pumps

Peristaltic pumps manufactured by ANKO Products, Inc., Bradenton, Florida were used to convey wastewater between tanks and reservoirs. The peristaltic pumps have a roller assembly and different tubing diameters to deliver controlled amounts of water. HDPE piping
was used. Anko 908-028 series peristaltic pump with 3/16 in. tubing supplied a 56ml/min flow rate to the GBCS apparatus.

4.4.3 Air Pumps

The tanks were aerated with Elite 800 air pumps, which supplied 1500-2000cc/min through a plastic pipe bubbler along the full length of the tank bottom, as shown on Figure 4.6.

Figure 4.6: Pipe Bubbler in the Tank Bottom Centerline
4.4.4 Geotextile Baffle Contact System (GBCS) Layout

To enhance the opportunity for microorganisms to attach to the baffles conditions they were placed at 2 in. spaces in an alternating offset pattern. As shown on Figure 4.1, the channels are 10 in. long with 2 in. turning lanes. The long, narrow channels with flexible borders also encouraged quiescent, laminar flow conditions to encourage sedimentation. Plastic covered steel hangers were used to support the suspended baffles, placed in the tank perpendicular to the direction of wastewater flow. Schematic figures of experiments are given in Figure 4.1 and 4.2. Since the densities of the geotextiles used in these experiments are lower than that of wastewater, ½ in. by 10 in. glass strips were attached on the bottom part of the geotextile samples and secured with plastic ties to prevent floating and keep the geotextiles in vertical submerged alignment. The same plastic ties were also used to hang the geotextiles to hangers. The bare edges of the steel hangers were painted with waterproof paint to prevent rust. No metal was exposed to the wastewater in the fish tanks.

4.5 Geotextiles Used

In Phase 1 of the study, 10 in. x 10 in. sized coupons of eight different geotextiles were used. Different types of woven (fiber and slit film) and nonwoven needle punched geotextiles (continuous filament and staple fiber) were tested. The geotextiles and selected properties are listed on Table 4.1, and expansion of Table 1.2. It was expected that the geotextiles with interior porosity, the nonwovens, would perform the best. However, the planar woven geotextiles were tested, including four grades of woven fiber fabrications to determine if the different thickness made a difference by itself.
Table 4.1: Published Properties of the Geotextiles Used in Screening Phase I

<table>
<thead>
<tr>
<th>Product Name/ Structure/ Polymer</th>
<th>Apparent Opening Size (AOS), mm</th>
<th>Permittivity, sec^{-1}</th>
<th>Puncture Resistance Lbs</th>
<th>Trapezoidal Tearing Strength, lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amoco 2130 W/F/PP GT1</td>
<td>0.6</td>
<td>0.05</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Amoco 1199 W/F/PP GT2</td>
<td>0.212</td>
<td>0.28</td>
<td>135</td>
<td>100 (MD), 60 (XD)</td>
</tr>
<tr>
<td>Amoco 2002 W/F/PP GT3</td>
<td>0.425</td>
<td>0.05</td>
<td>90</td>
<td>75</td>
</tr>
<tr>
<td>Geotex 315 ST W/SF/PP GT4</td>
<td>0.212</td>
<td>0.06</td>
<td>125</td>
<td>120</td>
</tr>
<tr>
<td>Trevira 1125 NW/CF/PET GT5</td>
<td>0.210-0.149</td>
<td>2.01</td>
<td>115</td>
<td>105 (MD), 95 (XD)</td>
</tr>
<tr>
<td>Amoco 4545 (NW/SF/PP) GT6</td>
<td>0.212</td>
<td>2.1</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Polyfelt TS700 NW/CF/PP GT7</td>
<td>0.12-0.18</td>
<td>1.6</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Amoco 4551 NW/SF/PP GT8</td>
<td>0.212</td>
<td>1.5</td>
<td>90</td>
<td>65</td>
</tr>
</tbody>
</table>

\( \text{W} = \text{Woven, NW} = \text{Nonwoven, F=} \text{Fiber, SF} = \text{Slit Film, ST} = \text{Stapled, CF} = \text{Continuous Filament, PP} = \text{Polypropylene, PET} = \text{Polyester} \)
4.6 Test Liquid Sampling and Analysis

The decision was made to use domestic wastewater, but its quality changes in storage. Consequently, the SEWPCF source was chosen due to its proximity which allowed collection of fresh samples. PWD analysis of the TSS and BOD$_5$ adds credibility to the results. SEWPCF of PWD uses an activated sludge process to treat an average dry weather flow of 75mgd, but it can treat up to 200mgd of wet weather flow from the combined sanitary and sewer system. The tributary area includes Center City, dense residential neighborhoods, and waterfront and industrial areas. The raw wastewater quality depends on the weather conditions and the season. The primary treatment effluent sample BOD$_5$ in this set of experiments ranged from 33 to 70 mg/l and TSS from 21 to 110mg/l. Between 30% to 50% of the BOD$_5$ had already been removed in physical treatments of grit removal, oil & grease flotation and sedimentation of large or dense particles, as described in Chapter 3. All but one sample used in this study was obtained at the outlet of the primary treatment tanks. As noted previously, to test the limits of the GBCS, one sample was obtained between the headworks and the primary tank inlet stems. displaying a BOD$_5$ of 114 mg/l and TSS of 300mg/l.

Grab samples were collected in the same manner for all phases. A submerged pump dropped downstream of the overflow weir at the end of the primary settling tanks was used to collect samples for the study. Seven gallon polyethylene containers were used to carry and store the weekly wastewater samples. The containers were washed with tap water after each use and rinsed with the sample water before filling. Samples were stored in a dark cold room of the Biology Department of Drexel University to arrest degradation.

Each batch was obtained at the beginning of a week. The as-pumped BOD$_5$ and TSS were measured, and the samples or rounds of primary effluent varied by a factor of two in TSS and
BOD$_5$, as shown earlier on Figures 1-2 and 1-3. Success with the combined flow samples not only showed that urban runoff did not adversely affect biological reactions, but produced TSS and BOD$_5$ variations that demonstrated the resiliency of the treatment method. Each weekly source batch was continuously refrigerated until use.

Five parameters, Biochemical Oxygen Demand (BOD$_5$), Total Suspended Solids (TSS), Ammonia (NH$_3$), Nitrate (NO$_3$) and Temperature were monitored. All vials were rinsed with the sample liquid before collecting the analysis sample itself. After collection, samples were stored in a dark refrigerator at 4°C. The influent and effluent of each tank in Phases II, III were sampled concurrently, while the BOD$_5$ and TSS were sampled once a week for each round and analyzed at the PWD Bureau of Laboratory Services. Temperature was measured each day with a mercury-in-glass thermometer. NO$_3$ and pH were measured almost every other day using a LaMotte Smart Colorimeter. This multi-wavelength instrument is an EPA accepted instrument that meets the requirements for colorimeters approved for the National Primary Drinking Water Regulations (NPDWR) and National Pollutant Discharge Elimination System (NPDES) compliance monitoring programs. All glassware used for the NH$_3$ and NO$_3$ analysis was prepared in the following manner: initial washing with hot tap water and rinsing several times with distilled water followed by air drying until the next use. The characteristics of wastewater used in Phase I of the study is given in Table 4.2, which repeats Table 1.1.
Table 4.2: Pilot (Phase I) Primary Effluent Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conc., mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD$_5$</td>
<td>33</td>
</tr>
<tr>
<td>TSS</td>
<td>21</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (COD)</td>
<td>151</td>
</tr>
<tr>
<td>Ammonia (NH$_3$)</td>
<td>13.5</td>
</tr>
<tr>
<td>Nitrate (NO$_3$)</td>
<td>1.82</td>
</tr>
<tr>
<td>Dissolved Oxygen (DO)</td>
<td>1.7</td>
</tr>
<tr>
<td>Phenol</td>
<td>0.04</td>
</tr>
<tr>
<td>Iron</td>
<td>0.95</td>
</tr>
<tr>
<td>Phosphate (as PO$_4^{2-}$)</td>
<td>0.22</td>
</tr>
<tr>
<td>Sulfates (as SO$_4^{2-}$)</td>
<td>40</td>
</tr>
<tr>
<td>pH</td>
<td>7</td>
</tr>
</tbody>
</table>

### 4.7 Phase I Tests

As noted earlier, four types of woven and four types of nonwoven geotextiles were batch tested for biofilm growth with exposure to the dilute primary effluent described on Table 4.2. For each of the four different woven types, six identical geotextile coupons were cut to 10 in. by 10 in. dimensions. The 24 woven coupons were placed in two tanks. Six Geotex 315ST and six Amoco 1199 coupons were placed in one tank. Six Amoco 2002 and six Amoco 2130 coupons were placed in another. Similarly 24 NW geotextiles coupons of the 4 different types were placed in two tanks. Six Trevira 1125 and six Polyfelt TS 700 coupons were placed in one tank and six Amoco 4551 and six Amoco 4545 coupons were placed in another. The weight of the geotextiles was measured before submerged in the wastewater. After 4 weeks of aerated incubation the coupons were extracted and air dried. The change in weight of geotextile coupons after the exposure to wastewater was recorded. Results are given in Table 4.3.
Table 4.3: Organic Residue from Immersion in Phase I Screening

<table>
<thead>
<tr>
<th>Product Name/Structure/ Polymer Type</th>
<th>Net GT coupon weight (gr) Coupon 1-6</th>
<th>Dried GT coupon weight after exposed to wastewater, (gr) Coupon 1-6</th>
<th>Total Biomass accumulated on GT (gr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amoco 2130 W/F/PP GT 1</td>
<td>7.73, 7.93, 7.80, 7.85, 7.79, 7.93</td>
<td>7.74, 7.94, 7.80, 7.86, 7.92, 7.93</td>
<td>0.01, 0.01, 0.00, 0.01, 0.13, 0.00 S 0.16</td>
</tr>
<tr>
<td>Amoco 1199 W/F/PP GT 2</td>
<td>16.00, 16.11, 15.67, 15.33, 15.55, 16.02</td>
<td>16.00, 16.11, 15.68, 15.40, 15.56, 16.02</td>
<td>0.00, 0.00, 0.01, 0.07, 0.01, 0.00 S 0.09</td>
</tr>
<tr>
<td>Amoco 2002 W/F/PP GT 3</td>
<td>12.55, 12.47, 12.63, 12.62, 12.50, 12.56</td>
<td>12.55, 12.48, 12.63, 12.68, 12.50, 12.57</td>
<td>0.00, 0.01, 0.00, 0.06, 0.00, 0.01 S 0.08</td>
</tr>
<tr>
<td>Synthetic Industries Geotex 315T W/SF/PP GT 4</td>
<td>18.25, 18.22, 18.14, 18.35, 17.95, 18.18</td>
<td>18.25, 18.22, 18.15, 18.36, 17.95, 18.18</td>
<td>0.00, 0.00, 0.01, 0.01, 0.00, 0.00 S 0.02</td>
</tr>
<tr>
<td>Trevira 1125 NW/CF/PET GT 5</td>
<td>15.60, 16.04, 16.07, 15.51, 14.96, 15.63</td>
<td>15.60, 16.04, 16.19, 15.59, 15.09, 15.77</td>
<td>0.00, 0.00, 0.12, 0.08, 0.13, 0.14 S 0.47</td>
</tr>
<tr>
<td>Amoco 4545 NW/SF/PP GT 6</td>
<td>9.80, 9.58, 9.76, 9.77, 9.45, 9.83</td>
<td>9.80, 9.58, 9.77, 9.77, 9.45, 9.83</td>
<td>0.00, 0.00, 0.01, 0.00, 0.00, 0.00 S 0.01</td>
</tr>
<tr>
<td>Polyfelt TS 700 NW/CF/PP GT 7</td>
<td>15.72, 17.82, 17.37, 17.38, 18.00, 17.10</td>
<td>15.80, 17.91, 17.78, 17.47, 18.07, 17.17</td>
<td>0.08, 0.09, 0.41, 0.09, 0.07, 0.07 S 0.81</td>
</tr>
<tr>
<td>Amoco 4551 NW/SF/PP GT 8</td>
<td>20.14, 24.10, 21.84, 23.72, 24.91, 19.64</td>
<td>20.19, 24.15, 21.89, 23.78, 24.96, 19.71</td>
<td>0.05, 0.05, 0.05, 0.06, 0.05, 0.07 S 0.33</td>
</tr>
</tbody>
</table>
The Phase I study results shown on Table 4.3 and summarized on Table 1.3 made it clear that nonwoven geotextiles attracted more biomass than woven ones. The reason is that the nonwoven (NW) geotextiles provide much more surface area for microorganisms growth than the woven types. Therefore, nonwoven geotextiles were used in the last two (pilot plant) phases of the study.

4.8. Phase II and III Procedures

Twenty gallons of fresh or refrigerated wastewater samples were added to the storage or reservoir tank each day and pumped at the rate of 56 ml/min into the baffle tanks, and removed by another pump at the same rate, as illustrated on Figure 4.1. The hydraulic detention time for each baffle tank was 22.5 hrs. The treatment tanks, but not the reservoir tank, were also aerated at 1500-2000cc/min through a plastic pipe bubbler along the bottom of the tank. Tanks were aerated for 24 hours a day. No initial seeding of the geotextile baffles was done. Bacterial colonization occurred in few days by filtration, with rapid acclimation as indicated by the rapid BOD$_5$ and ammonia removal. Biomass growth soon became visible, as shown on Figure 4.4.

In Phase II, two identical aerated baffle treatment tanks were used in series. Effluent from the end of the first treatment tank was pumped into the second treatment tank. The Phase II study used 15 baffles of Polyfelt TS 700, a needle punched continuous filament type of nonwoven geotextiles that showed the best biofilm residue retention in Phase I, as shown on Table 4.3. Each tank contained 15 geotextile baffles. The complete Phase II pilot plant is shown in Figure 4.7.
The same wastewater sample or run was used over a period of 5 days representing 100 gallons of throughput per run. Every 5 days, a different wastewater run was obtained and used over 3 months period. BOD$_5$, TSS, NH$_3$, NO$_4$ s were measured. The BOD$_5$ and TSS tests were done at Philadelphia Water Department labs, while the NH$_3$ and NO$_4$ analysis was done at Drexel.

Each baffle coupon was weighed before placement in the tanks. After a 3 month continuous set of runs, the baffles were removed from the tanks and air dried. The measured dry biofilm accumulation is described in Chapter 5.
4.9 Daily and Weekly Pollution Parameters Measurements

In Phase II, the influent and effluent of each tank were always sampled at the same time every other day for NH$_3$ and NO$_3$, and once a week, or round, for BOD$_5$ and TSS over the 3 month run. The collection jars were rinsed with the sample before sampling. All samples were stored in the dark at 4°C cold room. The LaMotte Smart Colorimeter, a multi-wavelength unit, is shown in Figure 4.8.

Figure 4.8: LaMotte Smart Colorimeter
4.10 Calculations

Using the water sample analysis results from the inlet and outlet of the GBCS (Figure 1.1a & 1.1b), the removal efficiency of the system was calculated by using the following equation, where “a” is the flux in the inlet water to the baffle system and “b” is the flux in the outlet water from the baffle tank. Units of “a” and “b” are mg/l. They were concentrations of considered parameters.

System Efficiency (%) = \{(a-b)/a\}x100
5.1. Phase I: Candidate Geotextiles Proof of Biodegradation Concept

As noted in the previous Chapter, the Phase I study, done from April 17 to April 24 of 2001, showed that nonwoven geotextiles with an interior porosity derived from the needle punched type of fabrication showed a residual organic content, indicating that they had indeed hosted biomass. Both basic types of needle punched fabrication were studied, continuous filament and staple fibers. The order of average residual biomass per test coupon, derived from Table 1.2, was:

1. Polyfelt TS 700 continuous fiber polypropylene (0.135 g/coupon)
2. Trevira 1125 continuous fiber polyester (0.078 g/coupon)
3. Amoco 4551 staple fiber polypropylene (0.055g/coupon)
4. Amoco 4545 staple fiber polypropylene (0.02g/coupon)

From the viewpoint of TSS and BOD₅ capture by filtration, the potential differences among the four total types could be the surface texture (continuous filament is smoother than staple fiber) and the material (polypropylene or polyester). Whether or not these were critical is unknown, but the most obvious difference from the screening test results was between the continuous and staple fibers. Consequently, the apparent best performer, Polyfelt TS 700 continuous filament was used in the pilot plant investigation of Phase II, and the staple fiber Amoco 4551 was used in the confirmatory Phase III.

The one week aerated incubation of the Pilot Sample of the SEWPCF primary treatment effluent was a form of extended aeration to demonstrate a “proof-of-concept” of using
geotextiles as treating biomass attachment media. Instead of recirculating an activated sludge in a low F/M ratio as in extended aeration, the active biomass (the “M”) was entirely generated from the microorganisms in the Pilot Sample with a “self-generated” activated sludge. The substrate “F” was both the dissolved and the suspended organics, as the biomass obviously grew, and then, without fresh substrate, it consumed its own protoplasm, leaving the organic cell residue as noted above. Not only was there a wide variation in this indicator of attached biomass (as opposed to microorganisms that stayed in suspension between coupons) between the various geotextiles (Table 4.3 and the list above), but a “blank”, i.e. a tank without any geotextiles was used. Table 5.1 illustrates the treatment that occurred, obtained by sampling and analyzing the tank liquid when the test coupons were extracted. As noted in Chapter 4, the tanks had been arranged such that the wovens were placed in two tanks, and the nonwovens were placed in two others. However, all five tanks had the same primary effluent dose (“Start of Phase I Study Values columns of Table 5.1) as well as the same aeration, detention time, and other conditions.

Table 5.1: BOD₅, TSS, NH₃-N, and NO₃-N Concentration Change for Phase I

<table>
<thead>
<tr>
<th>Prmtr. Tank No.</th>
<th>Start of Phase I Study Values, (mg/l)</th>
<th>End of Phase I Study Values, (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BOD₅</td>
<td>TSS</td>
</tr>
<tr>
<td>Tank1, W</td>
<td>33</td>
<td>21</td>
</tr>
<tr>
<td>Tank2, W</td>
<td>33</td>
<td>21</td>
</tr>
<tr>
<td>Tank3, NW</td>
<td>33</td>
<td>21</td>
</tr>
<tr>
<td>Tank4, NW</td>
<td>33</td>
<td>21</td>
</tr>
<tr>
<td>Tank5, Blank</td>
<td>33</td>
<td>21</td>
</tr>
</tbody>
</table>
The TSS and BOD$_5$ removal rates were of the same order of magnitude in all tanks, as would be expected with the low initial concentrations and a week’s detention time. The removals of NH$_3$-N were slightly higher in the two tanks with NW geotextiles compared to the tanks with woven geotextiles, but the ammonia reduction was only 40% in the blank tank. The conversion of ammonia to nitrate was also higher with the tank containing the continuous filament geotextiles than the tank with wovens, and substantially higher than in the blank tank. Altogether, biological activity of various types was observed to be higher in tanks with nonwoven geotextiles.

While not conclusive in engineering parametric terms, these results are a basic “proof of-concept” that geotextiles can indeed host microorganisms extracted from the influent to remove and decompose pollutants.

### 5.2 Overall Numerical Results for Phase II, Continues Filament Baffles

After screening tests done by using different types of woven and nonwoven geotextiles in Phase I, the production experiments were carried out by using Polyfelt TS 700 type geotextile. Two tanks in sequence were used to provide an intermediate sampling point, and also because it was not known what length of path or exposed baffle area was required to sorb the organic materials. Details of the experimental set-up are given in Chapter 4. A summary of the results for Runs 1-8 are given in Table 5.2, with the water quality at the end of the first tank (T1) and the second (T2) shown. Monitoring of the nitrogenous compounds did not commence until the second run, under the assumption that the acclimation time for both nitrifying and denitrifying bacteria would be well over a week, and also because Run 1 was the raw (except for screening) sample, of such a high TSS and BOD$_5$ concentration that accurate measurement of NH$_3$-N was questionable.
Table 5.2: Phase II Results for Runs 1-8

<table>
<thead>
<tr>
<th>Conc, mg/l</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Run 6</th>
<th>Run 7</th>
<th>Run 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inf BOD$_5$</td>
<td>114</td>
<td>56</td>
<td>70</td>
<td>72</td>
<td>33</td>
<td>52</td>
<td>73</td>
<td>63</td>
</tr>
<tr>
<td>Eff BOD$_5$, T1</td>
<td>11</td>
<td>6</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Eff BOD$_5$, T2</td>
<td>10</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Inf TSS</td>
<td>318</td>
<td>35</td>
<td>36</td>
<td>35</td>
<td>52</td>
<td>35</td>
<td>40</td>
<td>31</td>
</tr>
<tr>
<td>Eff TSS, T1</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Eff TSS, T2</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Inf NH$_3$-N</td>
<td>---</td>
<td>16.8</td>
<td>17.2</td>
<td>25</td>
<td>12</td>
<td>10.9</td>
<td>11.8</td>
<td>13.1</td>
</tr>
<tr>
<td>Eff NH$_3$-N, T1</td>
<td>---</td>
<td>0.40</td>
<td>0.53</td>
<td>0.21</td>
<td>0.08</td>
<td>0.15</td>
<td>0.93</td>
<td>0.60</td>
</tr>
<tr>
<td>Eff NH$_3$-N, T2</td>
<td>---</td>
<td>0.35</td>
<td>0.34</td>
<td>0.09</td>
<td>0.04</td>
<td>0.09</td>
<td>0.23</td>
<td>0.19</td>
</tr>
<tr>
<td>Inf NO$_3$-N</td>
<td>---</td>
<td>0.9</td>
<td>1</td>
<td>0.9</td>
<td>0.04</td>
<td>0</td>
<td>0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>Eff NO$_3$-N, T1</td>
<td>---</td>
<td>21.2</td>
<td>23</td>
<td>19.4</td>
<td>16.8</td>
<td>6.4</td>
<td>6.5</td>
<td>6.6</td>
</tr>
<tr>
<td>Eff NO$_3$-N, T2</td>
<td>---</td>
<td>22</td>
<td>22.8</td>
<td>18.2</td>
<td>15.8</td>
<td>5.6</td>
<td>5.0</td>
<td>6.8</td>
</tr>
</tbody>
</table>

The Run 1 TSS and BOD$_5$ concentrations were much higher than the other runs, with the test sample collected at the entrance of the primary settlement tank of the SEPWCF. Other samples (Runs 2-13) were collected at the end of the settlement tank of the same facility. For these samples, test influent raw BOD$_5$ varied between 33 to 73 mg/l. However, as of the end of the first treatment tank, at a loading of about 1.0 gpd/ft$^2$ of baffle area, the BOD$_5$ values decreased to the range of 2 to 11 in all samples. Hence, the ability of the second tank of geotextiles to make a meaningful contribution was diminished, such that its outflow BOD$_5$ ranged between 2-10 mg/l. The higher values were for the raw PWD wastewater sample (10mg/l and 11mg/l). With a preceding primary sedimentation step, the GBCS consistently produced effluent BOD$_5$ below 10 mg/l. Doubling the detention time did not make a significant change. Thus, for both medium and low strength wastewater, it appears that a detention time of 22.5 hours, a nominal loading rate (cross section) of 20 gpd/ft$^2$ one tank, and
a biofilm loading rate of 1.0 gpd/ft² geotextile is enough for the GBCS to remove excessive BOD₅. Influent and effluent values of BOD₅ are plotted on Figure 5.1.

![Figure 5.1: Phase II Influent and Effluent BOD₅ Concentrations](image)

Influent and effluent concentrations of TSS are plotted on Figure 5.2. The results are even better than for the BOD reduction, with TSS effluent from the first tank consistently being in the single digits, even with the 300 mg/l raw wastewater Run 1. This is a result of the three separate mechanisms of TSS removal, filtration, sedimentation and biofilm surface sorption. The capability for sedimentation, a result of the physical layout and the hydraulic loading rate, was constant through the two months of tests. The capacity for filtration decreased as the porosity of the upgradient baffles filled with biomass, thus reducing the permeability and the proportion of the flow short-circuiting through the baffles. However, it appears that this was compensated by the biofilm emergence on the baffle surfaces, allowing organic-organic sorption of colloids to occur. Again, TSS removal did not change significantly at the end of first and second treatment tanks because the effluent from the first tank, the influent to the
second, had already been clarified to TSS<10 mg/l. From the perspective of TSS removal, one GBCS tank was enough to remove excessive TSS.

Figure 5.2: Phase II Influent and Effluent TSS Concentrations

Influent and effluent concentrations of NH$_3$-N are shown on Figure 5.3. As noted Run 1 was not monitored for NH$_3$ as the sample was very concentrated. With a constant hydraulic loading, and a variation in influent ammonia by a factor of 2.5 (10.9 to 25 mg/l), the differences in conditions between Run 2 and Run 8 are biomass age and mass, which grew baffle by baffle as indicated on Figure 4.1. Other samples except for Run 1 were collected at end of primary settlement tank. Test influent raw NH$_3$ varied between 10.9 to 25 mg/l over Phase II. As of the end of first treatment tank, NH$_3$ values decreased to the 0.08 to 0.93 mg/l range, an average of 95% removal, and decreased about another 50% in the second treatment tank. Again, doubling the detention time from 22.5 hours to 45 hours didn’t make any significant change.
Influent and effluent concentrations of NO$_3$-N are plotted on Figure 5.4. The primary sedimentation influent NO$_3$ varied between 0 to 1 over Phase II, indicating that the ammonia had just been released from the organic nitrogen in the primary treatment, and thus had not yet had the opportunity to convert ammonia to nitrate. After treatment in the first tank, its effluent NO$_3$ increased to the range of 6.4 to 23mg/l and between 5.6 to 22.8 mg/l at the end of the second tank. However, the ammonia reduction as indicated on Figure 5.3 exceeded the nitrate concentration by a factor of two in the last three runs, implying partial conversion to nitrogen gas.
Concentrations given for \([\text{NH}_3-N]\) and \([\text{NO}_3-N]\) in Table 5.2 are beginning and end of the 5 day run test values. Effluent concentrations compared to raw wastewaters, at the end of the first and second GBCS tank concentrations were given in Figures 5.3 and 5.4. To observe the daily variations in concentrations of these two parameters, some daily concentrations were measured and given in Table 5.3. Daily concentration variations for every run of the test were plotted and given on Figure 5.5 thru 5.11. As can be seen from these figures, stabilizations of concentrations start around the run 5 and continue thru the end of the run 8. Since detention time was 22.5 hrs for each tank, samplings were done at the end of the second tank not before than 2 or 3 days. Monitoring samples were obtained at the fifth days for run 2 thru run 4 and then pattern of daily sampling was applied. As mentioned above, when sludge aged, concentrations reached steady state values as shown on Figures 5.8 thru 5.11.
Table 5.3: Run 2 to Run 8 Detailed [NH$_3$-N] & [NO$_3$-N] Concentrations Changes

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Day</th>
<th>[NH$_3$-N], mg/l</th>
<th>[NO$_3$-N], mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2</td>
<td>Day 0, T1, T2</td>
<td>16.8</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Day 5, T1</td>
<td>0.40</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>Day 5, T2</td>
<td>0.35</td>
<td>22</td>
</tr>
<tr>
<td>Run 3</td>
<td>Day 0, T1, T2</td>
<td>17.2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Day 5, T1</td>
<td>0.53</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Day 5, T2</td>
<td>0.34</td>
<td>22.8</td>
</tr>
<tr>
<td>Run 4</td>
<td>Day 0, T1, T2</td>
<td>25</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Day 5, T1</td>
<td>0.21</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td>Day 5, T2</td>
<td>0.09</td>
<td>18.2</td>
</tr>
<tr>
<td>Run 5</td>
<td>Day 0, T1, T2</td>
<td>12</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Day 4, T1</td>
<td>0.12</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Day 4, T2</td>
<td>0.14</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td>Day 5, T1</td>
<td>0.08</td>
<td>16.8</td>
</tr>
<tr>
<td></td>
<td>Day 5, T2</td>
<td>0.04</td>
<td>15.8</td>
</tr>
<tr>
<td>Run 6</td>
<td>Day 0, T1, T2</td>
<td>10.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Day 4, T1</td>
<td>0.15</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>Day 4, T2</td>
<td>0.10</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Day 5, T1</td>
<td>0.15</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>Day 5, T2</td>
<td>0.09</td>
<td>5.6</td>
</tr>
<tr>
<td>Run 7</td>
<td>Day 0, T1, T2</td>
<td>11.8</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Day 3, T1</td>
<td>0.96</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Day 3, T2</td>
<td>0.25</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Day 4, T1</td>
<td>0.96</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Day 4, T2</td>
<td>0.22</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>Day 5, T1</td>
<td>0.93</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Day 5, T2</td>
<td>0.23</td>
<td>5.0</td>
</tr>
<tr>
<td>Run 8</td>
<td>Day 0, T1, T2</td>
<td>13.1</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Day 3, T1</td>
<td>0.65</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>Day 3, T2</td>
<td>0.22</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>Day 4, T1</td>
<td>0.60</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>Day 4, T2</td>
<td>0.22</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>Day 5, T1</td>
<td>0.60</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>Day 5, T2</td>
<td>0.19</td>
<td>6.8</td>
</tr>
</tbody>
</table>
Figure 5.5: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 2

Figure 5.6: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 3
Figure 5.7: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 4

Figure 5.8: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 5
Figure 5.9: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 6

Figure 5.10: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 7
Figure 5.11: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 8

Table 5.4 expresses the results as removal efficiencies for the wastewater pollution parameters. It is also shown that there incremental removal efficiency with is negligible. The secondary treatment goal plus advanced treatment in removing ammonia was satisfied.

Table 5.4: Removal Efficiencies of Selected Parameters for Runs 1-8

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Run 6</th>
<th>Run 7</th>
<th>Run 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>E, BOD$_5$, T1</td>
<td>90</td>
<td>89</td>
<td>93</td>
<td>97</td>
<td>79</td>
<td>96</td>
<td>95</td>
<td>94</td>
</tr>
<tr>
<td>E, BOD$_5$, T2</td>
<td>91</td>
<td>89</td>
<td>96</td>
<td>97</td>
<td>79</td>
<td>96</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>E, TSS, T1</td>
<td>99</td>
<td>80</td>
<td>97</td>
<td>97</td>
<td>98</td>
<td>97</td>
<td>95</td>
<td>94</td>
</tr>
<tr>
<td>E, TSS, T2</td>
<td>99</td>
<td>91</td>
<td>97</td>
<td>97</td>
<td>98</td>
<td>97</td>
<td>95</td>
<td>94</td>
</tr>
<tr>
<td>E, NH$_3$-N, T1</td>
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<td>97</td>
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<td>98</td>
<td>92</td>
<td>95</td>
</tr>
<tr>
<td>E, NH$_3$-N, T2</td>
<td>----</td>
<td>98</td>
<td>98</td>
<td>100</td>
<td>99</td>
<td>99</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>
5.3. Phase II: Treatment Progress Details: Biofilm Sloughing and Aeration Cycling

NO$_3$-N removal (denitrification) reached the highest level in Run 6 and Run 7, after 30 days of biomass acclimation. It is reasoned that this occurred mostly in the first few baffles, when they reached the maximum mechanically supportable biofilm thickness. With a hydraulic gradient across the baffles, diffusion of decomposition byproducts and ammonia into the channels would be restricted by the adverse hydraulic gradient. Rather, solutes would be conveyed through the interior of a baffle en route to its “downstream” face. Oxygen transfer to the interior decreased with increased microorganism population. The progress on increased denitrification and excess biofilm sloughing were concurrent. Distressed aerobes in the interior would reduce their mechanical binding and slough off, but conditions would be favorable to growth of denitrifying bacteria using the decaying cell tissue as a carbon source. This would support nitrate conversion to nitrogen gas (N$_2$). The last stage of the excessive biofilm growth before a sloughing is shown on Figure 5.12.
Since the purpose of the experiments was achieved by Run 8, and the NO$_3$ concentration reached a steady state condition that was apparently governed by the biofilm thickness, it was appropriate to investigate changing the environmental conditions of the GBCS. In order to observe the baffle system’s resiliency with rapid changes in the systems, the oxygenation was studied in Run 9 of the Phase 2 study. The oxygen supply for the first tank was stopped while it continued in the second tank and wastewater was recycled through the first and second tanks to observe the effect of lack of oxygen to the GBCS, the effect of recycling and if recycling improved or worsen nitrate removal. The results are given in Table 5.5.
Table 5.5: Results of Run 9 in Phase II

<table>
<thead>
<tr>
<th>Run No. 9</th>
<th>BOD$_5$, mg/l</th>
<th>TSS, mg/l</th>
<th>NH$_3$-N, mg/l</th>
<th>NO$_3$-N, mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days,</td>
<td>T1 T2 T1 T2 T1 T2</td>
<td>T1 T2</td>
<td>T1 T2</td>
<td>T1 T2</td>
</tr>
<tr>
<td>Exp. Start day</td>
<td>79 79 72 72</td>
<td>13.9 13.9 0.3 0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 3</td>
<td>--- --- --- ---</td>
<td>11.5 10.7 0.1 1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observation of Excessive Biofilm Growth in First Tank</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 4</td>
<td>--- --- --- ---</td>
<td>11.6 10.2 0.2 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 5</td>
<td>--- --- --- ---</td>
<td>12.0 11.1 0.8 0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observation of Sloughing Biofilm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 6</td>
<td>--- --- --- ---</td>
<td>12.0 4.8 0.4 6.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 7</td>
<td>25 10 7 4</td>
<td>13.8 1.9 0.5 10.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 8</td>
<td>--- --- --- ---</td>
<td>12.6 0.8 0.3 9.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 9</td>
<td>--- --- --- ---</td>
<td>13.9 0.7 0.1 10.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These results show that cutting off oxygen supply in the first tank negatively affected its performance. It was observed that BOD$_5$, NH$_3$ and NO$_3$ removal rates dropped with the lack of oxygen supply in the first tank. In addition, recycling of wastewater could be another reason for the observation of lower removal rates. BOD$_5$ and NH$_3$ removals in the second tank followed the similar patterns of Run 8. Ammonia removal rates were considerably low for the day 3 thru day 5 of the Run 9. It was speculated that wastewater quality change happened in the first tank because of the lack of oxygen supply. This was obviously affecting what was happening in the second tank, because effluent of first tank was influent of the second tank. However, starting of the sixth day, almost all ammonia was converted to nitrate but denitrification was not recovered that fast. This can also be seen in Figure 5.13. In other words, high nitrate removal was not observed in second tank. The reason for this could be
either recycling of the wastewater or a sloughing biofilm. This was observed on the fifth day of the Run 9. Removal efficiencies for Run 9 are given in Table 5.6.

Figure 5.13: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 9

Table 5.6: Removal Efficiencies in Run 9

<table>
<thead>
<tr>
<th>Day</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E, BOD$_5$, T1</td>
<td></td>
<td></td>
<td></td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E, BOD$_5$, T2</td>
<td></td>
<td></td>
<td></td>
<td>87</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E, TSS, T1</td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E, TSS, T2</td>
<td></td>
<td></td>
<td></td>
<td>94</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E, NH$_3$-N, T1</td>
<td>17.3</td>
<td>16.5</td>
<td>13.7</td>
<td>13.7</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>E, NH$_3$-N, T2</td>
<td>23</td>
<td>27</td>
<td>20</td>
<td>66</td>
<td>86</td>
<td>94</td>
</tr>
</tbody>
</table>
5.4 Phase II: Biofilm Mass Retention Study

It had been demonstrated that only one tank, or alternatively, furnishing 1.0 gpd/ft\(^2\) or less of baffle surface was sufficient to meet secondary treatment standards as well as ammonia removal. It was further noted in the Run 9 experiment that lack of oxygen caused lower \(\text{BOD}_5\) and \(\text{NH}_3\)-N removals in the first tank of Run 9, and in the process, the first tank biomass had lost its treatment capability. Very low removals were shown in Table 5.6 for Tank 1. Hence, it was the vessel taken out of service, keeping the second tank with the full array of baffles to test the continuation of recovery in Runs 10 and Run 11. This presented an opportunity to measure the residual biomass in the first, main tank from the two months of biological activity. The baffles were removed from the tank and air dried. The arrangement for air drying of samples is shown in Figure 5.14. It can be seen that there is a gradation in biofilm color. The changes in dry biomass weights along Tank 1 are given in Table 5.7.

![Air Drying Geotextile Baffle Coupons](image-url)
Table 5.7: Accumulated Dry Biomass on Baffles in Tank 1 for Runs 1-9

<table>
<thead>
<tr>
<th>GT number</th>
<th>Distance from Entrance of Tank 1, inches</th>
<th>Fresh GT coupon weight (mg)</th>
<th>Dry baffle weight after two months in service (mg)</th>
<th>Net Dry Biofilm Weight (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>18.26</td>
<td>20.05</td>
<td>1.79</td>
</tr>
<tr>
<td>2</td>
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<td>3.41</td>
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<td>4</td>
<td>7</td>
<td>18.31</td>
<td>21.06</td>
<td>2.75</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>18.66</td>
<td>21.35</td>
<td>2.69</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>19.48</td>
<td>22.00</td>
<td>2.52</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td>18.27</td>
<td>20.50</td>
<td>2.23</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>20.01</td>
<td>22.30</td>
<td>2.20</td>
</tr>
<tr>
<td>9</td>
<td>17</td>
<td>19.98</td>
<td>21.95</td>
<td>1.97</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>18.98</td>
<td>20.68</td>
<td>1.70</td>
</tr>
<tr>
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<td>21</td>
<td>19.59</td>
<td>21.22</td>
<td>1.63</td>
</tr>
<tr>
<td>12</td>
<td>23</td>
<td>19.62</td>
<td>21.08</td>
<td>1.46</td>
</tr>
<tr>
<td>13</td>
<td>25</td>
<td>19.76</td>
<td>21.16</td>
<td>1.40</td>
</tr>
<tr>
<td>14</td>
<td>27</td>
<td>19.01</td>
<td>20.38</td>
<td>1.37</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
<td>19.99</td>
<td>21.34</td>
<td>1.35</td>
</tr>
</tbody>
</table>

The highest biofilm accumulation on the baffles was observed at the beginning of Tank 1 after the first baffle, which evidently served to dampen the inflow pumping effects. High biomass retention was visible from the second through the sixth baffle, with a slime coating that almost obscured the fabric, i.e., it grew out from the interior and coalesced on the surface to fully contact the flow through the channels. The baffles closer to exit of the tank didn’t collect as much biomass, with a discontinuous surface slime later. The dry biomass weight was plotted versus distance from the entrance of Tank 1 was shown on Figure 1.6, repeated herein as Fig 5.15. Since there had been sloughing off the first few baffles since Run 6, it can be concluded that the 3.41 g. maximum (dry weight) is the mechanically sustainable maximum biomass. With a two-sided surface area of 1.67 ft², the dry biomass density can be expressed as ranging from 3.41 g/ft², down to about 1.35 g at the last baffle (GT baffle No.=15 of Table 5.7).
With these impacts noted, and treating the oxygen ceasing and recycling as disturbances, the next step was to determine how long it would take for the GBCS to return to normal working condition. Although NH$_3$ and NO$_3$ removal performances in the first tank of Run 9 did not recover, continuous removal in the second tank of same run was observed. Therefore, in any case, the second tank, while marginally productive in continuous treatment, could act as a safety measure for shock loads or other disturbances.

To observe the time period for nitrification and denitrification, Runs 10 and 11 were run through what had been the second tank, now the only one. Previously, the biofilm had been barely visible in the substrate-starved Tank 2 position, but it grew over the next two runs, as expected. The treatment results from Runs 10 and 11 are given in Table 5.8, and the removal efficiencies are shown in Table 5.9.
Table 5.8: Phase II Results for Runs 10 and 11

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Day</th>
<th>Run 10</th>
<th></th>
<th>Run 11</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BOD$_5$</td>
<td>TSS</td>
<td>NH$_3$-N</td>
<td>NO$_3$-N</td>
</tr>
<tr>
<td>Day 0</td>
<td></td>
<td>60</td>
<td>39</td>
<td>12.8</td>
<td>0.33</td>
</tr>
<tr>
<td>Day 3</td>
<td></td>
<td>---</td>
<td>---</td>
<td>12.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Day 4</td>
<td></td>
<td>---</td>
<td>---</td>
<td>7</td>
<td>6.6</td>
</tr>
<tr>
<td>Day 5</td>
<td></td>
<td>---</td>
<td>---</td>
<td>6.9</td>
<td>6.1</td>
</tr>
<tr>
<td>Day 6</td>
<td></td>
<td>---</td>
<td>---</td>
<td>5.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Day 7</td>
<td>7</td>
<td>4</td>
<td>5.7</td>
<td>5.1</td>
<td>---</td>
</tr>
</tbody>
</table>

* PWD lab indicated disturbed test

Table 5.9: Removal Efficiencies of Selected Parameters for Run 10 and 11

<table>
<thead>
<tr>
<th>Removal %</th>
<th>Day</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>E, BOD$_5$,R10</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>88</td>
</tr>
<tr>
<td>E, BOD$_5$,R11</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>63</td>
</tr>
<tr>
<td>E, TSS, R10</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>90</td>
</tr>
<tr>
<td>E, TSS, R11</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>94</td>
</tr>
<tr>
<td>E, NH$_3$-N,R10</td>
<td>4.7</td>
<td>45.3</td>
<td>46</td>
<td>55.5</td>
<td>55.5</td>
<td></td>
</tr>
<tr>
<td>E, NH$_3$-N,R11</td>
<td>78.7</td>
<td>78.7</td>
<td>82.4</td>
<td>86.8</td>
<td>86.8</td>
<td></td>
</tr>
</tbody>
</table>

Since wastewater quality applied to second tank used for Run 10 and 11 changed from less oxygenated recycled wastewater to fresh SEPWCF effluent, restoration of ammonia and nitrate removals was observed. Ammonia dropped to 5.7 mg/l from 12.8 mg/l, while nitrate was 5.7 mg/l. Daily concentration changes for ammonia and nitrate were plotted on Figure 5.16, showing the adaptation mechanism after the disturbed system.
However, BOD$_5$ and TSS removals were not affected from influent wastewater change applied to the system. Another similar quality fresh wastewater was carried from SEPWCF and run through the tank as Run 11. While BOD$_5$ and TSS removal rates stayed same, NH$_3$-N removal has increased significantly. Daily ammonia and nitrate concentrations were plotted for Run 11 in Figure 5.17. This was reasoned the microorganisms were adapting the new conditions real fast. However, nitrate concentrations were not lowered the less than 8mg/l. Thick biofilm thickness was not observed by the end of the Run 11, therefore, in order to expect the nitrate removal aged thick biofilm was needed.

Figure 5.16: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 10
Figure 5.17: Daily NH$_3$-N and NO$_3$-N Concentrations for Run 11

TSS and BOD$_5$ concentrations measured on the last day of a run as had been the standard practice, was at or near previous levels in Run 10, with the system restored to normal working condition. Ammonia removal and some conversion of NO$_3$ to N$_2$ gas was observed as well, although not yet up to the original (before Run 9) levels. In order to observe further decrease Run 11 was tested. The lower percentage for Run 11 shown on Table 5.9 is, in part, the numerical result of this being a weak sample with regards to BOD$_5$ (30 mg/l), but on the higher side of the range tested with respect to TSS (62 mg/l). This unusually high TSS/ BOD$_5$ ratio after undergoing primary treatment is due to the SEWPCF handling a severe storm, such that some of the TSS was combined sewage that included scour of pipe inverts. The Phase II series of experiments using needle punched continuous filament geotextiles as the baffle material ended at the end of Run 11. The coupons were recovered taken from Tank 2 after nine samples processed under “starved” conditions (the downstream tank) and two samples or runs as the main treatment unit. The baffle coupons were air dried as was done with the Tank 1 baffles. The changes in the biomass weights along Tank 2 are given in Table 5.10, and
plotted on Figure 5.18, which repeats Figure 1.7. The same pattern of a lower first baffle biomass followed by higher retention for the next few is shown. Presumably, the unit dry biomass shown represents an intermediate point (two weeks service) approaching, but not yet attaining, the maximum biomass retention after two months that was found with the Tank 1 baffle (Figure 5.15). Sloughing had not yet been observed in Run 11, but the slime coating was. Tank 2 was secondary GBCS for the first 9 runs of the phase II, and primary for the runs 10 and 11. Therefore, biofilm thickness was low as mentioned above, such as slimy layer on the geotextiles, and relatively low air dried biofilms were measured.

Table 5.10: Dry Biomass Change for Tank 2 for Runs 10-11

<table>
<thead>
<tr>
<th>GT No.</th>
<th>Distance from Tank Entrance (in.)</th>
<th>Fresh baffle weight (mg)</th>
<th>Dried baffle weight after two weeks in service (mg)</th>
<th>Net Dry Biofilm Weight (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>19.37</td>
<td>21.04</td>
<td>1.67</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>19.81</td>
<td>21.92</td>
<td>2.11</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
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<td>21.84</td>
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<td>4</td>
<td>7</td>
<td>19.14</td>
<td>20.83</td>
<td>1.69</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>20.07</td>
<td>21.62</td>
<td>1.55</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>18.73</td>
<td>20.10</td>
<td>1.37</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td>19.09</td>
<td>20.23</td>
<td>1.14</td>
</tr>
<tr>
<td>8</td>
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<td>17</td>
<td>19.47</td>
<td>20.80</td>
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<td>19</td>
<td>19.61</td>
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<td>12</td>
<td>23</td>
<td>19.78</td>
<td>20.90</td>
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<td>19.82</td>
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<td>15</td>
<td>29</td>
<td>19.63</td>
<td>20.58</td>
<td>0.26</td>
</tr>
</tbody>
</table>
5.5. Phase III: Pilot Plant Using Staple Geotextile Baffles

As noted above, Phase III was intended to both confirm the treatment effectiveness of the GBCS. In Phase 3, one tank was re-packed identically to the Phase II arrangement with a set of fresh baffles of a different geotextile type (Amoco 4551, a staple fiber product). This pilot plant was operated through two more runs over two weeks, using the same wastewater source (SEWPCF). The results are shown on Table 5.11.
Table 5.11: Phase II Results for Runs 12 and 13

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Run 12, (mg/l)</th>
<th>Run 13, (mg/l)</th>
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<tbody>
<tr>
<td></td>
<td>BOD₅</td>
<td>TSS</td>
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<tr>
<td>Exp Start</td>
<td>31</td>
<td>26</td>
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<tr>
<td>Day 3</td>
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<td>---</td>
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<tr>
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<td>---</td>
</tr>
<tr>
<td>Day 5</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Day 6</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Day 7</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

As in Phase II, no initial seeding was used to inoculate the baffles. The basic indicator of biofilm growth is the rapid initiation of BOD₅ removal. High TSS (physical) and BOD₅ (biological) removal was indeed observed in Runs 12 and 13. However, the two week duration of Phase III was apparently not sufficient to fully establish the nitrifying and denitrifying bacteria populations. Decomposition of the relatively high BOD₅ of Run 13 may have caused this delay, especially considering that this value was three times the concentration of the TSS that carries the inoculant bacteria. Phase III removal efficiencies are shown on Table 5.12.
Table 5.12: Removal Efficiencies for Runs 12 and 13

<table>
<thead>
<tr>
<th>Removal Day</th>
<th>BOD₅</th>
<th>TSS</th>
<th>NH₃-N</th>
<th>NO₃-N</th>
<th>Run 12</th>
<th>Run 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Day 3</td>
<td>---</td>
<td>---</td>
<td>54</td>
<td>---</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Day 4</td>
<td>---</td>
<td>---</td>
<td>54</td>
<td>---</td>
<td>17</td>
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<tr>
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<td>---</td>
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<tr>
<td>Day 6</td>
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<td>---</td>
<td>53</td>
<td>---</td>
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<td>17</td>
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<tr>
<td>Day 7</td>
<td>94</td>
<td>96</td>
<td>53</td>
<td>97</td>
<td>70</td>
<td>16</td>
</tr>
</tbody>
</table>

To compare the removal efficiencies of rounds 1-11 in phase 2 and rounds 12 and 13 of phase 3, following Table 5.13 is given below.

Table 5.13: Comparison of Phase II and Phase III Removal Efficiencies

<table>
<thead>
<tr>
<th>Phase No. Removal,%</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Runs 1-8</td>
<td>Runs 9*</td>
</tr>
<tr>
<td>BOD₅</td>
<td>79-97</td>
<td>68-87</td>
</tr>
<tr>
<td>TSS</td>
<td>80-99</td>
<td>90-94</td>
</tr>
<tr>
<td>NH₃-N</td>
<td>89-100</td>
<td>0-95</td>
</tr>
</tbody>
</table>

* Starved air experiment  ** Restart Experiment
Chapter 6. Future Research and Scale-up Study

6.1 Introduction

At first glance, the geotextile baffle contact system (GBCS) can be thought of as a variation of a trickling filter. After initial innoculation that partially clogs the porous baffles, the influent flows tangentially over an attached biofilm, and organic substrate is sorbed from it. However, there are significant differences between trickling filters and the GBCS in operation and treatment byproducts. Trickling filters operate under unsaturated vertical flow and passive aeration, while the GBCS uses saturated horizontal flow and artificial aeration. There is a greater degree of reduction in the secondary treatment parameters (TSS and BOD$_5$) within the GBCS vessel, and also, nitrogenous compounds (NH$_4$ and NO$_3$). Rather than shedding excess biomass containing the sorbed organics for separation and decomposition downstream, the baffle system mineralizes much of substrate within the biofilm and decomposes settled TSS and excess biomass sludge within the reactor itself. While physically quite different, the GBCS system provides similar unit operations as an extended air (EA) type of activated sludge- suspended growth system. EA systems trade aeration costs for sludge disposal costs, producing not only secondary-quality effluent, but substantial ammonia removal and low sludge production.

It was shown that some types of geotextiles internally entrap suspended solids, and others do not. The key geotextile characteristic in use as a treatment media is interior porosity, but surface texture was also seen to be influential. The ultimate result is a thick biofilm that not only treats dissolved carbonaceous material, but also provides internal environments for conversion of ammonia and then, nitrate. The sinuous baffle layout encourages TSS removal by three processes: channel sedimentation, baffle matrix filtration, and surface sorption.
Filtration is the major mechanism in the formation of active biomass, but its contribution to treatment decreases as the biological floc in a baffle coalesces to form a continuous biofilm that may eventually project out from the baffle surface.

Despite the two months application of primary treatment effluent in Phase II, it is possible that steady state was not reached. Only the first few baffles “excessively clogged”, thus diverting flow as originally envisioned through the channels. It was evident that filtration was ongoing in downstream baffles. Hence, while the unit hydraulic loading rate normal to the filter, 20 gallons/day-ft$^2$, is almost in the same range as conventional trickling filters (Chapter 3), the optimum “depth” of the unit (i.e., length of the baffle array) along the nominal flow path is unknown. The trickling filter depths shown on Table 3.11 were determined empirically. The bench unit was 2.5 ft. long, providing 15 sq. ft. of active baffle area per sq. ft. of cross-section area. This is less than the 6 ft.-8 ft. depth customary with trickling filters. This shows the potential for better treatment in less reactor volume and lower operational head loss in full scale use. Resolving the optimum depth question, among others, is necessary in order to provide useable design parameters. This requires a long term, larger scale prototype test program.

### 6.2 Goals of Prototype Scale Study

The next logical next step in the development of the GBCS is a prototype scale parametric study that includes real-time comparison with a conventional trickling filter used as a “blank”. It is also possible to include a model extended aeration unit, but installing a sludge return capability is difficult, and as described below, placing the test array at a conventional activated sludge plant allows comparison with that type of treatment anyway. The result would be a design procedure (a presumptive one is shown in the next Chapter). Continuing
the laboratory bench scale project through Phase III became difficult in terms of transporting raw sewage samples to a campus laboratory. Obtaining the data to guide design requires larger reactors and wastewater volumes and longer runs. Thus, it is best to construct a prototype plant at an existing treatment facility. It is desired that the test liquid have the fluctuation in wastewater concentrations as was found at SEWPCF for credibility and assessment of robustness, but a higher strength test fluid is also desired. The primary tanks at SEWPCF consistently produced a dilute effluent because they were designed to handle large volumes of combined sewage from almost 100% of the tributary area. Hence, the logical site is a wastewater treatment facility with a larger proportion of residential dry weather flow (DWF) with a consistent higher BOD₅ and nitrogen content.

Among the issues to be addressed are:

1. Replication of the biofilm propagation and treatment study at the original HLR (1.0 gpd/ft² of baffle surface) and also at higher application rates. It is important to run an extended study over several months, monitoring the liquid quality channel by channel to determine optimum length and baffle area. Assessing the effects of variable organic and nitrogen loading rates is co-incident with this effort, to be indicated by continuously measuring the influent concentrations of the constituents of interest.

2. Testing a wider array of nonwoven geotextiles, varying by AOS, permeability, porosity, fiber denier and surface texture. Perhaps new products could optimize values of these parameters.

3. Economic feasibility study by determining the sensitivity to aeration, first by reducing the rate, then by intermittent bubbling.
4. Detailed study of sludge accumulation and decomposition

5. Comparing the results with conventional trickling filter media in one continuous flow pass

6. Testing the GBCS against shock influent wastewater overflows

7. Studying the biofilm morphology and formation in the geotextile pores in more detail.

For the large-scale parametric study, multiple reactors in parallel would use the same influent from a reservoir containing a source influent batch recovered directly from the plant flow.

**6.3 Experimental Layout (Pilot Plant)**

Figure 6.1 illustrates the layout of the proposed pilot plant. Since field applications would probably use precast concrete or fiberglass reinforced plastic (FRP) vessels, the scale up from the experimental tanks is straightforward. At this point, tanks 4ft. wide by 3ft. deep and 10ft. long are proposed. With a freeboard, the 10 sq.ft. cross-section would be a tenfold scale-up from the bench tests. The “boxes” would probably be 10ft. long in order to fully characterize both treatment and biofilm attachment. The trickling filter prototypes would be 4ft. diameter vessels, 8ft. deep. This provides slightly more surface area normal to flow, as there is concern about short-circuiting along the sides, which would unfairly bias the results.

Two 3,000 gallon reservoirs are also shown on Figure 6.1. This would allow one set of prototype units to be tested for several days with a single batch recovered from the primary tanks, while another set could either be tested with the same batch, a different one, or run-of-plant. Six reactor units are shown for each set. Four units could be furnished with the GBCS.
The two circular units would be coarse media trickling filter blanks. When the two sets are run on tandem with the same influent, the four baffle tanks could be run at different hydraulic loading rates (and thus, organic loading) with two blanks, which could have different media. Alternatively, the four baffle tanks could contain different geotextiles. Another test sequence would employ a common influent and geotextile, but different aeration intensity and continuity in the four baffle tanks.

A large scale study such as this requires careful selection of variables studied. It appears that the 2in. spacing between geotextile baffles, and 83% projection across the tank section appears to be a fortunate first try that worked very well. However, after the test sequences noted above, variations in baffle layout dimensions could be investigated as well. The final effluent from the tanks and filters would be returned to primary tank as shown on Figure 6.1.

Figure 6.1: Layout of the Proposed Pilot Plant
As indicated in Chapter 4, the BOD$_5$ concentration of the SEWPCF primary effluent varied from 33 to 72 mg/l, TSS from 31 to 52 mg/l, and NH$_4$ from 10.9 to 25 mg/l. The maximum removal rates achieved for BOD$_5$, TSS and NH$_4$ were 97%, 99%, and 100%, respectively. The prototype study is intended, in part, to confirm these removal rates at full scale. Moreover, a liquid with stronger influent is sought to determine if the same level of performance can be accomplished, i.e., BOD$_5$ and TSS effluents less than 10 mg/l and an NH$_4$ effluent of less than 2 mg/l. Daily sampling for these three parameters would give the best results on how to evaluate the different variables applied to the geotextile baffle contact tanks. Thicker and aged biofilm will bring NO$_3$ concentrations to a single digit values.

Although several kinds of woven and nonwoven geotextiles were tested in this study, and only those with internal porosity performed successfully, it was determined that the nonwoven geotextiles performed better. Study of a broad range of geotextiles with interior porosity would give better understanding of how the manufactured properties such as AOS and fiber texture affect the treatment efficiency. In doing so, the geotextiles can be manufactured specifically for wastewater treatment.

Another variable that can be tested in this scale up study is that higher TSS concentrations can be applied to the GBCS tanks in order to understand the capacity of the individual geotextile type. In this study, it was found that even with a maximum value of about 300 mg/l TSS, GBCS worked out efficiently.
Chapter 7. Applications and Design Examples

7.1 Anticipated Applications

As noted in Chapter 1, there are several types of aqueous discharges for which the GBCS may successfully remove organic pollutants prior to discharge to a natural water body:
- Urban runoff or combined sewer overflows (CSOs)
- Municipal and domestic wastewater

The main objective in the intermittent, high flow rate applications is to capture the suspended and colloidal solids to which pathogens and other bacteria are attached. This would improve water quality for both human contact and aquatic community. The performance of the GBCS in reducing TSS by sedimentation, filtration and sorption has been demonstrated. The units can be placed underground and require little hydraulic head, such that an end-of-pipe treatment unit as shown on Figure 1.13, repeated below as Figure 7.1 for a CSO. The deployment would be identical for a storm drain outfall. Capture efficiency has been shown implicitly to be high for relatively quiescent conditions, but would not necessarily be as efficient for the high velocity characteristic of the types of discharges. Following each event, the intercepted material would decompose and restore the sedimentation, filtration and attachment capacity. The residual organic biomass would also provide sites to adsorb dissolved material. Figure 1.13, illustrating an end-of-pipe CSO application, is shown below as Figure 7.1. The same basic end-of-pipe layout would be used for either application. However, the efficiency of GBCS performance has not been investigated for TSS capture in high velocity flows. Further study would be needed in that regard.
With respect to wastewater treatment, as described in Chapter 1, the GBCS could be retrofitted in an existing facility as a solution to the following issues:

1. Completing treatment at plants not producing effluent meeting discharge standards
2. Seasonal low flow period “polishing” of secondary effluent to reduce BOD$_{tot}$ and ammonia and/or remove nutrients by denitrification
3. Secondary treatment in rural areas after primary clarification in lagoons
4. Pretreatment for a septic system or rapid infiltration system.

Example designs are presented herein for two variations, improving longevity and performance of a septic system as an alternative to a sand filter, and secondary and advanced (ammonia removal) treatment for a small community of about 1000 persons. In the former, primary treatment is provided by a septic tank, and in the latter, by a primary clarifier, lagoon, or perhaps, an undersized “package plant”.

Figure 7.1: GBCS Added Urban Runoff and CSO Treatment Unit Layout
As noted in the text, the GBSC is, to some extent, physically a hybrid of a trickling filter and a lamella settler. In terms of minimizing sludge production by encouraging aerobic carbonaceous mineralization to the greatest extent possible, and nitrifying ammonia, the GBCS is similar to an extended aeration plant operating at a low F/M ratio and extended detention time. Finally, in also providing some degree of denitrification in the same unit, the GBCS is similar to a sequencing batch reactor (SBR). Each technique has its own design indices. For example, in suspended growth, hydraulic retention time is critical, but that does not appear to be relevant to the GBSC. Both particulate and dissolved organics are quickly removed from the influent. The time for actual biodegradation within the attached biomass is unknown. The appropriate design indices for treatment unit layout and dimensions extracted from this dissertation would be the surface settling rate and the baffle surface HLR, both expressed in gpd/ft\(^2\) units, but applied to different surfaces.

- Surface settling rate is the standard index of sedimentation. It is evident from the TSS removal rates and pattern (first few channels) that the 10 gpd/ft\(^2\) (footprint) in the laboratory experiments is excessively conservative. This conclusion is supported by this being 1/60\(^{th}\) of the value used in conventional clarifiers that do have turbulence. Any turbulence is reduced by the tubes in lamella settlers and the flexible baffles in the GBCS. It is assumed for the examples herein that a surface settling rate of 100 gpd/ft\(^2\) (footprint) will substantially reduce the finer organic particles that were not removed in primary sedimentation. For a given daily flow, this index sets the footprint area of the treatment unit.

- Ratio of HLR to baffle surface area. (gpd/ft\(^2\)). This is not just an index of available surface area to provide opportunity for sorption, it also represents the F/M ratio for the actual degradation. Since there is a finite biomass thickness on the baffles, and the HLR represents the organic loading rate, this is essentially an F/M ratio on a rate basis. The design value will
be that used in the experiments, 1 gpd/ft$^2$ (baffle surface area). For a given daily flow, this index sets the number of baffles in the treatment unit.

### 7.2 Septic System

The main control in onsite wastewater disposal systems is the unit infiltration capacity, in gpd/ft$^2$. The selected value determines the size of the leaching or sorption field. It is related to the permeability, but considerably reduced from that value to compensate for biological clogging. The more fine grained the soil, the higher the risk of clogging. This is not just the result of these soils having smaller pores that can be blocked by microorganism attachment or organic residue, but because high capillary moisture retention restricts air circulation. Thus, to keep an infiltration bed size within reason, it is often necessary to install a sand filter between the septic tank and the leaching field to reduce the organic loading on the latter. A sand filter is shown on Figure 7.2. Often, when it is necessary to elevate the infiltration surface to clear the water table (i.e., mound system), a sand filter is incorporated into the mound with GBCS, as shown on Figure 7.3. The GBCS system provides a more compact and accessible biological treatment unit to remove organics before infiltration, thus, clogging is eliminated. This assertion is supported by the over 90% removal of TSS and BOD$_5$ in the GBSC. The installation is particularly easy if there is a mounded system, as the GBSC can simply be inserted as a reactor vessel extension of the pump wetwell that must be installed anyway to accumulate septic tank overflow between pump cycles or doses. This expansion reactor is shown on Figure 7.3. The design problem is to select the dimensions of the reactor and the number of hanging geotextile baffles.
Figure 7.2: Intermittent Granular Filter (Orenco Systems, Inc.)

Figure 7.3: Septic System Designed with GBCS and Multiple Geotextile Layered Sand Filter
The design of the GBCS reactor for a 1000gpd flow rate (a typical household) follows the three indices. It was evident with the success in clarifying the raw wastewater in Phase II, Run 1, that a 10 gpd/ft² surface settling rate is excessively conservative. If it were arbitrarily increased to 50 gpd/sq.ft., this would still be 1/10 or lower than the criteria used in either primary or secondary clarifiers. Some conservatism is in order, however, as a leading cause of leaching field failure is overflow of grease from the septic tank. With a 1000 gpd flow, and 50 gpd/ft², surface settling rate, a surface area of 20 sq. ft. (e.g. 4ft. x 5ft.) would be sufficient. This second opportunity (after the septic tank) to remove grease provides assurance of reliability and longevity far superior to a sand filter, which can fail by grease clogging.

The hydraulic loading rate is selected to be 5.0gpd/sq.ft., as the intent is not to do all biodegradation in the vessel, but to reduce the organic loading on the infiltration surface. 350 net square feet of baffle biofilm attachment area are required under the 4ft. x 5ft. footprint. Assuming a 4ft. deep vessel, 4ft. wide, 75% projection across the width, and sludge clearance, each baffle would 1 yard x 1 yard. At 18sq.ft. per baffle, 200 sq. ft. required, 12 baffles would be required. At 2 in. spacing for 4ft. of the 5ft. length, 24 baffles will actually fit. There is probably no need for artificial aeration in the reactor, as, the pump drains the unit six or more times daily, as per the selected dosing interval, thus exposing the biofilm.

7.3 Small Community Application

With the GBCS biological treatment system developed and proven with a clarified municipal wastewater having wide concentration fluctuations, the most credible application is for secondary and/or advanced treatment of wastewater at small communities. The general
system layout including GBCS for a small community is shown on Figure 7.4. GBCS can be installed to current system as permanently or seasonally.

![Diagram of GBCS Application to a Small Community](image)

Figure 7.4: GBCS Application to a Small Community

While activated sludge is the treatment method of choice for larger communities, its mechanical complexity and need for operator attention makes it unfeasible below a certain flow range. In such cases, the common alternatives are:

- lagoons
- extended aeration
- trickling filters

Lagoons are the least expensive when there is available space, so the current choices for communities producing 100,000 gpd or less that do not have such room are suspended growth extended aeration and attached growth trickling filters. With more frequent requirement to
reduce nitrogenous constituents to protect the small streams to which community systems discharge, trickling filters are falling out of favor unless a downstream unit such as a wetland is available for this purpose. Compact extended aeration systems have been developed that produce a highly nitrified effluent, which takes care of the ammonia problem, and denitrification filters can be appended. This increase the mechanical complexity and need for operator attention. The method of choice for small systems when there are stringent discharge requirements is SBRs, which are particularly mechanically complex.

Thus, an alternative attached growth system is sought, to fill the “appropriateness” niche originally occupied by trickling filters. This is the basic dimension design for a GBCS that follows some form of existing secondary treatment the produces an effluent of similar quality as the SEWPCF combined sewage (hence oversized) primary effluent, i.e both TSS and BOD below 100 mg/l.

The design of the GBCS reactor for a small community of 1000 people with a 60 gal/capita.day produces 60,000 gpd of flow rate. To enhance TSS removal from the small community facility overflow, a required surface settling rate would be 100 gpd/ft², requiring a reactor surface area of 600 ft², e.g. 40ft. long, 15ft. wide, or alternatively two parallel trenches 30ft. long, 10ft. wide. With a criterion of 20gpd/ft², 3,000 net square feet of baffle biofilm attachment area is needed. Assuming 5ft. depth, the same 80% projection across the width, and 1ft. sludge clearance, each baffle would be 8ft. x 4ft., giving 64 sq.ft. per baffle, and thus, total of 50 baffles would be required, 25 in each tank. Artificial aeration could be supplied when needed.
Chapter 8. Summary and Conclusions

This geotextile baffle contact system (GBCS) project combined sanitary and geosynthetic engineering principles to investigate the use of geotextiles for treating wastewater by physical filtration and biological decomposition. This continued previous work at Drexel University, a study of biological clogging in the geotextile filters that protect landfill leachate collection systems (G.R. Koerner 1993). The current project studied treatment of clarified weak to medium concentration domestic wastewater, although a test with raw wastewater was also successful. Figures 8.1 and 8.2, reproducing Figure 4.1, shows the GBSC in plan view with the directions of influent flow, leaking through the baffles as well as following the sinuous channel nominally defined by them.

Figure 8.1: Short-Circuiting and TSS Capture to Form Biofilm
8.1 Applications

At this time, the primary GBSC application envisioned is as retrofits appended to existing facilities to bring a continuous flow of wastewater to the standards required for discharge. An example is reducing organic loading on septic system leaching fields to retard clogging. As described in Chapter 7, another use could be as the main biological treatment operation. It would be an alternate to slow rate trickling filters, extended aeration and sequencing batch reactors (SBR) which are often used for small communities (Metcalf & Eddy 1991), especially when ammonia removal is required. Perhaps the GBSC system can be “piggybacked” by placement in extended aeration or SBR reactors. While the GBSC physically appears similar to a trickling filter with high packing density (plastic media), it actually operates like a fixed film version of an extended aeration “package plant”. However, using geotextiles to capture suspended, colloidal and dissolved organic material also shows promise in treating weather derived sources of water pollution such as urban runoff and combined sewer overflow. The experiments used wastewater from a combined sewer service
area, so some samplings included the first flush of street runoff as well as sanitary flow. While aeration was found to be necessary for treatment of continuous wastewater flow, whether it is required in intermittent applications depends upon the discharge standards and the decomposition between events of material captured by the baffles.

8.2 Process Description

The process includes the following stages:

- Removal of solids from influent by filtration and sedimentation
- Growth of active biomass from microorganisms attached to suspended and colloidal particles
- Absorption of substrate from the influent
- Biodegradation that mineralizes carbonaceous material and releases ammonia
- Ammonia removal by evaporation or biological conversion to nitrate
- Anoxic denitrification
- Aerobic decomposition of sediment and excess biomass sloughing off baffles

Criteria were established in terms of both treatment and practicality. The former included producing effluent that meets the secondary treatment standards for TSS and BOD$_5$, and also substantial reduces nitrogenous content. The practical goals were compactness, low sludge production and simple, untended operation.

8.3 Unique Behavior of Biomass Growth in Baffle Filters

The first question was to determine which types of currently available geotextiles can efficiently support the processes listed above. It was found that only porous nonwoven
geotextiles of the needle punched type are suitable. A treating biomass floc grows from microorganisms attached to suspended or colloidal particles captured within the structure of the geotextile baffles, using the host organic particle as substrate. Eventually, the biomass coalesces and grows outward to project beyond the fabric surface to directly contact liquid flowing through the sinuous channels defined by the baffles.

The SEM photos indicate the continued existence of some open porosity, and thus a residual finite permeability. The gradient between channels maintains some seepage across even partially “clogged” baffles. The implication is that once substrate is sorbed into the biofilm, it is subjected to a sequence of treatment steps such that individual baffles continue to operate as individual depth filters. For example, solutes released from aerobic reactions in the biofilm surface are conveyed through the baffle interior through both aerobic and anaerobic zones, and then emerge on the other side (channel). With the depletion of readily decomposed materials already accomplished, the “downstream” biofilm on each baffle was noticeably thinner. The result is high ammonia conversion, to nitrate and substantial, if incomplete, denitrification. The perviousness of the fabric attachment produces a radically different behavior than that normally envisioned in the biofilm growing on the impermeable attachment media of trickling filters. As indicated on Figure 1.11, organic substrate is sorbed into the biofilms, but some nitrogenous byproducts are released back into the flowing liquid. The maximum stable biomass density found was about 2.0 grams (dry weight) per square foot of baffle surface. Sloughing off excess biomass commenced at higher biomass densities.

8.4 Satisfactory Treatment Results

The project satisfied the treatment criteria for wastewater that had already undergone primary treatment. The key economic and engineering feasibility parameters were aeration and vessel
dimensions. The two indices found appropriate for physical design were the hydraulic loading rate (HLR), expressed as gallons/day-sq. ft. (gpd/ft$^2$) of baffle surface and the surface settling rate, also expressed in gpd/ft$^2$ terms. The latter is used to determine the surface area of the vessel, but implicitly, the size of the particle that is settled out and the hydraulic detention time.

Operating the bench scale pilot plant baffle at 1.0 gpd/ft$^2$ HLR and 10 gpd/ft$^2$ surface settling rate reduced the primary effluent TSS and BOD$_5$ over 90%, to less than 5 mg/l. Ammonia was reduced over 90% to 1.0 mg/l and effluent nitrate (NO$_3$) to below 10 mg/l when the biofilm aged. The Phase I extended batch aeration tests indicated that about 40% of the ammonia removal was due to evaporation after release from organic nitrogen, and the rest was biologically converted to nitrate with microorganisms attached to the geotextiles. With the shorter detention time in the Phase II continuous plug flow tests and seepage through the clogged baffles, it is expected that the proportion of ammonia converted biologically is higher still. In the single raw wastewater test with influent TSS=318 mg/l and BOD$_5$ = 114mg/l, the effluent met secondary treatment levels (4mg/l and 10mg/l respectively). This indicated that the test HLR and surface settling rates used in the experiments were extremely conservative, perhaps by up to an order of magnitude for dilute wastewater. Doubling the HLR by connecting two GBCS tanks in a row did not affect removal efficiencies.

8.5 Comparison of Small Community Advanced Wastewater Treatment Systems

Most large metropolitan areas are served by central treatment plants. They generally use some variation of the highly efficient but mechanically complex conventional activated sludge process, which is discretized into a number of interacting stages. Moreover, most large cities are located on major waterways, such that the discharge standards are for secondary
treatment. In contrast, many smaller communities are located on smaller waterways, and are often required to do a higher degree of treatment, most often being a limitation on the effluent ammonia concentration. However, handling mechanical complexity is difficult without full time operator attention and sludge handling and disposal is major problem. Hence, small community systems use simplifications of large scale treatment methods. For example, extended aeration “package plants” often avoid a primary sedimentation stage by comminuting raw wastewater, and reduce sludge generation by maintaining a very low F/M ratio and long hydraulic retention times. However, activated sludge return and high aeration are the tradeoffs. SBRs eliminate the activated sludge return step, but require multiple batch chambers. Slow rate trickling filters are not artificially aerated, but have high sludge production and often operated cyclically.

Table 8.1 compares the engineering parameters of the GBCS system to these popular conventional biological treatment methods for small communities.

<table>
<thead>
<tr>
<th></th>
<th>Nitrification</th>
<th>Power</th>
<th>Sludge</th>
<th>Mechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Rate Trickling Filter</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>simple</td>
</tr>
<tr>
<td>Extended Aeration</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Sequencing Batch Reactors</td>
<td>high</td>
<td>medium</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>GBCS</td>
<td>very high</td>
<td>high</td>
<td>low</td>
<td>medium</td>
</tr>
</tbody>
</table>

It can be seen that, in providing a similar level of treatment, the GBCS can be one of an array of small community advanced biological treatment methods, a promising alternative. The major unknowns that prevent numerical comparison will be resolved by the parametric study
proposed in Chapter 6. At this point, the advantages of the GBCS are compactness and low sludge production. The main disadvantage is high power use, but this may decrease if the experimental 22.5 hour hydraulic detention is reduced, improving ranking relative to extended air treatment.
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Vita

Eyüp Nafiz Korkut holds a B.S.(1991) in Environmental Engineering from Istanbul Technical University, in Istanbul, Turkey, two M.S. (1993, 1996) one from Yıldız Technical University in Istanbul, Turkey and another from Drexel University in Philadelphia, PA, and a Ph.D. (2003) from also Drexel University, Philadelphia, PA. He has worked as a teaching and research assistant in Istanbul Technical, Yıldız Technical and Drexel Universities. He also participated fluoride tracing study of Philadelphia Water Department. He assisted with Geosynthetics classes and taught for the E4 program (Enhanced Educational Experience for Engineers) at Drexel University. He worked as a geotechnical engineer with Melick-Tully and Associates, PC, Mt. Laurel, NJ. Eyüp is the only son of Halit and Seniha Korkut from Gümüşhane, Turkey. Eyüp is married to Rasime Varan and resides in Philadelphia, PA.