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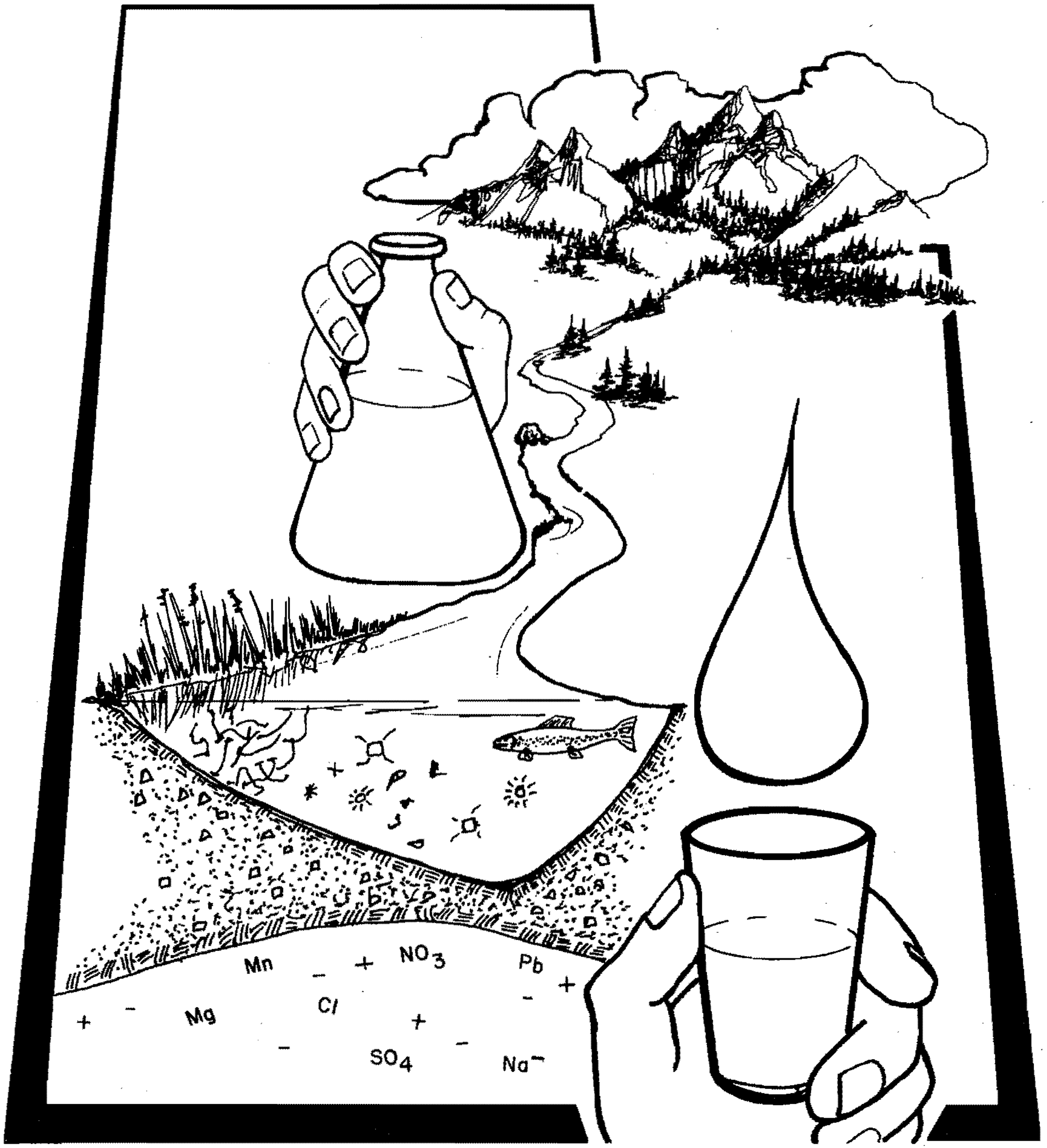

Utah Water Research Laboratory
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WATER QUALITY SERIES
UWRL/Q-81/01

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ABSTRACT

Tertiary filtration of secondary wastewater is frequently used to improve wastewater treatment plant effluent quality. Four experimental filter columns were operated at the Preston, Idaho, Wastewater Treatment Plant to evaluate the effectiveness of granular media, gravity filtration. The Preston plant is a trickling filter secondary treatment plant and services a population of approximately 3600 people.

Four filter medium configurations were studied. Multi-media, dual-media, and single-media beds were constructed with the following media configurations: (1) coal-sand-garnet; (2) coal-sand; (3) sand-garnet; and (4) all sand.

The filters were operated at two hydraulic loading rates. Effluents from the primary clarifier, trickling filter, and secondary clarifier were filtered to compare the difference in filter operation and performance when filtering different effluents. Wastewater quality parameters used to monitor filter performance were biochemical oxygen demand (BOD_5) and suspended solids.

The quality of filter influent affected the quality of the filter effluent. Typical total BOD_5 and suspended solids removal efficiencies were 30 percent and 75 percent, respectively. Soluble BOD_5 was not significantly removed by granular filtration. The four filter beds were equally effective in removing suspended solids and biochemical oxygen demand.

The coal layered filters operated for 22 hours maximum. The longest filter run time for the sand filters was 9 hours.

Filtration of the Preston treatment facility effluent did not consistently produce an effluent that would satisfy the 10 mg/ℓ BOD_5 effluent discharge requirement.

A survey conducted to review approval criteria and design standards for wastewater filters employed by state regulatory agencies indicated the following. Most state standards allowed the installation of either gravity flow filters or pressure filters. The majority of state agencies base the allowable hydraulic loading rate on the type and configuration of media employed. The majority of the design standards for wastewater filters permitted the following media types: (1) sand; (2) anthracite; (3) sand and anthracite; and (4) sand, anthracite, and garnet or ilmenite. All wastewater filter design standards called for backwash appurtenances complete with air scour or mechanical scour.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

INTRODUCTION

The impact of pollution on society is now recognized by nearly everyone, from the grade school pupil to the highest officials in the land. Much of the pollution of our waterways comes from municipal and industrial sources that are controllable. Water quality and effluent standards are becoming more and more strict. Removals of 80 or 90 percent of organic loads and suspended solids will not suffice. Not only will virtually complete removal of organics and solids be required, but removal of specific substances to very low levels will be a necessity. The concept of minimum pollution discharge from controllable sources is rapidly approaching. In most cities much progress could be made in controlling pollution by installing treatment processes now known. However, in many instances the best conventional treatment is not adequate for some of the present effluent quality requirements, and most certainly will not be adequate for future requirements. As a general philosophy, effluent quality standards are being set on the basis of the best available treatment technology [*Middleton and Stenburg*, 1972].

Filtration is one of the most important tertiary processes in the implementation of the Federal Water Pollution Control Act Amendments of 1972 and 1977. Since the passage of these Acts, there has been a trend toward more stringent effluent standards, *i.e.*, from the 30-30 (mg/ℓ biochemical oxygen demand and mg/ℓ suspended solids) standard to the 10-10 or even 5-5 standard for municipal effluents [*Van Dyke*, 1980].

Many existing secondary wastewater treatment plants cannot meet the minimum monthly average effluent standard of 30 mg/ℓ for suspended solids and biochemical oxygen demand established by the Environmental Protection Agency in 1973. The addition of tertiary filters will enable many plants to produce a higher quality effluent and meet the standards for water quality limited streams. A survey conducted in 1974 indicated that there were only 77 operating U.S. tertiary filters treating secondary effluents with a flow rate greater than 1135 cubic meters per day (m^3/d) [0.3 million gallons per day (mgd)]. Over 1500 plants will be required to install tertiary filtration to achieve water quality standards established by the 1972 Act [*EPA*, 1980].

The need for some form of tertiary treatment to improve the quality of the effluents is likely to increase in the future as the volume of effluents discharged to inland waters continues to rise. Various methods of tertiary treatment are available, but the method that seems to find most application in large works is that of rapid gravity filtration [*Tebbutt*, 1971]. Filtration is used for the removal of suspended matter that may interfere with subsequent treatment processes. Filtration may be necessary to meet usage requirements, including discharge to collection systems, ground waters, and receiving waters [*Tchobanoglous and Eliassen*, 1970].

PURPOSE OF STUDY

The general objective of this research was to determine the effectiveness of constant rate, gravity filtration in removing biochemical oxygen demand and suspended solids from secondary treated municipal wastewater and simulated secondary effluents. The results of this study will allow comparison of filtration with other tertiary treatment alternatives as a method of satisfying present and future water quality standards.

Specific Tasks

To achieve the general objective, the following specific tasks were accomplished.

1. Literature related to granular filtration of secondary wastewater was reviewed and evaluated.
2. Experimental filter studies were conducted to provide information on biochemical oxygen demand, soluble biochemical oxygen demand, and suspended solids removal by filtration.
3. Comparisons were made on the operation and performance of four different filter designs.
4. Design criteria were developed for each of the four filtration systems studied.
5. A survey was conducted to review approval criteria and design standards for wastewater filters employed by state regulatory agencies.

Scope of the Study

Four different types and configurations of granular media filters suggested by government agencies and commonly used in wastewater filtration were studied. Filter operation and performance were monitored and compared for each of the four filter configurations.

LITERATURE REVIEW

Introduction

Water filtration is among the most widely used and extensively investigated processes in the field of environmental engineering [*O'Melia and Stumm*, 1967]. Rapid filtration with downflow units has been used satisfactorily in the potable water treatment field for many years, and most wastewater filter installations are similar to the filters used for water treatment purposes. More efficient forms of filters, including mixed media beds and upflow units, have been used with some success in both water and wastewater treatment, but in most cases the conventional downflow unit is still adopted because of its simplicity [*Tebbutt*, 1971].

Filtration is accomplished by passing the wastewater to be filtered through a filter bed composed of granular material, with or without the addition of chemicals. Within the granular filter bed, the removal of suspended solids contained in the wastewater is accomplished by a complex process involving one or more removal mechanisms, such as straining, interception, impaction, sedimentation, and adsorption. The end of the filter run (filtration phase) is reached when the suspended solids in the effluent start to increase (breakthrough) beyond an acceptable level, or when a limiting headloss occurs across the filter bed. Ideally, both of these events should occur at the same time. Once either of these conditions is reached, the filtration phase is terminated, and the filter must be backwashed to remove the material (suspended solids) that has accumulated within the filter bed [*Metcalf and Eddy*, 1979].

Theory

The removal of suspended particles in a filter media is considered to involve two separate and distinct steps. First, the transport of suspended particles to the immediate vicinity of the liquid-solid interface (*i.e.*, to a grain of filter media or other particle retained in the bed), and second, the attachment of the particles [*Yao et al.*, 1971].

The suspended particles contact and become attached to the filter media through one or a combination of the following mechanisms: (1) interception, (2) sedimentation, (3) diffusion, (4) inertial momentum, (5) flocculation, and (6) fluid shear or velocity gradients. Interception is the result of the particle contacting the media because of its size. Sedimentation transport is a result of buoyant and drag forces on the particle. Both of the mechanisms affect particles with sizes of one micron and larger. The smaller particles are collected on the media (collector) by diffusion where particles in suspension are bombarded by molecules of the medium. This is known as Brownian movement of the particles. The first three transport mechanisms are illustrated in Figure 1 [*Yao et al.*, 1971]. Inertial impaction is the result of particles contacting the media because heavy particles will not follow flow streamlines. Flocculation occurs when large particles overtake smaller particles, join them, and form still larger particles [*Metcalf and Eddy*, 1979]. Fluid shear, either turbulent or laminar, affects particle transport because velocity differences or gradients can produce interparticle contacts among particles suspended in the fluid [*O'Melia*, 1980].

The operation of rapid filters is affected by a number of variables, some of which are considered at the design stage, and others which are significant during operation. These variables are: (1) depth of media, (2) grain size of media, (3) grain material, (4) rate of filtration, (5) inflow concentration, (6) type of suspension, and (7) water temperature [*Ives and Sholji*, 1965].

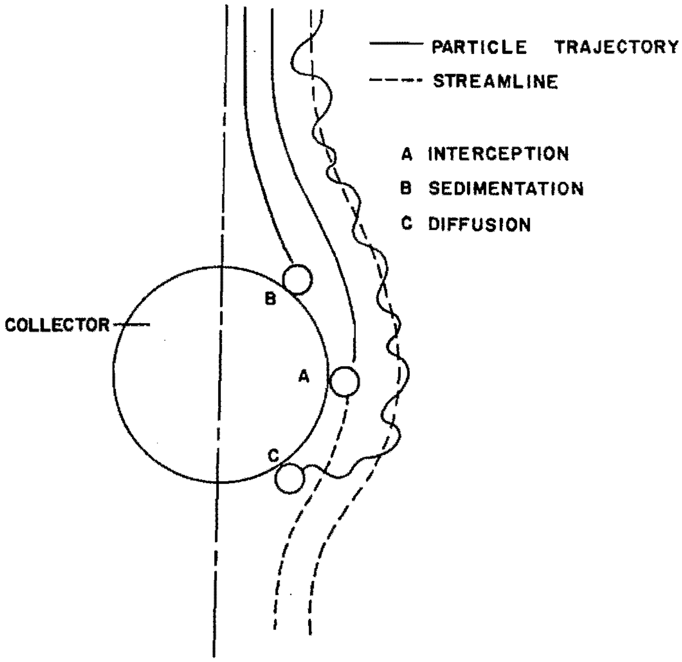


Figure 1. Basic transport mechanisms in water filtration [*Yao et al.*, 1971].

Filter Types

There are several ways to classify filters. They can be categorized according to the direction of flow through the filter bed, *i.e.*, downflow, upflow, biflow, radial flow, horizontal flow, fine-to-coarse, or coarse-to-fine. Filters are also classed according to the type and depth of filter media used as sand, coal, coal-sand, multilayered, mixed media, shallow bed, or deep bed. Filters are also described by flow rate. Slow sand filters operate at 2.0 to 5.3 liters per square meter per minute (ℓ/m²·min) [0.05 to 0.13

gallons per minute per square foot (gpm/ft^2)], and high rate filters operate at rates of 122.2 to 611.1 $\ell/\mathrm{m}^2\cdot\mathrm{min}$ (3 to 15 gpm/ft^2).

Filters may operate with pressure or gravity flow. Gravity filters are built with an open top and constructed of concrete or steel. Pressure filters are enclosed and ordinarily fabricated from steel in the form of a cylindrical tank. Gravity filters usually operate with 2.14 to 3.66 m (8 to 12 ft) of available head. Available head for a pressure filter may be as high as 105 m (346 ft) [*Culp and Culp*, 1974].

Filter Rate Control

There are three basic methods for controlling the rate of flow through the filter. These methods differ primarily in the way that the pressure drop (driving force) is applied across the filter bed. These methods are: (1) constant-pressure filtration, (2) constant-rate filtration, and (3) variable declining-rate filtration [*Cleasby*, 1969].

When operating under constant-pressure conditions, the total available pressure drop across the filter remains the same throughout the filter run. The rate of filtration is high at the beginning of the filter run because the filter permeability is high. As the filter becomes clogged with solids, the permeability decreases and flow rates drop [*Weber*, 1972].

In constant-rate filtration, a constant pressure drop is maintained across the filter system. The filter rate is held constant by means of a flow control valve. As filtration proceeds, the filter clogs with solids and the flow control valve is opened slowly to maintain a constant rate of flow. Constant-rate filtration may also be controlled by splitting the influent flow equally to the operating filters by means of an influent weir box on either filter. The effluent control weir must be located above the filter media surface to prevent accidental dewatering of the filter bed. This arrangement eliminates the possibility of negative pressures in the filter and the need for a flow control valve. The only disadvantage of influent-flow splitting is the additional depth of the filter box required [*Weber*, 1972].

The third method for filter operation is an intermediate of constant-pressure and constant-rate operation. Variable declining-rate operation is similar to constant-rate operation with influent-flow splitting but has one principal difference. As the filters served by a common influent header become clogged, the flow through the dirtier filters decreases more rapidly, causing the cleaner filters to pick up the capacity lost by the dirtier filters. The water level in all filters rises slightly as this happens, providing additional head needed by the cleaner filters as they receive the flow diverted from the dirtier filters. This method of operation causes a gradually declining-rate near the end of the filter run. The advantages of variable declining-rate operation over constant-rate operation include significantly better filter effluent quality, less required available head, and longer filter runs [*Weber*, 1972].

Filtration Rate

Investigations of filtration rate have demonstrated the effect of rate on effluent water quality. *Tchobanoglous and Eliassen* [1970] have shown that for a given sand size, varying the filtration rate had little effect on the suspended solids removal characteristics of the filter bed. In another study, effluent quality with media depths of 60.96 cm (24 in) was not significantly affected by a flow rate up to 244.2 $\ell/\mathrm{m}^2\cdot\mathrm{min}$ (6 gpm/ft^2) [*Baumann and Huang*, 1974]. In filtering biological floc at reasonably low influent solids concentrations (<30 mg/ℓ), the effect on effluent quality of rates up to 408 $\ell/\mathrm{m}^2\cdot\mathrm{min}$ (10 gpm/ft^2) is not very significant [*EPA*, 1975].

With uniform suspended solids concentrations and filtering characteristics, water treatment filter efficiency is a function of the filtration rate and the influent solids concentration. In wastewater filtration, however, filtrate quality is less dependent on rate and influent suspended solids concentration [*EPA*, 1974a].

The rate of filtration determines the volume of water that can be filtered daily. This rate also affects the period of a filter run and frequency of backwash which must be considered in economic comparisons. Figure 2 has been prepared to facilitate a comparison of the net water production to filter run and run length [*EPA*, 1975].

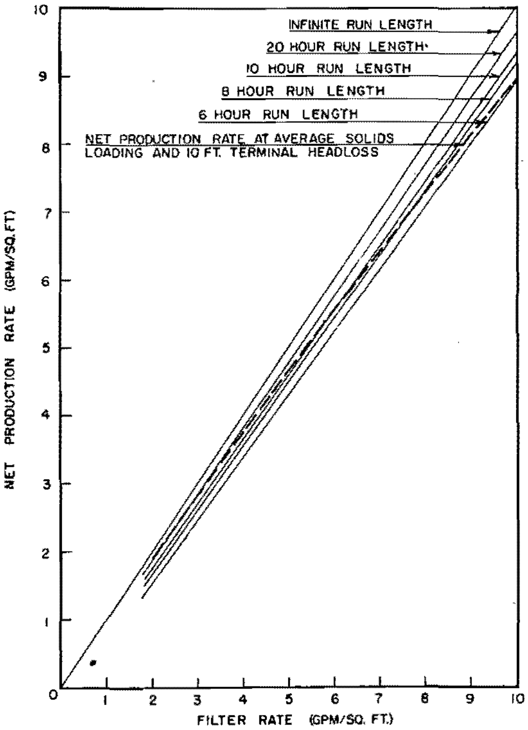


Figure 2. Net production rate versus filter rate for various run lengths [*EPA*, 1975].

Media and Depth

The selection of the size and depth of filter media and the appropriate filtration rate are interrelated. In general, filtrate quality is improved by the use of finer media, greater media depth, or lower filtration rates. Similarly, headloss generation rate is increased by finer media, greater media depth, and higher filtration rates. With some influent suspensions, these generalizations may not hold. For example, in the filtration of secondary effluents, filtration rate has little effect upon filtrate quality over the usual range of rates employed - 81.5 to 203.7 $\ell/m^2 \cdot min$ (2 to 5 gpm/ft^2). Increased media depth may not compensate for coarser media in achieving filtrate quality [*EPA*, 1974a].

The size of filter media (0.55 to 0.92 mm) does not greatly affect effluent quality but does significantly affect headloss development [*Baumann and Huang*, 1974]. It would seem that the suspended particles in the filter influent can be removed independently of filter particle size up to a grain size of about 1.0 to 2.5 mm [*Tebbutt*, 1971].

In multimedia filter beds, if the anthracite layer is greater than 41 to 51 cm (16 to 20 in), media placed below the anthracite contributes little to overall suspended solids removal [*Tchobanoglous*, 1970]. *Baumann and Huang* [1974] discovered that a sand depth of 30.48 to 38.1 cm (12 to 15 in) beneath 30.48 to 38.1 cm (12 to 15 in) of anthracite was sufficient and greater media depths did not increase solids removal.

Granular filter media commonly used in water and wastewater filtration include silica sand, garnet sand, and anthracite coal. These media can be purchased in a broad range of effective sizes and uniformity coefficients. The term "uniformity coefficient" designates the ratio of size of grain which has 60 percent of the sample finer than itself, to the effective size which has 10 percent finer than itself. "Effective size" indicates the size of grain (in millimeters) such that 10 percent (by weight) of the particles are smaller and 90 percent are larger than itself. The media have specific gravities approximately as follows: anthracite coal, 1.35 to 1.75; silica sand, 2.65; garnet sand, 4 to 4.2 [*EPA*, 1975].

Headloss and Run Length

Granular media filters remove suspended solids in one of the following ways" (1) by finer media at the top of the filter which form a relatively thin layer of deposited solids at the surface; (2) by removal of the solids within voids at depth within the porous media; and (3) by a combination of surface removal and depth removal. The more uniform the distribution of the solids throughout the depth of the filter media, the better the use of the available head [*EPA*, 1974a].

When solids are removed predominantly at the surface, rapid headloss develops and short filter runs are observed. In such cases, the headloss curve (headloss versus time) will be exponential. Increasing terminal headloss does not increase production per filter run significantly with this type of headloss pattern. With surface cake filtration, the filtration is dominantly achieved by the cake itself, and filtrate quality is constant throughout the run [*EPA*, 1974a].

Removal of the solids within the bed rather than just at the surface is termed depth filtration. Both surface and depth filtration usually occur to some degree in any application. In depth filtration, headloss tends to build up linearly with time or with solids accumulation. For downflow filtration, the farther the solids penetrate into the bed, the slower will be the rate of headloss buildup, but the sooner the solids will break through into the effluent [*EPA*, 1975]. Depth filtration is employed by creating a coarse to fine particle distribution in the direction of flow.

The lengths of filter run are often governed by the amount of available head. Depth filtration promotes longer filter runs because of the slower headloss accumulation.

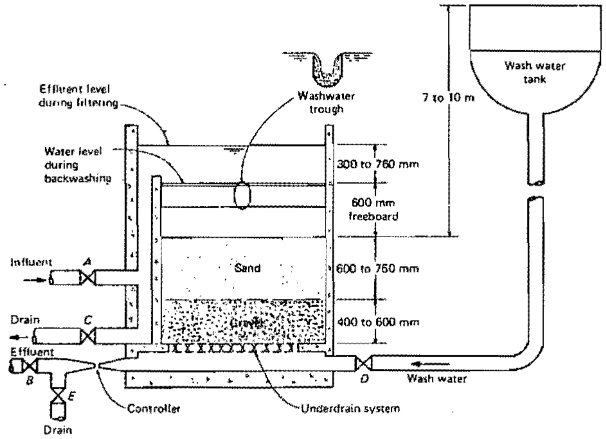
The length of filter run should be at least 6 to 8 hours to avoid excessive backwash water use, but less than about 36 to 48 hours to reduce anaerobic decomposition within the filter and possible detriment to the effluent quality. The desired run length can be achieved by selecting either the terminal headloss or the filtration rate or both [*EPA*, 1974a]. Run length is the result of an interaction of two variables: filtration rate and the influent suspended solids concentration [*Baumann and Huang*, 1974].

Filter Backwash

Backwashing the filter is the process employed to clean the filter bed. Usually this is accomplished by reversing the flow through the filter. Backwashing is performed at the end of the filter run when the water level has reached terminal headloss or when the filtrate quality falls below established criteria. Figure 3 is a sketch of a granular, downflow filter illustrating the operation and backwash phases.

A sufficient flow of wash water is applied until the granular filtering medium is fluidized (expanded). The material that has accumulated within the bed is then washed away. The wash water moving past the medium also shears away the material attached to the individual grains of granular medium. In backwashing the filter, care should be taken not to expand the bed to such an extent that the effectiveness of the shearing action of the wash water is reduced. In most wastewater treatment plant flowsheets, the wash water containing the suspended solids that are removed from the filter is returned either to the primary settling facilities, or to the biological treatment process [*Metcalf and Eddy*, 1979].

Surface wash, air-scour, and bed fluidization are modes of backwash employed especially for wastewater filters. The relative effectiveness of these methods of backwashing has been studied in detail. The following recommendations for backwashing wastewater filters were presented by *Cleasby et al.*, [1975].



How filter operates

1. Open valve A. (This allows effluent to flow to filter.)
2. Open valve B. (This allows effluent to flow through filter.)
3. During filter operation all other valves are closed.

How filter is backwashed

1. Close valve A.
2. Close valve B when water in filter drops down to top of overflow.
3. Open valves C and D. (This allows water from wash water tank to flow up through the filtering medium, loosening up the sand and washing the accumulated solids from the surface of the sand, out of the filter. Filter backwash water is returned to head end of treatment plant.

How to filter to waste (if used)

1. Open valves A and E. All other valves closed. Effluent is sometimes filtered to waste for a few minutes after filter has been washed to condition the filter before it is put into service.

Figure 3. Definition sketch for operation of downflow, granular-medium, gravity-flow filter [*Metcalf and Eddy*, 1979].

1. The cleaning of granular filters by the upward flow of water alone to fluidize the filter bed is inherently a weak cleaning method because particle collisions do not occur in a fluidized bed. This weakness was clearly demonstrated during wastewater filtration studies where the filter that was washed by water fluidization alone developed serious dirty filter problems such as floating mud balls, agglomerates at the walls, and surface cracks. These problems were observed when filtering either secondary effluent or secondary effluent that had been treated with alum for phosphorus reduction.

2. Heavy mud ball accumulations are undesirable because they contribute to higher initial head losses and shorter filter cycles. They may also cause poorer filtrate quality in some cases.

3. Filter cracking, which is a sign of compressible coatings on the filter media, allows deeper penetration of solids into the filter and may cause poorer filtrate quality in some cases, although quality detriment was not demonstrated in this research. The cracking and deeper penetration of solids reduces the rate of head loss development in the surface layer but increases it in the deeper layers of the filter.

4. The use of air-scour auxiliary or surface wash auxiliary is essential to the satisfactory functioning of wastewater filters. These methods did not completely eliminate all dirty filter problems, but both auxiliaries reduced the problems to acceptable levels so that filter function did not seem to be impaired.

5. Expansion of the coals and sands commonly specified in dual and mixed media filters is essential to their proper backwashing when using either air-scour or surface wash auxiliaries. A minimum of 25 percent expansion of each media is recommended under the most crucial warm season condition.

6. Special provisions are needed in the design and operation of air-scour systems.

Biochemical Oxygen Demand and Suspended Solids Removal

The variables that determine filter performance fall into two major groups: influent characteristics and physical characteristics of the filter. Physical characteristics of the filter include size of media, depth of media, and hydraulic loading rate. Influent characteristics are suspended solids (SS) concentration, strength of floc, and biochemical oxygen demand (BOD_5) concentration. Suspended solids removal efficiencies of secondary effluent using granular filtration range from 60 to 90 percent. Expected effluent SS from multimedia filtration is 10 to 20 milligrams per liter (mg/ℓ). The SS removal efficiency does not change significantly at loading rates below 408 $\ell/m^2 \cdot min$ (10 gpm/ft^2) [*EPA*, 1975].

Total biochemical oxygen demand ($TBOD_5$) consists of particulate ($PBOD_5$) and soluble BOD_5 ($SBOD_5$). The removal of particulate BOD_5 is related to SS removal. The filter primarily removes only suspended matter, and the effectiveness of the filter should be related to SS removal. Other parameters such as BOD_5, chemical oxygen demand, etc., may be considered, but they are removed mainly in proportion to the suspended solids removed. Biological activity, which occurs in the media bed, will tend to remove some soluble BOD_5, but this is not predictable [*Walters*, 1979].

Dawda et al. [1978] concluded that effluents containing less than 10 mg/ℓ of BOD_5 and SS can be produced by granular media filtration when a good quality secondary effluent (<30 mg/ℓ of BOD_5 and SS) is applied to the filters. During *Dawda*'s study, SS removal ranged between 70 and 80 percent, and $TBOD_5$ removal ranged from 30 to 60 percent most of the time.

The variable nature of the suspended solids present in final settling tank effluents make predictions of the performance of any form of tertiary treatment difficult, but it is generally assumed that rapid gravity filters if loaded at about 139 $\ell/m^2 \cdot min$ (3.4 gpm/ft^2) remove 70 to 90 percent of the applied suspended solids [*Tebbutt*, [1971].

Tertiary granular media filters are designed primarily for removal of suspended solids and the BOD_5 associated with suspended solids. However, removal of soluble BOD_5 occurs to some extent due to bacterial activity within the filter media [*EPA*, 1980].

A comprehensive study was conducted on full-scale tertiary filters at eight treatment plants. Mean filter influent total BOD_5 varied from 9 to 44 mg/ℓ at the eight plants, and mean effluent total BOD_5 varied from 3 to 25 mg/ℓ. Average secondary effluent suspended solids concentrations varied from 25 to 62 mg/ℓ and filter effluent suspended solids concentrations from 5 to 20 mg/ℓ [*EPA*, 1980]. Soluble BOD_5 tests were conducted using filtrate from a standard glass fiber filter. Soluble BOD_5 removal was reported at 30 and 44 percent for some plants. This soluble BOD_5 removal was probably attributable to biofilms attached to the filter media serving as adsorption sites for some components of the noncolloidal organics [*EPA*, 1980].

Typical suspended solids and BOD_5 removals obtained by filtering trickling filter effluents are shown in Table 1.

The single most important factor affecting filter performance is the quality of secondary effluent produced by the biological treatment. If good performance is exhibited by the biological treatment system, good filter performance can be expected. Conversely, if the biological facility is faulty, filtration will be more difficult and less successful [*EPA*, 1974b].

Influent Characteristics

The characteristics of wastewater solids governing filter performance are determined by the treatment processes ahead of filtration. In direct filtration of secondary biological effluent, the residual solids applied to the filter are predominantly biological floc grown in the treatment process [*EPA*, 1975]. Biological flocs are stronger and more resistent to shear than chemical flocs from alum or iron coagulants [*Tchobanoglous and Eliassen*, 1970].

The variability of the quality of effluent from the secondary process is also an important factor in filter design. *Tebbutt* [1971] reported several instances when the SS concentration changed by a factor of 2 within an hour. The random nature of suspended solids in the effluent from final settling tanks and from tertiary treatment units makes it almost impossible to comply with a standard with 100 percent confidence [*Tebbutt*, 1971].

Another factor that affects the character of secondary effluents is chlorine. Chlorination of secondary effluent modifies the filterability of the effluent from an activated sludge plant. The filtration efficiency of chlorinated water was decreased, but the rate of headloss increase was lower. The change of floc size, density, and floc strength all are responsible for the change in filter performance. The floc in the chlorinated effluent appeared to be smaller, lighter, and more fragile than that in the unchlorinated effluent [*Hsiung*, 1980].

Filter Design

An optimum design is achieved when all the available head is exhausted in a filter run at the same instant that SS begin to pass through the filter in excess of the desired effluent quality. It is difficult to produce an optimum design because the present level of filtration theory can only semi-quantitatively account for the interdependence of the design variables [*Baumann and Huang*, 1974]. Because of the variable nature of effluent quality and the difficulty in predicting hydraulic capacities of a filter, it is essential to conduct a pilot-plant study for at least 12 months to approach optimum economic design [*Tebbutt*, 1971; and *Baumann and Huang*, 1974].

Pulsed Bed Filtration

In conventional single-medium sand filters, most of the solids are removed at or near the surface of the sand bed forming a layer of solids. As a result, headloss accumulates very rapidly, the filter run is short, and a large portion of the filter bed is not utilized for solids storage. Dual and multi-medium filters are used to achieve greater solids penetration into the filter bed resulting in longer filter runs. Despite the advantage of longer filter runs, multi-medium filters require more stringent media specifications

Table 1. Expected filter performance for trickling filter plants [*EPA*, 1974b].

Percent Soluble BOD_5 Removed in Secondary Process							
85 percent				80 percent			
Filter Influent		Filter Effluent		Filter Influent		Filter Effluent	
BOD_5	SS	BOD_5	SS	BOD_5	SS	BOD_5	SS
mg/ℓ		mg/ℓ		mg/ℓ		mg/ℓ	
20-40	20-40	20-30	15-20	40-50	35-45	30-40	20-25
Run Time (hr) = 6-11				Run Time (hr) = 5-9			

and larger volumes of backwash water.

In pulsed-bed filtration, intermittent air pulsing of the filter bed is employed to loosen and mix solids retained in the surface layers of the filter. The air-pulse action moves the solid material deeper into the sand bed and decreases the rate of headloss buildup allowing longer filter runs. Average run lengths were increased by more than four times as a result of the air-pulse system. The pulsed-bed filter features a semi-automatic chemical clean cycle. Over a period of time, grease and biological slime will accumulate within the sand bed, clogging pores and reducing run lengths. The mild detergent and bleach solution is effective in removing the grease and biological slime within the surface layers restoring the sand to its original condition.

Because the single-medium filter employs an air-pulse system and chemical cleaning cycle, the filter can successfully be used to filter primary effluent. The air-pulse filter operation was developed by Hydro-Clear [*Matsumoto et al.*, 1980].

RESEARCH PROCEDURES

Location

The pilot plant study was conducted at the Preston City Wastewater Treatment Plant, Preston, Idaho. The current population of Preston is approximately 3600 people. The complete treatment process includes primary treatment, secondary treatment, and chlorine disinfection. The secondary treatment consists of a single stage, standard rate, trickling filter. There is one unit for each of the treatment processes. The design flow rate for the Preston plant is 3785 m^3/d (1 mgd). The average flow was approximately 3028 m^3/d (0.8 mgd) throughout the study period. A portion (33 percent) of the wastewater flow comes from infiltration into the sewage collection system. This problem is most serious during the summer months and tends to dilute the strength of the sewage. Wastewater flow charts at the Preston plant indicate infiltration flow rates were as high as 1136 m^3/d (0.3 mgd) during the study period.

Filter Column Design

The experimental filter operation consisted of four 15.24 cm (6 in) diameter filter columns. Each column consisted of a plexiglass base 1.23 m (4 ft) in length and a top portion constructed from 2.13 m (7 ft) of PVC pipe. The clear plexiglass base was used so that the filter media could be observed during operation of the filters. Window slots were constructed in the PVC pipe section so that water depth could be observed and measured. The available head above the media surface was 2.44 m (8 ft).

Filter effluent was discharged at the same elevation as the minimum water depth; therefore, headloss across the filter media was equal to the height of water above the filtrate outlet. This arrangement provides a method for immediate headloss determination, a constant rate of filtration without rate control devices, and eliminates the possibility of negative head in the filter and air binding due to gases coming out of solution that result from a negative head [*Cleasby*, 1969]. A diagram of an experimental filter column is shown in Figure 4. Inlet and outlet arrangements for both filter operation and backwash modes are illustrated.

The filters were operated at a constant flow rate. The flow rate was controlled by a distribution box placed above the filters, and wastewater was pumped to the box and distributed to the four filters. A constant water flow was maintained by four V-notch weirs (one for each filter column) which could be adjusted to achieve the desired loading rate.

Filter Media

Four different filter bed configurations were placed in the filter columns. Silica sand, garnet sand, and anthracite coal, all of which are commonly used in wastewater filtration, were used as the filter media. The four filter media configurations were as follows: (1) a mixed media, consisting of anthracite coal, sand, and garnet layers; (2) a dual media with anthracide coal followed by a layer of sand; (3) a dual media formed by covering garnet sand with a layer of silica sand; and (4) a sand filter.

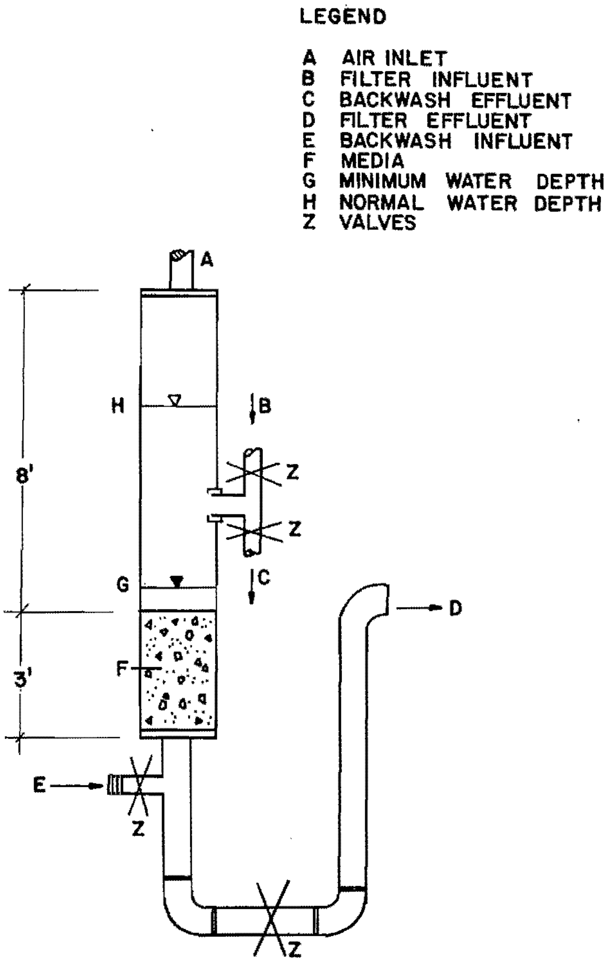


Figure 4. Basic design of experimental filter column.

Each of the filter beds was supported by a shallow gravel layer. The filter media and gravel were obtained from Neptune Microfloc. A FLEXCLEAN, plastic nozzle with small outlet slots was used for the under drain. The plastic nozzle was obtained from EIMCO, Salt Lake City, Utah.

The uniformity coefficient, effective size, and specific gravity for each media and overall filter bed depth are presented in Table 2.

Table 2. Filter bed configuration and media parameters used for each filter column.

Media Parameters	Configuration and Type of Filter Media			
	Mixed	Coal-Sand	Sand-Garnet	Sand
Top Coal Layer (Anthracite)				
effective size (mm)	1.0-1.1	1.0-1.1		
uniformity coefficient	<1.7	<1.7		
depth (cm)	38	46		
specific gravity	1.6-1.65	1.6-1.65		
Central Sand Layer				
effective size (mm)	0.4-0.55	0.4-0.55	0.4-0.55	0.45-0.55
uniformity coefficient	<1.8	<1.8	<1.8	<1.8
depth (cm)	38	30	38	76
specific gravity	2.6±0.5	2.6±0.5	2.6±0.5	2.6±0.5
Bottom Layer (Garnet)				
effective size (mm)	0.2-0.29		0.2-0.29	
uniformity coefficient	--		--	
depth (cm)	15		22	
specific gravity	4.0		4.0	
Total Depth (cm)	91	76	60	76

Operation of Experimental Filters

Loading rate, influent SS, and influent BOD_5 were each varied during the test period. The loading rate was varied by adjusting the weirs in the distribution box. The influent water quality (SS and BOD_5) was varied by changing the source of the water. Effluents from the secondary clarifier, primary clarifier, and trickling filter were used either singly or mixed as necessary to provide different filter influent water qualities. The hydraulic loading rates studied were 81.5 and 203.7 $\ell/m^2 \cdot min$ (2 and 5 gpm/ft^2). Chlorine residuals were not measured in any of the three water sources.

Backwash

The filters were operated continually five days of the week, and were backwashed every 24 hours or when excessive headloss developed. Potable water was used for backwash water. The backwash influent line contained a venturi-aspirator which was used to introduce a chlorine solution into the backwash water. The purpose of the chlorinated backwash was to control any bacterial growth and slime on the media surface. Such growth causes rapid headloss development and inhibits effective filter operation. The aspirator was also used to mix air with the backwash water which allowed an air-scour with water backwash. Backwashing usually lasted 10 to 15 minutes for each filter. The filter bed normally expanded 50 percent during the water backwash.

Water Sampling and Analysis

Water quality analyses were performed on the common influent and the four filter effluents. Samples were analyzed for suspended solids, volatile suspended solids, soluble BOD_5, and total BOD_5 according to procedures outlined in "Standard Methods for the Examination of Water and Wastewater" [*APHA*, 1975; and *Cowan et al.*, 1978]. Soluble BOD_5 was measured using the filtrate obtained when the water was filtered through a Whatman GF/C glass fiber filter. Composite samples were collected manually during the filter cycle. Sample frequency was either hourly or based on percent of filter cycle. The composite sample consisted of a minimum of four, equal-volume, grab samples. When sampling on percent of filter cycle, samples were taken at 0 percent, 30 percent, 60 percent, and 100 percent time intervals of the filter cycle. Particulate BOD_5 was determined from the difference between total BOD_5 and soluble BOD_5.

RESULTS AND DISCUSSION

General

Four different granular media configurations were evaluated as to their effectiveness as a tertiary wastewater treatment process. The characteristics of the filter influent and effluent were analyzed and the results are shown graphically in the following sections.

The four media are compared as to their effectiveness in removing suspended solids (SS), total biochemical oxygen demand (TBOD$_5$), soluble BOD$_5$ (SBOD$_5$), and particulate BOD$_5$ (PBOD$_5$). Headloss development for each filter is presented for each hydraulic flow rate. The different characteristics and filter operation of the three filter influent sources were filter backwashing and filter cycle performance.

A mathematical equation was developed to calculate total biochemical oxygen demand removal by the filters. The equation was used with BOD$_5$ removal data obtained with the experimental filter columns operated at the Preston Treatment Plant.

Influent Sources

Filter influent was collected from three different sources at the Preston Treatment Plant during the study. Effluent wastewater from the primary clarifier, trickling filter, and secondary clarifier was pumped to the experimental filters for filtration treatment. Mean concentrations of TBOD$_5$, SBOD$_5$, PBOD$_5$, suspended solids (SS), and volatile suspended solids (VSS) for the three sources of wastewater are listed in Table 3. Mean concentrations of each source were calculated by averaging composite filter cycle samples of the common filter influent.

Table 3. Sewage strength of effluent from the primary, secondary, and trickling filter treatment processes at the Preston Wastewater Treatment Plant.

	Wastewater Source		
Quality Parameter *	Primary Effluent	Trickling Filter Effluent	Secondary Effluent
Total BOD$_5$ (mg/ℓ)	36	24	17
Soluble BOD$_5$ (mg/ℓ)	15	11	8
Particulate BOD$_5$ (mg/ℓ)	21	13	10
Suspended Solids (mg/ℓ)	25	16	16
Volatile Solids (mg/ℓ)	16	8	7

* All values are average filter-cycle composites and due to rounding errors, totals may differ.

The low TBOD$_5$ and SBOD$_5$ concentrations measured in the primary clarifier effluent are indicative of dilute sewage. Sewage is considered dilute when contaminant concentrations are consistently below the typical range. Typical total BOD$_5$ concentrations of domestic primary effluent range from 80 to 200 mg/ℓ [*Metcalf and Eddy*, 1979]. The average organic load to the treatment plant is low because of infiltration into the sewer system.

Filtering primary water proved unfeasible because of rapid headloss development, especially at the 204 ℓ/m^2·min (5 gpm/ft^2) loading rate. At the lower loading rate, the coal filters operated up to eight hours. The primary water contained fibrous solids which would quickly blind the media surface. A surface mat was formed by solids on both the sand and coal media. This solids mat would break up during backwash, and inter-mix with the media. The air-scour backwash was effective in breaking up the solids mat into sufficiently small particles for removal. In order to successfully filter primary effluent using a granular media filter, effective backwash must be assured and a method be employed to increase run length. The air-pulse filter operation may be such a method [*Irwin and Garzonetti*, 1980; and *Matsumoto et al.*, 1980].

The average suspended solids concentration in the trickling filter effluent was the same value as the solids concentration in the secondary effluent. Filtration of trickling filter effluent did not cause filter operational problems, and the solids captured in the filter bed were readily removed by normal backwash procedures.

Although the gravimetric measurement of solids from the secondary and trickling filter effluents resulted in equal solids concentrations, the characteristics of the solids were different. Solids associated with the trickling filter effluent appeared larger than the secondary floc. Effluent from the trickling filter contained small flies, worms, snails, and other biota scoured from the trickling filter media. The large floc and biota were captured at the media surface resulting in rapid increase in headloss. Direct filtration of trickling filter effluent could feasibly be implemented at the Preston plant by using a larger sized coal which would enhance in-depth filtration and increase the length of filter run.

Filtration of secondary settled effluent provided the longest filter runs. In-depth filtration was achieved in the coal-layered filters. Most of the solids were captured in the top coal layer. Longer backwash was necessary to clean the filter bed because the solids would adhere to the coal media. Tables 12-26 in Appendix B contain filter performance data for each of the three sources of wastewater.

Influent and Effluent Relationship

Filter effluent BOD_5 (total, soluble, and particulate BOD_5), suspended solids, and volatile suspended solids concentration were plotted versus influent concentrations for each filter. A linear relationship was found to exist between the filter effluent and influent water quality concentrations. This relation was observed for each wastewater quality parameter examined.

The linear relation between influent and effluent qualities indicates that the effluent quality is highly dependent on the quality of the filter influent. This condition supports the statement that the single most important factor governing filter performance is the quality of the secondary effluent produced by the biological treatment process [*EPA*, 1974b].

Filter Media Performance

The four filter beds were composed of different granular media configurations. The coal-sand-garnet bed had a total depth of 90 cm (36 in). The depth of the sand-garnet bed was 60 cm (24 in). Both the coal-sand and all sand beds had a total depth of 76 cm (30 in). The characteristics of the media were presented in Table 2.

Mean filter influent and effluent concentrations of $TBOD_5$, $SBOD_5$, $PBOD_5$, and SS were calculated from combined data of both flow rates and three water sources. Mean concentrations, number of samples, and standard deviations are listed in Table 4 for each of the four filters studied. A comparison of the common influent wastewater qualities and the four filter effluent qualities is shown in Figures 5-8. There were no significant statistical differences (95 percent confidence) in the effluent $TBOD_5$, $SBOD_5$, $PBOD_5$, and SS from any of the filter media configurations.

Figures 9-18 are a series of linear plots of filter influent versus filter effluent concentrations. These linear plots show that the effluent quality from the four filters studied is directly related to the influent quality. The effect of the filter media on the effluent quality is represented by the slope of the linear relationship. As the slope increases, a decrease in performance is indicated. Conversely, an improvement in performance is indicated by smaller slopes. If the slopes of the linear relationships between influent and effluent for two filter types are equal, then the performance of each filter is equal.

A statistical test of the difference between two regressions are performed to determine the significance of the difference between slopes [*Steel and Torrie*, 1960]. At the 95 percent confidence level no two slopes were different for any one quality relationship. Therefore, there was no statistical difference (85 percent confidence) in the removal of BOD_5 and SS by any of the filter types evaluated.

Table 4. Mean influent and effluent $TBOD_5$, $SBOD_5$, $PBOD_5$, and SS concentrations and standard deviations for combined filtration data.

Wastewater Parameter	Filter Influent (mg/ℓ)	Filter Type 1	2	3	4
		Filter Effluent (mg/ℓ)			
TOTAL BOD_5					
Average *	24.2	16.1	16.3	15.9	16.1
Std. Dev. **	9.5	6.8	6.4	6.5	6.8
SOLUBLE BOD_5					
Average	10.6	9.6	9.4	9.0	9.2
Std. Dev.	4.7	4.6	4.4	4.8	4.7
PARTICULATE BOD_5					
Average	13.7	6.6	6.9	6.9	6.9
Std. Dev.	5.8	3.1	3.1	3.1	3.7
SUSPENDED SOLIDS					
Average	18.1	4.7	5.1	4.7	4.7
Std. Dev.	5.7	3.1	3.0	2.8	3.0

* Number of samples = 30 for all tests
** Std. Dev. = standard deviation
1 = coal-sand-garnet
2 = coal-sand
3 = sand-garnet
4 = all sand

BOD_5 and SS Removal

Total biochemical oxygen demand consists of a soluble portion and a particulate portion. Removal of either portion decreases the concentration of total BOD_5. Particulate BOD_5 removal is associated with suspended solids removal. Soluble BOD_5 removal is caused by biological activity, adsorption, or ion exchange within the filter bed.

A statistical analysis of the difference between two population means was performed to determine if the mean influent and effluent concentrations for $TBOD_5$, $SBOD_5$, $PBOD_5$, SS, and VSS differed [*Ott*, 1977]. The average effluent concentration was calculated using all four filter effluents. The statistical test was performed for both loading rates. The results of the statistical analyses are presented in Table 5.

The student's-*t* values for four of the five quality parameters were greater than the 99 percent test statistic. Therefore, the mean effluent concentration was significantly less than the mean filter influent at both hydraulic loading rates for total BOD_5, particulate BOD_5, suspended solids, and volatile suspended solids. In contrast, the soluble BOD_5 mean influent and effluent concentrations did not differ at the 95 percent confidence level for either loading rate. Although the student's-*t* value for the comparison of soluble BOD_5 removal of the lower loading rate was within 0.001 of being significant, error inherent in the BOD_5 test

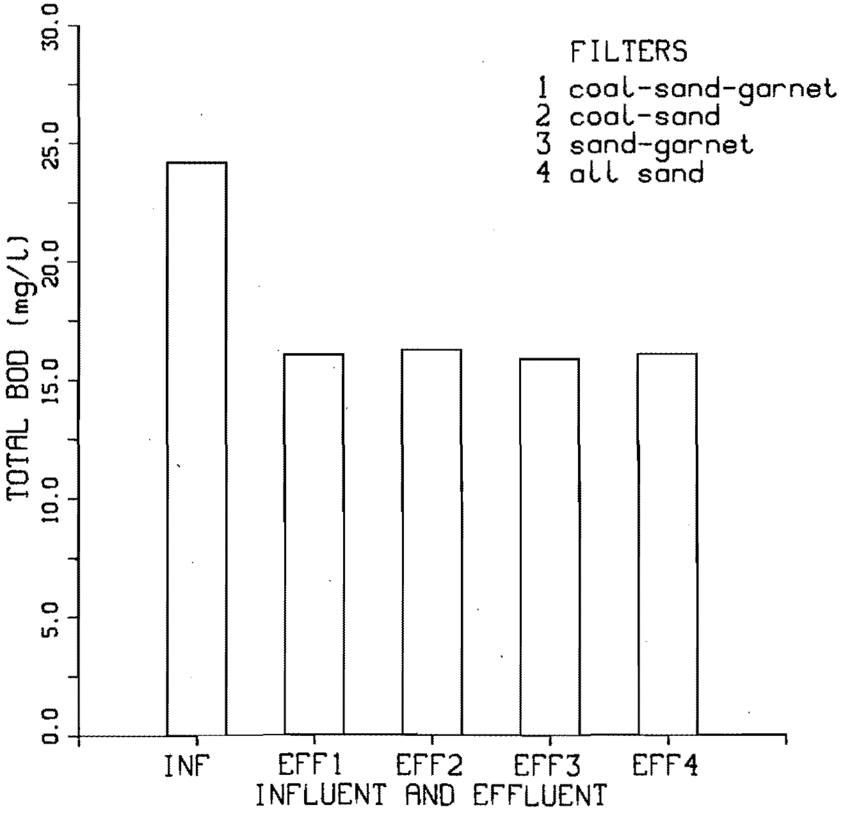


Figure 5. Comparison of the mean total BOD_5 concentrations in the common influent and the four filter effluents.

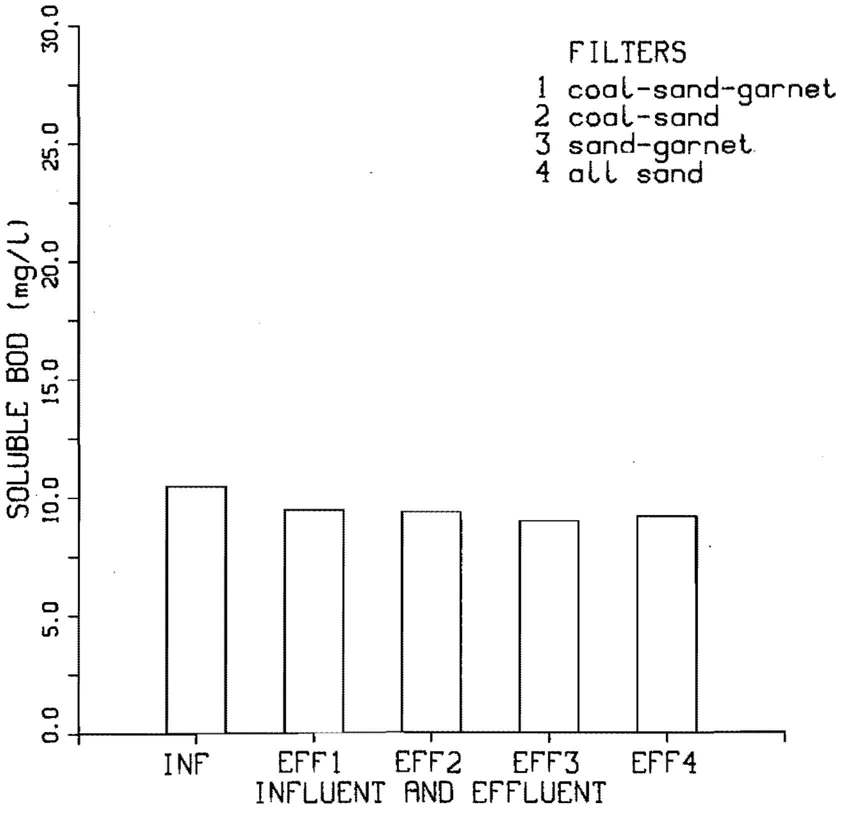


Figure 6. Comparison of the mean soluble BOD_5 concentrations in the common influent and the four filter effluents.

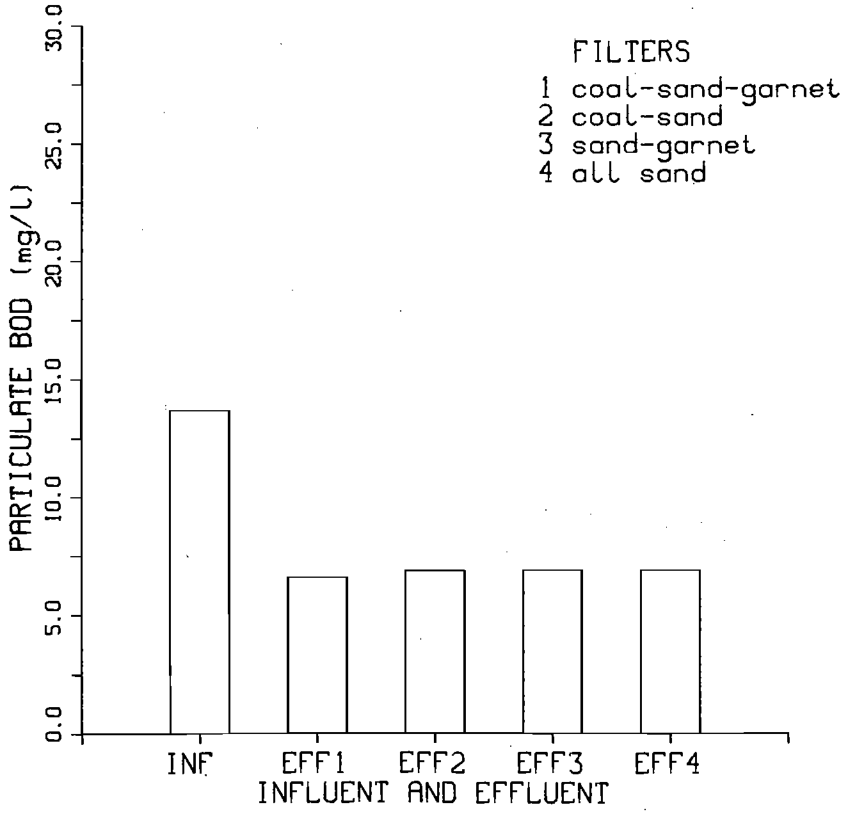


Figure 7. Comparison of the mean particulate BOD_5 concentrations in the common influent and the four filter effluents.

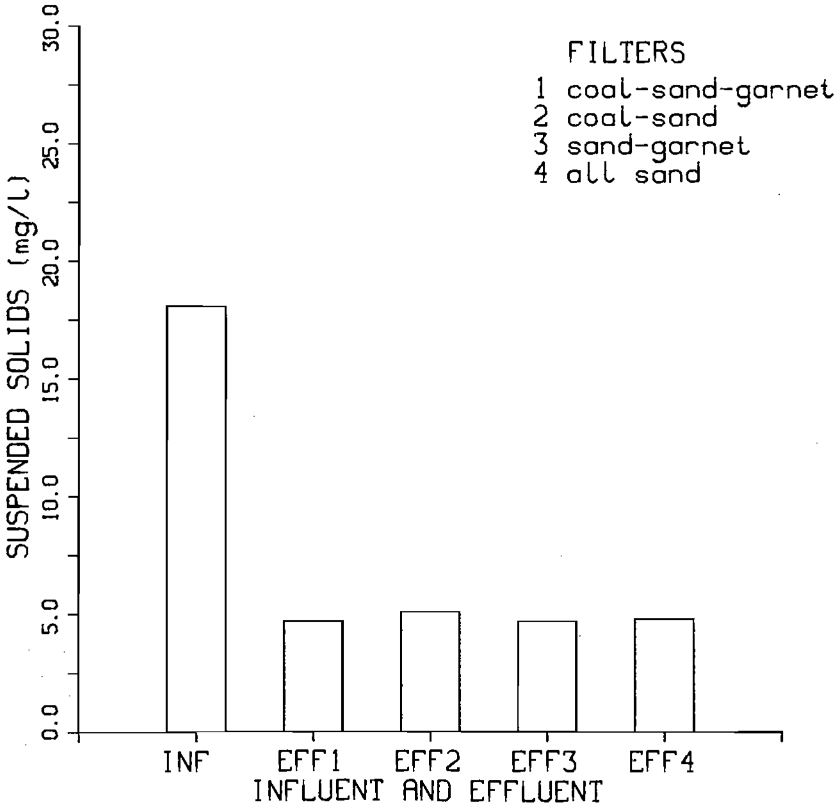


Figure 8. Comparison of the mean suspended solids concentration in the common influent and the four filter effluents.

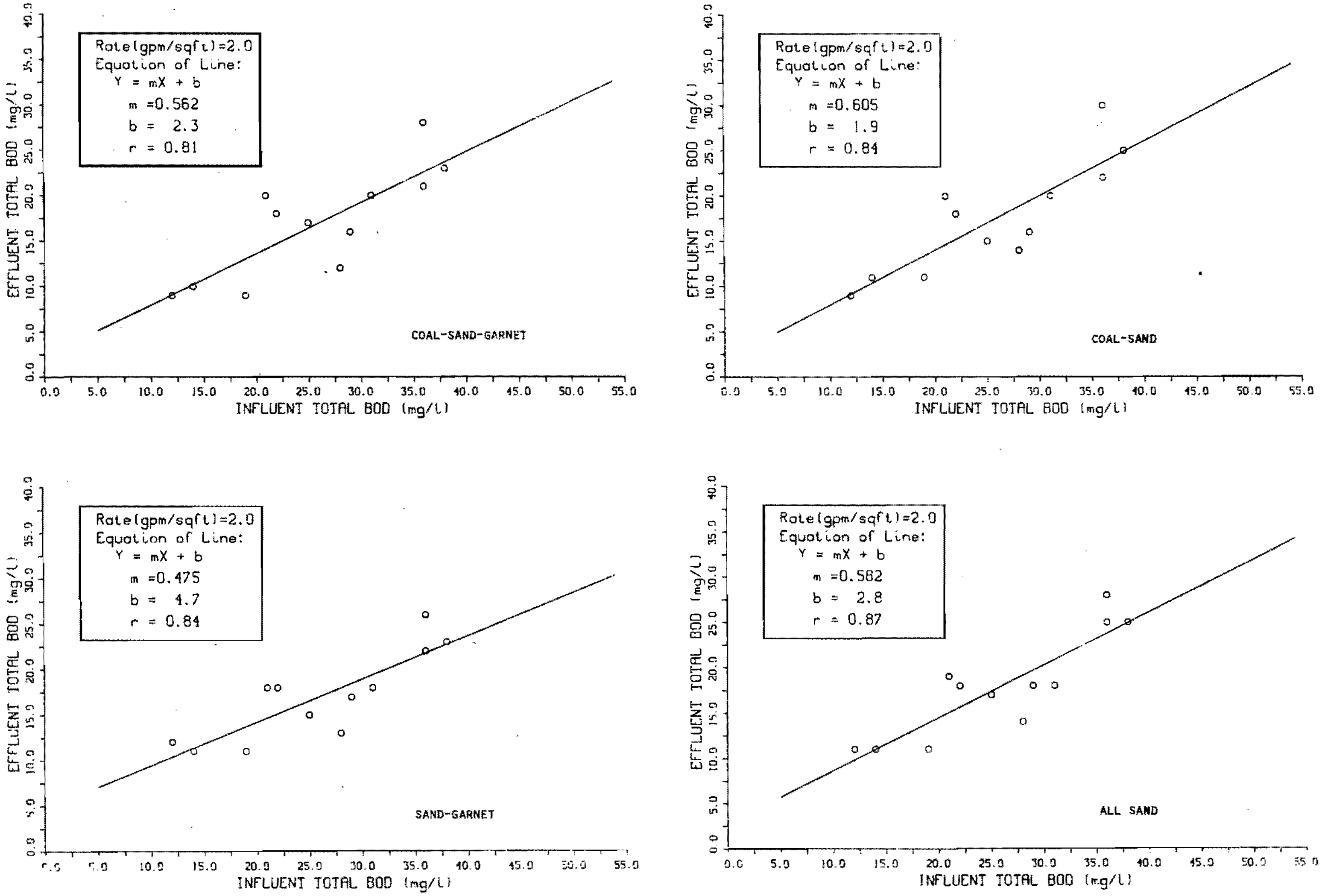


Figure 9. Relationships between influent and effluent total BOD_5 concentrations for each filter type at a hydraulic loading rate of 81.5 ℓ/m^2·min (2 gpm/ft^2).

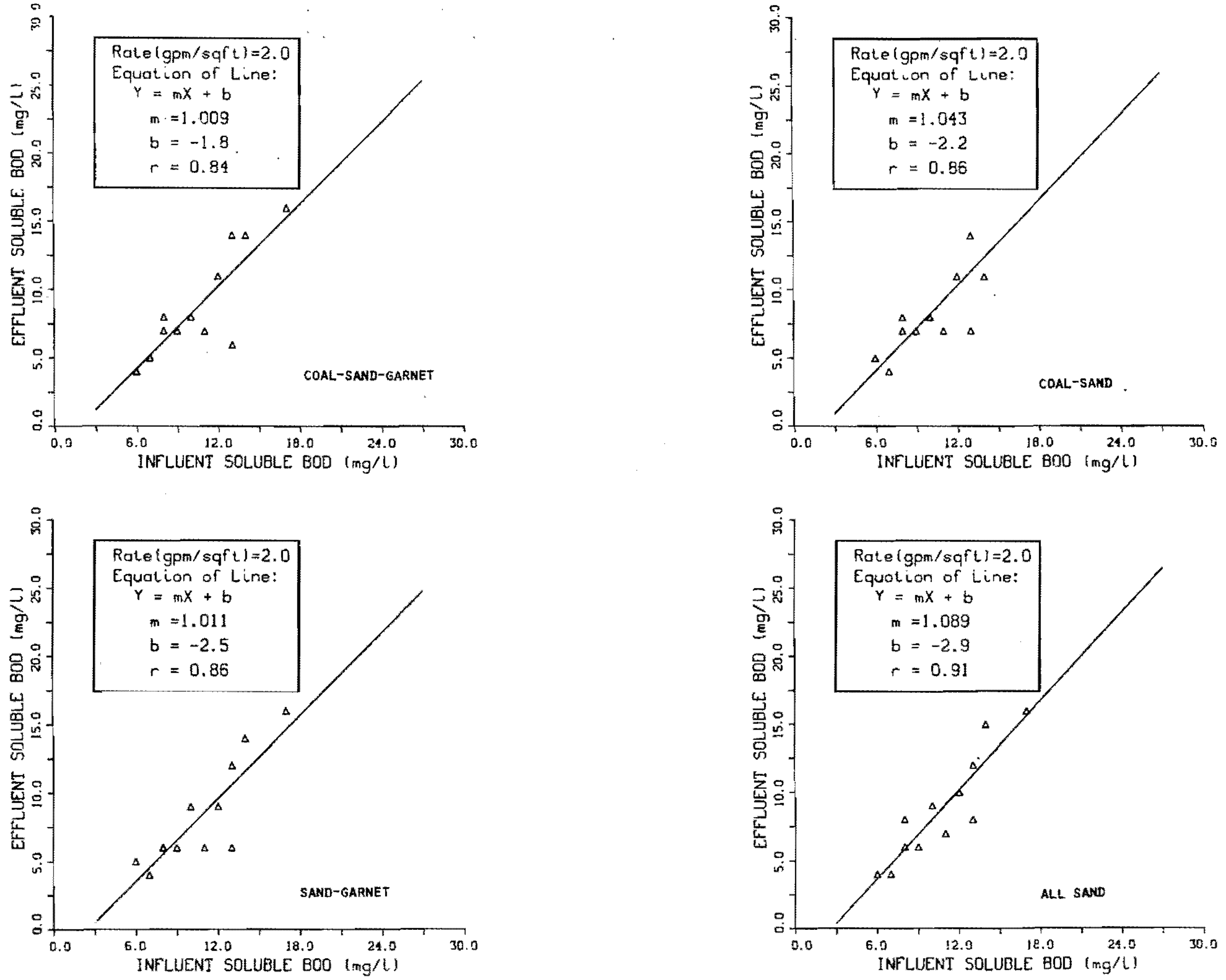


Figure 10. Relationships between influent and effluent soluble BOD_5 concentrations for each filter type at a hydraulic loading rate of 81.5 $\ell/m^2 \cdot min$ (2 gpm/ft^2).

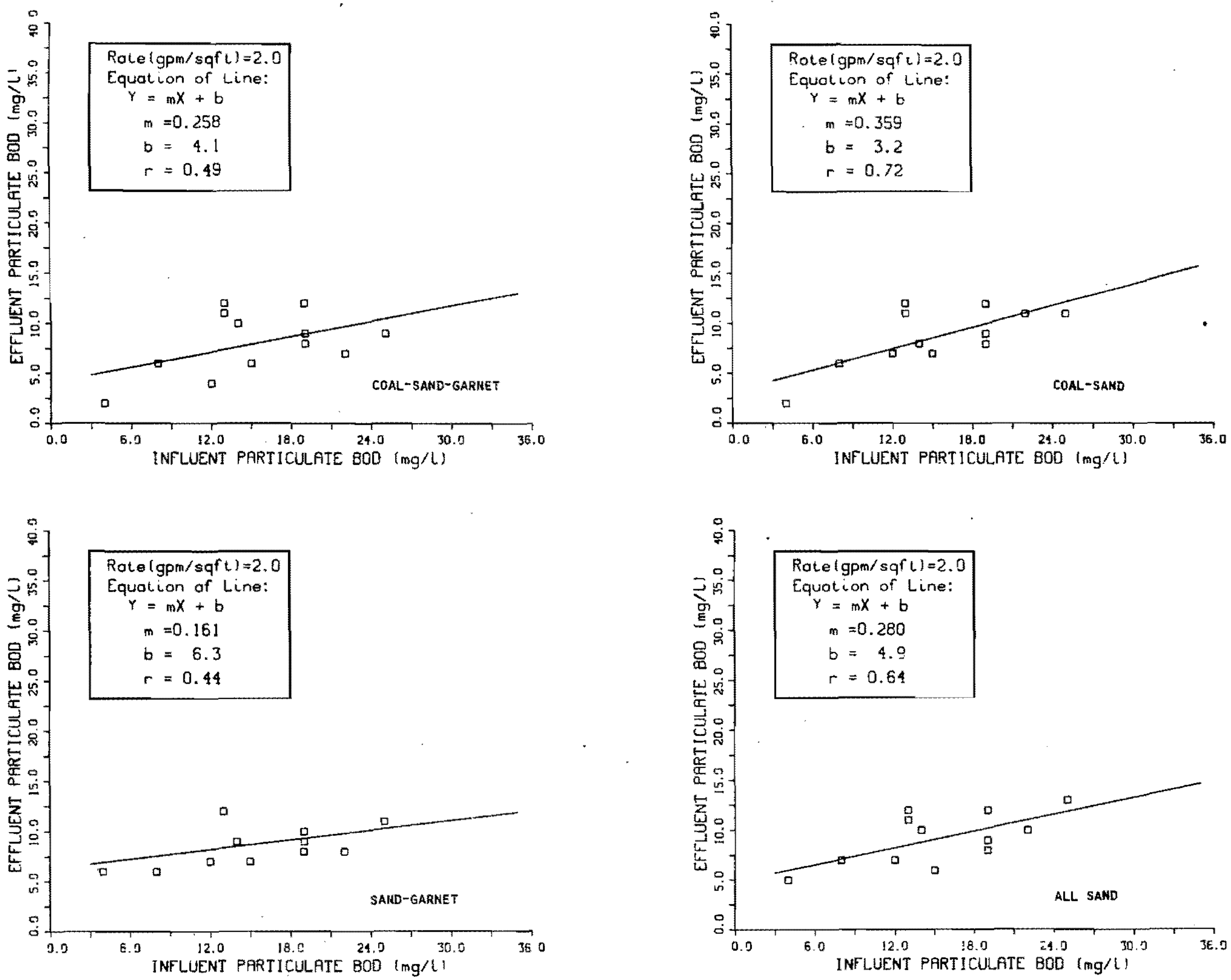


Figure 11. Relationships between influent and effluent particulate BOD_5 concentrations for each filter type at a hydraulic loading rate of 81.5 ℓ/m^2•min (2 gpm/ft^2).

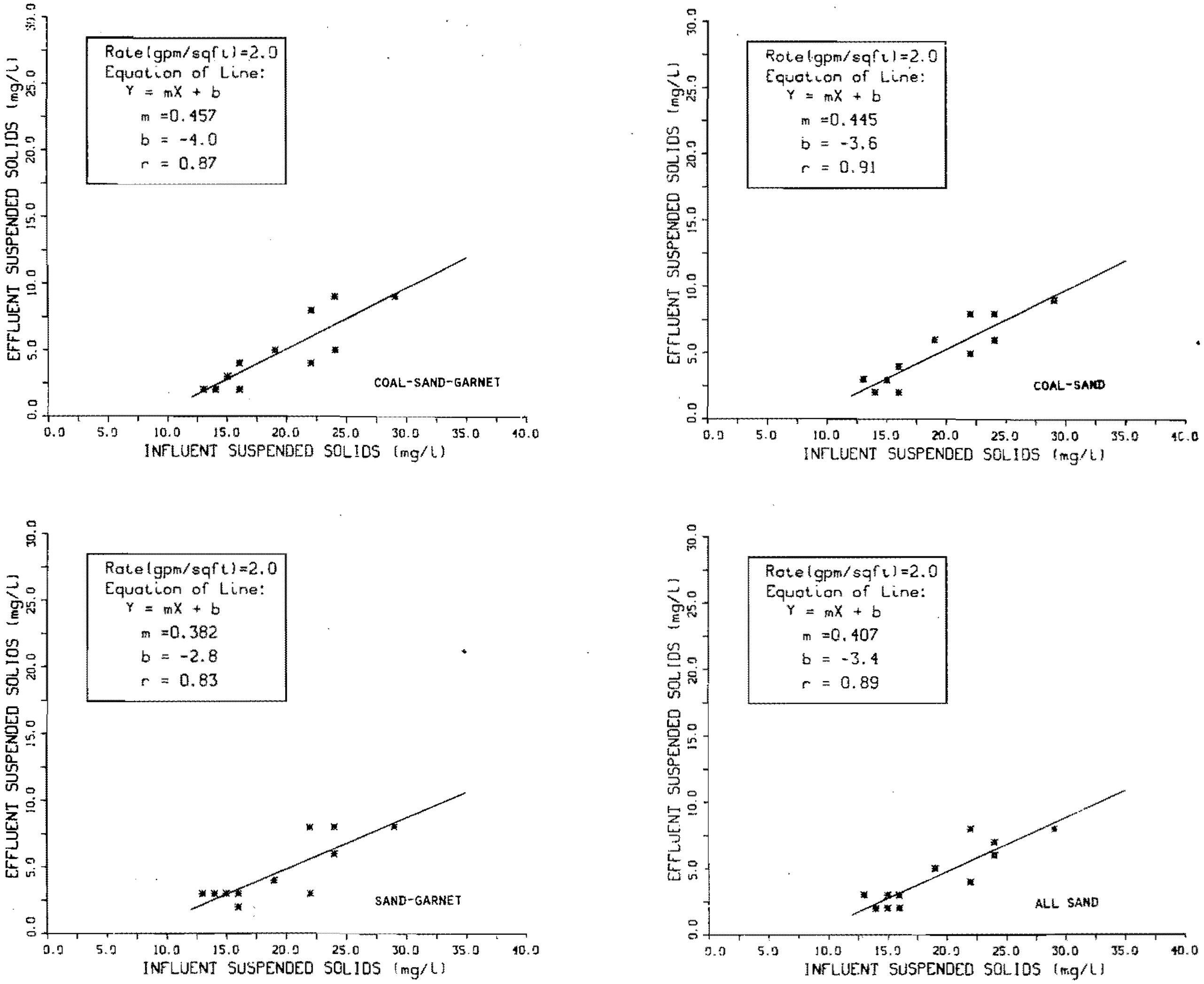


Figure 12. Relationships between influent and effluent suspended solids concentrations for each filter type at a hydraulic loading rate of 81.5 ℓ/m²•min (2 gpm/ft²).

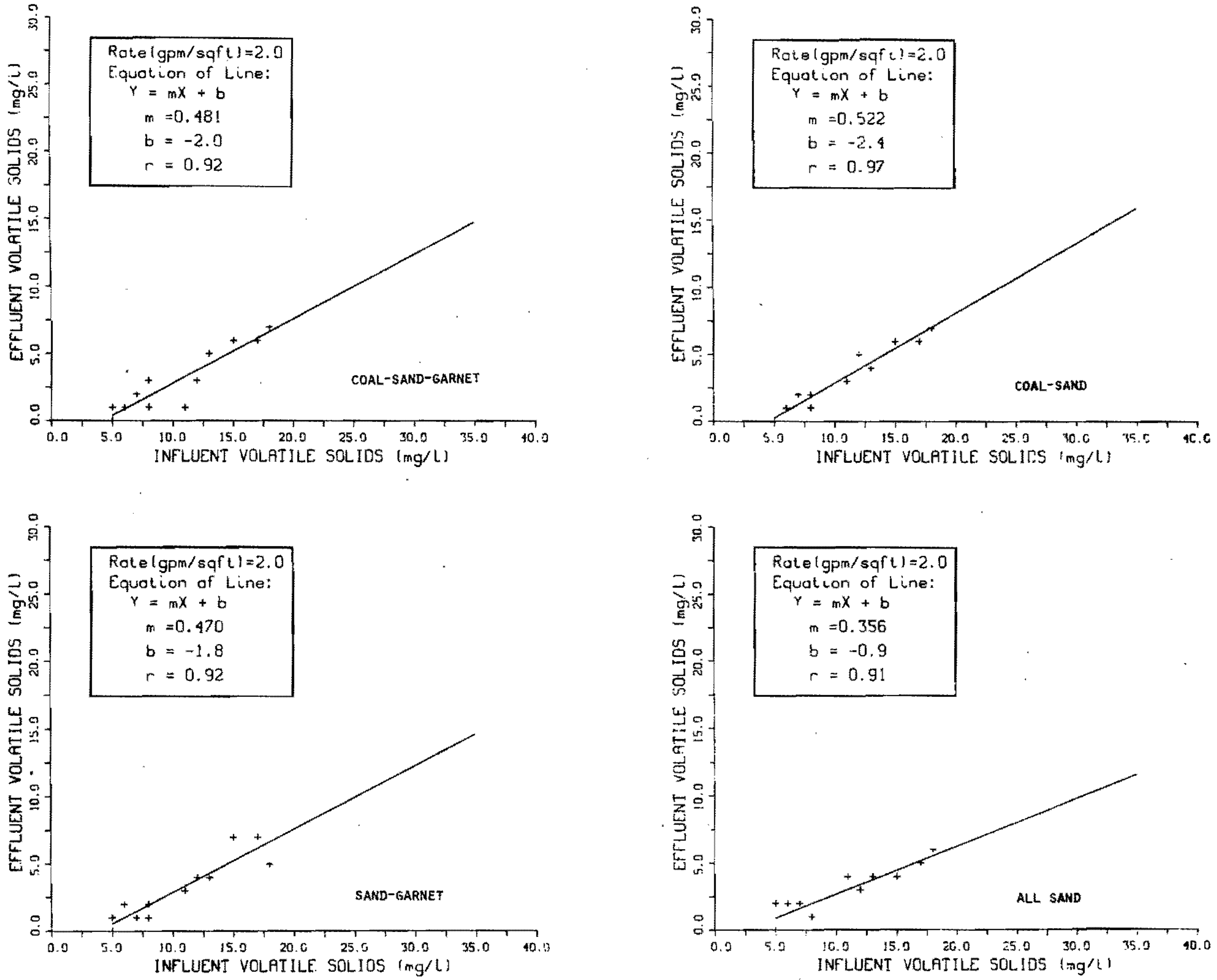


Figure 13. Relationships between influent and effluent volatile suspended solids concentrations for each filter type at a hydraulic loading rate of 81.5 ℓ/m²•min (2 gpm/ft²).

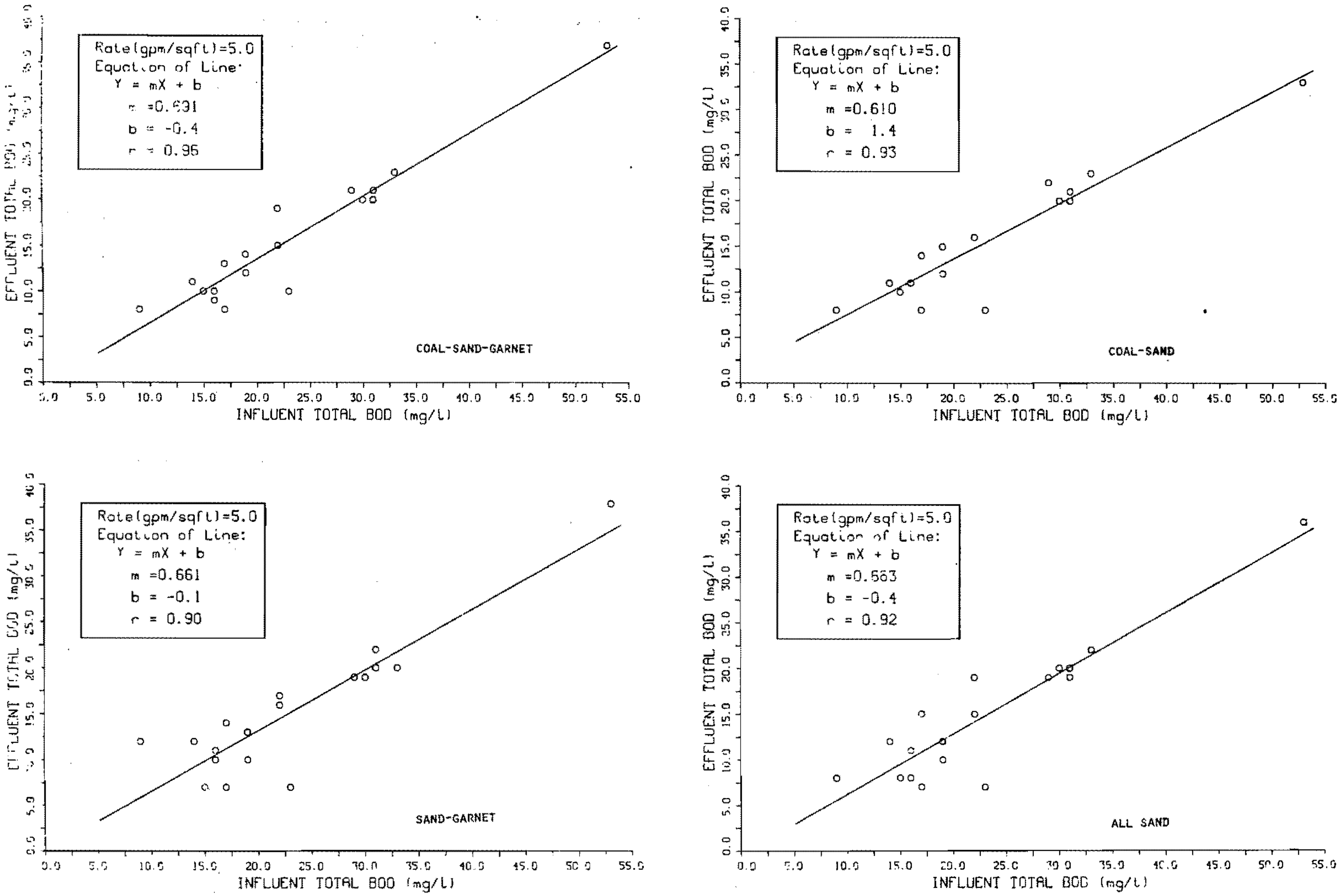


Figure 14. Relationships between influent and effluent total BOD_5 concentrations for each filter type at a hydraulic loading rate of 203.7 ℓ/m^2•min (5 gpm/ft^2).

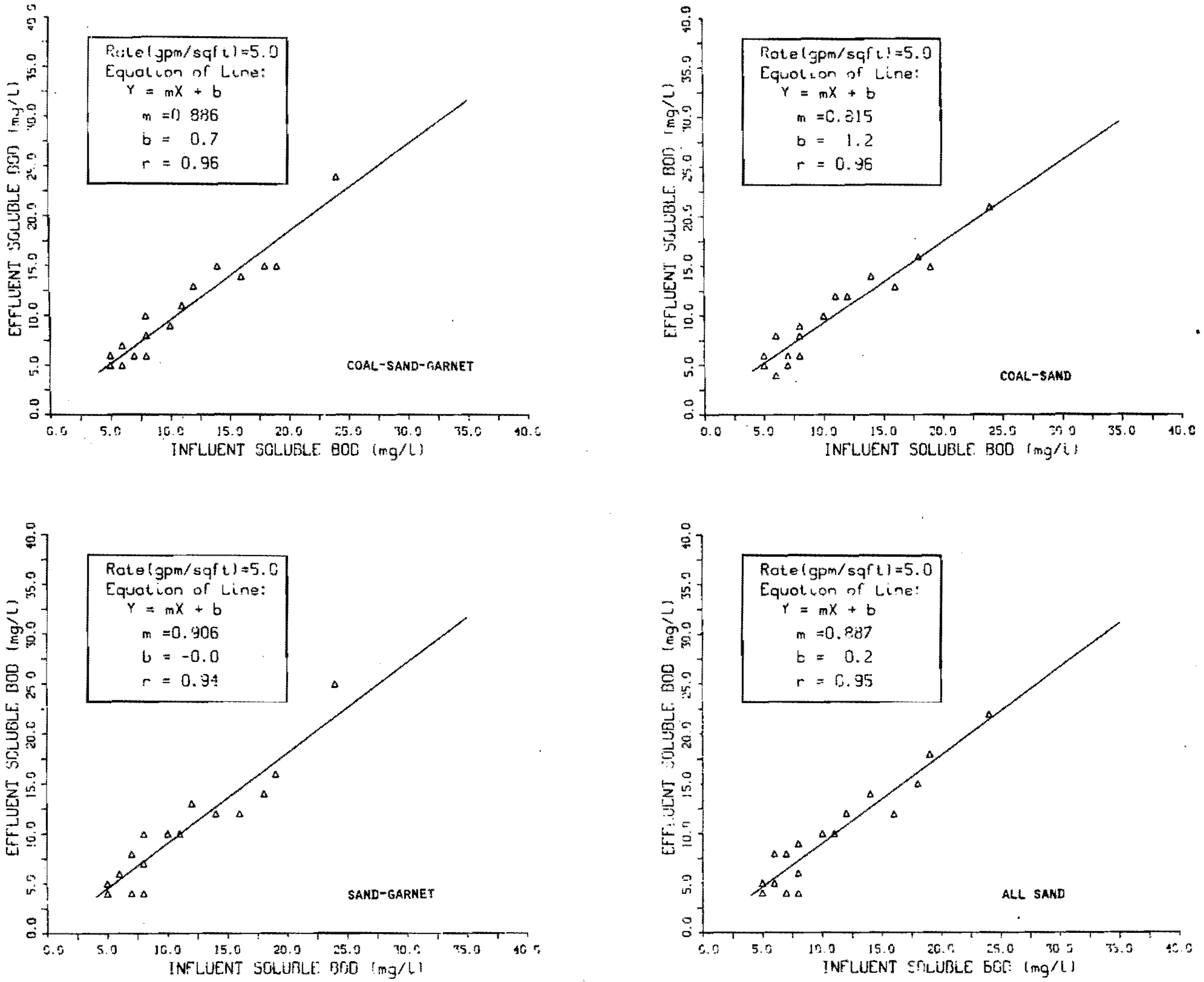


Figure 15. Relationships between influent and effluent soluble BOD_5 concentrations for each filter type at a hydraulic loading rate of 203.7 ℓ/m^2•min (5 gpm/ft^2).

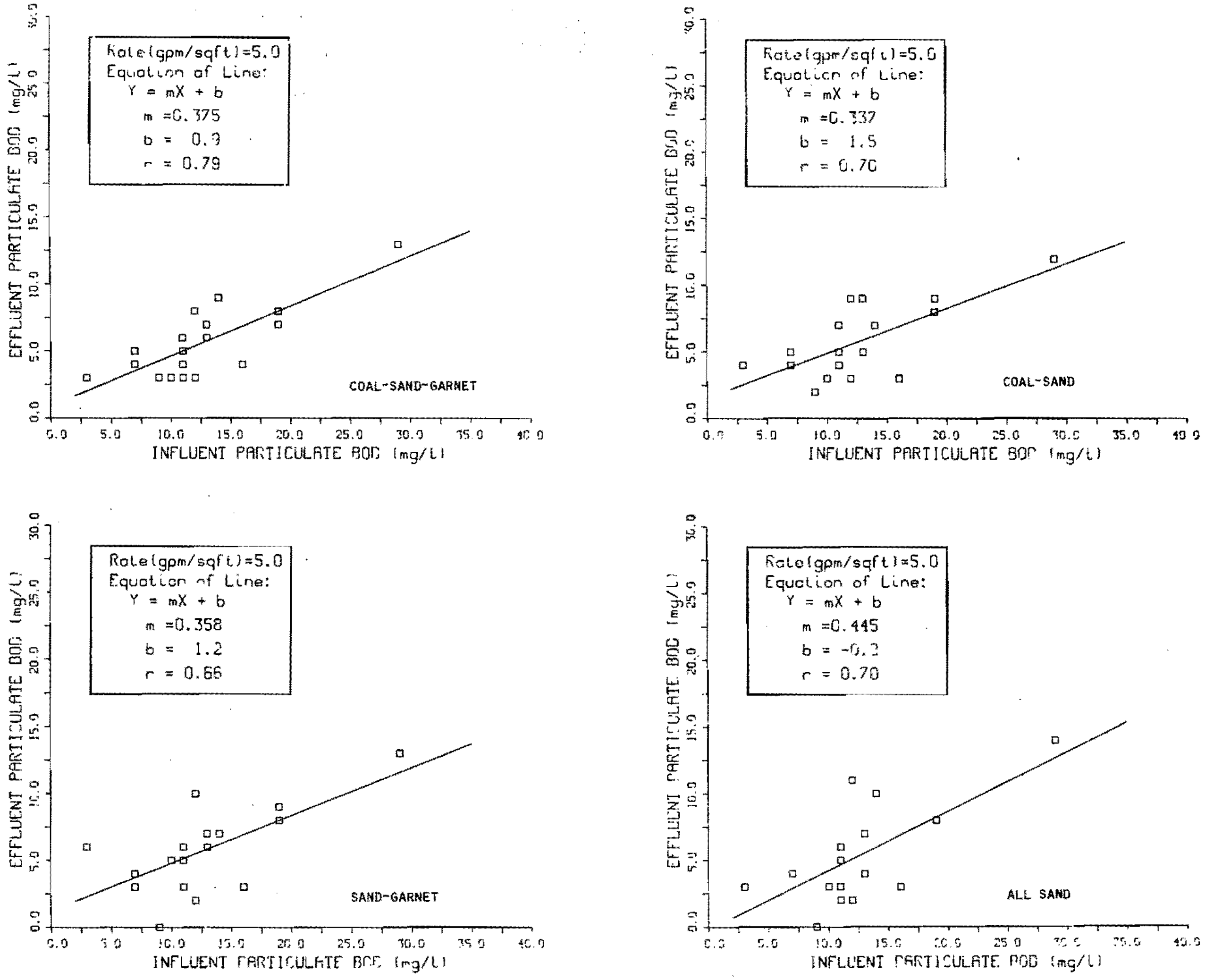


Figure 16. Relationships between influent and effluent particulate BOD_5 concentrations for each filter type at a hydraulic loading rate of 203.7 ℓ/m²·min (5 gpm/ft²).

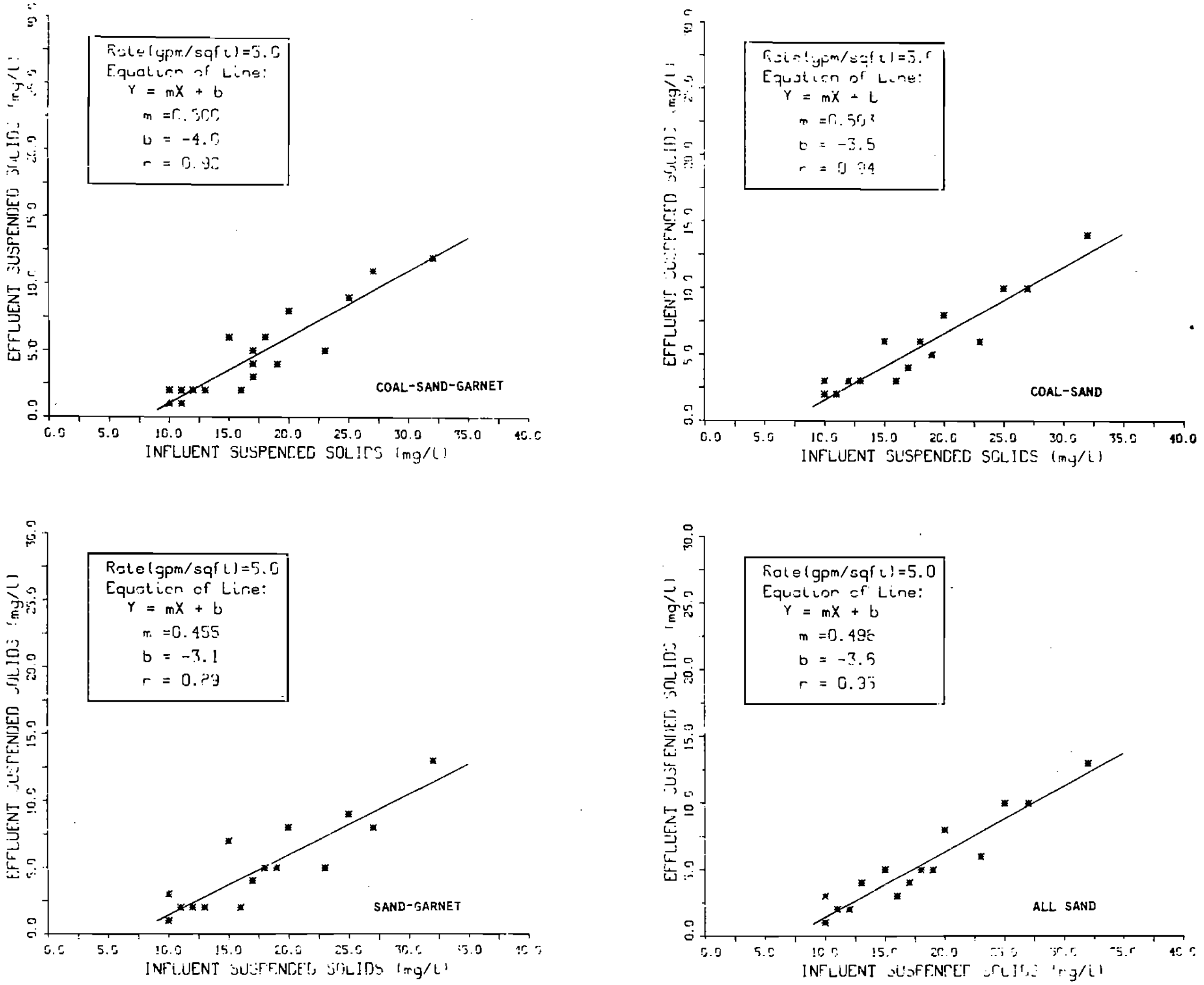


Figure 17. Relationships between influent and effluent suspended solids concentrations for each filter type at a hydraulic loading rate of 203.7 ℓ/m²•min (5 gpm/ft²).

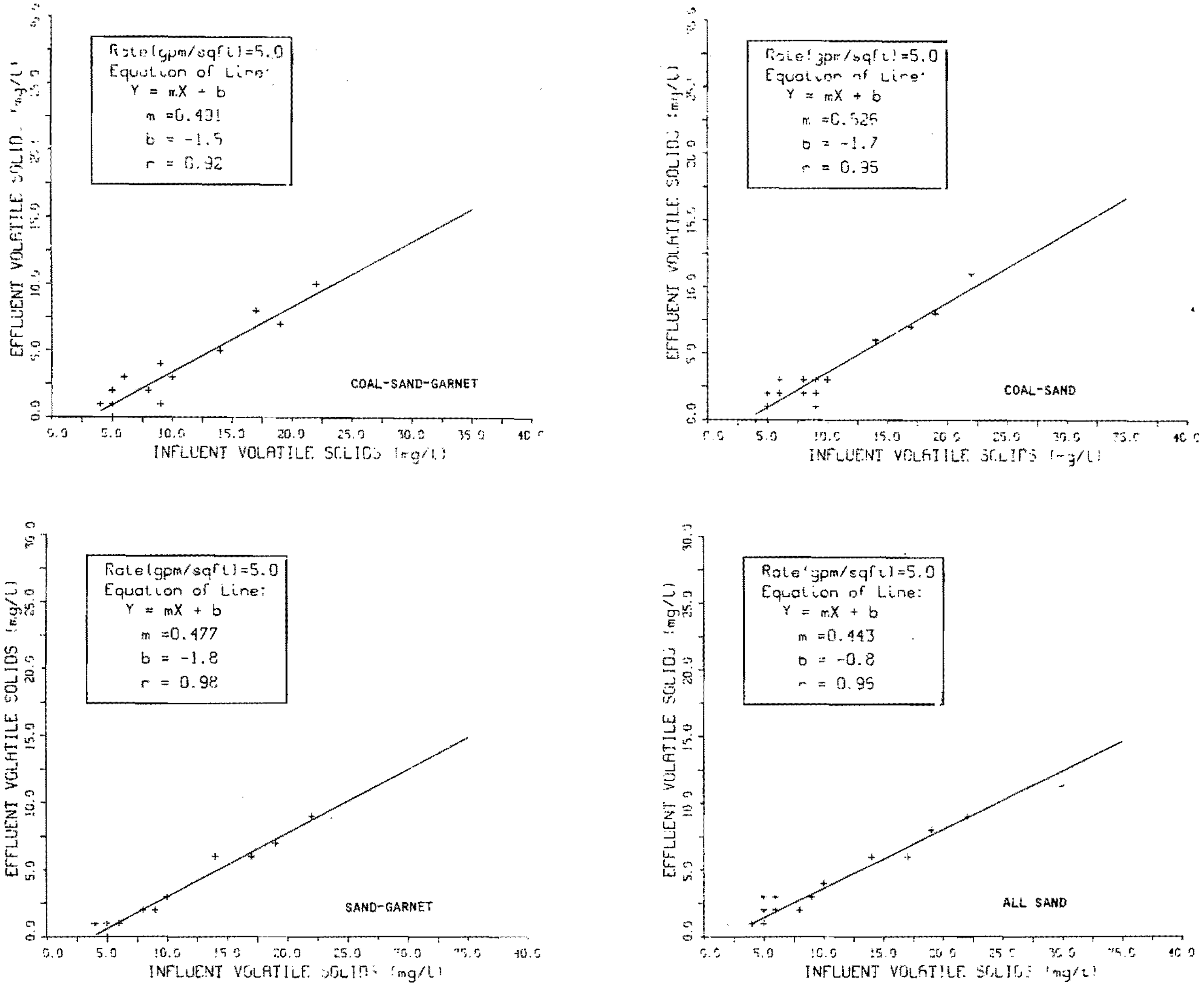


Figure 18. Relationships between influent and effluent volatile suspended solids concentrations for each filter type at a hydraulic loading rate of 203.7 ℓ/m²•min (5 gpm/ft²).

Table 5. Results of statistical analyses testing difference between mean influent and effluent concentrations for each quality parameter and hydraulic loading rate.

Quality Parameter (mg/ℓ)	81.5 $\ell/\text{m}^2\cdot\text{min}$				203.7 $\ell/\text{m}^2\cdot\text{min}$				Tabular Student's-t***	
									Confidence Level	
	$\overline{\text{INF}}$	$\overline{\text{EFF}}$	Percent Removed	Student's t*	$\overline{\text{INF}}$	$\overline{\text{EFF}}$	Percent Removed	Student's t**	t 95%	t 99%
Total BOD_5	25.9	17.4	33	4.246	23.1	15.3	34	3.817	1.645	2.326
Soluble BOD_5	10.7	8.7	18	1.644	10.5	9.7	8	0.606	1.645	2.326
Particulate BOD_5	15.3	8.7	43	5.803	12.6	5.6	55	7.206	1.645	2.326
Suspended Solids	19.1	4.6	76	14.65	17.4	5.0	71	11.89	1.645	2.326
Volatile Solids	10.4	3.0	71	8.152	9.2	3.0	67	7.024	1.645	2.326

* degrees of freedom = 58
** degrees of freedom = 88
*** degrees of freedom = 58

$\overline{\text{INF}}$ = average influent
$\overline{\text{EFF}}$ = average effluent

1 $\ell/\text{m}^2\cdot\text{min}$ = 0.0246 gpm/ft^2

must also be considered [*APHA*, 1975]. It is difficult to demonstrate soluble carbonaceous removal by granular filtration using the BOD_5 test.

The percent removals of each parameter for both flow rates were basically the same, except for soluble BOD_5 and particulate BOD_5. The influent and effluent soluble BOD_5 concentrations were small and a small change in concentration results in a noticeable change in removal efficiency.

The difference between particulate BOD_5 removals for the two flow rates is curious because of the solids removal efficiencies. Solids removal was comparable for both loading rates, yet the corresponding removals of particulate BOD_5 were greater at the higher loading rate than the lower. Figure 19 shows the relationship between PBOD_5 concentration and SS concentration for both filter influent and effluent and combined flow rates. Particulate BOD_5 concentration was directly related to suspended solids concentration. If solids were effectively removed by filtration, then the particulate BOD_5 was removed proportionately.

Each of the four filters evaluated was effective in removing total and particulate BOD_5, and suspended solids from the influent stream. Total BOD_5 removal was related to the particulate BOD_5 removal. Biochemical oxygen demand and SS removals were not affected by the hydraulic loading rates studied.

Headloss Development

Although hydraulic loading rate did not affect BOD_5 and SS removals, the flow rate did affect the period of time a filter performed. Increasing the hydraulic loading rate from 81.5 $\ell/\text{m}^2\cdot\text{min}$ (2 gpm/ft^2) to 203.7 $\ell/\text{m}^2\cdot\text{min}$ (5 gpm/ft^2) decreased the period of filter run by 50 percent. Media depth and configuration also affected the accumulation of headloss and consequently the period of filter run. The smaller the media effective size, the greater the headloss development. Figures 20-25 show the development of headloss with time for four filters.

The coal layered filters provide a longer filter run because the larger pore space allows for in-depth filtration to occur. Sand filters become clogged at the media surface and are primarily surface straining devices. Surface straining results in rapid headloss development and short filter runs. The longest filter run for the sand filter was 9 hours. The maximum run time for both the sand and coal filters occurred at the 81.5 $\ell/\text{m}^2\cdot\text{min}$ (2 gpm/ft^2) flow rate.

Headloss development in the coal-sand filter (Figures 23 and 24) increased at a greater rate than headloss development in the coal-sand-garnet filter. Typically, headloss would not terminate the filtration process as rapidly in the coal-sand filter as in the coal-sand-garnet, because the coal-sand-garnet has a greater overall depth and clean bed headloss. The increased headloss observed in the coal-sand filter was probably attributable to insufficient backwashing of the filter media. The

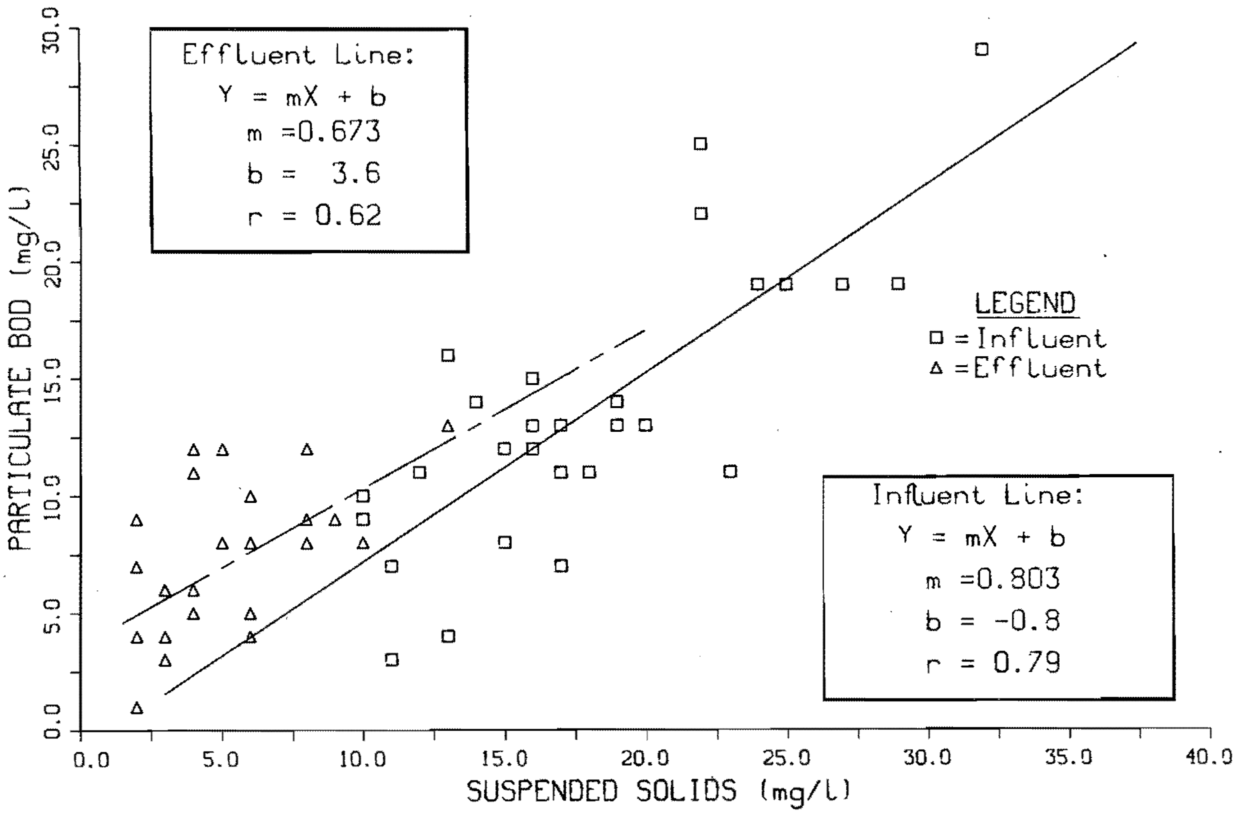


Figure 19. Relationship between particulate BOD_5 and suspended solids concentrations for both filter influent and effluent.

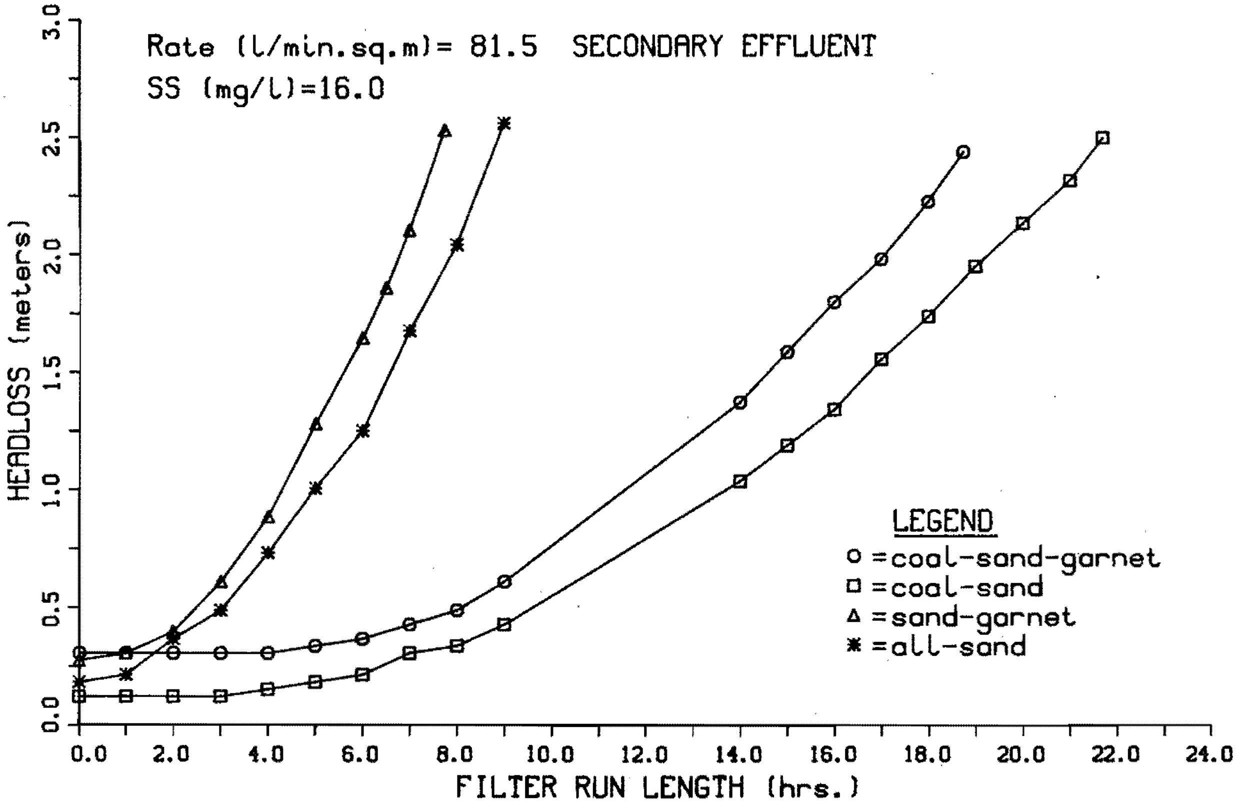


Figure 20. Headloss development curves for all filters using secondary wastewater as filter influent at a hydraulic loading rate of 81.5 ℓ/m²·min (2 gpm/ft²).

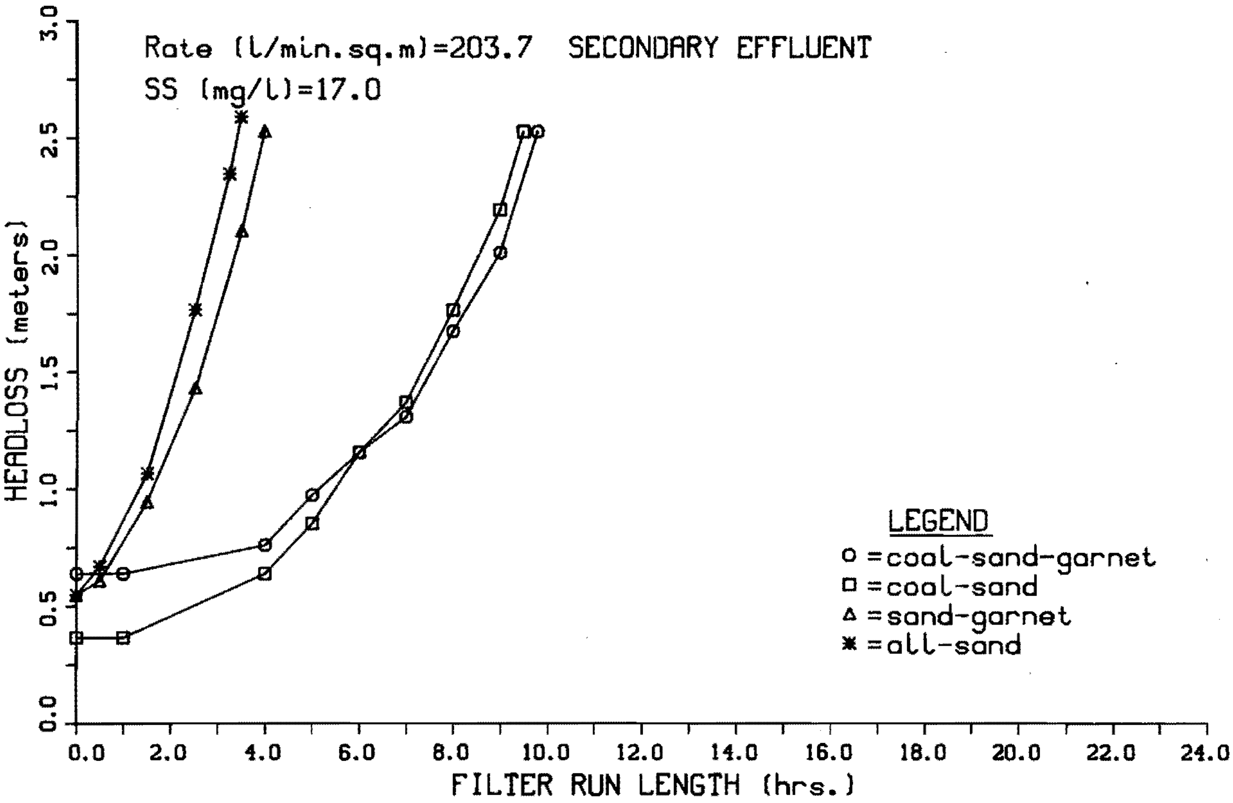


Figure 21. Headloss development curves for all filters using secondary wastewater as filter influent at a hydraulic loading rate of 203.7 ℓ/m²·min (5 gpm/ft²).

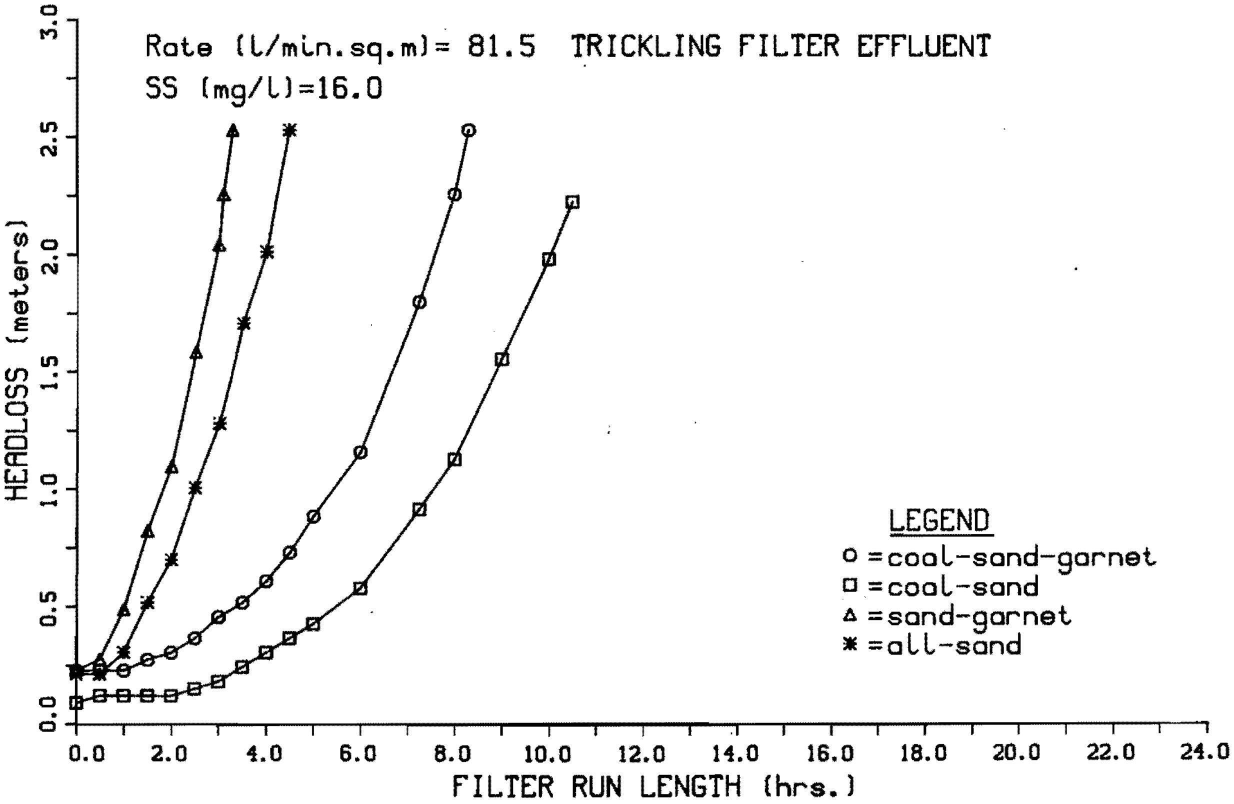


Figure 22. Headloss development curves for all filters using trickling filter effluent as filter influent at a hydraulic loading rate of 81.5 ℓ/m²·min (2 gpm/ft²).

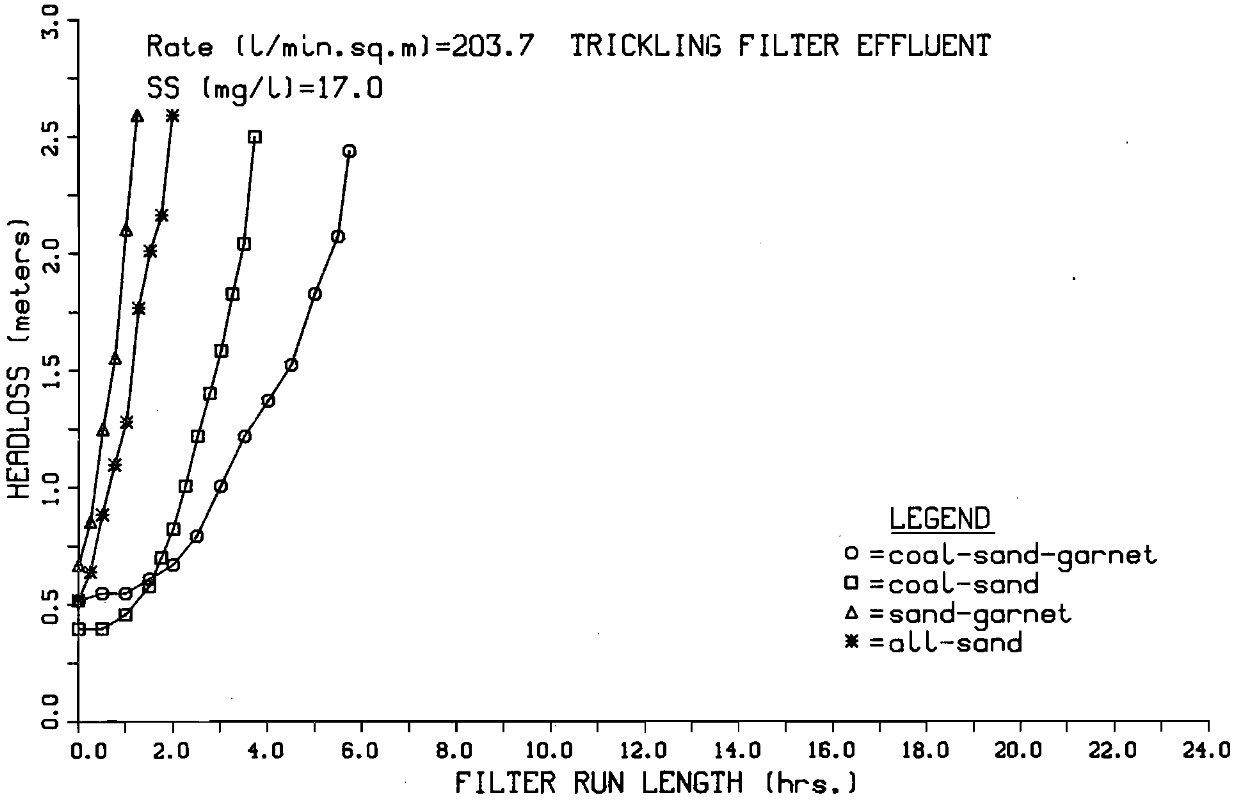


Figure 23. Headloss development curves for all filters using trickling filter effluent as filter influent at a hydraulic loading rate of 203.7 ℓ/m²•min (5 gpm/ft²).

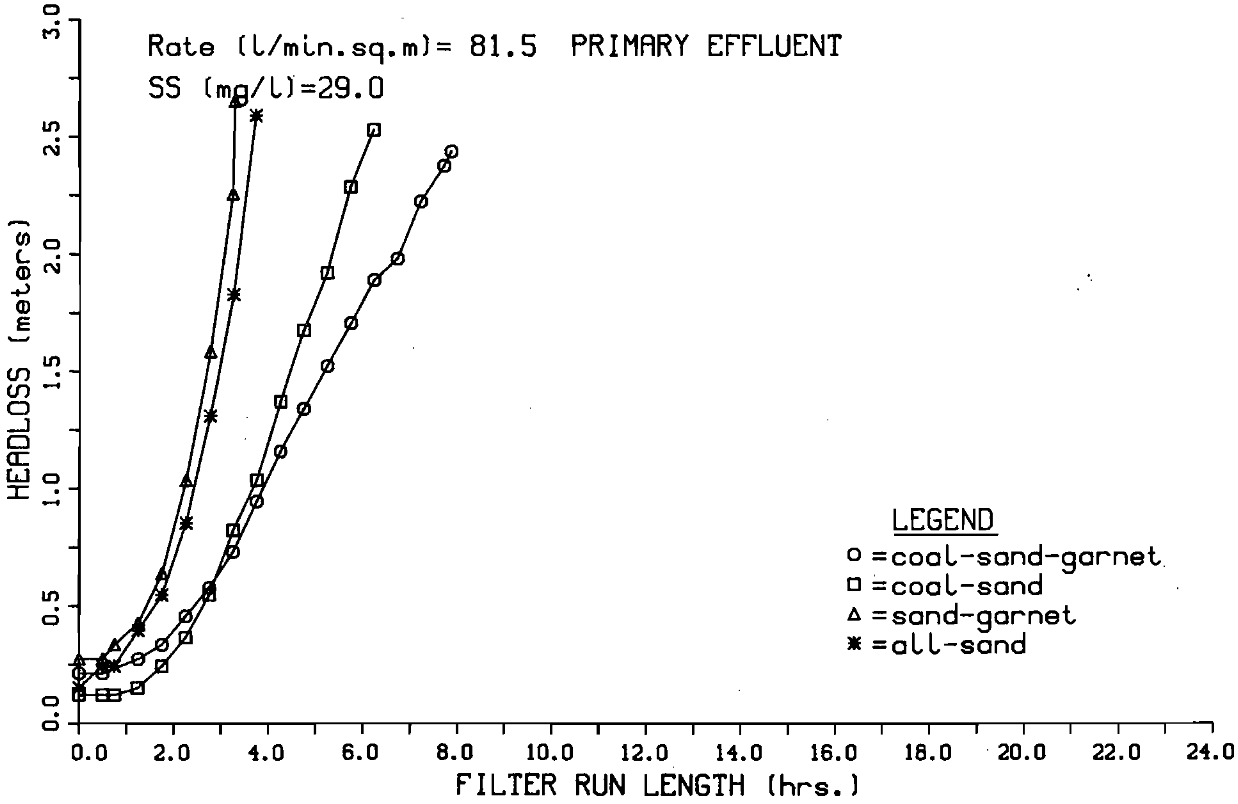


Figure 24. Headloss development curves for all filters using primary effluent as filter influent at a hydraulic loading rate of 81.5 ℓ/m²•min (2 gpm/ft²).

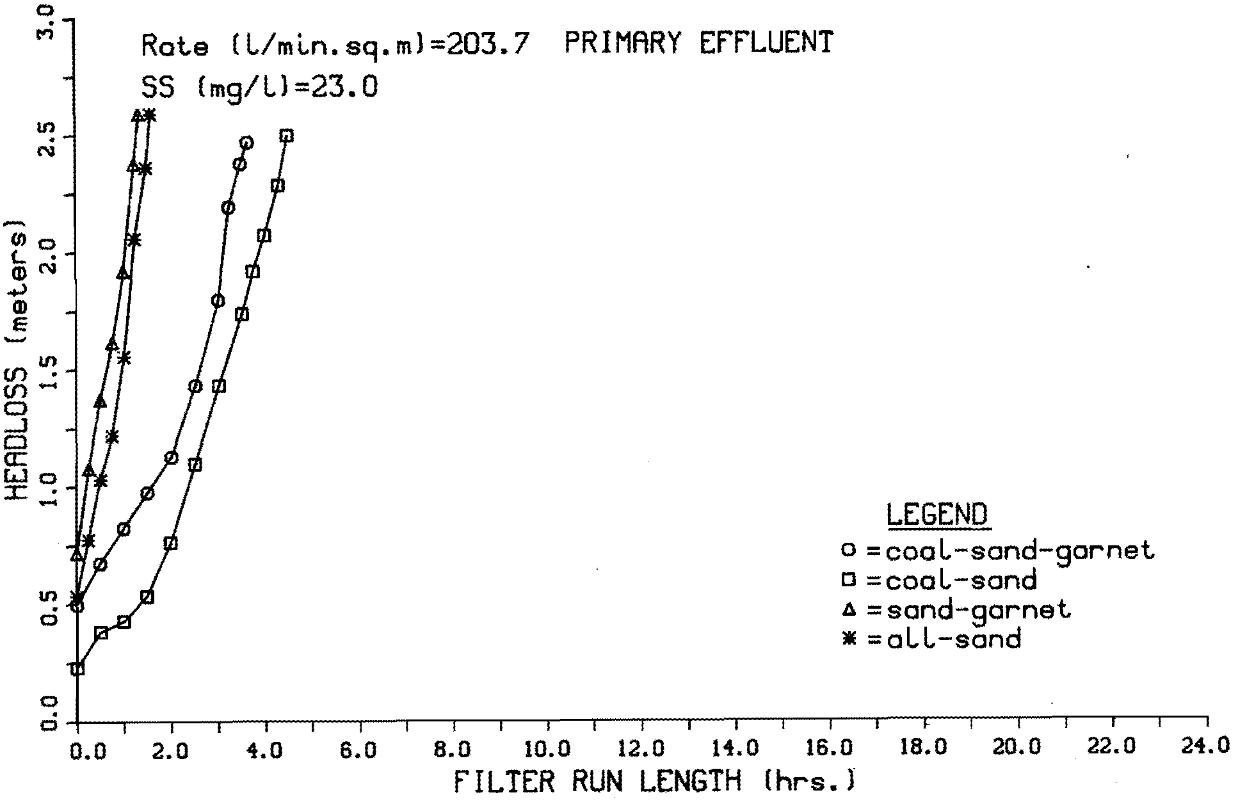


Figure 25. Headloss development curves for all filters using primary effluent as filter influent at a hydraulic loading rate of 203.7 ℓ/m²·min (5 gpm/ft²).

underdrain could have also contributed to the headloss increase because of partial clogging of the outlet pores in the plastic nozzle.

A curious situation occurred at the higher loading rate as shown on the headloss curves in Figures 21, 23, and 25. When the water depth above the media reached 1.2 m (4 ft) (same level as the filter influent inlet), the inlet hose to the filters would fill and cause the distribution box to overflow. This reduced the flow to the filters by approximately 25 percent, and the decrease in slopes of the headloss curves reflect this decline in flow rate (Figures 21, 23, and 25). The flow reduction did not occur when operating at the low loading rate.

The dual and mixed media filters with anthracite coal as the top media layer operated as in-depth filters. Depth filtration provides longer and thus more economical filter runs.

Backwash

The sand-garnet and all sand filters were more effectively cleaned by the air-scour backwash than the coal media filters. The higher specific gravity of the sand permitted a more turbulent action with the air-scour without loss of media. The lighter coal media was carried out of the filter with the backwash water during turbulent backwashing. This problem was eliminated by lowering the water level 15 to 20 cm (6 to 8 in) below the overflow level to prevent loss of filter media during the air-scour [*EPA*, 1974a]. There were fewer operational problems associated with the sand media than with the coal media during backwash.

During the air-scour backwash procedure, some movement of the gravel support layer was observed. This movement, caused by the concurrent air and water backwash, could cause clogging of the nozzle underdrain with fine sand or coal.

Biological growth within and on the media surface occurred because there was no chlorine residual in the filter influent. Biological growth and slime on the media inhibited effective backwashing. To prevent a slime build-up in the media, backwashing was accomplished using a chlorine solution >30 mg/ℓ of sodium hypochlorite (chlorox). With chlorinated backwash, filter operation and backwash were effectively managed.

When filtering secondary effluent, daily backwash was necessary, not only because of accumulated headloss, but for breaking up solids which would compact around the media, forming clumps and mudballs. Frequent backwash prevented such solids compaction and mudball formation. The sand filters did not exhibit this problem because the air-scour backwash was very effective in cleaning the sand media.

Filter Cycle Performance

The concentration of suspended solids in the filter influent varied throughout the day and during the length of filter run. Grab samples of both filter influent and effluent were taken at different times during the filter run and analyzed for suspended solids concentration. The grab samples were taken while filtering secondary wastewater in addition to the composite samples and analyzed separately. The SS concentrations are presented in Figure 16 for the common influent, coal-sand-garnet effluent, and all sand effluent. The variation in effluent SS concentrations does not appear to affect the effluent concentration for a constant hydraulic loading rate. Effluent quality increased with filter run as more solids are stored within the filter bed. The effluent solids concentration may increase upon filter breakthrough. Studies indicate, however, that pressure drops of as much as 9.1 m (30 ft) of water could be attained in filtration of trickling filter and activated sludge effluents through dual media filters without solids breakthrough [*Baumann*, 1977]. The effluent SS concentrations from both filters (Figure 26) were the same during the cycle.

BOD_5 Equation

A simple mathematical expression relating the filter effluent and influent total BOD_5 can be derived from the following steady-state, mass balance:

$$\text{Total } BOD_5 = \text{Soluble } BOD_5 + \text{Particulate } BOD_5 \quad (1)$$

At the filter effluent, Equation 1 can be expressed symbolically as follows:

$$T_e = S_e + P_e \quad (2)$$

where T_e, S_e, and P_e are the total, soluble, and particulate BOD_5 concentrations (mg/ℓ) in the effluent stream, respectively.

By using filter removal efficiencies, the effluent concentrations can be related to the influent:

$$T_e = (1 - E_t)T = (1 - E_s)S + (1 - E_p)P \quad (3)$$

where

T = influent total BOD_5 (mg/ℓ),

S = influent soluble BOD_5 (mg/ℓ),

P = influent particulate BOD_5 (mg/ℓ),

E_t = total BOD_5 removal efficiency,

E_s = soluble BOD_5 removal efficiency, and

E_p = particulate BOD_5 removal efficiency.

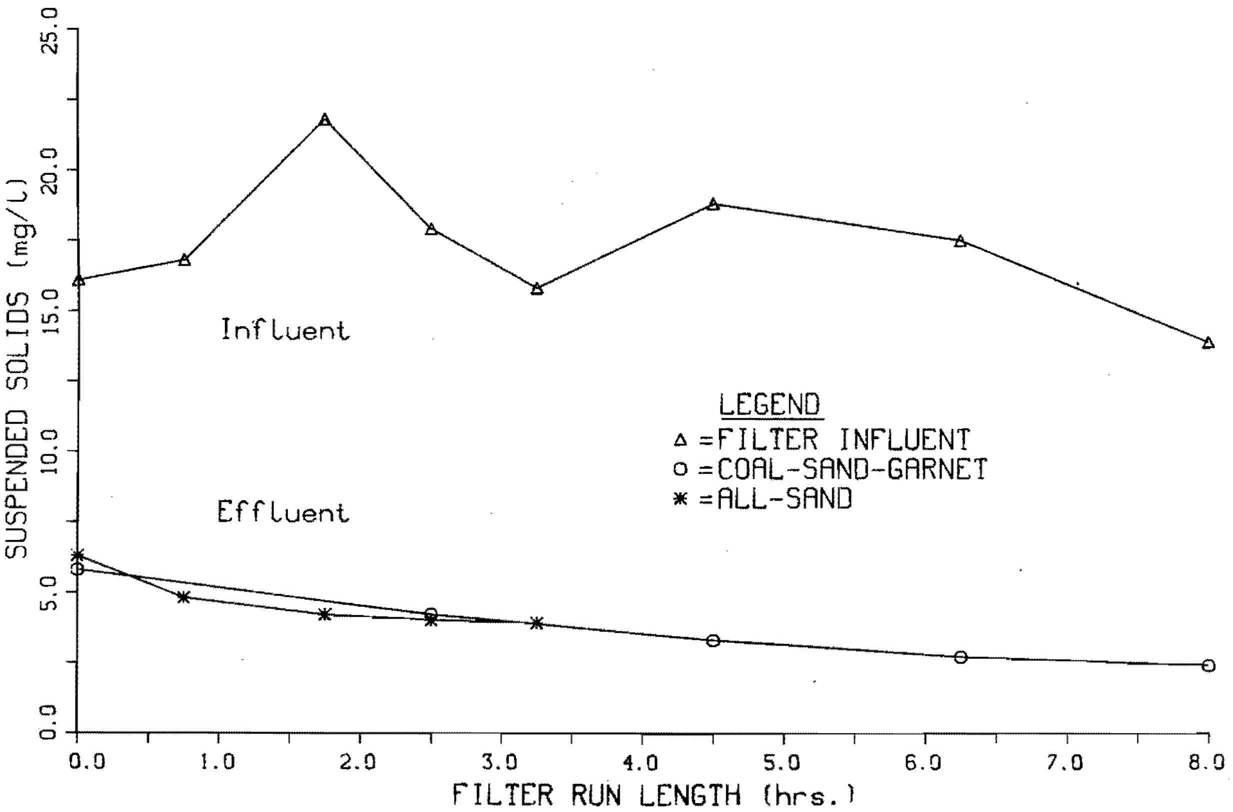


Figure 26. Variation of filter influent and effluent suspended solids concentrations during a filter run.

Using the relationship shown in Equation 1 for particulate BOD_5 and dividing by T yields the total BOD_5 removal expressed in terms of E_p, E_s, and influent soluble BOD_5 fraction ($f_s = S/T$).

$$E_t = -(E_p - E_s)f_s + E_p \tag{4}$$

or

$$T_e = T - (1 - f_s)E_pT - f_sE_sT \tag{5}$$

Using Equation 4 or 5, the effluent $TBOD_5$ concentration can be calculated if the filter removal efficiencies are known for soluble and particulate BOD_5. The equations could also be used to describe BOD_5 removal through other treatment processes.

Assuming that E_p and E_s are constant for a particular filter operation, Equation 4 becomes a linear relationship that can be used to calculate the effluent quality. The slope of Equation 4 is always negative for the condition $E_p > E_s$. Since granular filters are primarily solids removing devices, E_p will always be greater than E_s. Therefore, the $TBOD_5$ removal efficiency will decrease as the influent $SBOD_5$ fraction, f_s, increases.

By further assuming that the $SBOD_5$ removed (E_s) is equal to zero, the BOD_5 equation is reduced to:

$$E_t = -E_pf_s + E_p \tag{6}$$

or

$$T_e = T[1 - (1 - f_s)E_p] \tag{7}$$

From this expression, effluent BOD_5 is shown to be dependent on the amount of $PBOD_5$ in the filter influent and the ability of the filter to remove $PBOD_5$.

Use of BOD_5 Equation

Figure 27 is a plot of $SBOD_5$ versus $TBOD_5$ in the filter influent. The $SBOD_5$ fraction, f_s, is readily calculated from the relationship shown in Figure 27. The average fraction of $SBOD_5$ in the influent stream was 44 percent. The $PBOD_5$ removal efficiency, E_p, is shown in Table 8 in Appendix A. The average value for E_p from 30 combined values was found to be 50 percent with a standard deviation of 20 percent.

A graphical presentation of Equation 7 is shown in Figure 28. Effluent $TBOD_5$ is determined by locating the known influent $TBOD_5$ concentration on the horizontal axis, moving vertically until intersecting the appropriate percent $SBOD_5$ line, and then reading the value for effluent $TBOD_5$ from the vertical axis.

The BOD_5 equation was used to calculate effluent $TBOD_5$ for the filters studied at the Preston Treatment Plant. Figure 29 shows the relationships between the calculated value using the BOD_5 equation and the actual BOD_5 determined from the experimental study. The slopes in Figure 29 do not differ statistically (99 percent confidence).

Dawda et al. [1978] conducted a filtration study using trickling filter effluent and dual-media, SVG pilot-scale filter (Envirotech Corp.). The BOD_5 equation (Equation 7) was tested using the BOD_5 data from this study. The $PBOD_5$ removal efficiency, E_p, was calculated from *Dawda*'s data to be 69 percent. The calculated filter effluent

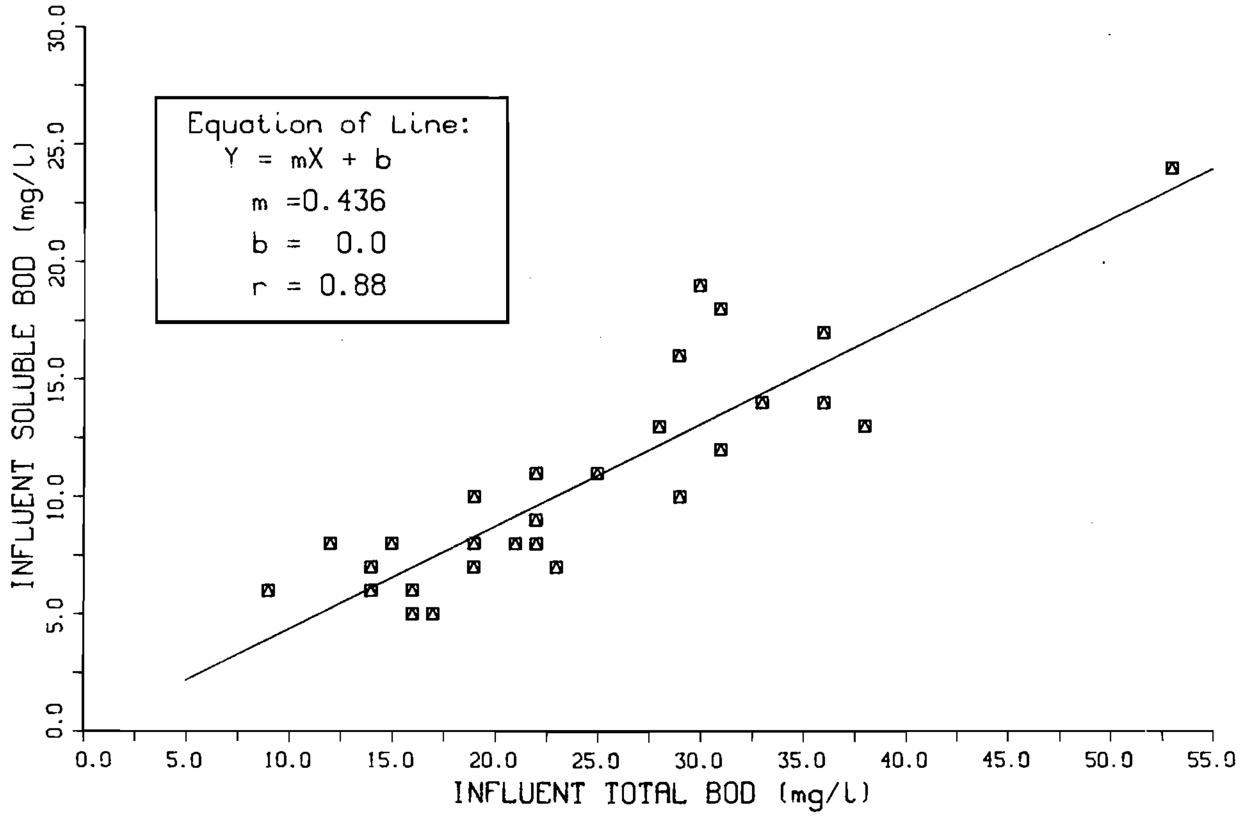


Figure 27. The relationship between soluble BOD_5 and total BOD_5 of the filter influent.

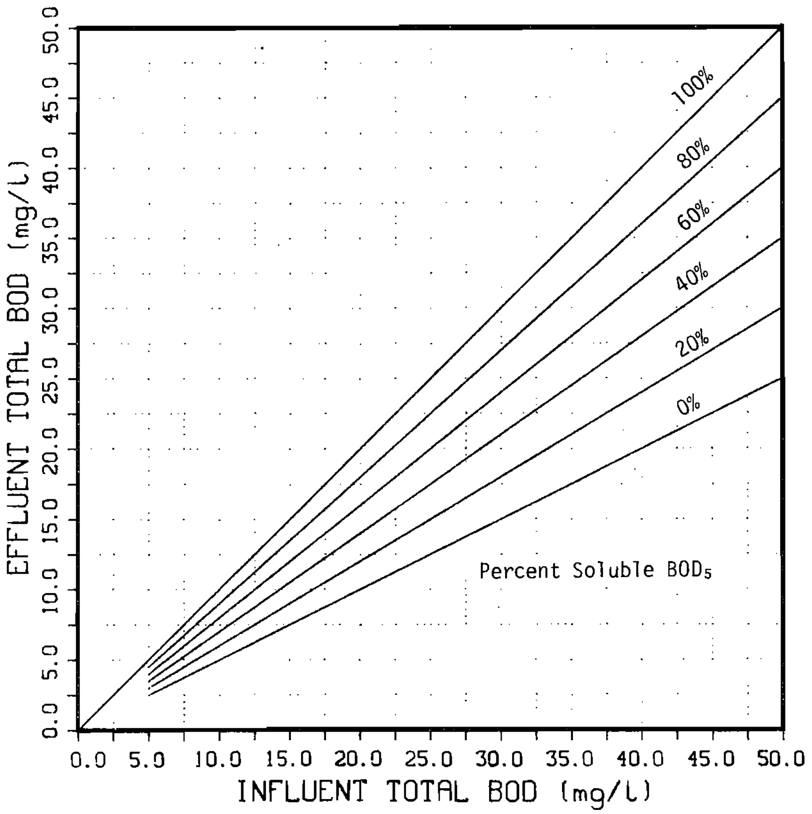


Figure 28. Graphical solution of Equation 7 to be used to predict filter effluent BOD$_5$ as a function of influent total BOD$_5$ and percent soluble BOD$_5$.

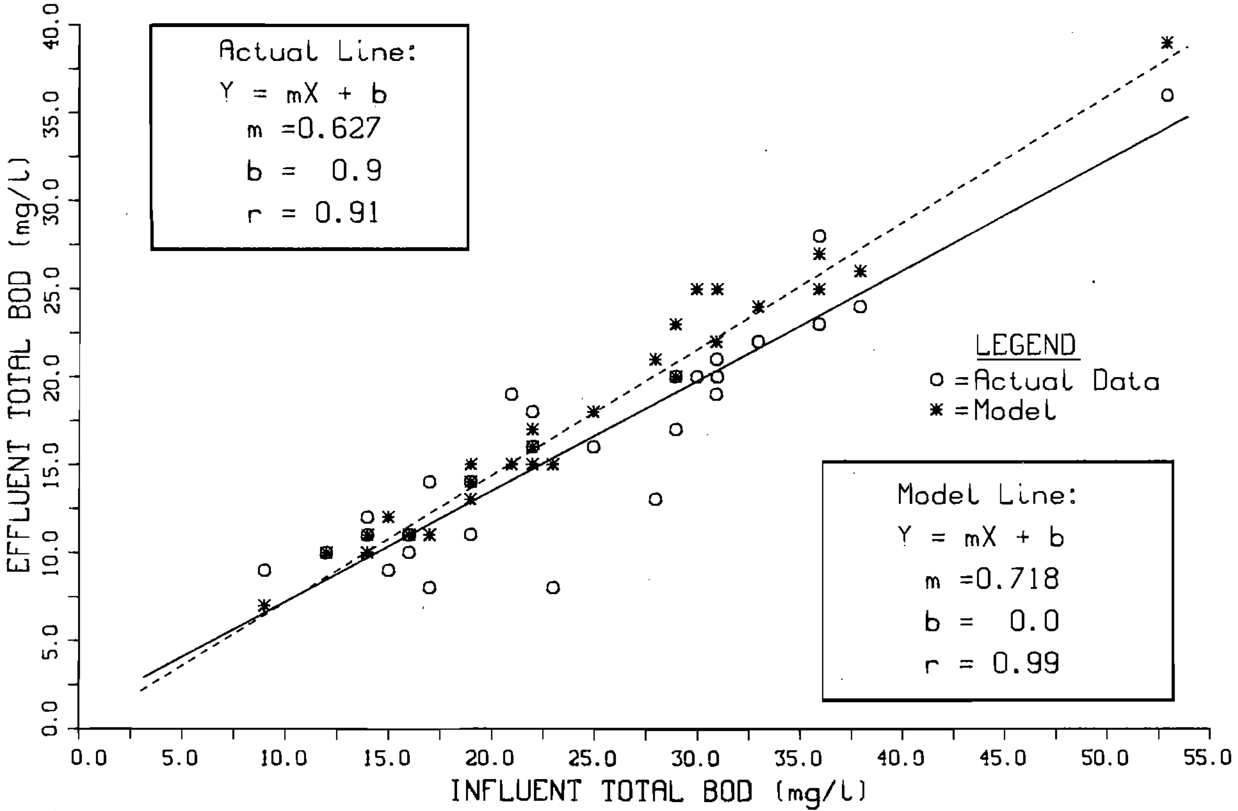


Figure 29. Relationship between filter influent and effluent BOD$_5$ concentration from data collected and from calculated effluent BOD$_5$ concentrations using the BOD$_5$ equation.

TBOD$_5$ concentration and BOD$_5$ data from *Dawda*'s study are listed in Table 6.

The BOD$_5$ equation was used to calculate filter effluent TBOD$_5$ knowing the filter effectiveness in removing PBOD$_5$ by filtration. There was no statistical difference (95 percent confidence) between the actual and calculated effluent TBOD$_5$ concentrations. The average calculated and actual effluent TBOD$_5$ concentrations were equal. Figure 30 shows the relationships between the calculated value using Equation 7 and the actual BOD$_5$ determined from *Dawda*'s study.

Comparing actual TBOD$_5$ data with calculated TBOD$_5$ concentrations using Equation 7 demonstrated that total BOD$_5$ was removed in the form of particulate BOD$_5$. Total BOD$_5$ removal is dependent upon the percent of PBOD$_5$ in the filter influent and the filter efficiency in removing PBOD$_5$.

Table 6. Calculated effluent TBOD$_5$ concentration using the BOD$_5$ equation and TBOD$_5$, SBOD$_5$, and PBOD$_5$ concentrations from the filtration study conducted by *Dawda et al.* [1978].

Filter Performance Data						BOD$_5$ Equation Effluent TBOD$_5$
Filter Influent Concentration (mg/ℓ)			Filter Effluent Concentration (mg/ℓ)			
TBOD$_5$	SBOD$_5$	PBOD$_5$	TBOD$_5$	SBOD$_5$	PBOD$_5$	
17	8	9	12	8	4	11
13	5	8	8	5	3	7
16	5	11	9	5	4	8
20	7	13	10	6	4	11
19	6	13	9	6	3	10
23	6	17	10	6	4	11
Average Concentrations:						
18	6.2	11.8	9.7	6	3.7	9.7

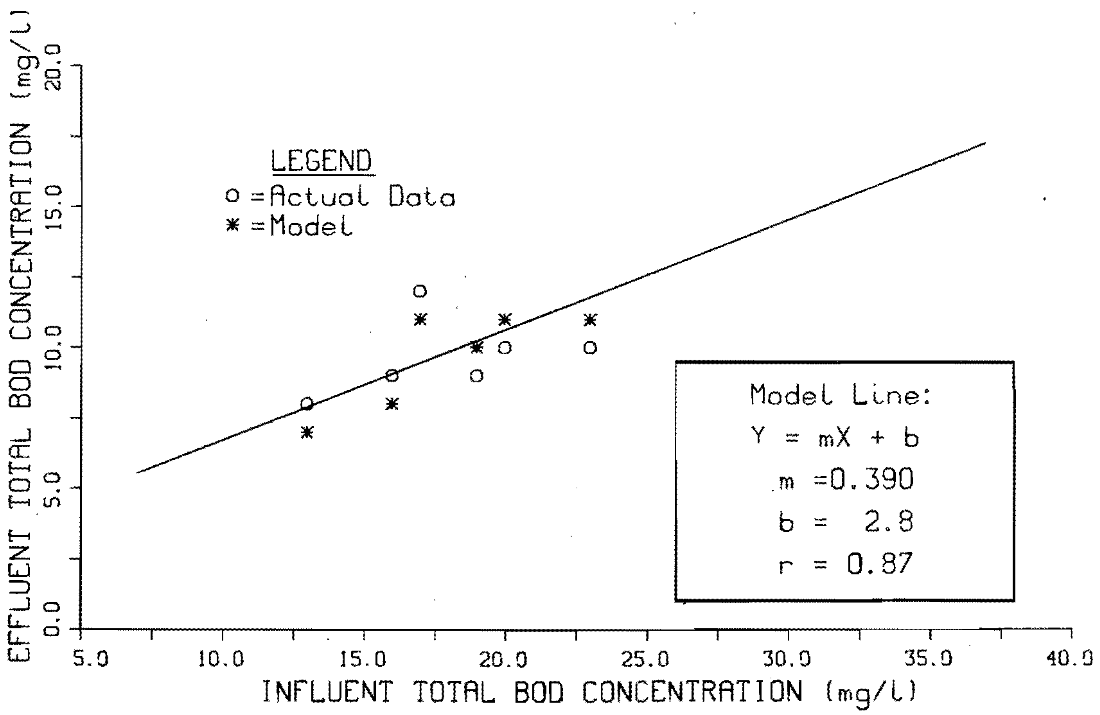


Figure 30. Relationship between filter influent and effluent from data collected by *Dawda et al.* [1978] and from calculated effluent BOD$_5$ concentrations using the BOD$_5$ equation.

FILTER DESIGN CRITERIA SURVEY

In order for officials of governmental agencies to assure that wastewater treatment plants produce quality effluents, design standards and criteria are adopted and imposed. Design standards for wastewater filters are also used to assure that the filter will function properly in producing a quality effluent.

Some of the criteria for design and operation of wastewater filters which are dictated by standards are: (1) type of filter apparatus employed; (2) media type, size, and depth; (3) filtration rate; (4) method and length of backwash; (5) sampling techniques; and (6) underdrain system. A survey was conducted to compare wastewater filter standards from each state agency in the United States. Each state was asked to send a copy of their standards dealing with wastewater filtration. Thirty-seven states responded to the request for information, and of this total 30 percent did not have design standards for wastewater filters. Of the 37 states that replied, 14 states have adopted the "Recommended Standards for Sewage Works" (10 State Standards).

Types of Filters

Most state standards allow the installation of either gravity flow filters or pressure filters. One state only allowed the use of gravity flow filters. A choice between upflow and downflow filters was also common.

Rate of Filtration

Allowable filtration rates for wastewater filters ranged from 81.5 ℓ/m^2•min (2 gpm/ft^2) to 488.9 ℓ/m^2•min (12 gpm/ft^2) depending upon the type and depth of filter media employed. The most common rate for a single, dual, or multi-media filters was 203.7 ℓ/m^2•min (5 gpm/ft^2). The majority of state agencies base the allowable hydraulic loading rate on the type and configuration of media employed. One state allowed hydraulic loading rates of 122.2 ℓ/m^2•min (3 gpm/ft^2) for single media, 163.0 ℓ/m^2•min (4 gpm/ft^2) for dual media, and 203.7 ℓ/m^2•min (5 gpm/ft^2) for multi-media filter configurations.

Media Type, Size, and Depth

The majority of the design standards for wastewater filters permit the following media types and configurations: (1) sand; (2) anthracite; (3) sand and anthracite; and (4) sand, anthracite, and garnet or ilmenite. The effective size for anthracite, sand, and garnet ranged from 0.8-2.0, 0.3-0.8, and 0.2-0.6 mm, respectively. The common depths for each layer in a multi-media filter were 38 cm (15 in) of coal, 30 cm (12 in) of sand, and 8 cm (3 in) of garnet. For a dual media filter the top coal layer was usually 46 cm (18 in) with a bottom sand layer of 30 cm (12 in). When single media was used, a minimum of 50 cm (20 in) of sand was imposed.

Backwash

All wastewater filter design standards called for backwash appurtenances complete with air scour or mechanical scour. One standard required 50 percent bed expansion during backwash while 12 standards required 20 percent expansion of each media layer. The other state standards specified minimum backwash rate that would assure adequate bed expansion during backwash. Backwash water flow rates ranged from 610.0 ℓ/m^2•min (15 gpm/ft^2) to 1222.2 ℓ/m^2•min (30 gpm/ft^2). The most common backwash flow rate was 815.0 ℓ/m^2•min (20 gpm/ft^2) with 10 minutes of backwash time. Backwash storage was also required with sufficient volume for two successive filter backwashes.

Summary

Table 7 is a list of all the states that responded to the survey. Hydraulic loading rate, depth and size of media, and backwash methods and procedures are each addressed in all of the design standards for wastewater filters. For complete details of the adopted standards for the design of wastewater filters, the particular state agency should be contacted.

Table 7. Summary chart listing those states that responded to the filtration survey and the name of document containing wastewater filtration standards.

State	Name of Document or Standard Employed	Comments
Alaska	none	
Arizona	Minimum Requirements for Design, Submission of Plans, and Specifications of Sewage Works	Rate: 81.5-488.9 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
California	Wastewater Reclamation Criteria	
Colorado	Filtration Standards	Rate: 122.2-326 $\ell/\mathrm{m}^2\cdot\mathrm{min}$ Media depth: 30-122 cm
Delaware	none	
Florida	none	Design for 90 % BOD and TSS removal
Georgia	Rapid Sand Filtration Design Criteria and Requirements	Sand effective size: 0.45-0.55 mm
Hawaii	none	Follow Public Health Regulations
Idaho	Criteria for Sewage Works Design 10 State Standards	Use only as guidelines
Illinois	10 State Standards	Rate: <203.7 $\ell/\mathrm{m}^2\cdot\mathrm{min}$ Backwash rate: >815 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
Indiana	10 State Standards	
Iowa	10 State Standards	
Kansas	none	
Kentucky	none	
Louisiana	10 State Standards	
Maine	10 State Standards	Use only as guidelines
Maryland	Filtration Process	Rate: 81.5-203.7 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
Michigan	10 State Standards	
Minnesota	10 State Standards	
Mississippi	EPA Suspended Solids Removal Manual	
Missouri	10 State Standards	
Montana	none	
New Jersey	Rules & Regulations for the Preparation and Submission of Plans for Sewer Systems and Wastewater Treatment Plants	Rate: 122.2 $\ell/\mathrm{m}^2\cdot\mathrm{min}$ Sand depth: >50 cm
New Mexico	10 State Standards	Use as guidelines
New York	10 State Standards	
Ohio	10 State Standards	
Oklahoma	Standards for Design of Water Pollution Control Facilities	Rate: 203.7 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
Pennsylvania	A Guide for the Preparation of Applications, Reports, and Plans. 10 State Standards	Rate: 203.7 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
Tennessee	Design Criteria for Tertiary Sand Filters	Rate: 40.7-163 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
Texas	Design Criteria for Sewage Systems	Rate: 122.2-203.7 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
Utah	Proposed Filtration Standards	Draft only
Vermont	none	
Virginia	Virginia Sewerage Regulations	Rate: 122.2 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
Washington	Criteria for Sewage Works Design	Rate: 122.2-244.4 $\ell/\mathrm{m}^2\cdot\mathrm{min}$
West Virginia	Filtration Regulations	Draft only
Wisconsin	10 State Standards	
Wyoming	10 State Standards	

SUMMARY, CONCLUSIONS, SIGNIFICANCE, AND RECOMMENDATIONS

Summary and Conclusions

Because of more stringent water quality standards for wastewater treatment plant effluents, it is frequently necessary to utilize advanced treatment processes to improve the overall performance of wastewater treatment plants. Tertiary filtration of wastewater secondary effluent is one such treatment process.

Removal of suspended solids and biochemical oxygen demand from secondary effluent of trickling filter operations is critical in order to meet present and future discharge requirements. The results of this experimental study will be helpful in determining if tertiary filtration of wastewater will upgrade existing processes sufficiently to satisfy quality standards.

Four filter columns were operated at the wastewater treatment plant located in Preston, Idaho, to examine the effectiveness of granular media, gravity filtration to remove BOD_5, soluble BOD_5, and suspended solids. The Preston plant produces a secondary effluent utilizing a trickling filter for the biological treatment process. Anthracite coal, silica sand, and garnet sand were the granular materials used as filter media. Four different filter bed configurations and depths were studied. Mixed media, dual-media, and single-media beds were constructed with the following media configurations: (1) coal-sand-garnet, (2) coal-sand, (3) sand-garnet, and (4) all sand.

The filters were operated at two hydraulic loading rates: 81.5 $\ell/m^2 \cdot min$ (2 gpm/ft^2) and 203.7 $\ell/m^2 \cdot min$ (5 gpm/ft^2). Wastewater effluents from the plant's primary clarifier, trickling filter, and secondary clarifier were filtered to determine the difference in performance when filtering different effluents.

Wastewater quality parameters used to monitor filter performance were biochemical oxygen demand (total, soluble, and particulate BOD_5), suspended solids, and volatile suspended solids.

A mathematical equation was developed to calculate the filter performance in removing total BOD_5. The equation was evaluated with data collected from the experimental study at Preston and from a filtration study conducted by *Dawda et al.* [1978].

The following conclusions are based on an analysis of data collected from the four types of filters operated at the Preston Treatment Plant.

1. Filter effluent quality is dependent on the influent quality for removal of BOD_5 and suspended solids from wastewater by granular filtration.
2. The coal-sand-garnet, coal-sand, sand-garnet, and all sand filters all performed the same in removing BOD_5 and solids by filtration.
3. Filter performance was generally independent of the two hydraulic loading rates employed [81.5 and 203.7 $\ell/m^2 \cdot min$ (2 and 5 gpm/ft^2)]. However, filter operation and length of filter run were affected by hydraulic loading rate. Increasing the loading rate from 81.5 $\ell/m^2 \cdot min$ (2 gpm/ft^2) to 203.7 $\ell/m^2 \cdot min$ (5 gpm/ft^2) reduced the length of filter run by 50 percent.
4. All filters were effective in removing total and particulate BOD_5, and suspended solids. Granular media filtration of wastewater was not effective in removing soluble BOD_5. Soluble BOD_5 removal may have been more significant at lower loading rates but was difficult to determine using the BOD_5 test.
5. Dual and mixed-media filters with a top coal layer provided longer, more economical filter runs. The coal media allows in-depth filtration, whereas the sand media filters were surface straining devices.
6. Suspended solids removals increased during the filter run.
7. The sand media was effectively backwashed by air-scour without loss of media. The lighter coal media was lost to the overflow during turbulent, air-scour backwash.
8. The mathematical BOD_5 equation describes filter performance in terms of $TBOD_5$ removal and demonstrated the dependence between influent and effluent quality. The equation was effective in calculating effluent $TBOD_5$ concentration using BOD_5 data from the filters studied at Preston and the filter tested by *Dawda et al.* [1978]. The BOD_5 equation demonstrated $TBOD_5$ removal was dependent upon the $PBOD_5$ removal efficiency of the filter.
9. Implementation of secondary wastewater filtration at the Preston Treatment Plant could produce an effluent of 10 mg/ℓ suspended solids, but could not satisfy a 10 mg/ℓ BOD_5 requirement.

Engineering Significance

Wastewater filtration with granular media is not a reliable treatment process for removing soluble biochemical oxygen demand ($SBOD_5$). Granular filtration is effective in removing suspended solids (SS) from wastewater. Wastewater filtration will reduce total BOD_5 ($TBOD_5$) concentrations in accordance with the solids reduction and the amount of $TBOD_5$ associated with the solid material. If a wastewater treatment plant produces an effluent containing a $TBOD_5$ concentration with a low percentage of soluble BOD_5, wastewater filtration will further reduce the $TBOD_5$ by removing particulate BOD_5 related to the solids. If a high percentage of the effluent $TBOD_5$ is attributed to soluble BOD_5, the filter will not be effective in removing $TBOD_5$.

In regard to present and future wastewater discharge requirements, wastewater filtration can produce an effluent which will meet a 10 mg/ℓ or even 5 mg/ℓ SS concentration. However, the capability of the secondary treatment process to reduce soluble BOD_5 must be carefully evaluated in order to impose or expect an effluent $TBOD_5$ concentration of 10 mg/ℓ or less upon implementation of granular media filtration.

Because the coal-sand-garnet, coal-sand, sand-garnet, and all sand filters were equally effective in removing BOD_5 and SS from wastewater, the type of media should be chosen from economic comparisons. The additional garnet layer in the multi-media and dual media filter beds did not improve the filtrate quality but created larger clean bed headloss and shorter filter runs. The dual, coal-sand, filter bed produced the longest runs and equivalent filtrate quality.

Recommendations

1. Conduct a filtration study to compare the performance of wastewater filters when filtering chlorinated influent versus unchlorinated influent.
2. Determine the minimum chlorine dosage in the backwash water required to effectively inhibit biological growth and slime accumulation on the media when filtering unchlorinated influent.
3. Determine the effect of filter influent chlorine concentrations on filter performance when filtering a chlorinated influent.
4. Examine the possibility of filtering primary wastewater effluent for further treatment or direct discharge.
5. Study the possibility of significant soluble biochemical oxygen demand removal by wastewater filtration when operating at filtration rates less than 81.5 $\ell/m^2 \cdot min$ (2 gpm/ft^2).

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APPENDICES

APPENDIX A

Filter performance data from pilot-scale study conducted at the Preston Wastewater Treatment Plant.

Table 8. Influent and effluent total BOD_5 data from all filters for both loading rates tested.

TOTAL BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
5-1-80	16.	10.	11.	11.	11.	5.0
5-17-80	17.	13.	14.	14.	15.	5.0
5-22-80	9.	8.	8.	12.	8.	5.0
6-19-80	22.	15.	16.	16.	15.	5.0
6-20-80	17.	8.	8.	7.	7.	5.0
6-21-80	23.	10.	8.	7.	7.	5.0
6-25-80	16.	9.	11.	10.	8.	5.0
6-26-80	19.	12.	12.	10.	10.	5.0
6-27-80	15.	10.	10.	7.	8.	5.0
6-28-80	30.	20.	20.	19.	20.	5.0
7-2-80	31.	21.	21.	20.	19.	5.0
7-3-80	33.	23.	23.	20.	22.	5.0
7-3-80	53.	37.	33.	38.	36.	5.0
7-4-80	29.	21.	22.	19.	19.	5.0
7-16-80	31.	20.	20.	22.	20.	5.0
8-7-80	14.	11.	11.	12.	12.	5.0
8-8-80	19.	14.	15.	13.	12.	5.0
8-13-80	22.	19.	16.	17.	19.	5.0
7-17-80	31.	20.	20.	18.	18.	2.0
7-18-80	36.	21.	22.	22.	25.	2.0
7-19-80	36.	28.	30.	26.	28.	2.0
7-23-80	38.	23.	25.	23.	25.	2.0
7-24-80	19.	9.	11.	11.	11.	2.0
7-25-80	25.	17.	15.	15.	17.	2.0
7-26-80	28.	12.	14.	13.	14.	2.0
7-28-80	29.	16.	16.	17.	18.	2.0
7-30-80	14.	10.	11.	11.	11.	2.0
7-31-80	22.	18.	18.	18.	18.	2.0
8-1-80	21.	20.	20.	18.	19.	2.0
8-2-80	12.	9.	9.	12.	11.	2.0
AVERAGE	24.2	16.1	16.3	15.9	16.1	
STD DEV.	9.5	6.8	6.4	6.5	6.8	
PERCENT REMOVAL		33.4	32.6	34.3	33.6	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 9. Influent and effluent soluble BOD_5 data from all filters for both loading rates tested.

SOLUBLE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
5-1-80	6.	7.	8.	6.	8.	5.0
5-17-80	5.	5.	5.	4.	4.	5.0
5-22-80	6.	5.	4.	6.	5.	5.0
6-19-80	11.	11.	12.	10.	10.	5.0
6-20-80	5.	5.	5.	5.	5.	5.0
6-21-80	7.	6.	5.	4.	4.	5.0
6-25-80	5.	6.	6.	5.	5.	5.0
6-26-80	10.	9.	10.	10.	10.	5.0
6-27-80	8.	6.	6.	4.	4.	5.0
6-28-80	19.	15.	15.	16.	18.	5.0
7-2-80	18.	15.	16.	14.	15.	5.0
7-3-80	14.	15.	14.	12.	14.	5.0
7-3-80	24.	24.	21.	25.	22.	5.0
7-4-80	16.	14.	13.	12.	12.	5.0
7-16-80	12.	13.	12.	13.	12.	5.0
8-7-80	7.	6.	6.	8.	8.	5.0
8-8-80	8.	8.	8.	7.	6.	5.0
8-13-80	8.	10.	9.	10.	9.	5.0
7-17-80	12.	11.	11.	9.	10.	2.0
7-18-80	14.	14.	11.	14.	15.	2.0
7-19-80	17.	16.	18.	16.	16.	2.0
7-23-80	13.	14.	14.	12.	12.	2.0
7-24-80	7.	5.	4.	4.	4.	2.0
7-25-80	11.	7.	7.	6.	7.	2.0
7-26-80	13.	6.	7.	6.	8.	2.0
7-28-80	10.	8.	8.	9.	9.	2.0
7-30-80	6.	4.	5.	5.	4.	2.0
7-31-80	9.	7.	7.	6.	6.	2.0
8-1-80	8.	8.	8.	6.	8.	2.0
8-2-80	8.	7.	7.	6.	6.	2.0
AVERAGE	10.6	9.6	9.4	9.0	9.2	
STD DEV.	4.7	4.6	4.4	4.8	4.7	
PERCENT REMOVAL		9.5	11.0	14.8	12.9	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 10. Influent and effluent particulate BOD_5 data from all filters for each loading rate tested.

PARTICULATE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
5-1-80	10.	3.	3.	5.	3.	5.0
5-17-80	12.	8.	9.	10.	11.	5.0
5-22-80	3.	3.	4.	6.	3.	5.0
6-19-80	11.	4.	4.	6.	5.	5.0
6-20-80	12.	3.	3.	2.	2.	5.0
6-21-80	16.	4.	3.	3.	3.	5.0
6-25-80	11.	3.	5.	5.	3.	5.0
6-26-80	9.	3.	2.	0.	0.	5.0
6-27-80	7.	4.	4.	3.	4.	5.0
6-28-80	11.	5.	5.	3.	2.	5.0
7-2-80	13.	6.	5.	6.	4.	5.0
7-3-80	19.	8.	9.	8.	8.	5.0
7-3-80	29.	13.	12.	13.	14.	5.0
7-4-80	13.	7.	9.	7.	7.	5.0
7-16-80	19.	7.	8.	9.	8.	5.0
8-7-80	7.	5.	5.	4.	4.	5.0
8-8-80	11.	6.	7.	6.	6.	5.0
8-13-80	14.	9.	7.	7.	10.	5.0
7-17-80	19.	9.	9.	9.	8.	2.0
7-18-80	22.	7.	11.	8.	10.	2.0
7-19-80	19.	12.	12.	10.	12.	2.0
7-23-80	25.	9.	11.	11.	13.	2.0
7-24-80	12.	4.	7.	7.	7.	2.0
7-25-80	14.	10.	8.	9.	10.	2.0
7-26-80	15.	6.	7.	7.	6.	2.0
7-28-80	19.	8.	8.	8.	9.	2.0
7-30-80	8.	6.	6.	6.	7.	2.0
7-31-80	13.	11.	11.	12.	12.	2.0
8-1-80	13.	12.	12.	12.	11.	2.0
8-2-80	4.	2.	2.	6.	5.	2.0
AVERAGE	13.7	6.6	6.9	6.9	6.9	
STD DEV.	5.8	3.1	3.1	3.1	3.7	
PERCENT REMOVAL		52.0	49.3	49.3	49.5	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 11. Influent and effluent suspended solids data from all filters for each loading rate tested.

SUSPENDED SOLIDS DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
5-1-80	10.	1.	3.	3.	0.	5.0
5-17-80	15.	6.	6.	7.	5.	5.0
5-22-80	11.	1.	2.	2.	2.	5.0
6-19-80	23.	5.	6.	5.	6.	5.0
6-20-80	16.	2.	3.	2.	3.	5.0
6-21-80	13.	2.	3.	2.	4.	5.0
6-25-80	18.	6.	6.	5.	5.	5.0
6-26-80	10.	2.	2.	1.	1.	5.0
6-27-80	11.	2.	2.	2.	2.	5.0
6-28-80	12.	2.	3.	2.	2.	5.0
7-2-80	17.	4.	4.	4.	4.	5.0
7-3-80	27.	11.	10.	8.	10.	5.0
7-3-80	32.	12.	14.	13.	13.	5.0
7-4-80	20.	8.	8.	8.	8.	5.0
7-16-80	25.	9.	10.	9.	10.	5.0
8-7-80	17.	3.	4.	4.	4.	5.0
8-8-80	17.	5.	4.	4.	4.	5.0
8-13-80	19.	4.	5.	5.	5.	5.0
7-17-80	29.	9.	9.	8.	8.	2.0
7-18-80	22.	8.	8.	8.	8.	2.0
7-19-80	24.	9.	8.	8.	7.	2.0
7-23-80	22.	4.	5.	3.	4.	2.0
7-24-80	15.	3.	3.	3.	2.	2.0
7-25-80	14.	2.	2.	3.	2.	2.0
7-26-80	16.	2.	2.	2.	2.	2.0
7-28-80	24.	5.	6.	6.	6.	2.0
7-30-80	15.	3.	3.	3.	3.	2.0
7-31-80	19.	5.	6.	4.	5.	2.0
8-1-80	16.	4.	4.	3.	3.	2.0
8-2-80	13.	2.	3.	3.	3.	2.0
AVERAGE	18.1	4.7	5.1	4.7	4.7	
STD DEV.	5.7	3.1	3.0	2.8	3.0	
PERCENT REMOVAL		74.0	71.6	74.2	74.0	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 12. Influent and effluent volatile suspended solids data from all filters for each loading rate tested.

	VOLATILE SOLIDS DATA					LOADING RATE (GPM/ SQ.FT.)
DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	
5-1-80	5.	1.	2.	1.	3.	5.0
5-17-80	6.	3.	3.	1.	3.	5.0
5-22-80	5.	0.	1.	0.	1.	5.0
6-19-80	9.	1.	1.	2.	3.	5.0
6-20-80	9.	1.	2.	2.	3.	5.0
6-21-80	5.	2.	1.	1.	2.	5.0
6-25-80	9.	4.	3.	2.	3.	5.0
6-26-80	5.	0.	0.	0.	0.	5.0
6-27-80	5.	1.	2.	1.	1.	5.0
6-28-80	4.	1.	0.	1.	1.	5.0
7-2-80	8.	2.	2.	2.	2.	5.0
7-3-80	19.	7.	8.	7.	8.	5.0
7-3-80	22.	10.	11.	9.	9.	5.0
7-4-80	14.	5.	6.	6.	6.	5.0
7-16-80	17.	8.	7.	6.	6.	5.0
8-7-80	6.	3.	2.	1.	2.	5.0
8-8-80	10.	3.	3.	3.	4.	5.0
8-13-80	8.	2.	3.	2.	2.	5.0
7-17-80	18.	7.	7.	5.	6.	2.0
7-18-80	17.	6.	6.	7.	5.	2.0
7-19-80	15.	6.	6.	7.	4.	2.0
7-23-80	11.	1.	3.	3.	4.	2.0
7-24-80	8.	1.	1.	1.	1.	2.0
7-25-80	5.	0.	0.	1.	0.	2.0
7-26-80	7.	2.	2.	1.	2.	2.0
7-28-80	12.	3.	5.	4.	3.	2.0
7-30-80	5.	1.	0.	0.	2.	2.0
7-31-80	13.	5.	4.	4.	4.	2.0
8-1-80	8.	3.	2.	2.	1.	2.0
8-2-80	6.	1.	1.	2.	2.	2.0
AVERAGE	9.7	3.0	3.1	2.8	3.1	
STD DEV.	5.0	2.6	2.7	2.5	2.2	
PERCENT REMOVAL		69.0	67.7	71.1	68.0	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

APPENDIX B

Filter performance data from pilot-scale filtration study conducted at the Preston Wastewater Treatment Plant. Tables 12-26 are tabulated results from filtering primary, secondary, and trickling filter effluents.

Table 13. Influent and effluent total BOD_5 data filtering primary effluent for each filter type and loading rate.

TOTAL BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/ SQ.FT.)
7-3-80	53.	37.	33.	38.	36.	5.0
7-4-80	29.	21.	22.	19.	19.	5.0
7-16-80	31.	20.	20.	22.	20.	5.0
7-17-80	31.	20.	20.	18.	18.	2.0
7-18-80	36.	21.	22.	22.	25.	2.0
7-19-80	36.	28.	30.	26.	28.	2.0
7-23-80	38.	23.	25.	23.	25.	2.0
AVERAGE	36.3	24.3	24.6	24.0	24.4	
STD DEV.	8.1	6.3	5.1	6.7	6.3	
PERCENT REMOVAL		33.1	32.3	33.9	32.7	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 14. Influent and effluent soluble BOD_5 data filtering primary effluent for each filter type and loading rate.

SOLUBLE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/ SQ.FT.)
7-3-80	24.	24.	21.	25.	22.	5.0
7-4-80	16.	14.	13.	12.	12.	5.0
7-16-80	12.	13.	12.	13.	12.	5.0
7-17-80	12.	11.	11.	9.	10.	2.0
7-18-80	14.	14.	11.	14.	15.	2.0
7-19-80	17.	16.	18.	16.	16.	2.0
7-23-80	13.	14.	14.	12.	12.	2.0
AVERAGE	15.4	15.1	14.3	14.4	14.1	
STD DEV.	4.2	4.2	3.8	5.1	4.0	
PERCENT REMOVAL		1.9	7.4	6.5	8.3	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 15. Influent and effluent particulate BOD_5 data filtering primary effluent for each filter type and loading rate.

PARTICULATE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/ SQ.FT.)
7-3-80	29.	13.	12.	13.	14.	5.0
7-4-80	13.	7.	9.	7.	7.	5.0
7-16-80	19.	7.	8.	9.	8.	5.0
7-17-80	19.	9.	9.	9.	8.	2.0
7-18-80	22.	7.	11.	8.	10.	2.0
7-19-80	19.	12.	12.	10.	12.	2.0
7-23-80	25.	9.	11.	11.	13.	2.0
AVERAGE	20.9	9.1	10.3	9.6	10.3	
STD DEV.	5.1	2.5	1.6	2.0	2.8	
PERCENT REMOVAL		56.2	50.7	54.1	50.7	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 16. Influent and effluent suspended solids data filtering primary effluent for each filter type and loading rate.

SUSPENDED SOLIDS DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/ SQ.FT.)
7-3-80	32.	12.	14.	13.	13.	5.0
7-4-80	20.	8.	8.	8.	8.	5.0
7-16-80	25.	9.	10.	9.	10.	5.0
7-17-80	29.	9.	9.	8.	8.	2.0
7-18-80	22.	8.	8.	8.	8.	2.0
7-19-80	24.	9.	8.	8.	7.	2.0
7-23-80	22.	4.	5.	3.	4.	2.0
AVERAGE	24.9	8.4	8.9	8.1	8.3	
STD DEV.	4.3	2.4	2.7	2.9	2.8	
PERCENT REMOVAL		66.1	64.4	67.2	66.7	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 17. Influent and effluent volatile suspended solids filtering primary effluent for each filter type and loading rate.

VOLATILE SOLIDS DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/ SQ.FT.)
7-3-80	22.	10.	11.	9.	9.	5.0
7-4-80	14.	5.	6.	6.	6.	5.0
7-16-80	17.	8.	7.	6.	6.	5.0
7-17-80	18.	7.	7.	5.	6.	2.0
7-18-80	17.	6.	6.	7.	5.	2.0
7-19-80	15.	6.	6.	7.	4.	2.0
7-23-80	11.	1.	3.	3.	4.	2.0
AVERAGE	16.3	6.1	6.6	6.1	5.7	
STD DEV.	3.5	2.8	2.4	1.9	1.7	
PERCENT REMOVAL		62.3	59.6	62.3	64.9	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 18. Influent and effluent total BOD$_5$ data filtering trickling filter effluent for each filter type and loading rate.

TOTAL BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/SQ.FT.)
6-20-80	17.	8.	8.	7.	7.	5.0
6-21-80	23.	10.	8.	7.	7.	5.0
6-25-80	16.	9.	11.	10.	8.	5.0
6-26-80	19.	12.	12.	10.	10.	5.0
6-27-80	15.	10.	10.	7.	8.	5.0
6-28-80	30.	20.	20.	19.	20.	5.0
7-2-80	31.	21.	21.	20.	19.	5.0
7-3-80	33.	23.	23.	20.	22.	5.0
7-24-80	19.	9.	11.	11.	11.	2.0
7-25-80	25.	17.	15.	15.	17.	2.0
7-26-80	28.	12.	14.	13.	14.	2.0
7-28-80	29.	16.	16.	17.	18.	2.0
AVERAGE	23.8	13.9	14.1	13.0	13.4	
STD DEV.	6.4	5.3	5.1	5.1	5.6	
PERCENT REMOVAL		41.4	40.7	45.3	43.5	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 19. Influent and effluent soluble BOD$_5$ data filtering trickling filter effluent for each filter type and loading rate.

SOLUBLE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/SQ.FT.)
6-20-80	5.	5.	5.	5.	5.	5.0
6-21-80	7.	6.	5.	4.	4.	5.0
6-25-80	5.	6.	6.	5.	5.	5.0
6-26-80	10.	9.	10.	10.	10.	5.0
6-27-80	8.	6.	6.	4.	4.	5.0
6-28-80	19.	15.	15.	16.	18.	5.0
7-2-80	18.	15.	16.	14.	15.	5.0
7-3-80	14.	15.	14.	12.	14.	5.0
7-24-80	7.	5.	4.	4.	4.	2.0
7-25-80	11.	7.	7.	6.	7.	2.0
7-26-80	13.	6.	7.	6.	8.	2.0
7-28-80	10.	8.	8.	9.	9.	2.0
AVERAGE	10.6	8.6	8.6	7.9	8.6	
STD DEV.	4.7	4.0	4.2	4.2	4.8	
PERCENT REMOVAL		18.9	18.9	25.2	18.9	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 20. Influent and effluent particulate BOD$_5$ data filtering trickling filter effluent for each filter type and loading rate.

PARTICULATE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/SQ.FT.)
6-20-80	12.	3.	3.	2.	2.	5.0
6-21-80	16.	4.	3.	3.	3.	5.0
6-25-80	11.	3.	5.	5.	3.	5.0
6-26-80	9.	3.	2.	0.	0.	5.0
6-27-80	7.	4.	4.	3.	4.	5.0
6-28-80	11.	5.	5.	3.	2.	5.0
7-2-80	13.	6.	5.	6.	4.	5.0
7-3-80	19.	8.	9.	8.	8.	5.0
7-24-80	12.	4.	7.	7.	7.	2.0
7-25-80	14.	10.	8.	9.	10.	2.0
7-26-80	15.	6.	7.	7.	6.	2.0
7-28-80	19.	8.	8.	9.	9.	2.0
AVERAGE	13.2	5.3	5.5	5.1	4.8	
STD DEV.	3.7	2.3	2.3	2.8	3.1	
PERCENT REMOVAL		59.5	58.2	61.4	63.3	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 21. Influent and effluent suspended solids data filtering trickling filter effluent for each filter type and loading rate.

SUSPENDED SOLIDS DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L) 1	2	3	4	LOADING RATE (GPM/SQ.FT.)
6-20-80	16.	2.	3.	2.	3.	5.0
6-21-80	13.	2.	3.	2.	4.	5.0
6-25-80	18.	6.	6.	5.	5.	5.0
6-26-80	10.	2.	2.	1.	1.	5.0
6-27-80	11.	2.	2.	2.	2.	5.0
6-28-80	12.	2.	3.	2.	2.	5.0
7-2-80	17.	4.	4.	4.	4.	5.0
7-3-80	27.	11.	10.	8.	10.	5.0
7-24-80	15.	3.	3.	3.	2.	2.0
7-25-80	14.	2.	2.	3.	2.	2.0
7-26-80	16.	2.	2.	2.	2.	2.0
7-28-80	24.	5.	6.	6.	6.	2.0
AVERAGE	16.1	3.6	3.8	3.3	3.6	
STD DEV.	5.1	2.7	2.4	2.1	2.5	
PERCENT REMOVAL		77.7	76.2	79.3	77.7	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 22. Influent and effluent volatile suspended solids data filtering trickling filter effluent for each filter type and loading rate.

VOLATILE SOLIDS DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
6-20-80	9.	1.	2.	2.	3.	5.0
6-21-80	5.	2.	1.	1.	2.	5.0
6-25-80	9.	4.	3.	2.	3.	5.0
6-26-80	5.	0.	0.	0.	0.	5.0
6-27-80	5.	1.	2.	1.	1.	5.0
6-28-80	4.	1.	0.	1.	1.	5.0
7-2-80	8.	2.	2.	2.	2.	5.0
7-3-80	19.	7.	8.	7.	8.	5.0
7-24-80	8.	1.	1.	1.	1.	2.0
7-25-80	5.	0.	0.	1.	0.	2.0
7-26-80	7.	2.	2.	1.	2.	2.0
7-28-80	12.	3.	5.	4.	3.	2.0
AVERAGE	8.0	2.0	2.2	1.9	2.2	
STD DEV.	4.2	2.0	2.3	1.9	2.1	
PERCENT REMOVAL		75.0	72.9	76.0	72.9	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 23. Influent and effluent total BOD$_5$ data filtering secondary wastewater for each filter type and loading rate.

TOTAL BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
5-1-80	16.	10.	11.	11.	11.	5.0
5-17-80	17.	13.	14.	14.	15.	5.0
5-22-80	9.	8.	8.	12.	8.	5.0
6-19-80	22.	15.	16.	16.	15.	5.0
8-7-80	14.	11.	11.	12.	12.	5.0
8-8-80	19.	14.	15.	13.	12.	5.0
8-13-80	22.	19.	16.	17.	19.	5.0
7-30-80	14.	10.	11.	11.	11.	2.0
7-31-80	22.	18.	18.	18.	18.	2.0
8-1-80	21.	20.	20.	18.	19.	2.0
8-2-80	12.	9.	9.	12.	11.	2.0
AVERAGE	17.1	13.4	13.5	14.0	13.7	
STD DEV.	4.5	4.2	3.8	2.8	3.7	
PERCENT REMOVAL		21.8	20.7	18.1	19.7	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 24. Influent and effluent soluble BOD$_5$ data filtering secondary wastewater for each filter type and loading rate.

SOLUBLE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
5-1-80	6.	7.	8.	6.	8.	5.0
5-17-80	5.	5.	5.	4.	4.	5.0
5-22-80	6.	5.	4.	6.	5.	5.0
6-19-80	11.	11.	12.	10.	10.	5.0
8-7-80	7.	6.	6.	8.	8.	5.0
8-8-80	8.	8.	8.	7.	6.	5.0
8-13-80	8.	10.	9.	10.	9.	5.0
7-30-80	6.	4.	5.	5.	4.	2.0
7-31-80	9.	7.	7.	6.	6.	2.0
8-1-80	8.	8.	8.	6.	8.	2.0
8-2-80	8.	7.	7.	6.	6.	2.0
AVERAGE	7.5	7.1	7.2	6.7	6.7	
STD DEV.	1.7	2.1	2.2	1.9	2.0	
PERCENT REMOVAL		4.9	3.7	9.8	9.8	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 25. Influent and effluent particulate BOD$_5$ data filtering secondary wastewater for each filter type and loading rate.

PARTICULATE BOD DATA

DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/SQ.FT.)
		1	2	3	4	
5-1-80	10.	3.	3.	5.	3.	5.0
5-17-80	12.	8.	9.	10.	11.	5.0
5-22-80	3.	3.	4.	6.	3.	5.0
6-19-80	11.	4.	4.	6.	5.	5.0
8-7-80	7.	5.	5.	4.	4.	5.0
8-8-80	11.	6.	7.	6.	6.	5.0
8-13-80	14.	9.	7.	7.	10.	5.0
7-30-80	8.	6.	6.	6.	7.	2.0
7-31-80	13.	11.	11.	12.	12.	2.0
8-1-80	13.	12.	12.	12.	11.	2.0
8-2-80	4.	2.	2.	6.	5.	2.0
AVERAGE	9.6	6.3	6.4	7.3	7.0	
STD DEV.	3.7	3.3	3.2	2.8	3.4	
PERCENT REMOVAL		34.9	34.0	24.5	27.4	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 26. Influent and effluent suspended solids data filtering secondary wastewater for each filter type and loading rate.

		SUSPENDED SOLIDS DATA				
DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/ SQ.FT.)
		1	2	3	4	
5-1-80	10.	1.	3.	3.	0.	5.0
5-17-80	15.	6.	6.	7.	5.	5.0
5-22-80	11.	1.	2.	2.	2.	5.0
6-19-80	23.	5.	6.	5.	6.	5.0
8-7-80	17.	3.	4.	4.	4.	5.0
8-8-80	17.	5.	4.	4.	4.	5.0
8-13-80	19.	4.	5.	5.	5.	5.0
7-30-80	15.	3.	3.	3.	3.	2.0
7-31-80	19.	5.	6.	4.	5.	2.0
8-1-80	16.	4.	4.	3.	3.	2.0
8-2-80	13.	2.	3.	3.	3.	2.0
AVERAGE	15.9	3.5	4.2	3.9	3.6	
STD DEV.	3.8	1.7	1.4	1.4	1.7	
PERCENT REMOVAL		77.7	73.7	75.4	77.1	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER

Table 27. Influent and effluent volatile suspended solids data filtering secondary wastewater for each filter type and loading rate.

		VOLATILE SOLIDS DATA				
DATE	INFLUENT (MG/L)	FILTER EFFLUENT (MG/L)				LOADING RATE (GPM/ SQ.FT.)
		1	2	3	4	
5-1-80	5.	1.	2.	1.	3.	5.0
5-17-80	6.	3.	3.	1.	3.	5.0
5-22-80	5.	0.	1.	0.	1.	5.0
6-19-80	9.	1.	1.	2.	3.	5.0
8-7-80	6.	3.	2.	1.	2.	5.0
8-8-80	10.	3.	3.	3.	4.	5.0
8-13-80	8.	2.	3.	2.	2.	5.0
7-30-80	5.	1.	0.	0.	2.	2.0
7-31-80	13.	5.	4.	4.	4.	2.0
8-1-80	8.	3.	2.	2.	1.	2.0
8-2-80	6.	1.	1.	2.	2.	2.0
AVERAGE	7.4	2.1	2.0	1.6	2.5	
STD DEV.	2.5	1.5	1.2	1.2	1.0	
PERCENT REMOVAL		71.4	72.8	77.8	66.7	

1 COAL-SAND-GARNET
2 COAL-SAND
3 SAND-GARNET
4 ALL SAND

CONVERSION: 1 GPM/SQ.FT. = 40.74 LPM/SQ. METER