Abstract

All currently available prefabricated stormwater treatment devices rely on the same few fundamental physical/chemical processes: settling, floatation, filtration, adsorption, and ion exchange. Over many decades of research and practical application, engineers have successfully applied a fundamental scientific understanding of these processes to design water and wastewater treatment works. This scientific understanding has been extended by empirically derived design criteria and “rules of thumb.” This approach to process design has likewise been used to develop design criteria for stormwater detention basins.

For this review, the available prefabricated stormwater treatment devices were organized by the fundamental processes applied. Manufacturers’ recommendations for application and operation of the devices was compared to relevant criteria and recommendations generally applied to the treatment of water, wastewater and stormwater.

Literature from the manufacturers of prefabricated stormwater treatment devices claims pollutant removal similar to (and sometimes greater than) what is achieved in wastewater treatment plants and stormwater detention basins, but in less space and with less time. This is simply not possible. Straining filters are susceptible to head loss (compromising hydraulic performance of inlets) and are also prone to clogging. A similar result can be expected from resinous material used in absorptive filters. Deep-bed filtration with sand or other media requires consistently low-turbidity influent, careful control of application rate and length of filter run, and periodic backwashing. Corroborating experience shows that successful application of filters to stormwater requires pretreatment by settling. Primary sedimentation of wastewater may be accomplished in as little as two to four hours; however, for stormwater, 24 hours is generally required to achieve removal of 60-80% of sediment. Some recommend 40 hours detention to settle out the finer clay particles in California sediment that typically adsorb toxic pollutants.

Municipal reviewers can use this methodology and these basic parameters to evaluate the applicability of prefabricated stormwater treatment devices to treating runoff from newly developed sites.

Contact: Samantha Salvia, Associate Engineer, Santa Clara Valley Urban RunoffPollution Prevention Program
EOA, Inc. 1410 Jackson Street, Oakland, CA 94612 • 510-832-2852 • Fax 510-832-2856 • ssalvia@eoainc.com
Introduction

Federal and state water-quality regulations require that newly developed sites incorporate best management practices (BMPs) to reduce the quantity of pollutants entering storm drains. BMPs may include operational practices, such as “good housekeeping,” or structural controls. Structural controls include site design features to reduce runoff (e.g. permeable pavements), landscape-scale controls (e.g. detention basins, grass swales, and constructed wetlands), and prefabricated treatment control devices. This report addresses the potential effectiveness of prefabricated treatment devices.

Prefabricated stormwater treatment devices range from “inlet” filters that can be inserted directly into storm drain inlets to large, multi-chambered sedimentation and filtration vaults. The manufacturers’ literature promoting these devices typically includes information regarding removal efficiency and effectiveness. However, these claims are rarely accompanied by adequate available supporting documentation (WWC 1999). Further, most manufacturers’ tests are performed under laboratory conditions and do not replicate conditions likely to be found in actual installations in the field. (UCLA 1998, WWC 1999, LWA 1999)

All currently available prefabricated stormwater treatment devices rely on the same few fundamental treatment processes. This report assesses the potential effectiveness of prefabricated stormwater treatment devices based on an understanding of fundamental processes rather than empirical data (i.e. the results of field or laboratory testing of actual devices). The report assesses the potential effectiveness of devices that employ each of these fundamental treatment processes. The report also proposes a methodology that municipal storm drain system operators can use to screen the various treatment devices available for purchase. This should help agency staff determine whether a particular product should be considered a potentially effective BMP.

Background

Like conventional water and wastewater treatment, stormwater treatment relies on a few basic physical, chemical, and biological processes. Physical/chemical processes applied to water, wastewater, and stormwater include filtration, sedimentation, and adsorption.

Designers of treatment facilities must overcome many challenges to successfully apply these basic processes to water and wastewater. The challenges include variability in flow, strength, and constituents. In general, treatment facilities have been more successful in removing conventional pollutants (floatables, biochemical oxygen demand and suspended solids), than they have in removing trace constituents or toxic pollutants such as heavy metals.

Over many decades of research and practical application, engineers have successfully applied a fundamental scientific understanding of a few physical and chemical processes — e.g. sedimentation, filtration, sorption, and ion exchange — to design water and wastewater treatment works. This scientific understanding has been extended by empirically derived design criteria and “rules of thumb.” The engineering literature integrates theoretical and practical guidance for designing settling basins, filters, and ion-exchange units to treat municipal or industrial wastewater prior to discharge or to treat ground or surface water for municipal water supply.

Treating stormwater entails greater challenges because (compared to wastewater or surface water) stormwater is even more variable in flow, strength, and constituents. The difficulty is further compounded because, while water and wastewater treatment is typically centralized (one facility may service an entire medium-sized city, or many cities) stormwater treatment devices are typically designed to serve a single site, or a small drainage catchment. Typically, no urban space is set aside for treating stormwater, and most prefabricated stormwater treatment devices are designed to work underground, within the existing storm drain system, or in very limited additional space.

Stormwater Characteristics

Stormwater exhibits great variability. Urban stormwater has many sources, including runoff from parking lots, roads, and other pervious and impervious surfaces. Pollutants in stormwater can include sediment, nutrients, bacteria and viruses, oxygen demanding substances, oil and grease, and toxic pollutants such as heavy metals and organic pesticides. The concentrations and ratios of these constituents vary with the intensity and timing of rainfall.
Variability makes stormwater inherently more difficult to treat than wastewater. Stormwater flows, constituents, and concentrations vary spatially and temporally, and characteristics may be specific to a given site. Stormwater, unlike wastewater, undergoes little mixing before it reaches the treatment site. Further, flow to wastewater treatment plants is continuous (although variable). Stormwater flows, by contrast, are intermittent.

Some factors affecting stormwater treatment include:

- Particle size distribution
- Types of contaminants
- Concentrations of contaminants
- Flow rate
- Volume to be treated
- Physical and chemical characteristics of contaminants (pH, temperature, etc.)
- Form of contaminants (in suspension, dissolved, attached to particles)

These differences combine to make stormwater treatment by prefabricated treatment devices a challenging prospect and suggest that stormwater treatment devices will not be able to achieve the same removal effectiveness as conventional water and wastewater treatment plants.

**Methodology**

Treatment devices are grouped into categories based on the fundamental processes used.

Each category is first evaluated based on the capabilities and limitations of the fundamental physical/chemical process. Then, the applicability of the process to stormwater treatment is addressed. Relevant experience and knowledge of water and wastewater treatment are applied to assess performance claims and to provide a benchmark for removal rates.

Manufacturers’ suggestions regarding performance and applicability are considered, including whether appropriate performance criteria were used. Percent removal is the most frequently cited performance claim. However, other measures (e.g. effluent concentration, hydraulic performance, and volume treated) may also be needed to evaluate the potential effectiveness of these devices.

Percent removal is usually calculated only for the water that is actually treated by the device. For example, a filter may remove 90% of suspended solids at low flow rates, but may also be designed to treat only a fraction of high influent flows (with most of the volume from high flows bypassing the device). It is necessary to consider the volume treated, as well as the percent removal, to obtain an accurate impression of how well the device is performing overall.

In general, pollutant removal is not linearly related to influent concentration. Typically, removal rates (i.e. input concentration/output concentration) are highest when influent concentrations of pollutants are high and yield progressively diminishing returns. (The first portion of removal is relatively easy to achieve, further reduction becomes more difficult, the last little bit of removal is nearly impossible.) Removal rates calculated at high influent concentrations should not be applied to the typically variable concentrations encountered in real stormwater flows.

Empirical results obtained in previous studies are reviewed and compared to the results of the assessment. At the end of the report, a procedure for evaluating stormwater treatment devices is suggested.

**Analysis of Devices**

**Filters**

There are many different types of filters used in stormwater treatment devices. They can be grouped into three basic types: strainers, granular media, and adsorptive filters. In strainers (which include drain inlet liners) the primary mechanism of removal is physical straining through a filter mesh. In granular media filters, sand is the most common media used in the filter beds. The mechanisms for removal in filters of this type are more complex than just physical straining. Adsorptive filters are filters that, in addition to straining and granular filtration, make use of chemical adsorption as an additional removal mechanism.

Current filtration theory emphasizes the trans-
port and attachment steps in describing the filtration process. Suspended particles may be attached to the surface of filter media due to diffusion, interception, gravity settling, or impingement, which are related to the surface area of the filter media. Filter efficiency is a function of physical and chemical characteristics of the filter bed, the filtration rate and the constituents of the influent water.

Filter design involves a tradeoff between hydraulic performance and filter effectiveness. Finer grained sands and finer meshes can remove smaller particles, but will also produce much greater loss of energy, or head, as the water flows through the filter. If the head loss is greater than the difference in inlet and outlet elevation, water will back up in the device and lead to overflows on the inlet side. Some devices are designed to allow these overflows to simply bypass the device. Backup of water in a filter can also cause resuspension of pollutants and loss of filter contents.

It is undesirable to subject filters to sudden changes in flow rates since this causes hydraulic shearing which may dislodge particles and carry them through the filter bed. This suggests that stormwater filtration systems should have upstream detention, to buffer rapid changes in flow. Resuspension, clogging and pass-through of fine particles are the most significant potential problems that might cause stormwater filtration systems to fail or be ineffective.

The three basic types of stormwater filters and the characteristics, processes and limitations associated with each are discussed below.

Storm Drain Liners

Storm drain liners are mesh screens or sacks designed to fit into storm drains catch basins and filter stormwater before it is discharged to the stormwater drainage system.

Evaluation of Fundamental Processes

A clean filter essentially acts as a strainer and theoretically will only effectively capture particles equal to or greater than the apparent opening size.

A possible exception is that, once a liner has accumulated filtered material, it may behave more like a precoat filter. Precoat filters have been used in industrial applications and for swimming pools for many years. The term “precoat” refers to the feeding of the filtering media into a stream of water in order to coat a fine cloth or screen with the media. Diatomaceous earth or perlite are the mediums most commonly used in precoat filters. In the case of storm drain liners, the sediment and suspended solids in the stormwater itself might serve as a filter media for subsequent stormwater influent.

The mechanism of solids removal with both precoat filters and storm drain liners is primarily straining. In precoat filters, the precoat medium is fine enough to remove almost all of the suspended solids. As the cake of solids forms, it becomes an additional filtering medium. Problems with precoat filters are encountered when inadequate precoating allows turbidity to pass through the filter. Intermittent or variable flow may cause media to slough off the screen.

In screening-type filters, head loss is proportional to the square of the filtration rate. This means that as flow increases, head loss increases exponentially. As head loss increases, so does the likelihood of overflow and bypass. This suggests that straining filters can compromise the hydraulic performance of storm drains — even before they clog with debris.

Empirical Corroboration

In general, both empirical studies and anecdotal evidence from actual use indicate that in the field, storm drain liners are prone to clogging. One study found that both a 32-mesh screen and a filter fabric insert clogged after only a few minutes when fine sediment from a typical parking lot was washed into the inserts (Interagency Catchbasin Insert Committee 1995). Manufacturer testing suggests the devices performed well in laboratory settings, demonstrating high removal rates for petroleum hydrocarbons, heavy metals, and suspended solids. However, these results are based on studies performed for very short periods of time with controlled flow rates (for example, 75 gpm/ft² for 30 minutes). These laboratory results do not necessarily translate into performance in the field. Further, even laboratory studies show that efficiency decreases with flow rate and with decreasing influent concentration (UCLA 1998). Actual stormwater will have intermittent high flow with varying influent concentration. This will likely lead to clogging of the liners and ponding of stormwater at the drain inlet.

Manufacturer’s studies did not include tests to determine the likelihood of resuspension of particles or leaching of metals from the captured solids. Many stormwater contaminants, including metals and some organics, can be attached to other particles. Often these contaminants are associated with fine particles which makes a device such as a stormdrain liner which can only remove larger sized
particles even less effective at actual contaminant removal. But even when these contaminants are attached to larger particles which will be trapped in the liner, there is a potential for leaching of the contaminants from the particles into the passing flow. The mechanisms governing the adsorption, dissolution, and suspension of metal and organic contaminants are much more complex than the simple physical straining process that removes sediment particles. In the field, with varying stormwater flow, temperature, pH, and constituent content, it is difficult to predict the extent to which contaminants will leach from captured particles. Most laboratory studies did not consider this aspect of liner functioning.

**Analysis**

Conventional precoat filters have demonstrated very high removal rates. However, these removals are achieved using a very fine filter media (i.e. diatomaceous earth) and an operation and maintenance routine that includes careful control of flow rates and regular backwashing. In diatomaceous earth filters, design filtration rates are usually from 1 to 3 gpm/ft². Filter runs may be from 12 to 150 hrs depending on filter and influent characteristics.

Some manufacturers of stormdrain liners claim silt removal rates in excess of 99% with filtration rates over 40 gpm/ft² (Siltsack proprietary information). If the liners are acting primarily as strainers then they will not remove much material that is smaller than the apparent opening size. The Unified Soil Classification system classifies silt and clay as particles whose size is less than 0.075mm. Storm drain liners reviewed for this report have apparent opening sizes between 0.106 mm and 0.850 mm. While the particles captured may be somewhat less than this opening size, this mesh size is too coarse to remove 99% of silt size particles.

If these liners are actually behaving more like precoat filters than pure strainers, they may be able to remove particles which are smaller than the mesh opening size. However, given that conventional precoat filters can only achieve such rates with much lower, carefully regulated flow rates and finer media, it’s unlikely that stormdrain liners achieve similar removal with intermittent flows, variably sized media, and higher flow rates.

**Conclusions**

Even if these stormdrain liners are not hydraulically compromised they will be unlikely to capture particles other than coarse sediment. They will not be able to achieve significant removal for fine particles and will not provide any removal of dissolved constituents. This means little or no removal of metals and nutrients.

Removal capabilities are irrelevant if there is no flow getting through the stormdrain liner. Empirical testing and experience has shown that stormdrain liners clog very quickly. These devices may be appropriate for areas with low flow and relatively coarse sediment. But even under these conditions they will require frequent (after every rain event) cleaning and maintenance to prevent significant headloss, clogging, and leaching.

**Granular Media Filters**

**Evaluation of Fundamental Processes**

Granular media filters are the most commonly employed filters for stormwater treatment. Sand is the media most commonly used. Sand filters contain a bed of sand with a depth that can range from less than one meter to several meters. For larger particles the primary mechanism of removal is simple straining. For particles smaller than the pore size in the media, the actual mechanisms which govern removal are very complex. They include processes such as diffusion, adsorption, and partitioning. Filter efficiency is a function of physical and chemical characteristics of the filter bed including porosity, and ratio of bed depth to mean grain size distribution. For most granular media filters, the majority solids removal takes place in the upper inches of the filter.

In sand filters, as void space is reduced by the accumulation of captured solids, head loss increases rapidly. The hydraulics of flow through a porous medium is governed by Darcy's law.

\[ V = -k \frac{\Delta h}{\Delta l} \]

where \( V \) = darcy velocity 
\( k \) = permeability 
\( \frac{\Delta h}{\Delta l} \) = hydraulic gradient

The above equation shows that headloss (\( \Delta h \)) is
directly proportional to flow velocity. Permeability is influenced by several factors including grain size and gradation, and composition of porous media. Thus, key design variables for a filter are media size, media gradation, and filtration rate. Important considerations in arriving at the appropriate media size and filtration rate are the particle size distribution in the influent water, the concentration of suspended solids in the influent water, and the desired removal efficiency.

Sand filters for water treatment were first employed in England in the mid-19th century. Filters were operated at low rates (0.04 to 0.12 gpm/ft²). Common filter runs range from one to six months. The filters are then cleaned by scraping about an inch of sand from the surface. These “slow” sand filters can be effective for treating most suspended solids, except for fine clays and other colloidal solids. The lack of success in treating U.S. surface waters is due in large part to typically high amounts of suspended clay. These solids penetrate deep into the filter so that the filter cannot be cleaned by the normal scraping methods (Weber 1972).

Later that century, filters developed in the U.S. were operated at much higher rates (1 to 4 gpm/ft²). The “rapid” sand filters currently used in water treatment plants may be operated successfully at rates up to 8 gpm/ft² (Weber 1972). Maintenance of low-turbidity influent, careful control of application rate and length of filter run, and periodic backwashing are key to successful operation of rapid-sand filters.

Rapid sand filters are also used in wastewater treatment plants, as a polishing step following treatment and secondary sedimentation. Design and operation is similar to that for water treatment, except that auxiliary scour (e.g. air or water jets) is typically needed during backwashing to successfully clean the filters (Metcalf and Eddy, 1979).

The principal problem in operation of sand filters is keeping the filter bed in good condition. Common results of excessively long filter runs and infrequent cleaning are breakthrough of turbidity, formation of mudballs (agglomerations of dirt and filtering medium), buildup of emulsified grease, and compression, contraction and cracking of the filter bed.

Based on experience with implementing sand filtration of stormwater at several hundred locations, the City of Austin proposed design criteria for stormwater filters. Perhaps the most important criterion recommended is a pretreatment detention basin sized for a 24-hour drawdown. (City of Austin, 1990, cited in State Stormwater Quality Task Force, 1993). Such a basin is required to avoid rapid clogging of the filter and is an integral part of the overall filtration system. Sand Filter Design for Water Quality Treatment (USEPA 1992).

A bypass is required to prevent back up during large storm events. A bypass will also be necessary because of the potential for clogging and headloss as the filter accumulates particles.

Stormwater treatment devices do not have the benefit of the space and operation and maintenance routine afforded large treatment plants. While rapid-sand filters at wastewater treatment plants are typically several feet deep and hundreds of square feet in area, stormwater filters operate in considerably smaller areas either as part of constructed and installed devices, or as inserts to stormdrain inlets.

Sedimentation prior to filtration is also an important component of an effective stormwater treatment system. Sedimentation prior to filtration reduces the contaminant load reaching the filter and ensures that flow arrives at the filter as sheet flow, reducing the chance of scour.

Leaching may compromise the effectiveness of sand filters in removing toxic pollutants. Many toxins (including metals) become more soluble at low pH. Unless the filter is backwashed after each event, anaerobic degradation of organic debris may lower the pH of the residual moisture in the filter. This could lead to leaching of toxins sorbed onto the filter media. The leached toxins could then be flushed from the filter during the next storm event.

Empirical Corroboration

Several monitoring studies of sand filtration systems were reviewed. The results of these studies suggest that sand filters within filtration systems which include sedimentation, can achieve moderate to high removal of many pollutants. The use of organic media may increase removal efficiencies over sand filters alone, particularly removal efficiencies of nutrients.

One study reported removal rates for sediment, BOD, total organic carbon, phosphorus and zinc in the 60-80% range. Mean storm removal rates for petroleum hydrocarbons and oil ranged from 55-84%. Another study found average annual removal efficiencies for total suspended solids in the range of 75-86%, lead 71-88%, and copper 33-60%. Total dissolved solids (31-35%) and fecal coliform (36-37%) removal was much lower, suggesting that fine
and soluble particles are less likely to be removed. Most monitoring studies found that sand filters can effectively remove particle loading, but not soluble components (particularly nitrogen) (Interagency Catch Basin Insert Committee 1995, LWA 1999). Other mechanisms are needed to help remove nutrients and other soluble pollutants.

A study prepared for the Sacramento Stormwater Management Program looked at several existing studies and concluded that what they described as "public domain" sand filters, meaning non-proprietary controls that can be designed and installed using information available in the public domain, are effective in the removal of TSS and are generally consistent in their performance from storm to storm. (LWA 1999)

**Analysis/Conclusions**

Sand and organic filters for stormwater have shown high removal rates for sediment and particulate metals, and moderate removal rates for nutrients and coliform bacteria. Stormwater filtration systems will require bypass to prevent overflow and not compromise the hydraulic integrity of the stormdrain. They should also include a sedimentation chamber as part of the filter system. Sedimentation reduces the loading reaching the filter and, to some degree, controls the flow.

The primary physical requirement of stormwater filtration systems is an adequate head differential between the inlet and outlet of the filter bed to allow gravity flow through the filter. Sand filtration systems will be most effective in treating stormwater from primarily impervious drainage area, with lower sediment and organic material load and less tendency to cause clogging. EPA recommends that the drainage area to the sand or organic filter be stabilized and not exceed five acres (EPA, 1992).

Sand filters used at water and wastewater treatment plants achieve high removal rates in part because of pretreatment and frequent backwashing. Lacking these, stormwater filters will not be able to achieve the same removal rates. However, if properly designed, sand filtration systems can perform very well for stormwater treatment. Public domain (non-proprietary) sand filtration systems have been shown to provide effective stormwater treatment for TSS, sediment, and particulate metals and may be more cost effective than proprietary devices. There is also more performance data available for public domain sand filters.

### 4.1.3 Adsorptive Filters

**Evaluation of Fundamental Processes**

Adsorptive filters make use of the same removal mechanisms as granular media filters, with additional emphasis on the mechanism of adsorption. Some adsorption may occur in sand filters; however, in adsorptive filters it is one of the primary removal mechanisms.

Adsorption is a specific term for the accumulation of a solute at a surface or interface, although many manufacturers use the term broadly to include related processes like ion exchange and absorption. Adsorption can be used to remove organic compounds and inorganic ions (metals) from water. Activated carbon is often used as adsorbent in water and wastewater treatment.

A plot of water phase concentration versus solid phase concentration gives the sorption isotherm. Two common models are used to describe isotherms, the Freundlich model and the Langmuir model. The Freundlich model is empirical, but fits a great deal of environmental sorption data:

\[
C_s = K C_e^n
\]  

Where \( C_s \) = equilibrium sorbed solute concentration  
\( C_e \) = equilibrium aqueous solute concentration  
\( K \) = constant related to capacity of adsorbent  
\( n \) = constant which is a function of the strength of adsorption

The Langmuir equation has a theoretical basis and can be written,

\[
\frac{C_s}{C_e} = \frac{1}{a b} + \frac{C_e}{a}
\]

Where \( C_s \) = equilibrium sorbed solute concentration  
\( C_e \) = equilibrium aqueous solute concentration  
\( a \) = constant related to the maximum sorbed solute concentration possible  
\( b \) = constant related to the energy of adsorption

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Two factors influence adsorption: surface area of adsorbent and nature of adsorbate. The amount of adsorption is a function of affinity for water as compared to its affinity for the absorbent, and is in part a function of pH. In general, adsorption of typical organic pollutants from water increases with decreasing pH.

Adsorption does not show a clear dependence on solubility. It is, however, influenced by temperature. Increasing temperature tends to decrease adsorption. However, normal temperature variations have only minor effects on adsorption process in water and wastewater treatment.

It is also a competitive reaction. This means that in the presence of multiple solutes there will be competition for sorption sites and thus a reduction in adsorption for individual solutes. Inorganic substances such as iron, manganese, and calcium salts or precipitates may interfere with adsorption because they tend to deposit on adsorbent and compete for adsorption sites. Displacement of previously adsorbed compounds by competition can result in an effluent concentration of a given compound that is greater than its influent concentration.

The removal of organic compounds by physical adsorption on porous adsorbents involves a number of steps, each of which can affect the rate of removal. These steps are: bulk solution transport, film diffusion transport, pore transport, adsorption. Predicting which of the several consecutive transport and reaction steps is rate-limiting is largely dependent on how the adsorbent is contacted with the water. For continuous flow systems, film diffusion will most likely be rate-limiting for normal flows. For very simple diffusion, the rate is expected to be proportional to concentration difference between the water and the adsorbent. It is not possible to predict an exact concentration-rate relation for the adsorption reaction, but it can be assumed that the rate of reaction will be concentration dependent.

A related process often included under the term adsorption is ion-exchange. Ion exchange is primarily used in water treatment for removal of hardness ions (softening) and for water demineralization. Its application to stormwater treatment is generally for the removal of metals.

Ion-exchange is a physical-chemical process by which ions are transferred from a solid to a liquid phase or vice-versa. Zeolites, or natural aluminosilicates, were some of the first materials used for ion-exchange and they remain a common ion exchange resin. They are used in some of the stormwater treatment devices currently available. Zeolites exchange sodium for divalent cations. (e.g. Ra2+, Ba2+, Pb2+, Sr2+, Cu2+, Ca2+, Zn2+, Fe2+, Mg2+) Ion exchange with zeolites tends to be nearly pH and particle size independent.

Like adsorption, ion exchange rate is a function of several factors including the composition of the water being treated. It is a competing, reversible reaction. Flow rate is particularly important to ion exchange effectiveness. Increasing flow rate decreases contact time and subsequently decreases the amount of exchange. Flow rates for ion-exchange in water treatment plant operations are usually between 5 and 10 gpm/ft2.

**Empirical Corroboration**

Empirical data on the performance of these devices under actual field conditions is sparse. One manufacturer provided empirical results that were based on laboratory tests admittedly not designed to reproduce actual environmental conditions. Fresh media were used for each test and contaminants were put through the filter and tested individually. Thus interactions and competition among contaminants was not reflected in the reported removal capacity, nor was the long term performance of the media as solutes accumulated. The filters were also not challenged in terms of flow rate and contaminant capacity. It is safe to conclude that removal rates in the field would not be as high as those reported in the study (over 99% for most of the hydrocarbons tested).

A study by the Interagency Catch Basin Insert Committee found that the inserts did not reduce silt and clay sized particles by more than 20mg/l and often exhibit removal efficiencies of zero under test conditions (moderate to high concentrations of particles less than 50 microns in diameter, delivered at a flow rate of 6gpm.) The units did capture some coarse particles, but their ability to retain trapped material was compromised in part by washout of previously trapped material. None of the units tested provided discernible removal of dissolved metals or those associated with fine sediments and there was no indication of nutrient removal. The filter surfaces tend to blind quickly even at low flow rates. (ICBIC 1995)

Another report based on monitoring of parking lot runoff found that clogging and subsequent bypassing limited the effectiveness of the units in removing metals. Although the data suggested the units might provide some oil and grease removal, problems associated with clogging and resultant
flooding indicated that the filters did not perform well overall. (WWC 1996)

Analysis/Conclusions

Adsorption and ion-exchange are processes that have been used successfully for water and wastewater treatment. However, their success in stormwater filters is compromised by the high and variable flow rates these devices will experience in the field. These are physical-chemical processes that require adequate contact time with the water. In water treatment plants, typical flow rates are on the order of 5 to 10 gpm/ft². Some stormwater treatment devices claim to successfully treat stormwater at flow rates of about 30 gpm/ft².

Adsorption and ion exchange are competitive reactions and thus removal will be highly dependent on the constituents in the stormwater being treated. They are also reversible reactions, which means that potentially contaminants could be re-exchanged with incoming stormwater if the media is not changed regularly. Further, available empirical data suggests that the drain insert design of most of these types of filters tends to lead to clogging and bypassing of the filter. “Improperly maintained inserts will at best fail to remove additional pollutants, and at worse, reintroduce previously captured pollutants” (WWC, UCLA, Psomas and Associates 1998) Overall, these in do not perform as well as currently accepted BMPs.

Gravity Separation

Gravity separation refers to the use of gravity to remove pollutants from water. This includes the processes of sedimentation and oil/water separation. Examples of such devices include settling basins, interceptors, and wet vaults. The basic theory of sedimentation and oil/water separation is discussed below, followed by an examination of existing empirical evidence.

4.2.1 Sedimentation

Evaluation of Fundamental Processes

Sedimentation uses gravity to remove particles from bulk fluid. Typically in wastewater treatment, water is passed through a basin, allowing particles to settle out. Sedimentation in wastewater does not lend itself to simple theoretical analysis because the particles involved are not regular in size, shape, or density. However, the theory of ideal systems provides a useful guide to interpreting behavior in more complex systems. With this in mind, Stoke’s Law is often used as a starting point for settling basin design:

Stoke’s law:

\[ v_s = \frac{g}{18\mu} (\rho_s - \rho)d^2 \]  

(4.4)

where \( v_s \) = terminal settling velocity
\( \mu \) = viscosity of the fluid
\( \rho_s \) = density of particle
\( \rho \) = density of fluid
\( d \) = diameter of particle
\( g \) = gravitational acceleration

Stoke’s equation represents the terminal settling velocity for discrete spherical particles. (Although most particles found in stormwater are not perfect spheres, the effect of non-sphericity is not pronounced at low velocities.) Terminal settling velocity is the velocity a particle reaches as its downward acceleration due to gravity is balanced out by drag forces. As can be seen from Stoke’s equation, the greater the density difference between the particle and the fluid (i.e., the heavier the particle), the higher the terminal settling velocity.

Two main factors govern which particles will settle out in a sedimentation basin. They are the particle’s settling velocity and the velocity of the fluid moving through the basin. Settling velocity, \( v_s \), can be expressed using the above equation. Horizontal velocity in a sedimentation basin, \( v_{basin} \), can be expressed in terms of flow and cross-sectional area as:

\[ v_{basin} = \frac{Q}{A_c} \]  

(4.5)

Where: \( v_{basin} \) = horizontal velocity of water through basin
\( Q \) = rate of flow through basin
\( A_c \) = cross-sectional area of basin

Particles whose settling velocity is sufficient that they will reach the bottom before reaching the
outlet of the basin will settle out. Thus if the horizontal velocity of the water in the tank is relatively slow, slowly falling particles can be retained. As the velocity of water moving through the basin increases, only the fastest falling particles can be retained. The critical ratio of water velocity to particle settling velocity must therefore be equal to the ratio of the sedimentation basin length (L), to depth of the tank (D), assuming a rectangular basin.

\[
\frac{v_{ba \sin}}{v_s} = \frac{L}{D}
\]  

(4.6)

Assuming length and depth of the basin are fixed, this relationship implies that as the velocity of fluid moving through the settling basin increases, the critical settling velocity of the particles, meaning the minimum settling velocity of particles that will be retained, also increases. The higher the critical settling velocity, the smaller the range of particle sizes that will be retained. This relationship can also be expressed in terms of residence time. Residence time, t, is equal to the amount of time a given parcel of water remains in the basin. For rectangular basins, it can be expressed as:

\[
t = \frac{L}{v_{ba \sin}}
\]  

(4.7)

Substituting into equation 4.6 and performing some algebra yields the following relationship:

\[
v_s = \frac{D}{t}
\]  

(4.8)

This implies that increasing residence time lowers the critical settling velocity and thus increases the range of size of particles that will be retained. Typical residence times in primary settling basins of wastewater treatment tanks range between 2 and 3 hours (ASCE/WEF 1991, Montgomery 1985).

In summary, the flow rate of water through the basin and the settling velocity of the particles in the water are the two factors governing which particles will settle out in a sedimentation basin. Sedimentation can be increased by lowering the flow rate of water through the basin or by increasing the volume of the basin. In general, the greater the residence time, the more particles will be able to settle out.

However, the settling of particles is not the only concern. Once particles have settled, conditions in the tank must be such that they will not be resuspended. The resuspension of previously settled particles is referred to as scour. The following equation represents the scour velocity for a particle.

\[
v_h = \left[\frac{8\beta (s - 1)gd}{f}\right]^\frac{1}{2}
\]  

(4.9)

Where: \(v_h\) = horizontal velocity that will cause scour

s = specific gravity of particle
\(\beta\) = dimensionless constant ranging from 0.04 to 0.06
f = Darcy-Weisbach friction factor (usu. 0.02-0.03)
d = diameter of particle
g = gravitational acceleration

In order to prevent scour, the horizontal velocity in the basin \(v_{ba \sin}\) must be less than the scour velocity for the particle of interest. Increasing tank depth reduces the possibility of scour. Frequent cleaning of basins also prevents resuspension of previously captured particles.

Empirical Corroboration

Recent research indicates that the effectiveness of separators in trapping pollutants varies widely. Treatment capability appears limited to removal of coarse-grained sediments, some particulate metals, and some hydrocarbons. Their variable performance is attributed to three factors: 1) frequent resuspension of previously deposited oil and sediments; 2) insufficient treatment volumes; and 3) short detention times.

Most devices which rely on gravity separation utilize both sedimentation and oil-water separation. Oil-grit separators, for example, typically consist of two or three rectangular settling chambers, baffled to allow sedimentation in one chamber and floatable and oil removal in another. One study of oil-grit separators found that over 80% of the trapped sediments were coarse grained grit and organic matter. (Schueler et al, 1992) The study also concluded that resuspension of sediments during large storm events was a problem.

A study by Washington metropolitan council of governments concluded that oil-grit separators
demonstrate poor retention characteristics and that the data strongly suggest that scour and resuspension of collected materials regularly occurs. French studies have shown that the average suspended solids removal efficiency of separators is about 50% (Aires 1995).

Analysis/Conclusions

The settling behavior of urban pollutants has been evaluated in several studies using settling column experiments. These experiments indicated that 60-70% of urban sediments settle out within the first 6 hours. The remaining sediment may take as much as two days to settle out. The studies reported an upper limit of about 40-50% organic matter and phosphorus removal after 48hrs. (Schueler 1987)

For landscape-scale detention basins, the California Storm Water Best Management Practice Handbook (1993) recommends a detention time of 24 to 40 hours. The handbook states that 24 hours generally provides a removal efficiency of about 60-80%. Forty hours is recommended in order to settle out the finer clay particles in California sediment that typically adsorb toxic pollutants.

Proprietary stormwater interceptors have detention times on the order of minutes. One manufacturer’s design criteria specify a minimum detention time of 5 minutes. The maximum detention time listed on a design table of flow rates and detention times was less than 2 hrs. (Jensen Precast, manufacturer’s literature) The Northern Virginia BMP Handbook (1992) states that the average detention time of a conventional oil/grease separator system is barely more than one hour (NVPDC 1992). Detention time within separators is frequently less than 30 minutes during storms (Galli 1992).

Based on the studies described above and the typical residence times of 2-4 hours used in highly controlled wastewater treatment plant sedimentation basins, stormwater interceptors with highly variable flow and detention times on the order of 5 min to 2 hrs can only be expected to settle out grit and large sand particles.

The particles that manufactured, high velocity interceptors do capture are susceptible to scour and resuspension if the devices are not adequately sized and properly maintained. Washout during storm events is a major cause of failure in stormwater sedimentation basins.

If adequately sized and maintained, interceptors may be able to provide removal of grit and coarse particles. These devices may be moderately effective for removing coarse particles and hydrocarbons adsorbed onto coarse particles, but they are not expected to be effective for removing fine particles or dissolved contaminants. Removal efficiencies are not expected to be better than those achieved in wastewater treatment plants and landscape scale detention basins.

4.2.2 Oil Separation

Evaluation of Fundamental Processes

The terms oil/grit separator, oil/water separator and oil and grease trap are used interchangeably to refer to treatment devices installed to remove hydrocarbons from stormwater runoff using gravity separation. These devices are adaptations of the American Petroleum Institute (API) separator. The separator is designed to slow water flow to allow settling of particles and phase separation. Particles settle out while oil and grease rise for removal. Just as sedimentation basin design requires estimating a particle’s terminal settling velocity, oil separator design requires estimating the droplet rise velocity. Stoke’s Law can be applied:

\[ v_T = \frac{g}{18\mu} \left( \rho_w - \rho_o \right) \cdot d^2 \]

Where:
- \( v_T \) = terminal rising velocity of oil droplets
- \( g \) = acceleration due to gravity
- \( \mu \) = absolute viscosity of water
- \( \rho_w \) = density of water
- \( \rho_o \) = density of oil
- \( d \) = droplet diameter

As seen from the above equation, the greater the density difference between the water and the oil, the faster the oil droplet will rise. The effect of temperature is captured in the viscosity term. Water’s viscosity increases with decreasing temperature. Increasing the viscosity term in the above equation results in a lower terminal rising velocity. Thus decreasing temperature inhibits oil-water separation.

The efficiency of a separator depends upon the flow rate: as the flow increases, the separator per-
formance decreases. The practical removal size is usually droplets whose diameter is greater than 150\( \mu \)m (API 1990).

**Empirical Corroboration**

Manufacturers claim efficiencies observed during the testing of oil-water separators are on the order of 97-99%. (Stormceptor manufacturer’s literature) However, the test method typically entails applying oil to a paved washpad with water added via a sprinkler to simulate rainfall. These synthetic events are necessary to evaluate the performance of a separator but do not necessarily reflect the processes which occur during actual rainfall conditions where rapidly changing flow rates, unknown oil mixtures, and other pollutants are present. Further, it is not clear that the inflow concentrations used in these studies were reasonably characteristic of concentrations found in stormwater where proper housekeeping BMPs are implemented.

Published research is difficult to find on how these units actually perform once placed in operation (EPA 1999) The Interagency Catch Basin Insert Committee study found that stormwater treatment devices had low overall oil and grease removal efficiencies because oil captured gravitationally during gentle storms was subsequently washed out during larger storms. (ICBIC1995).

**Analysis/Conclusions**

Stormwater runoff, even from retail gasoline operations, tends to have relatively low hydrocarbon concentrations. The upper limit for oil and grease concentration in stormwater is about 15mg/l. (Line et.al. 1997). The effectiveness of oil separators for such low concentrations is questionable. The API has stated that very few separators within the API design range achieve effluent oil concentrations lower than 100 mg/l. (API 1990). Oil/water separators used in stormwater treatment are different from those used in industrial settings, however according to a study by BASMAA, oil-water separator for stormwater usually can’t reduce below 20 mg/l (BASMAA 1997). Stormwater discharges are not subject to numerical limits, but to put this level of effectiveness in context, NPDES permits for wastewater discharges typically limit oil and grease to no more than 5 to 10 mg/L.

**Swirl Concentrators**

**Evaluation of Fundamental Processes**

Swirl concentrators use vortex separation as a mechanism for removing solids from bulk liquid. Flow entry into the device is designed so as to cause a swirling motion around the removal chamber. Swirl concentrators were first used in England in 1963 and adapted for use in combined sewer systems in the US in the mid-70s. They rely on the secondary flow current induced by the vortex to separate and draw solids downwards to a gutter while allowing “clear” water to overflow at the top of the separation chamber. This mechanism becomes increasingly ineffective with increasing flow rate due to increased uplift pressures on the solids progressively overcoming the effect of downward pressures on the solids due to the secondary current.

**Empirical Corroboration**

There are only a few devices on the market that use vortex separation as their main removal mechanism. Empirical data is limited and mostly laboratory-based. One manufacturer claims above 80% removal of total suspended solids. This is possible if relatively low flows were used in the tests. Removal is highly affected by flow.

**Analysis/Conclusions**

The variability in flow rate of stormwater may compromise the removal effectiveness. High storm flows would probably require bypass to prevent re-suspending previously captured particles. These devices may be effective for coarse particles, but are unlikely to capture fine particles and will be ineffective for dissolved pollutants.

**Deflection Screen**

A related device is a deflection screen. This device separates pollutants from bulk fluid by deflecting inflow away from the main flow stream into a pollutant separation chamber that contains a perforated screen which filters the water. One proprietary device that uses a deflection screen claims to overcome some of the limitations of vortex separation by using a filtration method for solid separation rather than relying on secondary flow currents. The fluid and associated solids contained within the separation chamber are kept in continuous motion by the circular flow action generated by the incoming flow. This motion keeps the solids in the containment chamber from blocking the perforated screen. Heavier solids ultimately settle in the containment sump.

This device is intended to remove trash, particulates, and floatables. Most testing has focused on the removal of gross solids. Deflection screens, like stormdrain liners, will be unable to capture particles smaller than the screen opening. Smaller screens
may cause clogging. Deflection screens may be effective for large debris removal, but are not expected to provide removal for coarse particles, dissolved pollutants, or oil and grease.

**Summary and Conclusions**

The fundamental processes employed by stormwater treatment devices (e.g. filtration, adsorption, ion-exchange, sedimentation) can all be used to treat water. However, the utilization of these processes requires sufficient space, time, and a design that respects fundamental engineering principles. Wastewater treatment plant design is based on a firm theoretical understanding coupled with years of experience and well tested criteria. Prefabricated stormwater treatment devices claim to accomplish the same (and sometimes greater) pollutant removal as wastewater treatment plants and landscape-scale BMPs in less space and with less time. This is simply not possible. At best these devices can be expected to treat stormwater for gross solids and coarse particles. With the exception of sand filters, their effectiveness in removing fine particles is limited. This is significant since most pollutants are associated with fine particles. Few of these devices are capable of providing any kind of treatment for dissolved contaminants. All will require frequent maintenance and cleaning to prevent problems such as clogging, excessive headloss, resuspension of captured particles, leaching of contaminants, and wash-out.

**Recommendations**

The following tabulated summary of recommendations be used to review proposals to install prefabricated stormwater treatment devices.

For each type of fundamental treatment process used, the device shows key features and considerations associated with the device design and the site to which it may be applied.

None of the devices reviewed for this study appear to be suitable for the removal of pollutants (except for trash and debris) in runoff from typical Bay area urban sites.
References


California Storm Water Best Management Practice Handbook: Municipal. 1993 March


UCLA 1998. letter from Dr. Michael Stenstrom, UCLA Prof Civil Eng. to Mr. Paul Corn of United Pumping Services (manufacturer of Drain Pac Filters) detailing results of lab tests performed on Drain Pac Filters. September 25.


### Summary of Recommendations for Selecting and Using Prefabricated Stormwater Treatment Devices

<table>
<thead>
<tr>
<th>Fundamental Treatment Process Used</th>
<th>Key Device Features/Considerations</th>
<th>Site Features/Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Filtration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Straining</strong></td>
<td>1/4&quot; or larger open screen for catching trash and debris. Fabrics or other media not recommended due to clogging. Clean after each storm event.</td>
<td>Effective for trash and debris only. Ineffective for fine sediment or other pollutants.</td>
</tr>
<tr>
<td><strong>Granular Media</strong></td>
<td>Use in treatment train preceded by detention/settling basin with 24-hour drawdown. Frequent cleaning and/or media replacement required. Include bypass for large events.</td>
<td>Protect slopes from erosion; control run-on of sediment. Avoid use in areas where vegetative debris may collect and blind filter.</td>
</tr>
<tr>
<td><strong>Adsorptive</strong></td>
<td>Not recommended because of tendency to clog and potential for release of absorbed pollutants back into water.</td>
<td>Not recommended.</td>
</tr>
<tr>
<td><strong>Gravity Separation</strong></td>
<td>Detention volume should roughly equal the runoff volume produced by a 1/2 inch storm. 40-hour drawdown recommended (or 24-hour if used with sand filter).</td>
<td>Protect slopes from erosion, control run-on of sediment to avoid excessive frequency of cleaning. Provide access for removal of sediment; plan for disposal.</td>
</tr>
<tr>
<td><strong>Swirl Concentration</strong></td>
<td>Use manufacturer's recommendations.</td>
<td>Effective only on trash and debris. Ineffective for fine sediment or other pollutants.</td>
</tr>
</tbody>
</table>