Article 105

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Developments in Sand Filter Technology to Treat Stormwater Runoff

The use of sand filtration to improve water quality is not a new concept. Slow sand filtration has been used for decades to treat wastewater and purify drinking water in many parts of the globe. In this respect, sand filtration has been demonstrated to be both an economical and effective option for removing pollutants.

The City of Austin, Texas first pioneered the use of sand filters to treat urban stormwater runoff in the early 1980s. The earliest designs consisted of a simple off-line sedimentation chamber and an 18- inch bed of sand (Figure 1). The first flush of runoff is diverted into the first sedimentation chamber. In this chamber coarse sediments drop out and the runoff velocities are reduced. Runoff is then spread over the sand filter bed where pollutants are trapped or strained out. A series of perforated pipes located in a gravel bed collect the runoff passing through the filter bed and subsequently return it into the stream or channel.

This type of sand filter was developed in Austin because no other stormwater management practice works well in the Texas hill country. High rates of evapo-transpiration and frequent droughts ruled out the use of ponds and marshes. Thin clay soils and a desire to protect groundwater quality eliminated the use of infiltration practices. Low soil moisture during the hot and dry summers made it difficult to establish dense and vigorous cover needed for vegetative practices. Stormwater designers were thus forced to create a closed and self-contained practice with an artificial filtration media. Hence, the sand filter was developed.

Sand filters have many advantages. They have a moderate to high pollutant removal capability, possess very few environmental limitations, require small amounts of land, and can be applied to most development sites, large or small. Compared to most other stormwater management practices, they have fewer limitations and constraints. These qualities have made

Figure 1: Original Sand Filter Design Developed in Austin, Texas (City of Austin, 1988)

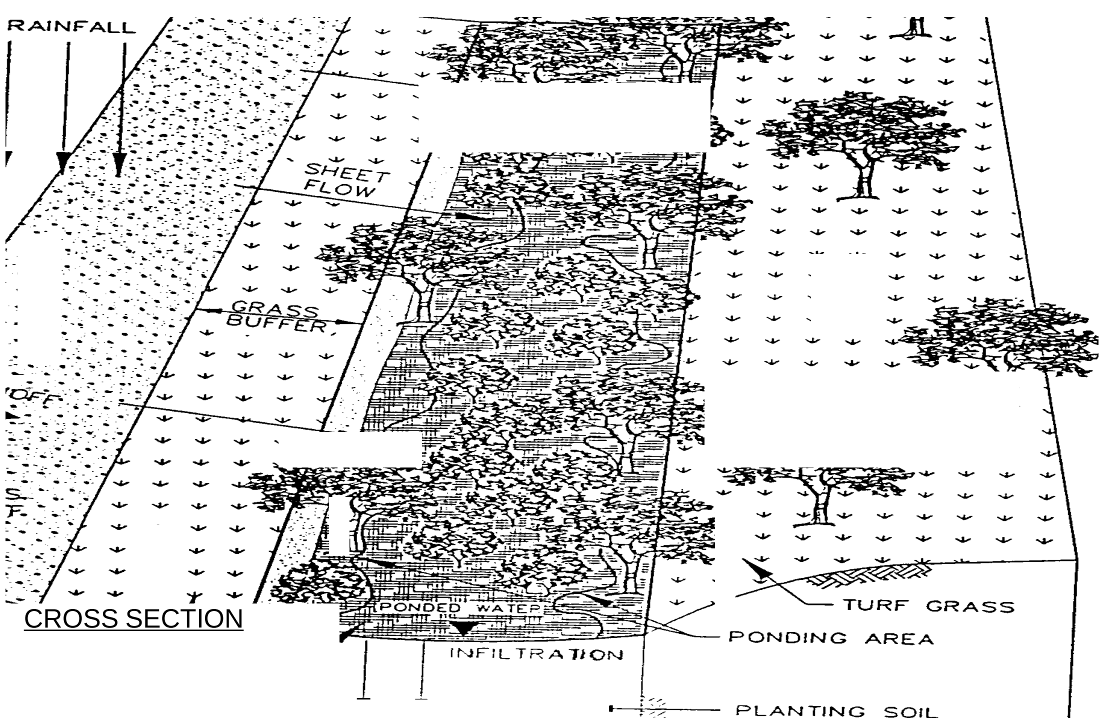

Table 1: Comparison of Sand Filter Design Variants								
DESIGN VARIABLES	**Austin Sand Filter** Full Sedimentation	**Austin Sand Filter** Partial Sedimentation	**District of Columbia Under-ground Sand Filter**	**Delaware Sand Filter**	**Alexandria Stone Reservoir Trench**	**Texas Vertical Sand Filter**	**Peat Sand Filter**	**Washing-ton Com-post Filter System**
Applicable Development Situations and Drainage Area	Most sites can serve 1 to 30 acres		No more than 10 impervious acres of high urban D.A.	No more than 5 acres of impervious parking lot	2 to 3 acres max. of com-mercial or multi-family	Primarily roadway runoff to date	1 to 50 acres	1 to 50 acres
Filter Bed Profile	18" sand, 4-6 inches of gravel. A layer of sod on the surface of the filter bed is optional.		Gravel or Enkadrain screen over 30" of sand	18" of sand	2-4 feet of stone, over 18" of sand and 6" of gravel	Up to 6 feet of sand sup-ported by gabions on either side	Grass on 12" of peat and 2 feet of sand, then gravel	One foot of compost over 8" of rock and gravel
Filter Bed Area (sf/Ia)	100	180	200	360	183	N/A	436	200 ft per cfs
Total Treatment Volume	First 1/2" of runoff with 24 hr. drawdown sediment chamber	First 1/2" of runoff S.C. = 20% of WQV	First flush of runoff (0.3" to 0.5")	First 1" of runoff	First 1/2" of runoff	First 1/2" of runoff	First 1/2" of runoff	N/A
Pretreatment Method	Dry sediment chamber	Dry sediment chamber	3 foot wet micropool plus gravel or geo-textile screen	Shallow wet pool	Wet micropool stone blanket	Dry sediment chamber	Wet micropool	Dry sediment chamber
Pretreatment Volume	sc >> fb	sc ~= fb	sc >> fb	sc = fb	sc < fb	sc >> fb	0.1 acre-inch sc < fb	sc < fb
Performance Monitoring Data Available?	Yes, 4 sites with 2 more in progress		No, 2 in progress	No, 2 in progress	No	No, 1 in progress	No	Yes, 2
No. Currently Installed	~500	~500	~50	~25	~10	~5	~5	25

Notes: sf/Ia = square foot of filter bed area per impervious acre
sc = sedimentation chamber   fb = filter bed

Figure 2: Cross-Section of Sand Filter Design Variations

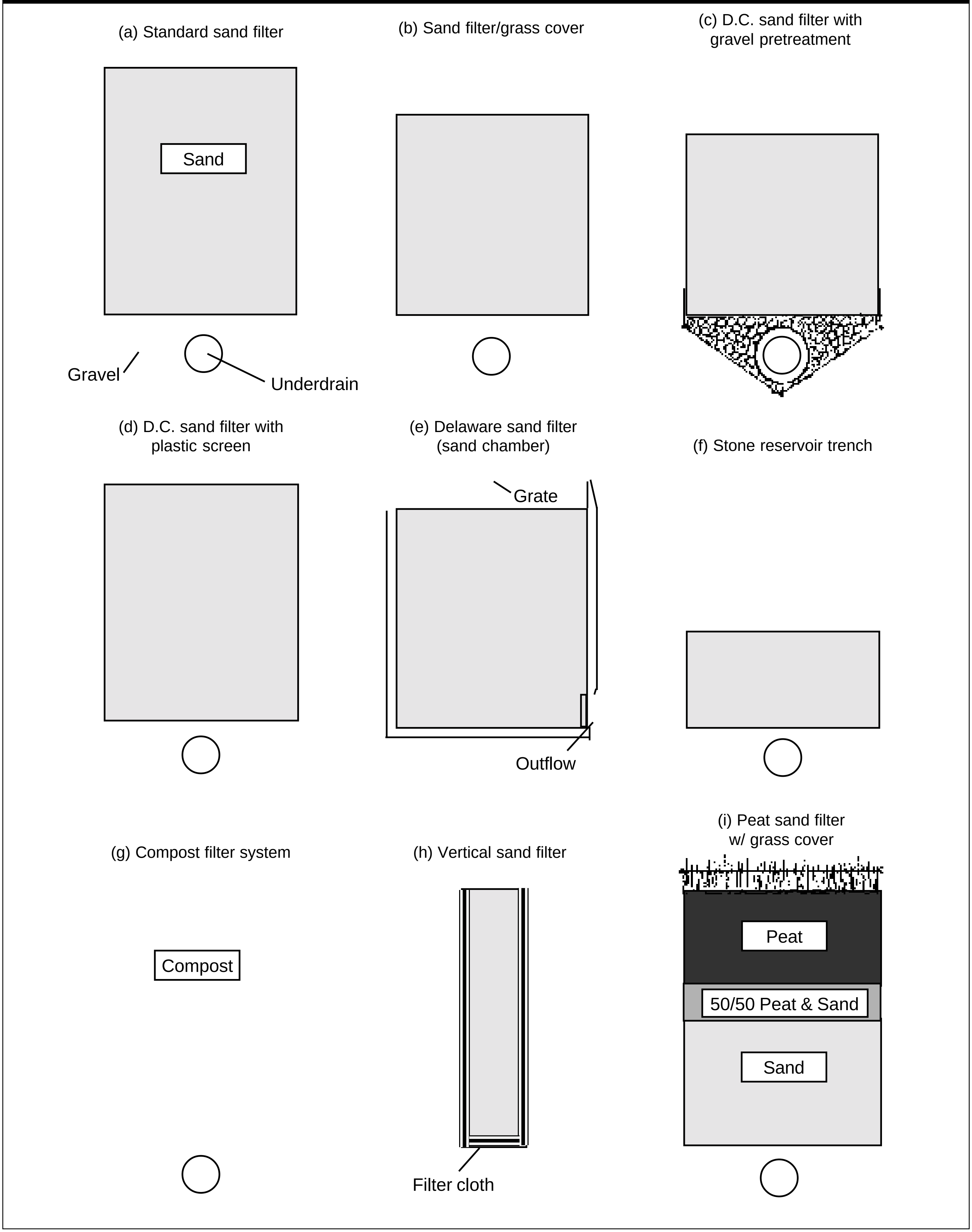

Table 2: Comparison of Sand Filter Design Variants

Filter Type	Design Issues
Austin Sand Filter Full Sedimentation	Requires basin liner, 2:1 length to width ratio. Sand must have a grain size ≤ concrete sand.
Austin Sand Filter Partial Sedimentation	Requires more frequent sand replacement than full sedimentation design. Requires basin liner.
District of Columbia Underground Sand Filter	Need head-room, must avoid underground utilities. Must ensure each chamber is watertight, may require 4 - 8 ft. of head.
Delaware Sand Filter	Requires very little head. Grate covers each chamber for access. Need to consider structural design with traffic load. Can freeze in northern climates.
Alexandria Stone Reservoir Trench	Not recommended for parking lots.
Texas Vertical Sand Filter	Most filtration may occur in small area of filter. Ability to withstand clogging has not been demonstrated.
Peat Sand Filter	Need to select appropriate peat. Peat may not always be available. Difficulty in operating during winter conditions.
Washington Compost Filter System	Leaf compost must be carefully selected and replaced regularly.

the sand filter an attractive alternative stormwater practice for many communities across the country.

This article examines recent developments in the use of sand filtration to improve the quality of urban stormwater runoff. It summarizes what is known about the performance and operation of sand filters, based both on recent research and the experience of engineers and public works officials that have installed and maintained them.

Design Variations of the Sand Filter

The versatility of the sand filter is reflected in the numerous design variations that have been developed to address many different climatic and development conditions. Nearly a dozen variants of the basic sand filter design are currently in use, and engineers and practitioners continue to create more. Some of the more common designs are compared in Tables 1 and 2, and illustrated in Figure 2.

In general, sand filter designs can be grouped into two broad categories:

- Designs that are well established
- Designs that are still somewhat experimental (due to a lack of implementation experience and/or performance monitoring data)

Each sand filter design utilizes a slightly different profile within the filter bed (Figure 2). The required surface area of the filter is usually a direct function of the impervious acreage treated, and varies regionally due to rainfall patterns and local criteria for the volume needed for water quality treatment. In addition, designs often differ with respect to the type and volume of pretreatment afforded.

The most common form of pretreatment is a wet or dry sedimentation chamber. Gravel or geotextile screens are sometimes used as a secondary form of protection. The relative volume dedicated to pretreatment versus filtration tends to vary considerably from one area to the next (Table 1). Nearly all sand filters are constructed off-line. Runoff volumes in excess of the water quality treatment volume must be bypassed to a downstream quantity control structure.

Feasibility of Sand Filters

Some kind of sand filter can be applied to almost any development site. The primary physical requirement is a minimum of two or three feet of head differential existing between the inlet and outlet of the filter bed. This is needed to provide gravity flow through the bed.

Otherwise, use of sand filters is only limited by their cost and local maintenance capability. Sand filters are particularly suitable for smaller development sites where other stormwater practices are often not practical. These include the following:

- Infill developments
- Ultra-urban downtown areas
- Gas stations and fast food establishments
- Commercial and institutional parking lots
- Small shopping centers
- Townhouse and multifamily developments
- Confined industrial areas

Care should be exercised in approving sand filters for individual lots and residential developments, as most homeowners lack the incentives or resources to regularly perform needed sand replacement operations. The State of Florida is considering limitations on the use of sand filters in residential areas, given the generally poor maintenance record of homeowner associations (Livingston, 1994).

Pollutant Removal Performance of Sand Filters

Presently, performance monitoring data for sand filters is rather sparse. Frequently cited are results from four sand filters that were sampled in Austin, Texas in the late 1980s (Table 3). However, at least seven additional performance monitoring studies are now in progress in Texas, Delaware, Florida, Virginia, the District of Columbia, and Washington with results expected in the next six to 18 months.

Initial monitoring results suggest that sand filters are very effective in removing particulate pollutants such as total suspended solids, lead, zinc, organic carbon, and organic nitrogen (City of Austin, 1990). Removal rates in excess of 75% were frequently observed for each of these parameters. Removal rates for coliform bacteria, ammonia, ortho phosphorus, and copper were moderate, and quite variable. Results ranged from 20 to 75% in the four sand filters tested in Austin.

Negative removal rates were frequently reported for total dissolved solids (TDS) and nitrate-nitrogen. The negative TDS rate may be due to the preferential leaching of cations from organic matter trapped on the surface of sand filter. Similarly, the nitrate export observed in three of the four sand filters may indicate that nitrification is taking place in the filter bed. In the nitrification process, microbial bacteria converts ammonia-nitrogen into the nitrate form of nitrogen. The apparent loss of ammonia through the filter bed, coupled with the production of excess nitrate, strongly suggests that nitrification is taking place.

Table 3: Pollutant Removal Performance of Four Sand Filters in Austin, TX — Pollutant Removal Accounts for Bypassed Flows (ERMD, 1990)

Parameter	Highwood	Barton Creek	Joleyville	Brodie Oaks
Total solids	86	75	87	92
Total dissolved solids	(-35)	1	31	46
BOD (5-day)	29	39	52	77
Total organic carbon	53	49	62	93
Nitrate	(-5)	(-13)	(-79)	23
Ammonia	59	43	77	94
Total Kjeldahl nitrogen	48	64	62	90
Total nitrogen	31	44	32	71
Total phosphorus	19	59	61	80
Fecal coliforms	37	36	37	83
Fecal strep	50	25	65	81
Copper	33	34	60	84
Lead	71	88	81	89
Zinc	49	82	80	91
Iron	63	67	86	84

The pollutant removal behavior of stormwater sand filters is quite comparable to that reported for sand filters used in wastewater treatment (Ellis, 1987). There are some differences between the two systems, however. Wastewater sand filters typically contain finer sand, are cleaned more frequently, and subject to more uniform and controlled flow than their stormwater counterparts. Consequently, wastewater filters exhibit slightly higher removal rates for sediment, phosphorus, and organic carbon (often in excess of 90%), but seldom can achieve more than 20% removal of nitrate (again, due to nitrification).

The one exception where wastewater filter consistently outperformed stormwater filters was bacteria removal. Wastewater filters frequently reduced bacteria levels by 90%, compared to a 25 to 65% removal for stormwater sand filters.

Prospects for Improving the Performance of Stormwater Filters

Designers are constantly refining the basic sand filter design to increase the level and consistency of nutrient and bacteria removal. A popular approach has been to add an additional organic layer to the filter bed to increase pollutant removal capability. A series of organic media have been used including a top layer of grass/soil, grass/peat or compost, a middle layer of peat, activated carbon, and even zeolites.

Very few of these "sandwich systems" have been extensively monitored so far. The Highwood sand filter (see Figure 2) had a top layer of grass sod over the sand filter, and generally performed slightly worse than the other three Austin filter systems (City of Austin, 1990). The stormwater compost system which relies exclusively on an organic filtering medium (see article 109) also had negative or low removal of TDS, nitrate, and phosphorus (Stewart, 1992). The limited data on sandwich systems so far indicates that the sandwich layer could actually be a source for some pollutants, while effectively trapping others.

Another option to improve sand filter performance is to create a permanently saturated, anaerobic zone at the bottom of the filter bed. Conditions in this zone are favorable for denitrification, which might substantially improve the rate of nitrate removal. Some caution may be in order as anaerobic conditions could possibly lead to loss of other pollutants (Harper and Herr, 1992). Other untested methods for enhancing performance may include increasing the surface area of the filter bed, specifying the use of finer sand, and increasing the depth of the sand layer.

It should be noted that sand filters, as an off-line practice, will always bypass some fraction of runoff during larger storm events. This runoff will be untreated. Depending on local water quality sizing criteria, the volume of untreated runoff can amount to 10 to 20% of the annual runoff volume produced at the site.

Perhaps the most reliable option for improving sand filter performance is to combine a filter with another stormwater practice such as an extended detention pond, wet pond, or shallow marsh. For example, the best performing sand filter in Austin monitoring project was at Brodie Oaks, which combined a retention pond with a sand filter (see Table 3).

Sand Filter Maintenance

Regular maintenance is an essential component of the operation of a sand filter. At least once a year each

filter should be inspected after a storm to assess the filtration capacity of the filter bed. Most filters exhibit diminished capacity after a few years due to surface clogging by organic matter, fine silts, hydrocarbons, and algal matter. Maintenance operations to restore the filtration capacity are relatively simple—manual removal of the top few inches of discolored sand followed by replacement with fresh sand. The contaminated sand is then dewatered and land-filled.

The key point is that the operation of the sand filter requires replacement of the surface sand layer on a relatively frequent basis, just as in wastewater sand filter applications. If periodic sand replacement is not conducted, the filter will not be effective. Livingston (1994) reports chronic clogging problems in many of the sand filters installed in residential areas in Florida due to lack of maintenance and off-site sediment deposition.

In some cases sand filters can continue to function after partial clogging. For example, Shaver and Baldwin (1991) reported that a demonstration sand filter accumulated several inches of deposits over the sand filter bed after six years, but it still functioned, at least partially. Based on the one sample obtained from a Delaware site, sand filter deposits appear to have the same degree of sediment contamination as pond muck and thus may not pose a risk for land disposal (Shaver and Baldwin, 1991). However, this conclusion should be considered provisional until further testing of more filter sediments are obtained from sites that are heavily influenced by automotive or industrial uses.

A number of techniques are being developed to reduce the frequency of sand replacement or to make the operation more convenient.

- **Surface Screen.** Underground sand filters in heavily urbanized areas tend to receive large quantities of trash, litter, and organic detritus. To combat this problem, the District of Columbia specifies the use of a wide mesh geotextile screen (EnkaDrain 9120) on the surface of the filter bed to trap these materials. During maintenance operations the screen is rolled up, removed, cleaned, and reinstalled.
- **Careful Selection of Sod.** Some sand filters that are constructed with a grass cover crop have lost significant filtration capability soon after construction. The clogging is often traced to sod that has an unusually high fraction of fine silts and clays. In other situations, grass roots grow into the sand layer and improve the filtration rate.
- **Limiting Use of Filter Fabric to Separate Layers.** Often the loss of filtration capacity occurs where filter fabric is used to separate different layers or media within the filter bed, such as in "sandwich" filters. As a general rule, the less use of filter fabric to separate layers, the better. In many situations, layers of different media can be intergraded together at the boundary (e.g., 50:50 peat/sand), or by a shallow layer of pea gravel.
- **Providing easier access.** During sand replacement operations, heavy and often wet sand must be manually removed from the filter bed. It is surprising that so few designs help a maintenance worker conveniently perform this operation. It is not uncommon that sand must be lifted six feet or higher to get it out of the filter bed. Yet typically no ramps, manhole steps, or ringbolts are provided to make the operation easier.

  Engineers should also keep in mind the ergonomics of maintenance when designing access to the sand filter. In some cases, heavy grates or large diameter manhole covers are specified that cannot be opened without the use of a portable winch.
- **Pretreatment**. The frequency of sand replacement can also be reduced by devoting a greater volume to runoff pretreatment in the sedimentation chamber. Several designs provide up to 50% of the total runoff treatment volume in the sedimentation chamber.
- **Visibility and Simplicity.** When tinkering with new sand filter designs, two key principles should be kept in mind. First, the filter should be visible, i.e., that it be easily recognized as a stormwater practice (so that owners realize what it is) and can be quickly located (so that it can be routinely inspected). This often requires the designer to consider the appearance and aesthetics of the final product so that it does not come to resemble

Table 4: Construction Costs for Various Types of Sand Filters

Region (Design)	Cost/Imperv. Acre
Delaware	$10,000
Alexandria (Del.)	$23,500
Austin (>2 acres)	$16,000
Austin (>5 acres)	$ 3,400
DC (underground)	$14,000
Denver (Urbonas and Stahre, 1993)	$30 - $50,000
OIL-GRIT SEPARATOR	$ 8,000
INFILTRATION TRENCH (WCC, 1992)	$ 800-1200
PONDS (WCC, 1992)	$ 400-1200

a concrete sandbox. The second principle is that the design should be kept as simple as possible. Experience has shown that overly complex designs create greater operation and maintenance costs.

- **Imperviousness.** Limit sand filters only to sites that are entirely impervious.

Economics of Sand Filters

Constructing sand filters can be expensive (Table 4). Construction costs often range from $10,000 to $20,000 per impervious acre treated, depending on the design. Sand filters can cost as much as five to 10 times more per unit of runoff treated than conventional stormwater practices, exclusive of land costs.

It should be noted, however, that many sand filters require little or no developable land (since they are located underground or on the margin of parking lots), which can make filters a more competitive option. The drawback is that sand filter do not provide stormwater quantity control. Thus, savings in land consumption may be offset by the costs of constructing additional stormwater quantity controls elsewhere on the site.

In many small, highly urbanized development situations sand filters are often the only practical stormwater quality practice, making cost comparisons meaningless. Indeed, the relatively high treatment cost for sand filters may prove useful as a benchmark to set and justify waiver fees for small development sites, when no stormwater practice options are practical.

Economies of scale do exist for sand filters. It is, for example, much cheaper to build a filter serving a large drainage area than a small area. Tull (1990) reports construction costs of $16,000/acre for a filter on one acre compared to $2,700/acre for one built on 20 acres. In addition, construction costs for sand filters can be expected to drop over time. These savings reflect greater use of precast or modular components, better construction specifications, and greater experience on the part of contractors. For example, Bell and Nguyen (1993) report a drop of nearly 50% in the cost of constructing underground sand filters over a five year period.

Not much is known about the cost to maintain sand filter over the long term, or, for that matter, the cost of sand replacement operations. Given the importance of maintenance, the collection of such information should be a key priority.

Regional Design Considerations

Communities that are considering sand filters in their arsenal of watershed protection techniques should keep in mind several regional design issues.

- Sand filters have yet to be widely applied in colder northern climates. Clearly, an extended cold snap could freeze the sedimentation chamber and perhaps even the surface of the filter bed (particularly for designs with relatively shallow chambers). If this happens, the filter may be temporarily rendered partially or entirely ineffective. It is therefore quite prudent to design a bypass that will route excess runoff directly into the storm drain system or stream channel under these conditions. A few designs, such as the peat sand filter, are not designed to operate in the winter months.

- The delta-T of sand filters has yet to be measured to determine if they contribute to warming of sensitive cool or cold-water streams. On one hand, sand filters might cool incoming runoff since it must pass through the sand and gravel layers of the filter bed. On the other hand, cooling may be more than offset by warming in the sedimentation pool or from concrete surfaces.

- Sand filters need not always be lined by concrete to work effectively. In regions where groundwater quality is not a critical concern (e.g., communities that allow or encourage the infiltration of stormwater), the bottom and sides of the filter bed can be contained by geotextile or even soil liners. The filter bed is excavated, permeable filter fabric used to line the bottom and sides of the structure, and then sand added.

Further Research and Development

Sand filters are a very promising and potentially useful stormwater practice. Yet, much more still needs to be learned before they can be routinely and cost-effectively applied in many regions of the country. Questions include the following:

- How well does the design filtration rate hold up over time? Does it vary from season to season due to leaf fall or frozen conditions? Does the filtration rate recover as organic surface deposits gradually decompose?

- Research into these questions will help to define "run-time" of a filter (i.e., how often sand must be replaced). To optimize removal, engineers have found it necessary to accurately predict how long wastewater filters will run before they must be backflushed or replaced. The same kind of operational data will ultimately be needed for stormwater filters.

- Can the efficiency of pretreatment be improved? Would a gravel filled sedimentation chamber be more effective than an empty one?

  Some researchers have concluded that gravel

filters are superior to conventional sedimentation basins for pretreatment in wastewater sand filters (Ellis, 1987; Wegelin, 1983). So far, this approach has not been used for stormwater sand filters, possibly because of the difficulties in cleaning a gravel chamber.

- Should additional media be added to sand filters to increase their nutrient removal capability?

  Clearly, there are some risks that these additional layers of organic material could reduce the run time of the filter, or even possibly be a source of pollutant leaching. Some researchers are even testing inorganics including ferric chloride and aluminium sulfate precipitates. Only through controlled laboratory column experiments with various combinations of filter media can these questions be answered.

In addition to the above, there are several interesting questions about sand filters that remain. Do sand filters contribute to downstream warming? Are accumulated deposits on the filter bed toxic or hazardous when the filter serves a highly automotive or industrial site? Are there better combinations of sand grain size or filter bed depth that might improve the effectiveness of a sand filter? What is the optimal type and volume of pretreatment? What design refinements can reduce construction or maintenance costs?

An Overall Assessment

The design of sand filters is evolving rapidly, and promises to remain a fertile ground for innovation for years to come. Some experimental approaches will prove successful, while others will doubtless be discarded. The arrival of additional performance monitoring information over the next several years should help to define, and hopefully standardize, the most effective design concepts.

Ultimately, however, the growth in the application of sand filters will be constrained by cost and maintenance factors. Continued effort is needed to monitor the operation of sand filters. Such data could yield reductions in the costs of constructing and maintaining filters. If such cost reductions can be realized, sand filters will become an attractive option over a much wider range of development conditions.

—TRS

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