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Further Developments in Sand Filter Technology

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

Since these lines were written in *Techniques* in 1994, no less than a dozen research studies have been launched to improve on the performance of the basic sand filter design. These efforts include field and bench studies on a wide array of alternative design configurations and filter media. A few of these efforts have been reported in *Techniques* (see articles 107 and 108), but this large body of emerging research is best assessed as a whole. Towards this end, this article profiles the pollutant removal capability and operational experience reported for this new generation of stormwater filters.

For comparison, it is helpful to begin with a recent performance study of a traditional sedimentation/sand filter monitored by the City of Austin (1997). Known as the Barton Creek Plaza (BCP), this sand filter served just less than three acres of a shopping center parking lot in Austin, Texas, and treated approximately 0.65 watershed-inches of runoff. Stormwater runoff first entered a large sedimentation basin (7,000 cubic feet) before discharging over a sand filter bed (390 square feet). The filter bed was three feet deep, and was composed of 0.02 to 0.04 inch diameter concrete sands. The sand filter was located off-line, and was estimated to bypass about 30% of the annual runoff volume without effective treatment. Three automated samplers were deployed to measure pollutant concentrations entering the sediment basin, leaving the sediment basin, and leaving the sand filter. Nine paired storms were monitored in 1996 and 1997, and the computed removal efficiency is reported in Table 1.

Research findings from the BCP sand filter generally reinforce prior monitoring research on the potential and limitations of traditional sand filter treatment. Generally, the removal of particulate pollutants, such as total suspended solids, trace metals and organic nutrients, was quite high. However, removal rates for soluble pollutants, such as ortho-phosphorus, nitrate-nitrogen, and total dissolved solids, were quite low, and sometimes even negative. Removal of bacteria was also quite variable, as evidently the warm, dark and damp environment of the sand filter sometimes served as a source for bacteria. It is interesting to note that much of the observed pollutant removal occurred in the sedimentation basin rather than within the sand filter at the BCP facility (see Table 1), which suggests that both sedimentation and filtration must be combined for optimal treatment. In general, the outflow concentrations from the BCP system were on the low end of those reported for most stormwater treatment practices (see article 65).

The pollutant removal capability of traditional sand filters may not be high or reliable enough for watershed managers that desire higher levels of nutrient or bacteria removal (Glick *et al.*, 1998). Consequently, researchers have had a strong interest in testing whether organic media may be a more effective substitute for sand as a filter medium. In this regard, the use of compost or peat-sand mixes has frequently been proposed.

Performance of Peat Sand Filters

Two peat sand filters were recently tested by the Lower Colorado River Authority (LCRA, 1997). The first system, known as McGregor Park, treated the runoff from a 3.8 acre office parking lot. Before entering the peat sand filter, runoff was pre-treated in a small extended detention pond. The peat sand filter had a surface area of more than 200 square feet, and had a three-foot deep bed, composed of 18 inches of hemic peat over 18 inches of sand, with a layer of calcitic limestone interspersed between. The entire off-line facility was designed to treat the runoff from the first inch of rainfall. A schematic of this peat sand filter design is portrayed in Figure 1.

A second system, known as the underground facility, served a 1.5 acre office parking lot, but had a much different configuration. Runoff first entered an expanded catch basin with a small permanent pool (about 0.05 site-inches of capacity) and floating sorbent pillows for enhanced oil/grease removal. After this initial pretreatment, runoff was then directed into a series of "infiltrator" tubes which spread it over a large but shallow underground filter bed. The bed was about 3,200 square feet in area, and was composed of a mix of hemic peat and sand that was typically only 12 to 18 inches thick. Tom Curran and his colleagues at LCRA sampled more than 20 storms at each of the peat sand filters over a three-year period, and their estimates of its pollutant removal performance are presented in Table 2.

At first glance, removal rates achieved at both peat sand filters were generally comparable to those achieved by traditional sand filters. Removal rates for total nitrogen, total organic carbon and zinc, however, were somewhat higher. It was evident that both peat sand filters were nitrate "leakers." The performance of the underground peat sand filter was reasonably impressive, given that limited pretreatment was provided by the expanded catch basin. The researchers found that the innovative catch basin alone reduced the concentration of most stormwater pollutants by about 10 to 25%.

The McGregor Park peat sand filter was notable in that it recorded reasonably high removal rates for both total and ortho-phosphorus (47% and 57%, respectively), and also had a much higher removal rate for nitrogen (50%) than was customary for a traditional sand filter. Unfortunately, the sampling design did not allow the research team to determine whether the bulk of removal occurred in the extended detention pond or in the peat sand filter bed. Another notable finding from the study was that little, if any, organic carbon leached from the hemic peat (which is composed of 87% organic carbon, by weight). Removal rates for total organic carbon were not high, but were generally positive (10 to 20%), suggesting that well-aged peat may not become a long-term carbon source in a peat sand filter.

Performance of a Compost Filter

William Leif (1999) recently monitored two small compost filters used to treat bridge and highway runoff in Everett, Washington. Each compost filter was initially installed in a six by 12 foot precast concrete vault. The first filter served about 0.25 acres of bridge deck and was termed the "deck" filter. The second served about 0.75 acres of road runoff and was termed the "bridge approach" filter. The compost at the bridge approach filter was plagued by clogging, and was ultimately replaced by a canister unit (see Lenhart and Wiggington, 1999). Even with this modification, hydraulic problems were still encountered at the bridge approach compost filter that were thought to be caused by surface algal growth on the filter bed (dry weather flows at the bridge approach filter kept the media continuously moist). As a result, most of the sampling data was collected for the deck filter.

Table 1: Performance of the Barton Creek Plaza Sedimentation/Sand Filtration System (N=9) (COA, 1997)

Water Quality Parameter	Mean Outflow Concentration from the BCP System	Removal Efficiency (a)	
		Sed. Basin	System (b)
Total Suspended Solids	32 mg/l	57	89
BOD	4.7 mg/l	33	51
COD	25 mg/l	34	55
TOC	7 mg/l	(-19)	(-4)
Nitrate-N	0.96	3	(-61)
TKN	0.89	33	50
NH3	0.14	7	53
Total Nitrogen	1.83	28	17
Total Phosphorus	0.11	49	59
Dissolved Phosphorus	0.09	23	3
Cadmium	0.49 ug/l	-10	44
Copper	2.9 ug/l	6	72
Lead	2.3 ug/l	34	86
Zinc	22.6 ug/l	48	76
Fecal Coliform	18,528 per 100 ml.	(-63)	(-85)
Fecal Streptococci	2,573 per 100 ml	(-35)	69

(a) EMC method used to compute removal efficiency (b) note that removal rates drop by about 20% if the untreated stormwater bypass is factored in.

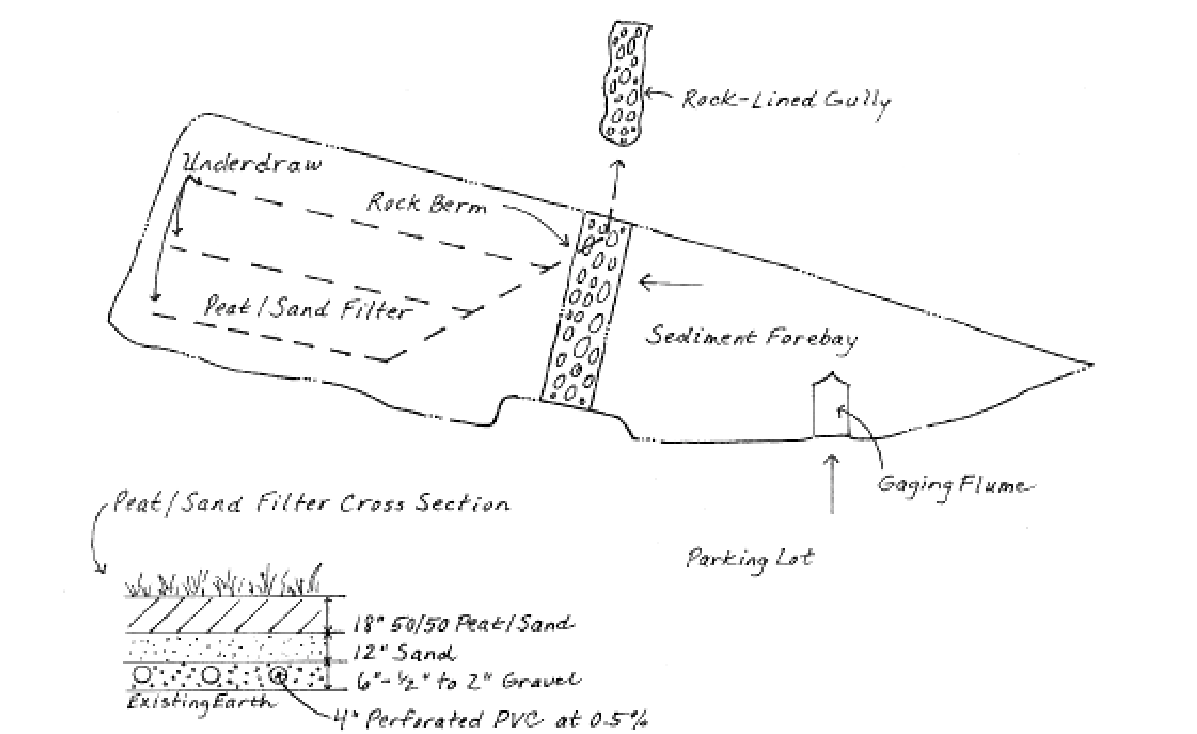

Figure 1: Schematic of the McGregor Park Peat Sand Filter

The pollutant removal performance of the two compost filters was rather modest (see Table 3). For example, removal of total suspended solids was less than 50%, and phosphorus removal was consistently negative. Removal of metals and hydrocarbons was moderate, and the content of these pollutants increased by a factor of two to three within the compost media itself during the course of the monitoring program. The performance of the Everett compost filters was considerably lower than earlier monitoring reports for compost filters (see article 109). The modest performance could have been due to the low inflow concentrations present at the Everett filters, which were clearly on the low end of the range for typical stormwater runoff (see Table 3). In addition, the study design did not measure the pollutant reduction achieved by upstream pretreatment. Clogging, algal growth, and the decomposition of the compost also may have played a role in diminishing the performance of the compost filters.

Performance of Other Sand Filter Amendments

Testing of both sand filters and organic filters has generally revealed that they have, at best, a modest capability to remove phosphorus from runoff. Consequently, researchers have evaluated several alternative media specifically intended to boost phosphorus removal in traditional sand filters. The most extensive testing effort so far occurred at the Lakemont stormwater treatment facility in King County, Washington (KCDNR, 1998). The original stormwater facility was constructed to reduce phosphorus loads delivered to Lake Sammamish from a 253-acre residential catchment. The facility design included two off-line sand filter cells, with runoff pretreatment provided by a wet vault. The sand filter cells were retrofit to improve phosphorus removal. In the first cell, 55 tons of calcitic limestone were rototilled into the sand filter to create a filter media composed of 90% sand and 10% limestone (by volume). In the second cell, processed steel fiber (PSF, a sort of industrial steel wool) was incorporated into the sand to create a filter media composed of 95% sand and 5% PSF.

Intensive storm monitoring by KCDNR (1998) indicated that both amendments showed some promise in improving the phosphorus removal capability of traditional sand filters. Limited monitoring of the calcitic limestone amendment resulted in 67% removal of total phosphorus (but only 18% of soluble ortho-phosphorus-KCDNR, 1998). Somewhat higher removal was noted for the processed steel fiber amendment. Sampling, which is continuing, indicated that the PSF amendment removed about 68% of the total phosphorus and 50% of the soluble phosphorus. The researchers cautioned, however, that the greater removal must be balanced against the higher cost of the amendments, and their increased tendency to degrade the hydraulic performance of the sand filter over time.

Performance of Vertical Sand Filters

Most sand filters are horizontal in that they spread runoff over a uniform bed of sand, which acts as the filter bed. Vertical sand filters take a different approach by directing flows through a vertical sand or gravel section. The vertical approach is attractive since it sharply reduces the space needed for a filter bed. Skeptics, however, have predicted that vertical sand filters will be subject to poor hydraulic performance, since the lowest layers of the filter are continuously exposed to flows during every storm event and are therefore more prone to clogging.

Sean Tenney and his colleagues at the University of Texas recently tested the feasibility of vertical sand filters in the sensitive Edward's aquifer region of Central Texas. The vertical sand filters (VSFs) were used to treat a few acres of highway runoff, and their basic design is shown in Figure 2. Runoff first enters a hazardous material trap, and then the first half inch of runoff is diverted into a concrete sedimentation basin. The outlet of the basin is a VSF, which consists of two stone-filled baskets or gabions that form a porous barrier supporting the filter media (which initially consisted of a three foot thick layer of medium-sized sand). The VSF filters were designed to completely drain the sedimentation basin with one to two days after a storm. In reality, however, the filters clogged shortly after they were installed. Hydraulic monitoring indicated that sediment basins were still 20 to 50% full two days after storms (see Figure 3). The poor hydraulic performance was caused by clogging at the bottom portion of the sand filter, often along the permeable filter fabric used to hold the sand in place.

The research team then modified the VSF concept by substituting pea gravel for sand as the primary filtering media. This modification greatly improved the hydraulic performance of the vertical filter, and the sedimentation basins typically drained in five hours or less. The research team then monitored the pollutant removal performance of this new VSF configuration during 10 storm events in 1995, each of which ranged from 0.2 to

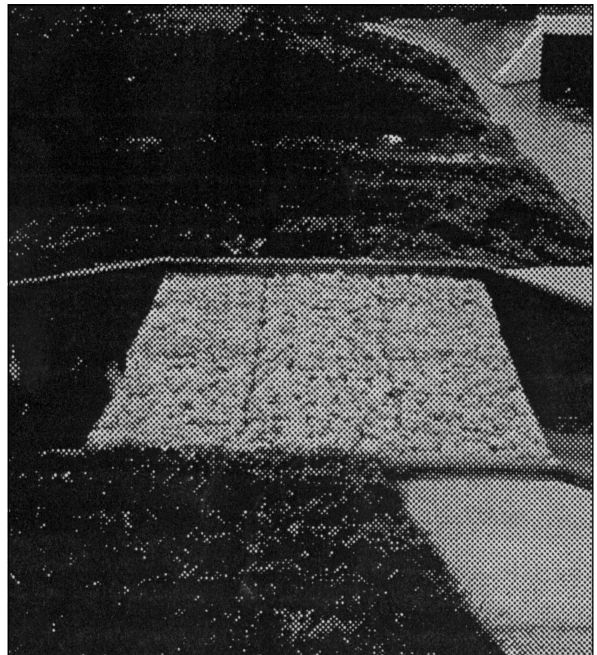

Figure 2: Typical Vertical Sand Filter Supported by Gabions (CRWR, 1995)

Table 2: Performance of Two Peat Sand Filter Systems Near Austin Texas (LCRA, 1997)

Water Quality Parameter	The McGregor Park Facility Peat Sand Filter w/ Surface Extended Detention N=21		The Underground Facility Peat Sand Filter w/ Catch basin Pretreatment N=21	
	Outflow EMC (mg/l)	Removal Rate (%)	Outflow EMC (mg/l)	Removal Rate (%)
TSS	6 mg/l	88	12	84
TOC	9.8	18	9.3	11
Total P	0.098	47	0.19	48
Ortho-P	0.013	57	0.071	3
Nitrate-nitrogen	0.55	(-15)	0.56	(-96)
TKN	0.44	61	0.55	61
Total Nitrogen	0.86	51	1.1	30
Total Zinc	0.018	83	0.01	89
Note that removal rates for lead, cadmium and chromium could not be computed because most inflow values were below detection. EMC= event mean concentration, all units in mg/l				

Table 3: Performance of a Compost Filter in the Field (Leif, 1999)		
Water Quality Parameter (a)	**Median Removal Rate (%)**	**Median Effluent Concentration**
Total Suspended Solids	43	16 mg/l
Total Lead	50	4 ug/l
Total Copper	33	5 ug/l
Total Zinc	29	32 ug/l
Total Phosphorus	-88 (b)	0.06 mg/l
Total Petroleum Hydrocarbons	20 (c)	1.4 mg/l
Chemical Oxygen Demand	37	1.0 mg/l
Fecal Coliforms	moderate (d)	about 400 to 500 counts/100ml

Notes: (a) Median removal rates based on ten paired storm samples monitored at both facilities (b) negative removal rates were recorded during all storm events (c) low TPH concentrations in inflow to filter limited performance (d) data could not be fully analyzed because of QA/QC with many microbial samples.

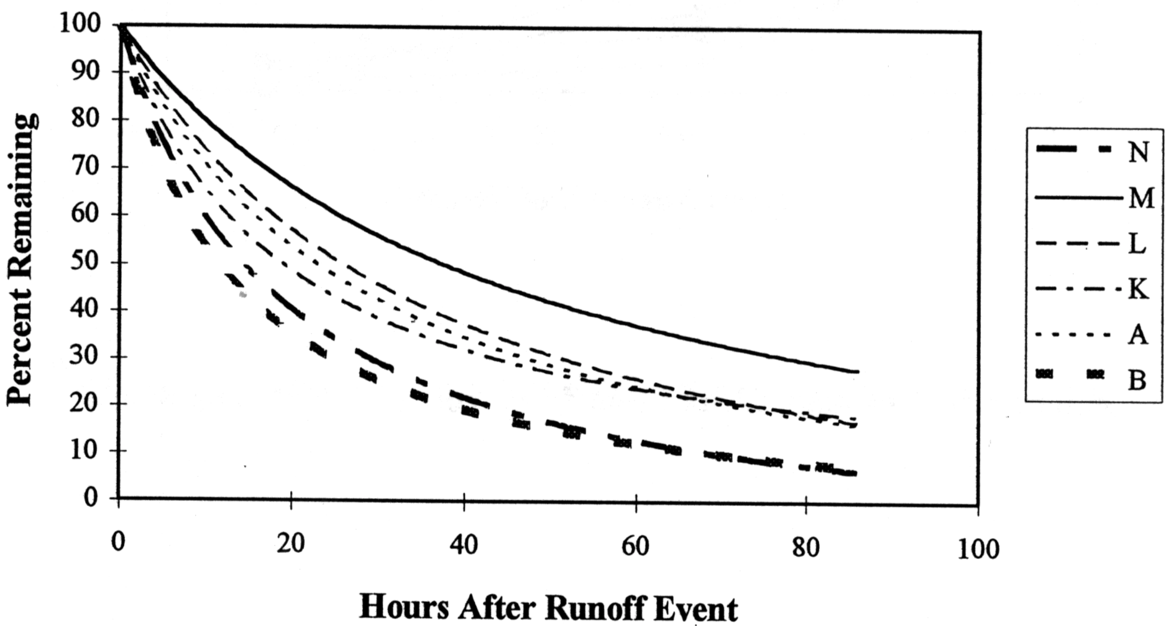

Figure 3: Hydraulic Performance of Six Vertical Sand Filters in Texas - Percent of Runoff Reamining in Sdimentation Chamber as a Function of Time

Table 4: Performance of a Vertical Gravel Filter (Tenney *et al.*, 1995)	
Water Quality Parameter	**Mass Reduction (%)**
TSS	60
VSS	39
BOD	26
COD	1
Total Carbon	(-48)
Dissolved Carbon	(-101)
Nitrate-N	(-36)
Oil/Grease	18
Chromium	(-28)
Zinc	63
Copper	32
Total Phosphorus	low

1.5 inches in depth. The results can be found in Table 4.

Overall, the removal rates for the vertical gravel filter were rather mediocre— about what would be expected for a poorly designed dry extended pond. Most of the observed removal occurred behind the VSF rather than within it (i.e., pollutants dropped out in sedimentation basin rather than within the gravel filter). Tenney and his colleagues reported that 60% of the sediment and total zinc were trapped behind the filter, with removal of most other pollutants in the 15 to 30% range. Surprisingly, the vertical gravel filter exhibited negative removals for both total and dissolved organic carbon. The team concluded the source of the organic carbon was the decay of leaf litter that had been trapped in the sedimentation basin.

The mediocre performance of the vertical gravel filter was primarily attributed to the short and unreliable detention times achieved by the VSF "outlet." Given the gabion design, it was very difficult to achieve longer detention times in the sedimentation basin without clogging the VSF filter. The research team concluded that horizontal sand filters are better than vertical sand filters for stormwater quality treatment. However, despite their poor performance, vertical gravel filters may be helpful in creating "dry sedimentation chambers" to pretreat runoff before it enters sand filters or extended detention ponds in arid climates.

Testing Alternative Filtering Media in the Laboratory

A number of researchers have investigated the pollutant removal performance of alternative filter media in the laboratory. The typical experimental approach is to fill a three or four foot tall filtering column with the test medium. Each filter column is then periodically dosed with known concentrations of stormwater runoff, either collected in the field or formulated in the lab. The change in pollutant concentration is measured at various depths through the filtering column using special sampling ports. After repeated trials, the overall removal rate is determined based on the change from the initial concentration to the concentration measured at the bottom of the column..

Filtering column studies are quite useful, since they allow researchers to quickly and inexpensively screen many media combinations before they are implemented in the field. These studies not only indicate the pollutant removal potential of various media, but also evaluate how each media affects the hydraulic performance on a filter. To date, researchers have tested a wide variety of possible filtering media, including Brady sand, Zeolites, compost, soil mixes, pea gravel and processed steel fibers. However, when evaluating these studies, it is always important to keep in mind that pollutant removal achieved under controlled lab conditions is usually much higher than that which can be attained in actual field conditions.

Perhaps the most extensive series of filtering column experiments was conducted by Tenney *et al.* (1995). This research team at the University of Texas evaluated a wide range of potential filter media. In their first experiment, they compared the potential removal of "Brady sand" to the concrete sand used in most filters. Brady sand is a well-graded sand mixture in which 80 to 100% of the sand particles are between 0.05 and 0.10 cm. The researchers found little difference in the pollutant removal attained by the two kinds of sand, and reported that the more commonplace concrete sand had a greater hydraulic conductivity.

The team's remaining experiments evaluated the potential of Zeolites and compost as a filtering medium (Table 5). Zeolites are a naturally occurring mineral, similar in structure to quartz, which has a high cation exchange capacity. Given their high affinity for absorbing pollutants, Zeolites are frequently used to soften and purify home drinking water. In the stormwater filter tests, however, sand filters with Zeolites performed no better than regular sand. Other researchers have reported slightly better results with other zeolite combinations, particularly in the removal of ortho-phosphorus (Lenhart and Wiggington, 1999).

Tenney *et al.* (1995) also evaluated the feasibility of compost as a filtration medium, and reported mixed results (Table 5). Removal for total suspended solids and some trace metals was higher than concrete sand, but removal was consistently negative for both nitrate, phosphorus and dissolved carbon. Decomposing compost was thought to be the source of these elevated concentrations in the compost filtering column. On the positive side, the compost filter removed about half of the incoming oil and grease, which was the highest rate achieved by any filter combination tested, and approached TPH removal rates reported for compost canisters in a California parking lot study (Woodward Clyde, 1998).

HEC (1996) found that filtering columns containing a mix of 95% sand and 5% chopped granular steel wool was capable of consistently achieving a 75 to 85% removal rate for both total and soluble phosphorus.

Surprisingly, few filter column studies have explored the ability of soil mixes to remove stormwater pollutants. Davis *et al.* (1998) recently conducted a series of experiments to evaluate the pollutant removal potential of bioretention filters in Prince George's County, Maryland (Coffman and Winogradoff, 1999). Their experimental apparatus consisted of a 50-square foot box that simulated the dynamics of a bioretention area. The sampling box was 42 inches deep, and consisted of juniper plants rooted in a prepared sandy loam soil, with an inch or two of shredded mulch over the surface.

The large sampling box was dosed with synthetic runoff, and the change in pollutant concentrations was noted with depth. The research team also conducted other experimental trials to see how pH, flow rates, initial concentrations, flow duration, mulch depth and other factors affected pollutant removal.

A second set of experiments was conducted on a 30-inch deep bioretention area in a parking lot that was dosed with synthetic runoff. The results of both bioretention filter experiments are shown on Table 6. As can be seen, the nutrients and metal removal rates were generally quite high in both the lab and field bioretention experiments. The only exception was nitrate-nitrogen, which, as we have seen, is notoriously difficult to remove with any filtration medium.

Clearly, the combination of plants, mulch and sandy loam rivaled or surpassed the nutrient and metal removal rates for other filter media. It is important to keep in mind, however, that the effluent concentrations from the bioretention filters were about the same as other filtration systems. Still, the bioretention filters were found to sequester metals, as the research team documented metal uptake in plants and metal adsorption on the mulch. While further replication is needed, these initial experiments suggest that bioretention filters are quite promising with respect to pollutant removal.

Operational Concerns of Stormwater Filters

At the same time stormwater managers seek to increase pollutant removal, they also want to maintain the hydraulic performance of the filter. A filtering media that chronically clogs is of little or no value, given that routine maintenance is likely to be the exception rather than the rule in most communities. Several investigators have examined the increased risk of clogging associated with filtering, as measured by sharp drops in hydraulic conductivity. A greater clogging risk was noted in field studies of compost, calcitic limestone, vertical sand and processed steel fibers filters. Some clogging of traditional sand, peat-sand and bioretention

Table 5: Comparative Removal of Stormwater Pollutants in Experimental Filter Columns (Tenney *et al.*, 1995)

Water Quality Parameter	Sand	Sand with Zeolites	Compost
Total Suspended Solids	74%	46%	82%
Total Organic Carbon	24	27	12
Oil and Grease	40	21	52
Nitrate-nitrogen	(-66)	(-314)	(-269)
Total Phosphorus	34	26	(-162)
Total Copper	34	13	55
Total Zinc	40	51	75
Total Lead	18	31	26
results are from 16 to 31 doses of actual stormwater runoff through the filtering column			

Table 6: Performance of Soil/Mulch Filter (Bioretention Filter) (Davis *et al.*, 1998)

Water Quality Parameter Analyzed	Laboratory Test of Large Bioretention Filter		Field Test of Bioretention Filter	
	% Removal	Outflow Concentration	% Removal	Outflow Concentration
Total Phosphorus	81	0.10	65	0.18
Total Nitrogen	43	1.2	49	2.0
TKN	68	0.9	52	1.7
Ammonia-nitrogen	79	0.5	92	0.22
Nitrate-nitrogen	23	0.26	16	0.33
Copper	93	0.005	97	0.002
Lead	97	<0.002	<95	<0.002
Zinc	96	<0.025	<95	<0.025

Box test was a fifty square foot test bioretention area that had a filtering depth of 3.5 feet; field test was a 2.5 foot deep bioretention area in a parking lot that was dosed with synthetic runoff. Outflow concentrations are in units of mg/l

filters has been anecdotally reported, but does not seem as pervasive as that reported for other filtering media. It is worth noting that the price of a fancier filtering media is usually accompanied by some loss of hydraulic conductivity over time. A stormwater manager can address this issue by either selecting a medium that is less prone to clogging or subjecting the filtering media to less of an hydraulic load (i.e., less depth of flow).

Implications for Stormwater Designers

When faced with this veritable blizzard of new data, how can stormwater designers decide which kind of sand filter media will best meet their particular stormwater treatment objective? Some initial guidance is offered below, with the proviso that it must be continuously refined to reflect new research findings.

1. The basic sand filter design works well for many small development sites that do not require unusually high pollutant removal requirements. The basic sand filter appears to be capable of removing approximately 80% of incoming sediment, 40% of total phosphorus, and 60% of most metals. In addition, it appears to be quite effective in removing hydrocarbons, which is particularly important for stormwater hotspots. Basic sand filter bacteria-removal performance is mixed, and other practices should be considered when bacteria removal is the prime stormwater treatment objective. Sand filters are also consistent nitrate-leakers, and consequently may not be a wise choice in coastal watersheds where nitrogen removal is a priority. Likewise, designers working in phosphorus-sensitive watersheds may want to use other media to boost phosphorus removal rates, since sand filters show little ability to remove soluble forms of phosphorus that are most important in reducing eutrophication.

Sand filters also have no ability to remove chlorides or dissolved organic carbon (but then again, few other stormwater practices have much capability in this regard). It is important to bear in mind that the sedimentation chamber is absolutely essential in the basic sand filter design. Sedimentation storage prior to the filter accounts for much of the observed pollutant removal in the system, and helps to reduce the bypass of untreated runoff from these off-line practices.

2. Bioretention areas appear to remove pollutants at a higher rate than basic sand filters, although this conclusion is based on limited monitoring data. Hopefully, future monitoring will demonstrate that the soil filtration of bioretention areas can achieve 60% phosphorus removal and 90% removal of metals and hydrocarbons. More research is needed to confirm whether they also can reliably remove sediment and bacteria, but the soil filtration mechanism used in bioretention should promote high removal rates for these parameters.

3. Organic filter media, such as peat sand and compost, show some promise in removing higher levels of hydrocarbons and metals, and should be seriously considered for hotspot sites. They do not, however, appear to perform much better than basic sand filters when it comes to removing nutrients. Indeed, the gradual decomposition of organic media can result in the export of nitrate and soluble phosphorus. Further monitoring

is needed to determine whether these media have any value in reducing bacteria levels in urban runoff. Lastly, the experience with the Snohomish compost filters clearly indicates that organic filters are a very poor choice if they are likely to encounter dry weather flows.

4. Several media appear to be useful when phosphorus removal is the primary stormwater treatment objective. The evidence shows that soil filtration, whether present in bioretention areas or dry swales, can boost phosphorus removal rates to about 60 or 70%. Incorporating calcitic limestone or processed steel fiber amendments within sand filters also appears to improve phosphorus removal, but it remains to be seen whether the cost and loss of hydraulic performance make it worth the effort. The use of peat sand filters is a third strategy, given that they can remove as much as 50% of total phosphorus, but it should be noted that most of the removal was for organic forms of phosphorus that are not as biologically available. Several media demonstrated little or no ability to boost phosphorus removal rates, including zeolites, compost and pea gravel.

5. The vertical sand filter concept appears to be fundamentally unsound, as it is prone to chronic and insurmountable clogging problems. However, they may have some value when used as a vertical pea gravel filter, for pretreatment for sand filters or extended detention dry ponds in arid or semiarid climates.

In summary, the current round of research on stormwater filters has yet to discover a “wonder medium,” but it has uncovered several media that can provide incremental improvements in overall removal for some pollutants. The next generation of research should focus on the relative value of sand filtration versus soil filtration for stormwater treatment. Such data will be critical in determining whether it makes more sense to continue to try to improve on sand filtration, or simply shift over to practices that utilize soil filtration, such as bioretention. ***-TRS***

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