Compacted Urban Soils and their Remediation

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Abstract

The effects of urbanization on soil structure can be extensive. Infiltration of rain water through soils can be greatly reduced, plus the benefits of infiltration and biofiltration devices can be severely jeopardized. Our research group (along with others), have been studying disturbed urban soils for several decades, both in the laboratory and in the field. The effects of compaction on infiltration capacities and plant growth for different types of soils have been the greatest interest, along with methods to restore soils to their natural capacities. Stormwater pollutant movement through urban soils, along with the benefits and problems associated with different soil amendments (and groundwater contamination potential) has also been examined during our research. Long-term infiltration performance degradation associated with clogging (and therefore the need for pre-treatment and other suitable design issues), pollutant retention capacity, and effects of snowmelt on clayey soils are other areas of current research interest. This short review paper will focus on soil compaction and some basic restoration recommendations.

Infiltration in Disturbed Urban Soils

Soil disturbance/compaction in urban areas occurs during construction cutting and filling operations, general grading operations, and other processes of running heavy equipment over the soil. After construction, continued compaction can occur with site activities such as walking, sports, and even parking heavy vehicles on grassed areas. Slow improvements in soil compaction may occur with time in relatively undisturbed areas by deep rooted plants or by soil insects or other boring animals. Basically, soil infiltration performance is usually significantly degraded compared to natural soil conditions and is commonly overlooked during hydrologic analyses and design. Knowing the likely effects of this soil compaction on urban hydrological conditions is critical for designing safe drainage systems. Restoring the infiltration capacity of a soil is also possible and can provide significant benefits in stormwater management. The following discussion presents observations from a number of field and laboratory measurements and describes likely degraded infiltration rates for a variety of conditions. A later discussion presents comments pertaining to restoring infiltration rates.

Field Tests of Compacted Soil Infiltration Rates

A series of 153 double ring infiltrometer tests were conducted in disturbed urban soils in the Birmingham, and Mobile, Alabama, US, areas as part of an EPA project that investigated disturbed urban soils and soil amendments (Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Hue. *Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity*. U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA 600/R-00/016. Cincinnati, Ohio. 231 pgs. December 1999, available at: http://www.unix.eng.ua.edu/~rpitt/Publications/BooksandReports/Compacted%20and%20compost%20amended%20soil%20EPA%20report.pdf). The tests were organized in a complete 2^3 factorial design to examine the effects of soil-water, soil texture, and soil density (compaction) on water infiltration through historically disturbed urban soils. Ten sites were selected representing a variety of desired conditions (compaction and texture) and numerous tests were conducted at each test site area. Soil-water content and soil texture conditions were determined by standard laboratory soil analyses. Compaction was measured in the field using a cone penetrometer and confirmed by the site history. During more recent tests, compaction is directly measured by obtaining samples from the field from a known volume (digging a small hole and retrieving all of the soil into sealed bags that are brought to the lab for moisture and weight analyses. The hole that is carefully cleaned of all loose soil is then filled with free-flowing sand from a graduated cylinder to determine the volume. The laboratory dry weight of the excavated soil is dived by the hole volume to obtain the density). From 12 to 27 replicate tests were conducted in each of the eight experimental categories in order to measure the variations within each category for comparison to the variation between the categories.

Soil infiltration capacity was expected to be related to the time since the soil was disturbed by construction or grading operations (turf age). In most new developments, compacted soils are expected to be dominant, with reduced infiltration compared to pre-construction conditions. In older areas, the soil may have recovered some of its infiltration capacity due to root structure development and from soil insects and other digging animals. Soils having a variety of times since development, ranging from current developments to those about 50 years old, were included in the sampling program. These test sites did not adequately represent a wide range of age conditions for each test condition, so the effects of age could not be directly determined. Other analyses have indicated that several decades may be necessary before compacted loam soils recover to conditions similar to pre-development conditions, if not continually compacted by site activities.

Figures 1 and 2 are 3D plots of this field infiltration data, illustrating the effects of soil-water content and compaction, for both sands and clays. Four general conditions were observed to be statistically unique. Compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with higher soil-water content conditions (the factor usually considered by most rainfall-runoff models). Clay soils, however, are affected by both compaction and soil-water content. Compaction was seen to have about the same effect as saturation on clayey soils, with saturated and compacted clayey soils having very little effective infiltration.

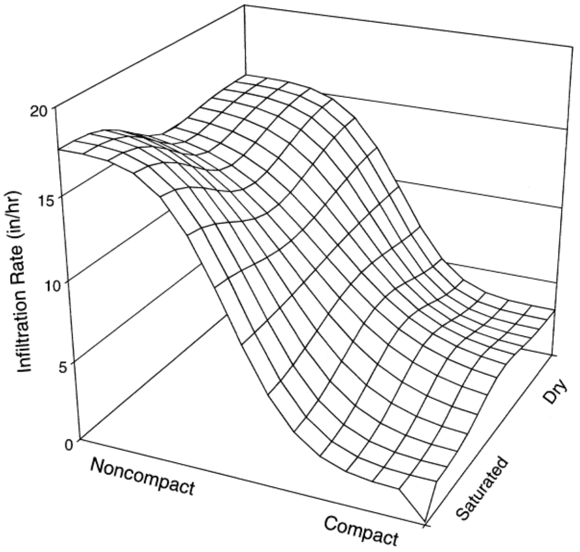

Figure 1. Three dimensional plot of infiltration rates for sandy soil conditions.

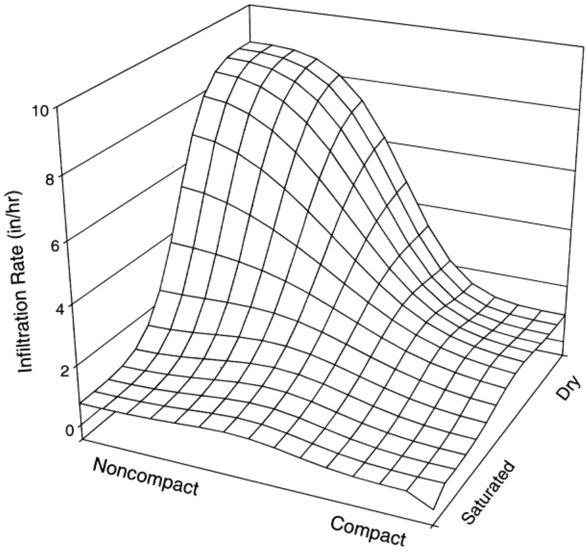

Figure 2. Three dimensional plot of infiltration rates for clayey soil conditions.

Laboratory Controlled Compaction Infiltration Tests

We use three levels of compaction to modify the density of soil samples during controlled laboratory tests: hand compaction, Standard Proctor Compaction, and Modified Proctor Compaction. Both Standard and Modified Proctor Compactions follow ASTM standard (D 1140-54). The Standard Proctor compaction hammer is 24.4 kN and has a drop height of 300 mm. The Modified Proctor hammer is 44.5 kN and has a drop height of 460 mm. For the Standard Proctor setup, the hammer is dropped on the test soil 25 times on each of three soil layers, while for the Modified Proctor test, the heavier hammer was also dropped 25 times, but on each of five soil layers. The Modified Proctor test therefore results in much more compacted soil, and usually reflects the most compacted soil usually observed in the field. The hand compaction is done by gentle hand pressing to force the soil into the test cylinder with as little compaction as possible. A minimal compaction effort is needed to keep the soil in contact with the mold walls and to prevent short-circuiting during the tests. The hand compacted soil specimens therefore have the least amount of compaction.

A series of controlled laboratory tests were conducted for comparison with the double-ring infiltration tests and to represent a wide range of soil conditions, as shown in Table 1. Six soil samples were tested, each at three different compaction levels described previously. Small depths of standing water on top of the soil test mixtures (4.3 inches, or 11.4 cm, maximum head) was also used. Most of these tests were completed within 3 hours, but some were continued for more than 150 hours. Only one to three observation intervals were used during these tests, so they did not have sufficient resolution or enough data points to attempt to fit to standard infiltration equations. However, these longer-term averaged values may be more suitable for infiltration rate predictions due to the high natural variability observed during the field tests. As shown, there was very little variation between the different time periods for these tests, compared to the differences between the compaction or texture groupings. The sandy soils can provide substantial infiltration capacities, even when compacted greatly, in contrast to the soils having clays that are very susceptible to compaction.

Table 1. Low-Head Laboratory Infiltration Tests for Various Soil Textures and Densities (densities and observed infiltration rates)

	Hand Compaction	**Standard Compaction**	**Modified Compaction**
Sand (100% sand)	Density: 1.36 g/cm^3 (ideal for roots) 0 to 0.48 hrs: 9.35 in/h 0.48 to 1.05 hrs: 7.87 in/h 1.05 to 1.58 hrs: 8.46 in/h	Density: 1.71 g/cm^3 (may affect roots) 0 to 1.33 hrs: 3.37 in/h 1.33 to 2.71 hrs: 3.26 in/h	Density: 1.70 g/cm^3 (may affect roots) 0 to 0.90 hrs: 4.98 in/h 0.90 to 1.83 hrs: 4.86 in/h 1.83 to 2.7 hrs: 5.16 in/h
Silt (100% silt)	Density: 1.36 g/cm^3 (close to ideal for roots) 0 to 8.33 hrs: 0.26 in/h 8.33 to 17.78 hrs: 0.24 in/h 17.78 to 35.08 hrs: 0.25 in/h	Density: 1.52 g/cm^3 (may affect roots) 0 to 24.22 hrs: 0.015 in/h 24.22 to 48.09: 0.015 in/h	Density: 1.75 g/cm^3 (will likely restrict roots) 0 to 24.20 hrs: 0.0098 in/h 24.20 to 48.07: 0.0099 in/h
Clay (100% clay)	Density: 1.45 g/cm^3 (may affect roots) 0 to 22.58 hrs: 0.019 in/h 22.58 to 47.51 hrs: 0.016 in/h	Density: 1.62 g/cm^3 (will likely restrict roots) 0 to 100 hrs: <2X10-3 in/h	Density: 1.88 g/cm^3 (will likely restrict roots) 0 to 100 hrs: <2X10-3 in/h
Sandy Loam (70% sand, 20% silt, 10% clay)	Density: 1.44 g/cm^3 (close to ideal for roots) 0 to 1.17 hrs: 1.08 in/h 1.17 to 4.37 hrs: 1.40 in/h 4.37 to 7.45 hrs: 1.45 in/h	Density: 1.88 g/cm^3 (will likely restrict roots) 0 to 3.82 hrs: 0.41 in/h 3.82 to 24.32 hrs: 0.22 in/h	Density: 2.04 g/cm^3 (will likely restrict roots) 0 to 23.50 hrs: 0.013 in/h 23.50 to 175.05 hrs: 0.011 in/h
Silty Loam (70% silt, 20% sand, 10% clay)	Density: 1.40 g/cm^3 (may affect roots) 0 to 7.22 hrs: 0.17 in/h 7.22 to 24.82 hrs: 0.12 in/h 24.82 to 47.09 hrs: 0.11 in/h	Density: 1.64 g/cm^3 (will likely restrict roots) 0 to 24.62 hrs: 0.014 in/h 24.62 to 143.52 hrs: 0.0046 in/h	Density: 1.98 g/cm^3 (will likely restrict roots) 0 to 24.62 hrs: 0.013 in/h 24.62 to 143.52 hrs: 0.0030 in/h
Clay Loam (40% silt, 30% sand, 30% clay)	Density: 1.48 g/cm^3 (may affect roots) 0 to 2.33 hrs: 0.61 in/h 2.33 to 6.13 hrs: 0.39 in/h	Density: 1.66 g/cm^3 (will likely restrict roots) 0 to 20.83 hrs: 0.016 in/h 20.83 to 92.83 hrs: 0.0066 in/h	Density: 1.95 g/cm^3 (will likely restrict roots) 0 to 20.83 hrs: <0.0095 in/h 20.83 to 92.83 hrs: 0.0038 in/h

Comparing Field and Laboratory Measurement Methods

A soil infiltration study was recently conducted by Redahegn Sileshi, a PhD student in the Department of Civil, Construction, and Environmental Engineering at the University of Alabama, in July 2011 at four test sites located in areas that were affected by the April 27, 2011 Tornado that devastated the city of Tuscaloosa, AL. Double-ring infiltration measurements (using three Turf-Tec infiltrometers at each location) were conducted to determine the infiltration characteristics of the soils in typical areas where reconstruction with stormwater infiltration controls is planned. The small field double-ring (4 inch, 10 cm, diameter) test results were compared to large (24 inch, 60 cm, diameter, 3 to 4 ft, 1 to 1.2 m, deep) pilot-scale borehole tests to identify if the small test methods can be accurately used for rapid field evaluations. The borehole tests required drilling a hole and placing a Sonotube cardboard concrete form into the hole to protect the hole sides. The borehole was 2 to 4 ft deep (depending on subsoil conditions). The bare soil at the bottom of the tube was roughened to break up any smeared soil and back-filled with a few inches of coarse gravel to prevent erosion during water filling. The tubes were filled with water from adjacent fire hydrants and the water elevation drop was monitored using a recording depth gage (a simple pressure transducer with a data logger).

In addition, controlled laboratory column tests were also conducted on surface and subsurface soil samples under the three different compaction conditions to see if depth of the test (and response to compaction) affected the infiltration results. The test sites were all located adjacent to fire hydrants (for water supply for the large borehole tests) and are located in the City's right-of way next to roads. Figure 3 shows some of the features of these tests.

Figure 3. Photographs showing borehole drilling, Sonotube infiltration tube installation, double-ring infiltration measurements, and laboratory column tests.

The soil densities of the surface soils were 1.7 g/cc (ranged from 1.6 to 1.9 g/cc). The median soil particle size averaged 0.4 mm (ranging from 0.3 to 0.7), and the soil had a clay content of about 20%. Figure 4 shows the saturated infiltration rate for the different locations and test methods.

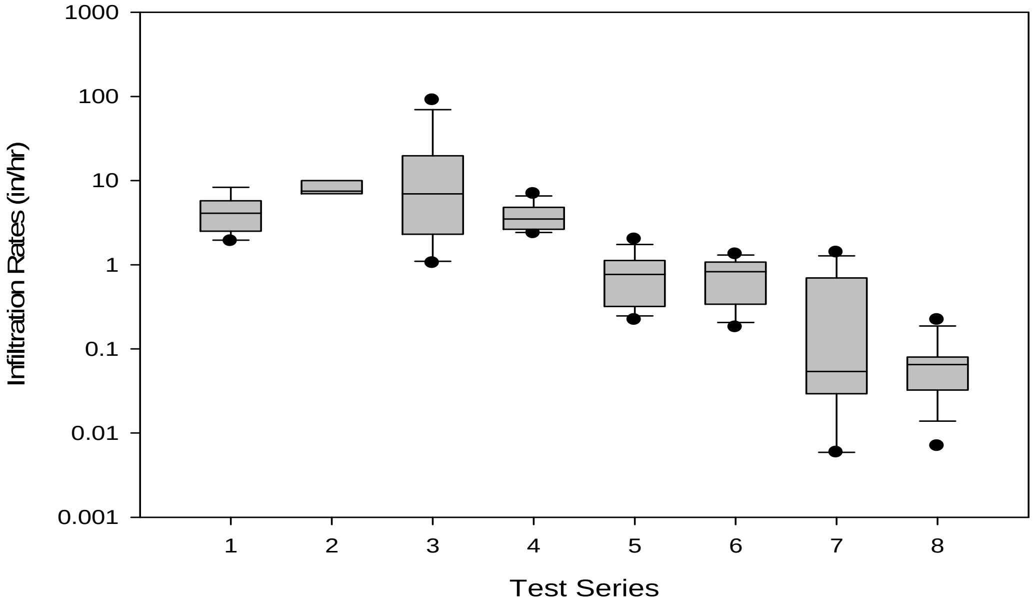

Figure 4. Box and whisker plots comparing saturated soil infiltration rates (in/hr). Test series descriptions (12 replicates in each test series except for the borehole tests which only included 3 observations):

1) Turf-Tec small double ring infiltrometer
2) Pilot-scale borehole infiltration tests
3) Surface soil composite sample with hand compaction (1.4 g/cc density)
4) Subsurface soil composite sample with hand compaction (1.4 g/cc density)
5) Surface soil composite sample with standard proctor compaction (1.6 g/cc density)
6) Subsurface soil composite sample with standard proctor compaction (1.6 g/cc density)
7) Surface soil composite sample with modified proctor compaction (1.7 g/cc density)
8) Subsurface soil composite sample with modified proctor compaction (1.7 g/cc density)

Using the double ring infiltrometers, the final saturated infiltration rates (of most significance when designing bioinfiltration stormwater controls) for all the test locations was found to average about 4.4 in/hr (11 cm/hr) for the 12 measurements and ranged from 1.9 to 8.3 in/hr (4.8 to 21 cm/hr). The borehole test results were about twice these values. The laboratory column tests indicated that surface and subsurface measurements were similar for all cases, but that compaction dramatically decreased the infiltration rates, as expected. The slightly (hand) compacted test results were similar to the Turf-Tec and the borehole test results, indicating that these sites, even in the road rights-of-ways, were minimally compacted. These areas were all originally developed more than 20 years ago and had standard turf grass covering. They were all isolated from surface disturbances, beyond standard landscaping maintenance. It is not likely that the tornado affected the soils. The soil profile (surface soils vs subsurface soils from about 4 ft, 1.2 m) did not affect the infiltration rates at these locations. Due to the relatively high clay content, the compaction tests indicated similarly severe losses in infiltration rates as found in prior studies, of one to two orders of magnitude reductions, from about 25, to 2, to 0.1 cm/hr, usually far more than the differences found between different soil textures.

Summary of Compaction Effects on Infiltration Tests

These recent tests indicated that the three soil infiltration test methods resulted in similar results, although the small –scale Turf-Tec infiltrometers indicated reduced rates compared to the borehole tests. Another study, summarized below, however indicated that the Turf-Tec infiltrometers resulted in substantially greater infiltration rates than observed in a failing bioinfiltration device, compared to actual infiltration rates during rain events. Therefore, if surface characteristics are of the greatest interest (such as infiltration thru surface landscaped soils, as in turf areas, grass swales or in grass filters), the small-scale infiltrometers work well. These allow a cluster of measurements to be made in a small area to better indicate variability. Larger, conventional double-ring infiltrometers are not very practical in urban areas due to the excessive force needed to seat the units in most urban soils (usually requiring jacking from a heavy duty truck) and the length of time and large quantities of water needed for the tests. In addition, they also only measure surface soil conditions. More suitable large-scale (deep) infiltration tests would be appropriate when subsurface conditions are of importance (as in bioinfiltration systems and deep rain gardens). The borehole and Sonotube test used above is relatively easy and fast to conduct, if a large borehole drill rig is available along with large volumes of water (such as from a close-by fire hydrant). For infiltration facilities already in place, simple stage recording devices (small pressure transducers with data loggers) are very useful for monitoring during actual rain conditions.

In many cases, disturbed urban soils have dramatically reduced infiltration rates, usually associated with compaction of the surface soils. The saturated infiltration rates can be one to two orders of magnitude less than assumed, based on undisturbed/uncompacted conditions. Local measurements of the actual infiltration rates, as described above, can be a very useful tool in identifying problem areas and the need for more careful construction methods. Having accurate infiltration rates are also needed for proper design of stormwater bioinfiltration controls. In situations of adverse infiltration rates, several strategies can be used to improve the existing conditions, as noted below.

Strategies to Improve Urban Soil Performance

A growing area of research is the investigation of the use of soil amendments and re-aeration to improve the infiltration performance of urban soils, and to provide additional protection against groundwater contamination. The following are brief reviews of some of these restoration options.

Mechanic Soil Restoration

Figure 5 shows three approaches that have been used for successful mechanical restoration of compacted urban soils. Re-aeration using an agricultural spader tillage implement has been successfully used to restore compacted soils in disturbed areas. This is not a typical rotary tiller that can form a hardpan, but uses a shoveling action to lift up the soil. The Tortella Spader from Italy is a preferred spader implement. Dramatic restorations in soil structure are possible with the spader, while deep chisel plowing has also been used, but less successfully. Insects and other soil boring organisms, along with plant activity, can also help restore soil density, but usually require long periods and some organisms (such as the fire ant activity shown here) may not be very desirable!

 Tortella Spader (Italian farm implement) (http://www.bdimachinery.net/29.html)	 Deep chisel plowing to restore infiltration in prarie wetland/infiltration area (Wisconsin Dept. of Natural Resources photo).	 Fire ant activity aerating soil.

Figure 5. Spader, deep chisel plow, and natural insect processes generally resulting in successful mechanical soil restoration.

Figure 6 shows two common mechanical soil restoration processes that are generally less successful. Shallow lawn aerators were tested (available from home care rental outlets), but were found not be very successful as most soil compaction occurs in the top several inches, or more, of soil, and these devices only affect the first few inches. The backhoe was trying to restore a newly built terraced biofilter facility that prematurely failed. The media/soil mixture contained large fractions of clays (visually obvious) and the new construction in the surrounding area could also have resulted in erosion materials entering the biofilters. The contractor was working the surface down to about a foot in depth in an attempt to mix the clayey surface soils with sandier subsoils. This was marginally successful as the working depth was relatively shallow and the heavy equipment was working the clayey material while it was still saturated, resulting in likely further compacted conditions.

Lawn aerators during compaction restoration tests

Back-hoeing terraced biofilters containing excessive clays in soil (and with possible damage from construction erosion silts).

Figure 6. Less successful mechanical soil restoration efforts.

Mechanical soil restoration is most useful for large areas at construction areas to improve the infiltration capacity of compacted soils to reduce runoff from the landscaped areas. It works best in areas having suitable soils (low clay content) or if sand or other amendments are being added during the tillage operation. Mechanical restoration with large tillage equipment is destructive to any existing vegetation so it requires replanting if conducted after vegetation has been established. Lawn aerators are attempted in areas of established lawns, but because of their shallower depths, can’t usually affect the full zone of compaction. Top dressing of compost and/or revegetation of deep rooted plants (if they can become established in the compacted soils) may be successful in established areas, but the results may be marginal. In those cases, it may be best to periodically establish rain gardens in low lying areas of the vegetated areas where the compacted soil can be removed and replaced with a suitable soil mix and then replanted. These can be established along the natural drainage path and provide an opportunity for improved drainage. Some have established dry wells in compacted soils in vegetated areas with great success in improving drainage, but with attendant groundwater contamination concerns. Discussions of groundwater contamination potential associated with stormwater infiltration are beyond the scope of this short article, but the reader is referred to a comprehensive earlier EPA report: Pitt, R., S. Clark, and K. Parmer, *Protection of Groundwater from Intentional and Nonintentional Stormwater Infiltration,* U.S. Environmental Protection Agency, EPA/600/SR-94/051, PB94-165354AS, Storm and Combined Sewer Program, Cincinnati, Ohio, 187 pgs. May 1994, available at: http://www.unix.eng.ua.edu/~rpitt/Publications/BooksandReports/Groundwater%20EPA%20report.pdf .

Sand Amendments to Improve Soil Structure

Improvements to soil structure (in order to improve infiltration rates) can usually be accomplished by adding sand to the native soil in an area. Sand apparently provides vertical support and resistance to compaction by bridging between discrete sand particles. Adding large fractions of sand obviously effectively dilutes the fraction of the fines in the soil mixture also.

Another task of Redahegn Sileshi's Ph.D. research at the University of Alabama included investigating a poorly functioning biofilter adjacent to campus (Figure 7). Extended surface ponding was often observed following heavy rainfall events at this site. Infiltration rate measurements of the ponded water were manually recorded after five rainfall events between July 2010 and April 2011. Small-scale Turf-Tec infiltrometers were also used to measure infiltration rates at several locations along the biofilter when the biofilter was dry, and biofilter media samples were brought to the laboratory for column testing. The media was classified as sandy clay loam, with 20% clay and 80% sand (3% organic matter content). The median size of the samples ranged from 300 to 4,000 um, and *in-situ* density measurements indicated surface dry density values of about 1.9 g/cc, corresponding to severely compacted conditions (close to "modified" compaction conditions for this soil). Poor vegetation growth also indicated compacted conditions.

Figure 7. Ponded water on the biofilter surface observed after rainfall event (the vegetation cover is very poor indicating likely serious compaction).

Field double ring infiltrometer tests using the small Turf-Tec infiltrometers indicated saturated infiltration rates of about 4.5 in/hr (11 cm/hr) (range of 1.5 to 10.5 in/hr, 3.8 to 27 cm/hr, for 12 tests), which are relatively high for this material. However, measurements of the infiltration rates of the ponded water after actual rains indicated saturated rates of only about 0.5 in/hr (1 cm/hr) with little variation. This significant difference between the infiltration test methods is in contrast to the previously reported comparison. In this case, the compaction of the biofilter media extended to the bottom of the excavated trench, with likely increasing compaction with depth due to the media placement methods. The small-scale surface infiltration measurements did not include sufficient water to saturate the system and only indicated more favorable surface conditions. Therefore, care needs to be taken when using any surface infiltration method when evaluation a facility with depth. A trench or borehole infiltration test would be more reliable in this case, or the preferred *in-situ* measurements with recording depth sensors during actual rains.

As noted, biofilter media material was brought to the laboratory for extending testing. Figure 8 shows box and whisker plots of the different test conditions, comparing different compaction conditions with varying amounts of sand amendments. The sand that was added was a locally available filter sand having a median particle size of about 0.7 mm and a uniformity coefficient of about 3.

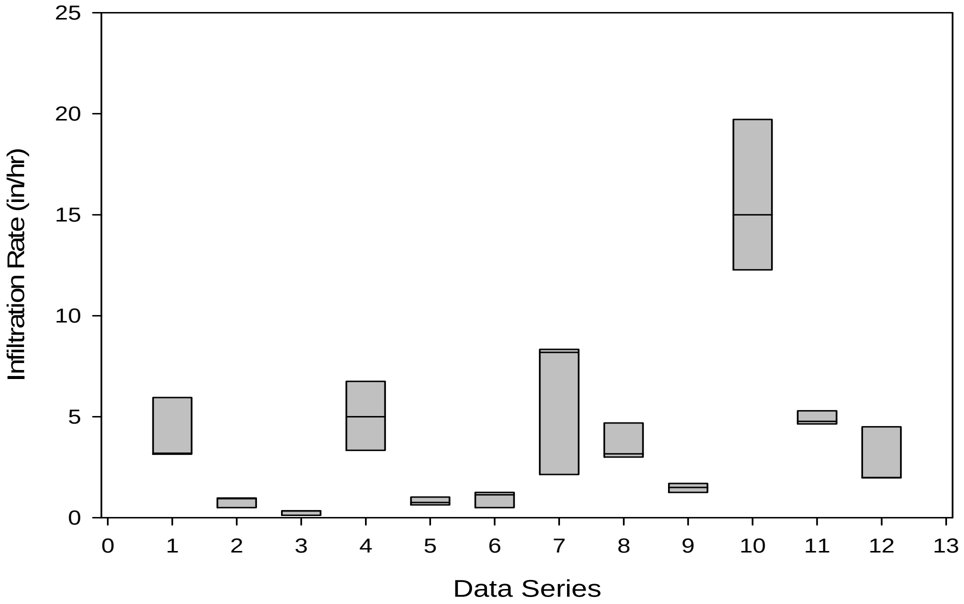

Figure 8. Effects of filter sand additions to poorly functioning biofilter soil (COV of infiltration rates ranged from 0.15 to 0.45). Data Series:

1: hand compaction with 0% sand
2: standard compaction with 0% sand
3: modified compaction with 0% sand
4: hand compaction with 10% sand
5: standard compaction with 10% sand
6: modified compaction with 10% sand
7: hand compaction with 25% sand
8: standard compaction with 25% sand
9: modified compaction with 25% sand
10: hand compaction with 50% sand
11: standard compaction with 50% sand
12: modified compaction with 50% sand

The plots indicated major percentage benefits by adding the sand, even at only 10% for the most severely compacted material (increased from about 0.25 to 1 in/hr, 0.6 to 2.5 cm/hr), while the sand addition had less of a benefit for the lightly compacted material at this low sand addition (from about 4 to 5 in/hr, 10 to 12 cm/hr). The percentage benefits were similar for all compaction conditions for the large sand additions (25 and 50% sand). The benefits of lesser compaction were much greater than the sand addition benefits. However, added sand prevented this very poor media material from completely shutting off, even with severe compaction (averaging at least about 1 in/hr, 2.5 cm/hr, with 10% sand, about 1.5 in/hr, 4 cm/hr, with 25% sand, and about 3 in/hr, 8 cm/hr, with 50% sand).

Organic Soil Amendments

Organic material amendments are commonly added to soils used in biofilters and to area landscaping soils to enhance infiltration performance, and for other benefits. Many state standards in the US describe the organic material that can be used for biofilter amendments, sometimes specifying the source of the material, the organic matter content, other physical and chemical characteristics, and the amounts to be added. However, the range of acceptable materials is very large, with inherently wide ranges in their benefits. These specifications are also periodically updated in response to observed problems with their use. Professional groups (such as the LID committee of the ASCE) are also involved in collecting experiences associated with the different materials for the development of more universal guidance. Basically, there are several categories of organic soil amendments, including: composted waste materials (usually municipally collected yard wastes or sanitary sewage sludge, or "beneficial solids"); harvested peat; or processed agricultural wastes (such as coir peat).

An early test of using compost amendments for enhancing soil infiltration and pollutant leaching was conducted by Pitt, *et al.* (1999, reference cited earlier). These extended tests were conducted in the Seattle area using two different commercially available composts (sewage sludge and yard waste derived composts) in several test plots that were fully instrumented for surface and subsurface runoff quality and quantity monitoring. New test plots and older existing test plots were also compared. Figure 9 shows one of the older established test plots and the subsurface flow monitoring station.

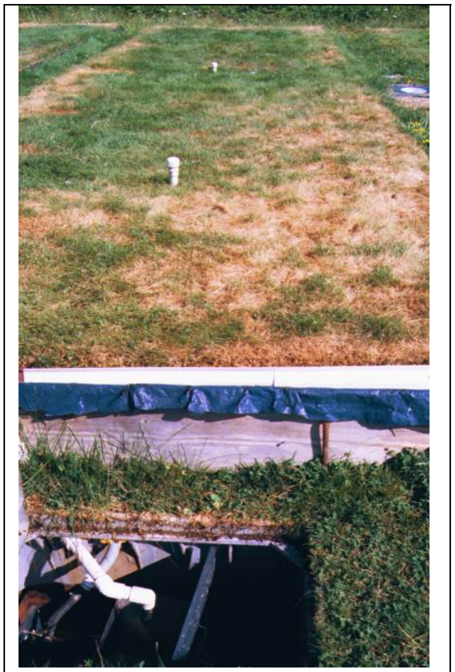

Figure 9. Instrumented test plot.

The compost-amended soils resulted in significant reductions in both surface runoff and subsurface infiltration. The surface runoff was reduced by about 90% and the subsurface infiltration was reduced by about 70%, as shown in Table 2. It was interesting to note that the surface runoff and the subsurface runoff both decreased compared to the soil-only sites. This was due to the increased evapotranspiration that occurred at the compost-amended soil sites. The shallow soils in the Seattle area overlay low-permeable subsoils, preventing increased deep infiltration, even with enhanced surface infiltration. The original concept of using the compost-amended soils in this area was to retain moisture in the surface soils longer than current conditions, making it more susceptible to evapotranspiration. However, there were increases in concentrations of many constituents in the surface and subsurface runoff due to degradation and leaching of the compost during the first year of these measurements. The compost amendments also significantly decreased the amount of surface runoff leaving the test plots, resulting in overall decreased mass discharges to the surface: all of the surface runoff mass discharges from the amended soil test plots were reduced from 2 to 50 percent compared to the unamended discharges. However, many of the subsurface flow mass discharges increased, especially for ammonia (340% increase), phosphate (200% increase), plus total phosphorus, nitrates, and total nitrogen (all with 50% increases). Most of the other constituent mass discharges in the subsurface flows decreased (not shown on the table, except for zinc). Tests at the older test plots (about 3 years old) indicated less export of leached materials as the composts continued to stabilize with age.

Table 2. Changes in Pollutant Discharges from Surface Runoff and Subsurface

Flows at New Compost-Amended Sites, Compared to Soil-Only Sites

Constituent	Surface Runoff Discharges (mass), Amended-Soil Compared to Unamended Soil	Subsurface Flow Discharges (mass), Amended-Soil Compared to Unamended Soil
Runoff Volume	0.09	0.29
Phosphate	0.62	3.0
Total phosphorus	0.50	1.5
Ammonium nitrogen	0.56	4.4
Nitrate nitrogen	0.28	1.5
Total nitrogen	0.31	1.5
Copper	0.33	1.2
Zinc	0.061	0.18

In contrast to these initial releases of nutrients, compost, especially derived from municipal leaf waste, has a high potential for the removal of heavy metals, organics and other pollutants, protecting groundwaters, or decreasing these stormwater pollutants in stormwater if used in biofilters with underdrains. In contrast, sand is quite inert, with minimal permanent pollutant reductions.

Nutrient leaching from compost amendments has been noted by many researchers, resulting in the preferred use of more stable organic materials in some areas. One of the earliest alternative organic materials used for soil amendments is peat. Besides improving the infiltration characteristics of soils (as do compost amendments), peat has been extensively studied for its treatment effectiveness for both industrial wastewater and stormwaters. Peat can be very effective at removing many metals and hydrocarbons down to very low concentrations because of the variety of binding sites (carboxylic acid, etc.) found in the humic materials and lignins in the peat and its high cation exchange capacity (CEC). Peat also has been shown to be very fast in removing heavy metals from stormwater, with less required residence times than other amendments. Theoretically, peat's ability to treat metals is directly related to its degree of decomposition, with Sphagnum peat, the least decomposed, being less able to treat metals than Carex peat, which is more decomposed. However, stormwater tests have shown excellent removals of several heavy metals with Sphagnum peat to low levels that would meet stringent numeric permit limits. Sphagnum peat is also readily available at commercial nurseries. However, the release of humic and fulvic acids (increased color) and decreasing pH levels in the treated water, are disadvantages of peat, especially for Sphagnum peat. Both compost and peat release nutrients in the first flush of water from a biofilter or amended soil if microanaerobic environments develop in the media between storms. One disturbing trend with commonly available peat is the abundance of "enriched" peat being sold at gardening centers. Because peat is relatively low in nutrients, fertilizers are being added to the peat to enhance its use as a household growing media. It is therefore critical that any peat being used as a soil or biofilter media amendment not to be contaminated with added nutrients.

Historical peat harvesting methods, as shown in Figure 10, can be destructive, resulting in large ponds that are very acidic and non-supportive of aquatic wildlife. Current peat harvesting in many areas is now less destructive, but many agencies are still reluctant to encourage its use for stormwater management, with preferred beneficial uses of local waste products. One such material that has fewer problems than the composted materials mentioned previously is coir peat that has been used as a growing medium in horticulture operations by improving water retention with minimal leaching of nutrients. Coir is a fiber from the husk of coconuts and is therefore a waste material from processing coconuts for milk and oil and is becoming commonly available in gardening stores. However, it is not a local product in most areas (like composted yard wastes or sewage sludge) and likely requires extensive shipping. Stormwater research has been conducted using coir peat as an amendment (mainly in biofilters) and it has been shown to be quite effective, especially in systems focusing on nutrient control.

Large-scale peat harvesting.

Destructive peat mining resulting in acidic shallow lakes.

Figure 10. Historical destructive peat harvesting.

Exotic Soil Amendments

Besides the use of sands and organic matter amendments, many other materials have been studied as soil and biofilter amendments, mostly to enhance pollutant capture, while offering long service life. These materials are usually only used for special circumstances where high levels of treatment of critical pollutants are needed, such as when underdrain water is directed to the surface, or to protect groundwaters. Data are becoming available to guide stormwater managers in the selection of these materials for specific objectives. Recently, Pitt and Clark studied several materials for their ability to provide excellent stormwater treatment to meet very stringent numeric discharge limits of metallic and organic toxicants, and other pollutants (Pitt, R. and S. Clark, *Evaluation of Biofiltration Media for Engineered Natural Treatment Systems*. Geosyntec Consultants and The Boeing Co., 1050 pages. June 5, 2010, available at: http://www.boeing.com/aboutus/environment/santa_susana/water_quality/tech_reports/techreports_10-10-19_FinalMediaReport051010.pdf). This extensive research effort examined several mineral and organic amendments singly and in combination for pollutant reductions, along with service life, resistance to clogging, needed retention time, and infiltration rates, including: a granular activated carbon (GAC), two zeolites, two sands, and a peat moss, with the goal of treating numerous constituents, including dioxins, mercury, perchlorate, oil and grease, heavy metals, and radioactive components, along with numerous conventional constituents, to very low numeric permit limits. Two series of column tests, one focusing on long-term pollutant removal behavior and the other on the effect of depth/contact time on removal and using stormwater as the base test fluid, showed that a media mixture containing virgin coconut-hull granular activated carbon (GAC), a surface modified zeolite (SMZ), and rhyolite sand (R), was able to treat these constituents to the very low permit limits under a wide range of likely site conditions. As noted below, the GAC was likely the most important component in this mixture:

- When the influent had a comparatively high concentration of TCDD (usually the most common form of dioxin of interest), the removals by all media were excellent and generally were below the very low permit benchmark limit of 2.8 x 10^{-8} µg/L for all media tested. The media that tended to have the best removal performance of TCDD were those with the higher amounts of GAC in the mixture.
- All of the media mixtures were also able to reduce gross alpha radioactivity to the analytical detection limits, but gross beta radioactivity removals were not, with removals seen only for the R-SMZ mixtures.
- All media mixtures were able to remove uranium, although the mixture with peat moss reached breakthrough at volumetric loadings of 60 – 80m.
- All media mixtures were able to provide excellent removal of mercury. Increases in column depth resulted in decreased effluent mercury concentrations.
- The R-SMZ and R-SMZ-GAC mixtures were able to treat perchlorate to the detection limit.

In terms of metals removal, soil is composed of many different types of reaction sites, resulting from the natural processes that generate the soil – decomposition of organic matter at the surface and leaching into the lower soil horizons and degradation of the underlying rock through weathering processes. Many generalizations have been made in the literature about chemical behavior of soils based on textural designations; however, soil texture does not define the soil's pollutant removal ability. The soil's two physical properties of interest – porosity and intrinsic permeability – dictate the rate of water transport, and thus dictate the minimum contact time the pollutants have with the medium. If the pollutant can react with the soil in that time, it is reasonable to assume that pollutant removals will be good.

Much of the groundwater protection offered by soils is associated with its ability to remove cationic (positively-charged) pollutants, measured as cation-exchange capacity (CEC). The CEC of a material is defined as the sum of the exchangeable cations that can be adsorbed at a given pH and is used to evaluate the ability of a soil to attract and retain phosphorus, heavy metals, and other targeted cations of concern. The CEC is pH-specific. As the organic content of the soil increases, so does its CEC content. Natural soils therefore vary widely in their CEC content. Organic soil amendments, such as compost, increase the CEC of a soil that is naturally low in organic material or clays. Peat has a very large CEC and small amounts added to soils substantially increase the overall CEC content of the mixture.

As treatment progresses, it is expected that CEC should therefore generally diminish over time in a soil used to treat stormwater runoff because the quantity of exchangeable cations decreases as cations, such as metals, are removed from the infiltrating water. However, field monitoring data shows that this does not necessary occur. Apparently, other removal processes, besides ion exchange, are important in the removal of pollutants by soils. Seventy to eighty percent of the organic matter by weight in soils is humic substances (condensed polymers of organic compounds). They have a wide range of molecular weights and a large number of functional groups which participate in reactions in the soil that remove large quantities of pollutants. Heavy metal and soil colloid (including soil clays, humic substances or combinations) interactions result from ion exchange, surface adsorption, or chelation reactions. Humic substances may form complexes with heavy metals because of their oxygen-containing functional groups on their surface. The retention of heavy metals in native soils by the clays and humics varies with ionic strength, pH, clay mineral type, functional group type, and types of competing cations.

Summary of Compacted Soil Restoration Methods

Mechanical restoration of compacted clayey soils must be carefully done to prevent the development of a hardpan and further problems. Spading implements are the safest methods for large scale improvements. However, if large fractions of clay are present in the soil, the addition of sand and possibly also organic amendments may be needed. The use of periodic rain gardens in a large compacted area allows deeper soil profile remediation in a relatively small area and may be suitable to enhance drainage in problem locations.

To address water quality concerns and numeric effluent limits, water and soil chemistry information is needed in order to select the best amendments for a soil or biofilter media. As summarized by Clark and Pitt (Clark, S. and R. Pitt. "Filtered Metals Control in Stormwater using Engineered Media." *ASCE/EWRI World Environment and Water Resources Congress*. Palm Springs, CA, May 22-26, 2011. Conference CD.), the removal of "dissolved" metals from stormwater by soils and amendments will need to be based on the ratio of valence states to determine the proportion of ion exchange resins versus organic-based media in the final media mixture. As more of the metal concentrations have either a 0 or +1 valence charge, or as more are associated with organic complexes, the smaller the fraction of an ion exchange resin, such as a zeolite, is needed. For metals such as thallium, where few inorganic and organic complexes are formed and where the predominant valence state is +2, increasing the amount of zeolite in the final media mixture is important for improving removal. Therefore, the final media mixture will be based on the pollutants of interest and their water chemistry. The capacity for pollutant removal by soils is directly related to OM and CEC content for many metals. Organic media provides a wide range of treatment sites besides increasing the CEC. Activating an organic media, such as granular activated carbon, will increase the number of surface active sites for treatment, but this media will not sustain plant growth by itself. As an example, copper removal capacity is related to soil carbon content, and CEC, plus, soil Mg content relates to the ability of the media to participate in ion exchange reactions.

Therefore, at least one component in an amendment media mixture should provide excellent ion exchange, such as would be found with a good zeolite. This media should be able to participate in reactions with the +2 metals and a portion of the +1 metals, although the +1 metals may not be as strongly bound and may be displaced if a more preferable exchangeable ion approaches the media's removal site. Soil OM, soil C, and soil N all relate to the organic matter content and indicate that these are sites that may participate in a variety of reactions and may be able to remove pollutants that do not carry a valence charge. Therefore, mixtures of amendments may be needed for effective removal of a range of pollutants: an organic component should be incorporated, along with a GAC. In most cases, sand may also be needed for structural support (to minimize compaction) and for controlling the flow rate to a level that allows for sufficient contact time.