R. Pitt
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Non-Paved Area Urban Hydrology

Contents

Summary

This memo summarizes several research projects that my research team has been involved with over the years that have investigated nonpaved area runoff. Most of our work in this area has focused on disturbed urban soils, where compaction and texture (and moisture) effects affecting infiltration were studied. We have also examined pavement subbases and gravel material used in underdrains. We have also monitored urban runoff characteristics from watersheds that have included substantial amounts of nonpaved areas (such as industrial storage areas). Unfortunately, we have not had the opportunity to monitor drainage areas that were comprised solely of nonpaved parking or storage areas. The following are brief summaries of these selected research projects.

- Our earliest tests were for compacted urban soils, where we measured infiltration rates for clayey and sandy soils *in-situ* at different levels of compaction and moisture (Pitt, *et al.* 1999). We quantified the detrimental effects of compaction and moisture for different soil textures. Obviously, any of the severely compacted soils had much smaller infiltration rates, compared to uncompacted soils, with compacted sandy material having more infiltration capacity than compacted clayey soils. These initial field tests were supplemented with laboratory column tests that examined a wider range of soil materials with specified compaction and density levels (Sileshi 2013). Besides a range of typical soil textures, he produced specific mixtures of fine to coarse sands at known textures and uniformities for different compaction levels. For the coarser material, more homogeneous materials withstood compaction and had much less detrimental effects on infiltration than materials having a broad size range of material: as the uniformity coefficient increased (greater mixture of different particle sizes), infiltration rates greatly decreased. Again, for the coarser materials (pea gravels and coarse gravels), compaction was not as important as for the finer textures, while uniformity was very important. Obviously, "clean" gravels barely hindered flow at all and compaction had no effect on its density or infiltration rates. Eppakayala (2015) conducted double ring infiltration tests at an industrial site's non-paved storage areas. The soil was covered with a thin/spotty layer of gravel and highly compacted. He was not able to measure any infiltration capacity at any of the several locations he tested in the storage areas. However, non-compacted native soil indicated infiltration rates as expected based on the textures and densities.

- Detailed field and laboratory tests were conducted on pavement subgrade base materials during a study that examined the role of high edge drains on rigid (concrete) and flexible (asphalt) pavement structures (Pitt and Durrans 1995). This subgrade material is similar to the material placed at unpaved parking and storage areas. We instrumented a number of highway sections with moisture sensors directly beneath the pavement in the subgrade base material, and deeper in the base material, and along the highway shoulders. These continuous moisture measurements were used with rainfall measurements to calibrate edge drain one- and two-dimensional drainage models. Calibration was challenging as the assumed flows through the subgrade base material was much poorer than expected. The compacted material was well graded (having a wide range of particle sizes and a substantial amount of the intermediate particle sizes) and laboratory and *in-situ* infiltration tests indicated almost zero infiltration rates. Laboratory permeability tests were conducted on harvested base material with varying sizes of fines removed. As expected, the permeability increased dramatically with the removal of the fines from the base materials, as also shown in prior studies.

- A number of our urban watershed stormwater monitoring projects had various amounts of nonpaved parking and storage areas, although we have not monitored these areas by themselves (except by manual sheetflow quality sampling during rains or snowmelt) (Pitt 1999; Pitt 2014; Eppakayala 2015; and Pitt, *et al.* 2016). During model calibration processes, we have found that these nonpaved areas have similar hydrologic behavior as flat roofs; they have similar (moderate) initial abstractions and no infiltration.

In summary, nonpaved areas have a wide range of infiltration characteristics. Urban soils are greatly affected by compaction, while coarse materials are mostly affected by the uniformity of the material. Typical gravel parking and storage areas are well-graded, having a wide range of particle sizes represented. They are also greatly compacted. They therefore have poor infiltration capacities, but can have moderate initial abstractions affecting the runoff amounts. Coarse materials that are poorly graded ("clean"), can have very high infiltration rates. Highway subgrade drainage layers, in contrast, are usually well-graded (unless used beneath porous pavement) and heavily compacted with little infiltration capacity.

The following are excerpts from the various reports referenced above. The full reports are also attached.

Report Excerpts

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.

The following are excerpts from a summary paper of this EPA report and later supplementary tests.

Pg 1. 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.

Pg 2. 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 soilwater 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.

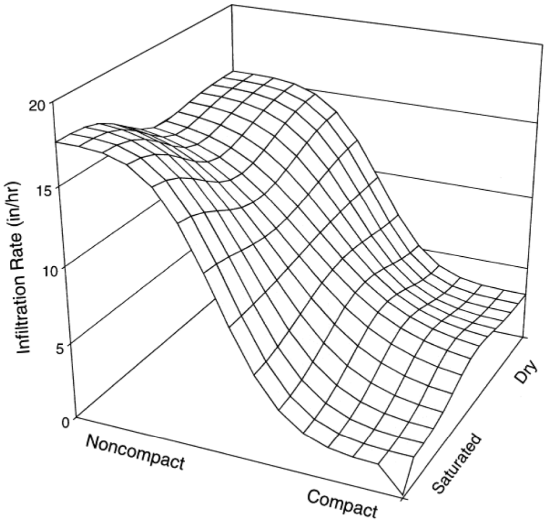


Figure 1. Three dimensional plot of infiltration rates for sandy soil conditions.

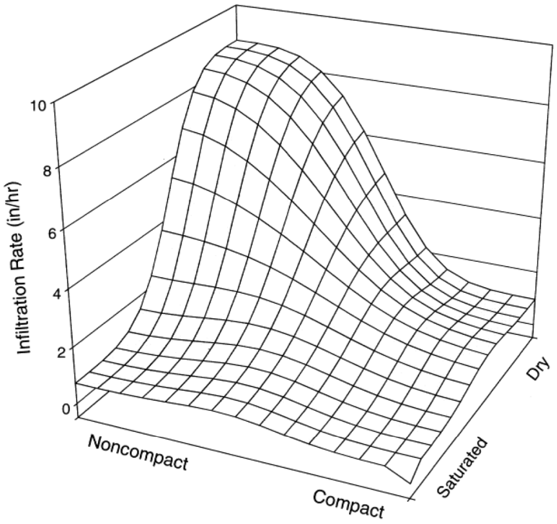


Figure 2. Three dimensional plot of infiltration rates for clayey soil conditions.

Pg 3. 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

Pg 5. 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.

Pitt, R. and S.R. Durrans. Drainage of Water from Pavement Structures. Alabama Dept. of Transportation. 253 pgs. September 1995.

Pg 2-2
2.3 Previous Infiltration/Percolation Studies
Unfortunately, impervious area runoff loss estimates, and especially pavement infiltration, are assumed to be much more accurate than warranted. When extensive field studies have been conducted simultaneously with modeling efforts, major differences in "actual" and modeled infiltration parameters have been noted (Pitt, 1987). Current prediction methods used to estimate the amount of water infiltrating into pavements have serious problems.

Pg 2-6
2.4 Previous Pavement Drainage Studies
Water that infiltrates into a pavement either through cracks and joints, or through the asphaltic layer itself, will move through the various layers making up the pavement structure and the underlying natural sub grade materials. The actual movement of the infiltrated water is quite complicated as there are several different layers of porous media involved, the flow is often unsaturated in some or all of the layers, and the flow may in some cases be affected by thermal conditions and evaporation.

One of the earliest studies performed to study the movement of water in pavement structures was performed by Cedergren (1956), who applied classical flow-net types of techniques to solve idealized problems of steady-state flow in saturated soils and roadway bases.

Pg 4-2
4.3 Field Pavement Infiltration Tests
Numerous field tests of in-situ infiltration rates were conducted in order to supplement the above laboratory tests. These tests allowed pavement observations of infiltration rates for a variety of highway conditions, specifically the effects of small and large cracks.

Pg 5-1
5.1 Overview
The previous two sections of this report have focused on the collection of data and on the physical effects related to the amount of water that will enter a pavement structure. It is the purpose of the

present section to discuss mathematical modeling that has been performed with respect to the prediction of the movement and fate of that water once it has entered the aggregate and soil sublayers in the pavement structure. The present section also discusses efforts that were performed to instrument and monitor rainfall and base course saturation conditions at several locations in the Birmingham metropolitan area.

Pg 5-11

5.4 1-Dimensional, Event-Based Simulations

As noted in Section 5.3, the computer code entitled SUBDRAIN (McEnroe and Zou, 1993) was employed in this study for I-dimensional analyses of the drainage of an initially fully saturated base course layer. An illustration of the pavement and base course geometry that is inherent to the SUBDRAIN modeling code is shown in Figure 5.3. It is assumed for simulation purposes that the phreatic surface is initially coincident with the plane of the interface between the top of the base course and the bottom of the pavement, and the simulation of the drainage of the layer proceeds through time until further drainage is not possible. It is assumed by the program that both the pavement and the subgrade underlying the base course are impermeable.

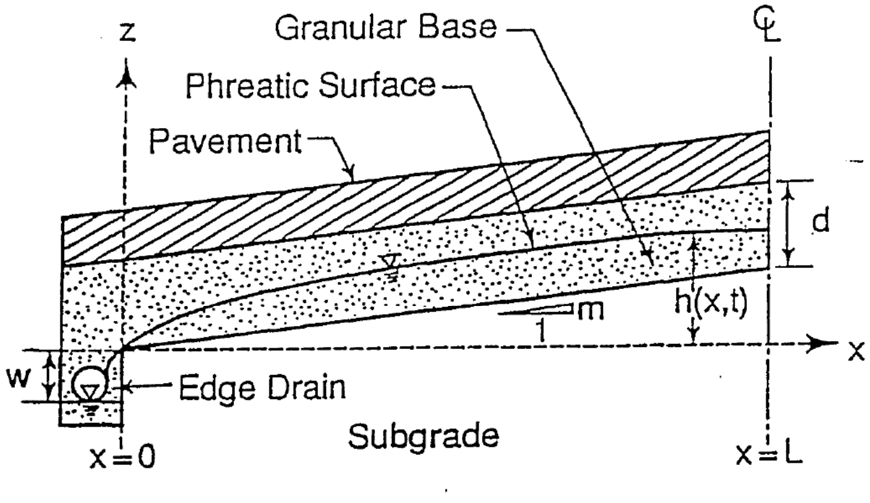


FIGURE 5.3
Pavement Cross Section as Used in Program SUBDRAIN
(Source: McEnroe and Zou, 1993)

Pg 5-15

5.4.2 Edge Drain Effects. To see how the presence of edge drains affects the base course drainage characteristics, SUBDRAIN was again executed with the same parameter values as shown in Figure 5.4, except that the edge drain depression distance w (see Figure 5.3) was taken to be 12 inches. Results that were obtained in this case are:

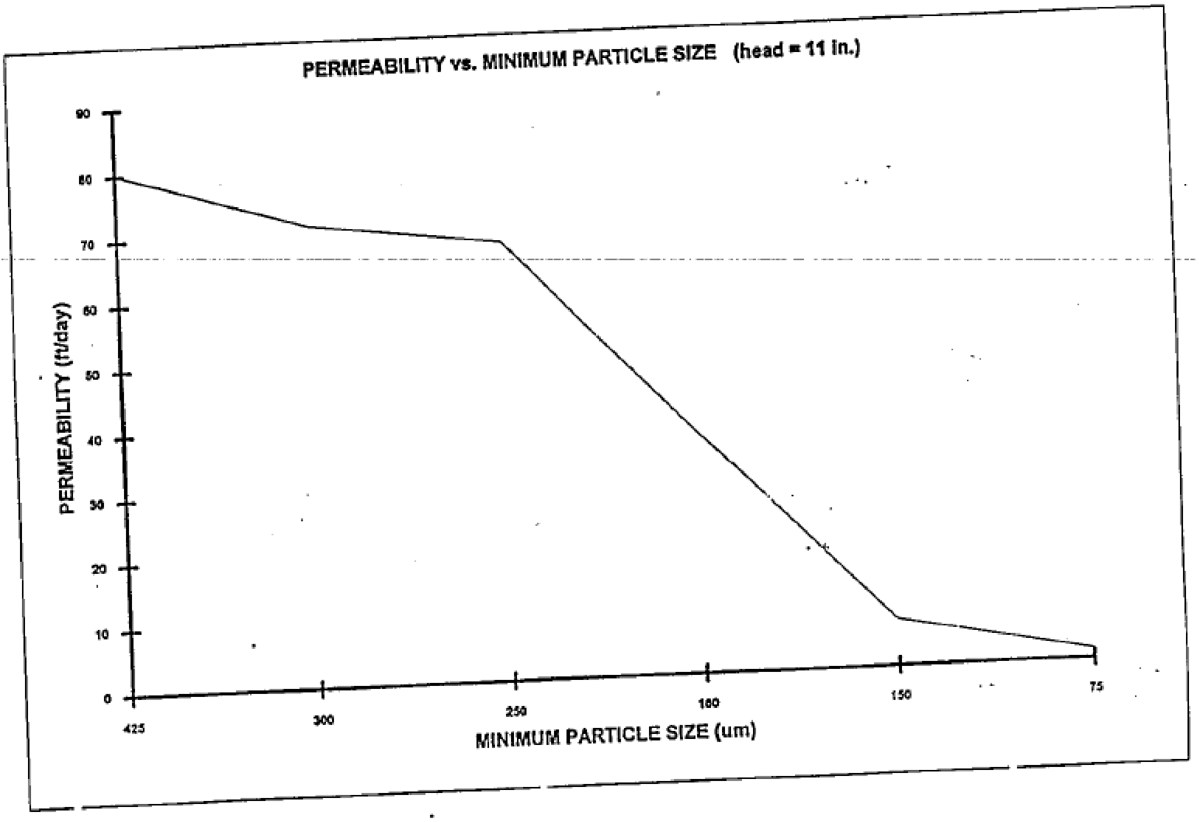
Minimum saturation after prolonged gravity drainage: 20.2 percent
Elapsed time to reach 85 percent saturation: 3.1 hours
Elapsed time to attain 50 percent drainage: 18.0 hours

Pg 5-41
5.7.1 Laboratory Measurements of Highway Base (Drainage Layer) Material UAB's soil testing laboratory was used to analyze permeability of some typical construction materials. However, the in-situ determinations will be the most accurate. Cedergren (1974) has found that permeabilities of typical pavement structures vary over a broader range than most any other engineering parameter, and are usually over-estimated. This supports the reliance on actual field measurements as much as possible in this proposal. Various soil tests (sieve analyses, porosity, residual moisture content; and permeability) were conducted on the limestone aggregate drainage layer material to determine values of these parameters which affect subsurface drainage.

Pg 5-43
As expected, the material having more fines had a greater moisture retaining capacity. Removing the fines reduced the capillary forces that could hold the water, with about a 25 percent improvement in gravity drainage.

Constant head permeability" tests were conducted to determine the permeability constant of the drainage layer material for use in the modeling procedure. The permeability was found to be 18.2 m/day (60.1 ft./day) at 20^0 C. These permeability tests were conducted many times using a variety of heads. After these tests were completed, fine particles were systematically removed from the samples, and permeability tests were again conducted, as shown on Figures 5-31 and 5-32. The permeability testing Procedure began by-placing-a-compacted sample of drainage layer material in a Soiltest CN-405 Permeameter and attaching it to a large Soiltest CL - 278E Reservoir. The valve between the reservoir and the permeometer was then opened, allowing water to flow into the permeometer. A bleed valve was opened to allow saturation and escape of air from the sample. Upon saturation, the bleed valve was closed, and one minute was allowed for steady state flow to be established through the sample. Once steady state was achieved, several measurements of water exiting the permeometer were taken and the average flow rate was calculated. Once the average flow rate was known, the permeability constant for the material was calculated by dividing the average flow rate by the cross-sectional area of the soil sample.

Figure 5-31. Permeability Changes when Removing Fine Particles



Pg 5-46
5.7.2 Continuous Moisture Measurements at Test Sites
This work element directly examined pavement drainage times and percentage moisture levels for typical types of Alabama highway locations. The continuous moisture measurements were made at four locations representing areas having edge drains and areas not having edge drains, and having and not having known drainage problems. All of these tests were conducted on flexible pavement sites. These tests represented a 2^3 complete factorial experimental design (Box, et al. 1978) and were analyzed using Design-Ease (Stat-Ease, Minneapolis, Mn).

Pg 5-48
Each site was monitored using a tipping bucket rain gauge (Weather Measure model 6011), three electronic moisture sensors (AquaTel 29 from Global Water) and a continuously recording data logger (UL 16 from Global Water). Base material moisture, sub grade moisture, and rain were recorded every five minutes. Two of the moisture sensors were located in the outside lanes of the test areas and were placed beneath the pavement and about 50 mm above the bottom of the crushed limestone base layer

or about 0.5 m (18 inches) below the pavement surface. Two sensors were used to obtain redundant data in order to measure the consistency of the moisture levels and to have a back-up in case one of the sensors was damaged (as happened at the H-79 good site).

After the moisture sensors were placed, new base material was carefully placed to the bottom of the pavement layer and pavement patching material was packed to the pavement surface. Three different surface patching methods were used because of problems in permanent sealing of the disturbed pavement surfaces. Loop sealant was initially used to seal any cut seams and the surface of the asphalt patch. However, this did not hold up for more than a few weeks. An epoxy sealant was then used for the top 10 mm of patch which worked very well, especially after being overcoated with a pavement adhesive tape along the long cracks.

The third moisture sensor was placed on the roadway shoulder at a depth equal to the bottom of the base material. This sensor was placed in sub grade material and was used to indicate the presence of shallow local groundwater that may· infiltrate upwards into the base material.

Pg 6-5
It may be observed from these discussions that the drainage conditions revealed by the field studies are opposite to what was initially expected based on observed roadside moisture levels and pavement repair problems at the sites. Reasons for this cannot be currently explained, but may be related to site-specific groundwater and/or temperature conditions.

Pg 6-6
Numerical modeling that was performed in this project has provided results that are qualitatively, but not quantitively, similar to those obtained as a result of the field and laboratory tests. Two types of event-based numerical simulations have been accomplished (I-dimensional and 2-dimensional) to study base course layer drainage times, and I-dimensional continuous simulations have also been performed to study the behavior of subsurface moisture on a continuous time basis as well.

The saturation results of the I-D continuous simulations, while not very consistent with the actual field measurements of moisture levels, do display the same qualitative behavior. Namely, there tends to be a rise in moisture level when rainfall occurs, and the moisture level then recedes during inter-event periods. The moisture level as modeled never drops below a certain minimum degree of saturation, whose value depends on the pavement geometry and the hydraulic properties of the base course material. A comparison of the model results shown in Figure 5.27 with the actual rainfall and moisture data collected for the field monitoring sites shows that the model tends to show a much more certain and predictable rise in moisture at the beginning of rainfall events. The recession of moisture as reflected by the model is also, much smoother and consistent than the frequently "bumpy" nature displayed by the field data. These differences are likely due to the fact that while the model assumes that the base course layer is nice and homogeneous, there is in reality an existence of heterogeneity and preferential pathways in the layer. As noted earlier, there are also heat effects which should be considered (at least in some cases), and there is almost certainly some air-trapping that occurs when rainfall events provide the water for infiltration.

Sileshi, Redahegn. Soil Physical Characteristics Related to Failure of Stormwater Biofiltration Devices. Ph.D. Dissertation. Department of Civil, Construction, and Environmental Engineering. The University of Alabama. Tuscaloosa, AL. 707 pgs. 2013.

Pg iii A controlled laboratory column tests conducted using various media to identify changes in flow with changes in the mixture characteristics, focusing on media density associated with compaction, particle size distribution (and uniformity), and amount of organic material (due to added peat).

The results of this research indicated that soil compaction has dramatic effects on the infiltration rates;

Pg 249 7.2.1 Laboratory Column Flow Tests
The effects of different compaction levels on the infiltration rates through various sand-peat mixtures, and soil, were examined during laboratory column testing in The University of Alabama environmental engineering laboratories. A Four inch (100 mm) diameter PVC pipe (Charlotte Pipe TrueFit 100 mm PVC Schedule 40 Foam-Core Pipe) purchased from a local building supply store in Tuscaloosa, AL was used to construct the columns for these tests. Laboratory columns, each 3 ft (0.9 m) long, were constructed as shown in Figure 112. The columns were filled with about 2 inches (5 cm) of cleaned pea gravel purchased from local suppliers. To separate the gravel layer from the media layer, a permeable fiberglass screen was placed over the gravel layer and then filled with the different media listed in the previous section. The media layer was about 1.5 ft (0.5 m) thick. The bottom of the columns had a secured fiberglass window screen to contain the media.

Three levels of compaction were used to modify the density of the media in the columns during the tests (Figure 113): hand compaction, standard proctor compaction, and modified proctor compaction. Both standard and modified proctor compaction follow ASTM standard (D 1140-54). The standard proctor compaction hammer is 24.4 kN and has a drop height of 12 in (300 mm). The modified proctor hammer is 44.5 kN and has a drop height of 18 in (460 mm). For the standard proctor setup, the hammer is dropped on the test media 25 times on each of three media layers, while for the modified proctor test, the heavier hammer was also dropped 25 times, but on each of five thinner media layers. The modified proctor test therefore results in much more compacted media, and usually reflects the most compacted soil observed in the field. Hand compaction is done by gently hand pressing the media material into the test columns with as little compaction as possible, but with no voids or channels. The hand compacted media specimens therefore have the least amount of compaction. The densities were directly determined by measuring the weights and volume of the media material added to each column.

Figure 112. Lab Column Infiltration Tests (Left To Right): Bottom of the Columns Secured with a Fiberglass Window Screen (Upper Left), Biofilter Media (Lower Left), and Media Compaction.

The infiltration rates through the mixture media were measured in each column using municipal tap water. The surface ponding depths in the columns ranged from 11 - 14 inches (28 - 36 cm), generally corresponding to maximum ponded water depths in biofilters. The freeboard depths above the media to the top of the columns were about 2 - 3 inches (50 - 75 mm). Infiltration rates in the media were determined by measuring the time it took the infiltrated water to fill known volumes in the containers under the columns. These measurements were conducted every several minutes and repeated until apparent steady state infiltration rates were observed. The laboratory column setups for the infiltration measurements in the different media are shown in Figure 113.

Figure 113. Laboratory Column Setup for Infiltration Measurements.

Pg 304. Similar tests were conducted using the coarse media and for low and high solids concentrations, as summarized in Table 100. These results show that the effluent concentrations are larger than the influent concentration for many columns, indicating continued releases of fine silts from these materials, even after the extensive media washing before the tests. Tests were conducted using two different controlled flow rates, as uncontrolled flows would be very high for these coarse materials. The orifices used to reduce the flows corresponded to the likely range of conditions associated with underdrains that are used with these materials. Table 101 shows flow rates through the coarse media for low and high concentrations. Figure 139 show the simple SSC line performance plots of these controlled tests for the two different solids concentrations and two different flow rates. These line plots illustrate the poor particle retention for these coarse materials.

Table 100. Laboratory Column Coarse Media (average concentrations)

	Influent	Effluent			
		0.25 inch dia. orifice and pea gravel	1 inch dia. orifice and pea gravel	0.25 inch dia. orifice and coarse gravel	1 inch dia. orifice and coarse gravel
	Low Concentration Tests				
SSC (mg/L)	57	199	164	101	95
TDS (mg/L)	119	134	114	120	118
Turbidity (NTU)	24	21	24	30	21
Conductivity (µS/cm)	139	158	161	156	157
	High Concentration Tests				
SSC (mg/L)	439	712	899	642	693
TDS (mg/L)	159	166	141	131	152
Turbidity (NTU)	94	183	202	173	189
Conductivity (µS/cm)	205	209	208	203	205

Table 101. Approximate Flow Rates through the Coarse Media for the Different Tests

Solid concentration (mg/L)	Trial	Pea gravel		Coarse gravel	
		0.25 in orifice dia.	1 in orifice dia.	0.25 in orifice dia.	1 in orifice dia.
		Q (L/s, gal/min)	Q (L/s, gal/min)	Q (L/s, gal/min)	Q (L/s, gal/min)
Low	1	0.29 (4.66)	0.29 (4.76)	0.29 (4.66)	0.38 (6.05)
	2	0.35 (5.55)			
High	1	0.39 (6.16)	0.39 (5.55)	0.39 (6.16)	0.32 (5.04)
	2	0.35 (5.55)	0.32 (5.04)	0.32 (5.04)	
	3	0.32 (5.04)	0.35 (5.04)	0.35 (5.55)	

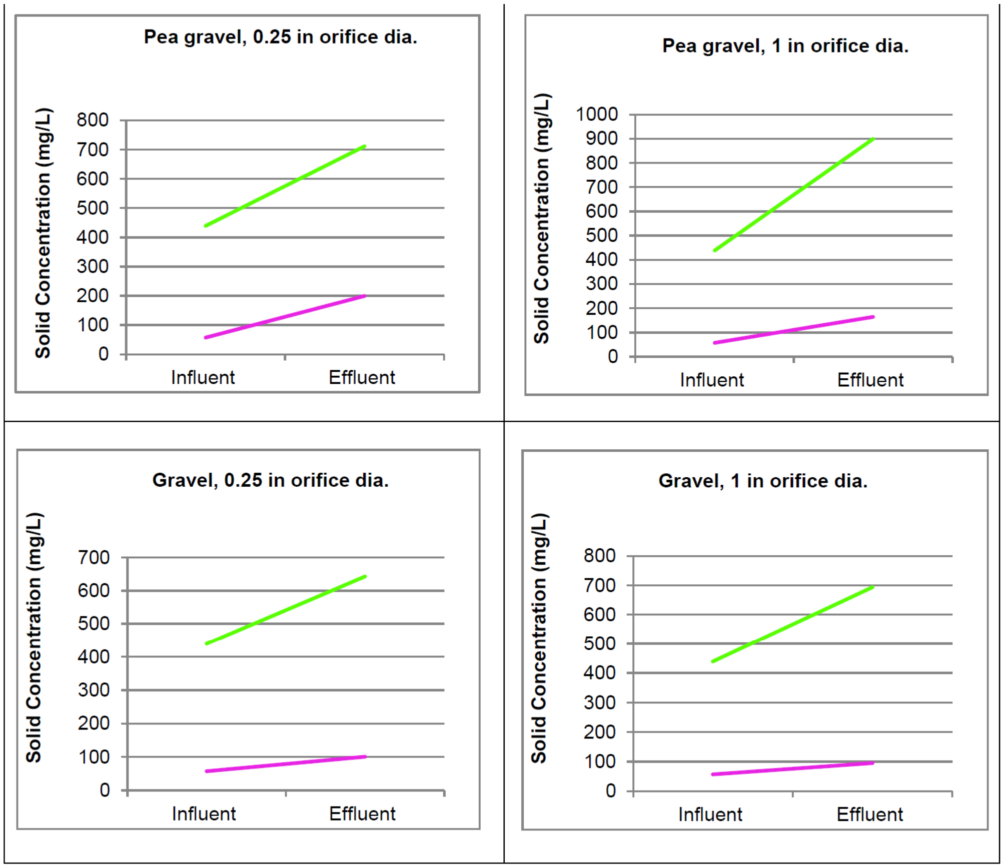


Figure 139. Controlled Lab Column SSC Test Results for Coarse Media

Pg 309. Table 103 shows descriptions of the coarse media used during the tests. A one-way ANOVA test was conducted to determine whether group influent and effluent means were significantly different from one another. If the ANOVA test results indicated that there was no statistical difference in the mean values, the mean values from the different groups were combined and a one-way ANOVA tests was repeated. The one-way ANOVA test for the low solids concentration tests indicated that there were no statistically significant differences between the effluent SSC values from lab columns 1, 2, and 4. These mean values were combined and a one-way ANOVA test was conducted again. Table 104 shows a statistical summary for the final combined results. The one-way ANOVA results for the high solids concentration tests indicated that there were no statistically significant differences between the effluent SSC values from lab columns 1, 2, 3, and 4. Detailed calculation results are attached in the Appendix G.

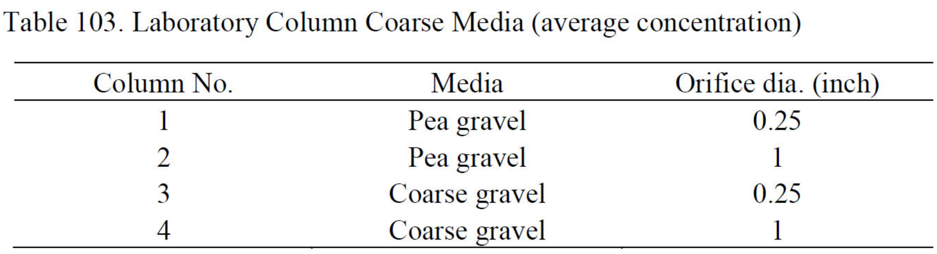


Table 103. Laboratory Column Coarse Media (average concentration)

Column No.	Media	Orifice dia. (inch)
1	Pea gravel	0.25
2	Pea gravel	1
3	Coarse gravel	0.25
4	Coarse gravel	1

Pg 330. The results of the full-factorial analyses of infiltration and particulate trapping with a wide range of sand mixtures indicated that texture and uniformity of the media mixture have the greatest effect on the measured final infiltration rates of the media, followed by interactions of texture and uniformity; compaction; interactions of texture and organic content of the material; and interactions of uniformity and organic content of the material. The organic matter in the biofilter media did not have a significant effect by itself on the infiltration rate compared to the other factors (texture, uniformity, and compaction). However the organic matter serves as a reservoir of nutrients and water in the biofilter media and increases water infiltration into the media.

Compaction did not significantly affect the infiltration rates for the mixtures having large amounts of sand and little peat; however infiltration studies conducted previously indicated that compaction significantly affected typical soil infiltration rates having normal organic content, especially if high in fines (Sileshi et al., 2012a). These test results also indicated that the infiltration rates through all sand-peat mixture columns were greater than the infiltration rates through only soil media for the three levels of compaction (modified proctor, standard proctor and hand compaction). However, mixing the soil media with filter sand or peat improved the infiltration capacity of the media and also reduced the impact of compaction on the infiltration rates. Soil compaction has dramatic effects on the infiltration rates of most underlying soils; therefore care needs to be taken during stormwater treatment facilities construction in urban areas to reduce detrimental compaction effects. Overall, mixing the soil media with filter sand or peat improved the infiltration capacity of the media and also reduced the impact of compaction on the infiltration rates.

Also pg 646 to 663 for appendix info on gravel tests

Pitt, R. "Small storm hydrology and why it is important for the design of stormwater control practices." In: Advances in Modeling the Management of Stormwater Impacts, Volume 7. (Edited by W. James). Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press. 1999. Pp 61 – 91.

Pg 26. Volumetric Runoff Coefficients
Table 5 is a summary of the volumetric runoff coefficients (Rv, the ratio of runoff to rainfall volume) for different urban surfaces and rain depths from detailed source area runoff tests and through calibrating the general runoff model (Pitt 1987). Flat roofs and unpaved parking areas behave strangely similar because of similar detention storage volumes and no infiltration. Large impervious areas have the largest runoff yields because of very poor pavement under-drainage. The drainage path through the

pavement base is relatively thin and very long, making it very difficult for infiltrated water to drain from the base. Street widths are much narrower than the widths of large impervious areas and the base water can drain much more effectively. Pitched roofs have no infiltration rates, but do experience limited initial losses associated with flash evaporation and sorption of moisture in leaves and other roof or gutter debris. After three inches (no longer a "small" rain) the runoff yields from all impervious surfaces are similar (within 10%), but the differences can be very large for the small rains of most concern in water quality evaluations.

Table 5. Summary of Volumetric Runoff Coefficients for Urban Runoff Flow Calculations (Pitt 1987).

Runoff Coefficients for Directly Connected Areas:

Rain Depth		Flat roofs* (or large unpaved parking areas)	Pitched roofs*	Large impervious areas*	Small impervious areas and streets	Sandy soils	Typical urban soils	Clayey soils
mm	inches							
1	0.04	0.00	0.25	0.93	0.26	0.00	0.00	0.00
3	0.12	0.30	0.75	0.96	0.49	0.00	0.00	0.00
5	0.20	0.54	0.85	0.97	0.55	0.00	0.05	0.10
10	0.39	0.72	0.93	0.97	0.60	0.01	0.08	0.15
15	0.59	0.79	0.95	0.97	0.64	0.02	0.10	0.19
20	0.79	0.83	0.96	0.97	0.67	0.02	0.11	0.20
30	1.2	0.86	0.98	0.98	0.73	0.03	0.12	0.22
50	2.0	0.90	0.99	0.99	0.84	0.07	0.17	0.26
80	3.2	0.94	0.99	0.99	0.90	0.15	0.24	0.33
125	4.9	0.96	0.99	0.99	0.93	0.25	0.35	0.45

*If these "impervious" areas drain for a significant length across sandy soils, the sandy soil runoff coefficients will usually be applied to these areas, however, if these areas drain across clayey soils, the runoff coefficients will be reduced, depending on the land use and rain depth, according to the following table:

Reduction factors for different rain depths (mm):

	1	3	5	10	15	20	30	50	80	125
Strip commercial and shopping centers:	0.00	0.00	0.47	0.90	0.99	0.99	0.99	0.99	0.99	0.99
Other medium to high density land uses, with alleys:	0.00	0.08	0.11	0.16	0.20	0.29	0.46	0.81	0.99	0.99
Other medium to high density land uses, without alleys:	0.00	0.00	0.11	0.16	0.20	0.21	0.22	0.27	0.34	0.46

If low density land uses, use clayey soil runoff coefficients.

The impervious and roof area values are for directly connected surfaces. If runoff is allowed to drain across grass areas, then the runoff yield may significantly decrease. However, sufficient length of drainage across the pervious surface in good condition is needed. For a relatively small paved surface, short pervious drainage paths are all that are needed. If the paved area is large, or if the pervious area has clayey or compacted soils, then much longer drainage paths are needed before significant infiltration occurs.

Table 5 does not accurately incorporate the effects of disturbed urban soils presented earlier, but the runoff coefficients shown generally bracket the range of likely conditions expected. Some users have had good success using an intermediate soil Rv value, half way between the clayey and sandy soil conditions shown, and only using the extreme values for more unusual cases. The four urban soil categories identified earlier better represent the conditions encountered, and appropriate coefficients are currently being developed.

The runoff coefficients and indirect connection correction values were determined from calibrating the small storm hydrology model for large urban watersheds having variable complexities in Toronto and in Milwaukee (Pitt 1987). The first calibrations were conducted for simple areas. The first area was the large parking area of a commercial shopping area. The runoff coefficients for this area were used to determine the runoff relationships from large flat roofs from another shopping area that was made of mostly paved large parking and roof areas in order to determine runoff characteristics for flat roofs. The next step was to evaluate runoff data for two high density residential areas that had very little pervious areas and had all of the impervious areas directly connected. The street runoff was subtracted from the total area runoff observations to obtain information solely for pitched roofs. Finally, two medium density residential areas were studied in areas that had clayey soils and all of the impervious areas were directly connected. Roof, street and other impervious area runoff information was subtracted to obtain clayey soil runoff coefficients. Similarly, a medium density residential area was studied in an area having sandy soils to obtain sandy soil runoff coefficients. Finally, two medium density residential areas having unconnected impervious areas were studied to obtain correction coefficients.

Pitt, R., S.E. Clark, V. Eppakayala, and R. Sileshi. 2016. Don't Throw the Baby Out with the Bathwater – Sampling Collection and Processing Issues Associated with Particulate Solids in Stormwater. 49th International Conference on Water Management Modeling. Toronto, Ontario. Computational Hydraulics International. February 24-25, 2016.

Pg 13. Particulate Characteristics in Stormwater from a Heavy Industrial Site
The following discussion summarizes recent results from monitoring of a heavy industrial site in the southeast US focusing on particulate characteristics. These data were also compared to various rain characteristics in an attempt to explain some of the observed variability.

The site is a heavy industrial facility located in the southeastern United States (specific location and industry is client confidential). The 6 ha site is a heavy industrial land use having several buildings (galvanized metal roofs), driveways, loading docks, and highly compacted pervious areas. Almost all of the roofs and impervious areas are directly connected to drains, except for a few roofs draining directly to compacted soils. Land use characteristics of the site are as shown in Table 3.

Table 3. Detailed land use characterization of test site

	Industrial Land use (ha)
Roofs	
Roofs Flat - drains to asphalt/concrete	0.004
Parking/Streets/Sidewalks/Driveways	
Paved concrete parking/storage - smooth - directly connected	0.18
Driveways/loading dock -concrete- directly connected	1.94
Non-paved Areas	
Non-paved storage areas (compacted soils)	3.29
Open areas (dry pond)	0.29
Special Areas	
Galvanized metal roofs- directly connected	0.09
Galvanized metal roofs - drains to soil	0.17
Other galvanized materials- directly connected to drains	0.08
Total Area (acres)	6.05

Pg 21.

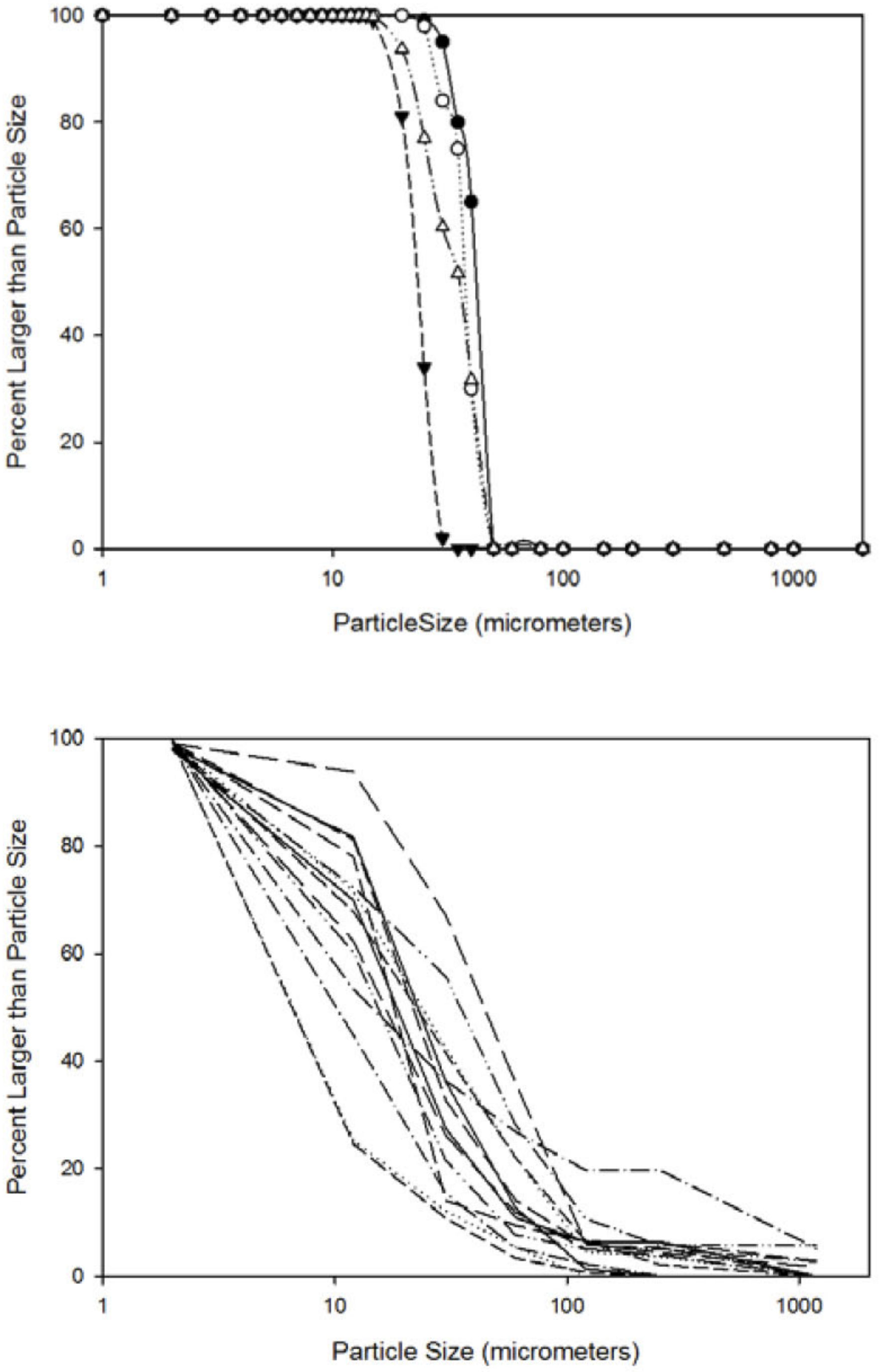


Figure 16. Non-paved parking and storage area runoff particle size distributions (for TSS shake and pour data on top; SSC below)

Pitt, R. The Use of WinSLAMM at Naval Bases to Predict Stormwater Pollutant Sources and to Identify Treatment Options. U.S. Navy, NESDI, SPAWAR Systems Center Pacific, San Diego, CA 92152. February 17, 2014. 211 pgs.

Pg 52. Land Development Characteristics at Norfolk, VA, Area Naval Facilities
Naval Amphibious Base Little Creek – Outfall 07
Little Creek Outfall 07 is located in the Naval Amphibious Base Little Creek. A complete data survey is available for this outfall describing the surface coverage and area of each surface type. Outfall 07 is comprised of industrial land use, with buildings and light to moderate laydown concrete and unpaved (but compacted) areas. The watershed area for this outfall is approximately 3 acres. This site has pervious areas accounting for 15% of the total watershed area. An aerial photograph of the watershed is shown in the following figure.

Pg 54.

Pg 56

Land Use Development Characteristics for Little Creek OF-07 (continued)

99 ONPIA11 - Light laydown unpaved - drains to soil	0
99 ONPA11 - Light laydown unpaved - drains to vegetation	0
100 ONPA12 - Moderate laydown unpaved - drains to soil	1.42
101 ONPA12 - Moderate laydown unpaved - drains to vegetation	0
102 ONPA13 - Heavy laydown unpaved - drains to soil	0
103 ONPA13 - Heavy laydown unpaved - drains to vegetation	0
Total Area (acres)	3.01

Pg 59. Land Development Characteristics at St. Juliennes Creek Annex

St Juliennes Creek Annex – Outfalls 40 and 41

St Juliennes Outfalls 40 and 41 are located in the St Juliennes Creek Annex. A complete data survey is available for this outfall describing the surface coverage, and area of each surface type. Outfalls 40 and 41 are comprised of industrial land use, with buildings, parking/storage areas, landscaping and light to moderate laydown concrete and unpaved areas. The watershed area for this outfall is approximately 26 acres. This site has pervious area (heavily compacted) accounting to 18% of the total watershed area. An aerial photograph, along with different land use characteristics are shown in the following figures.


03/28/2013


173-1
03/28/2013


06

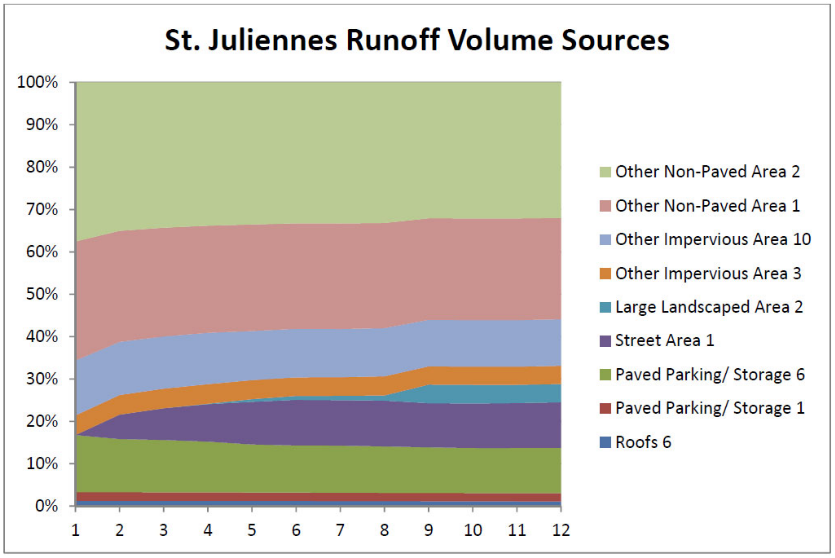
Pg 65.

99 ONPIA11 - Light laydown unpaved - drains to soil	0
99 ONPA11 - Light laydown unpaved - drains to vegetation	5.04

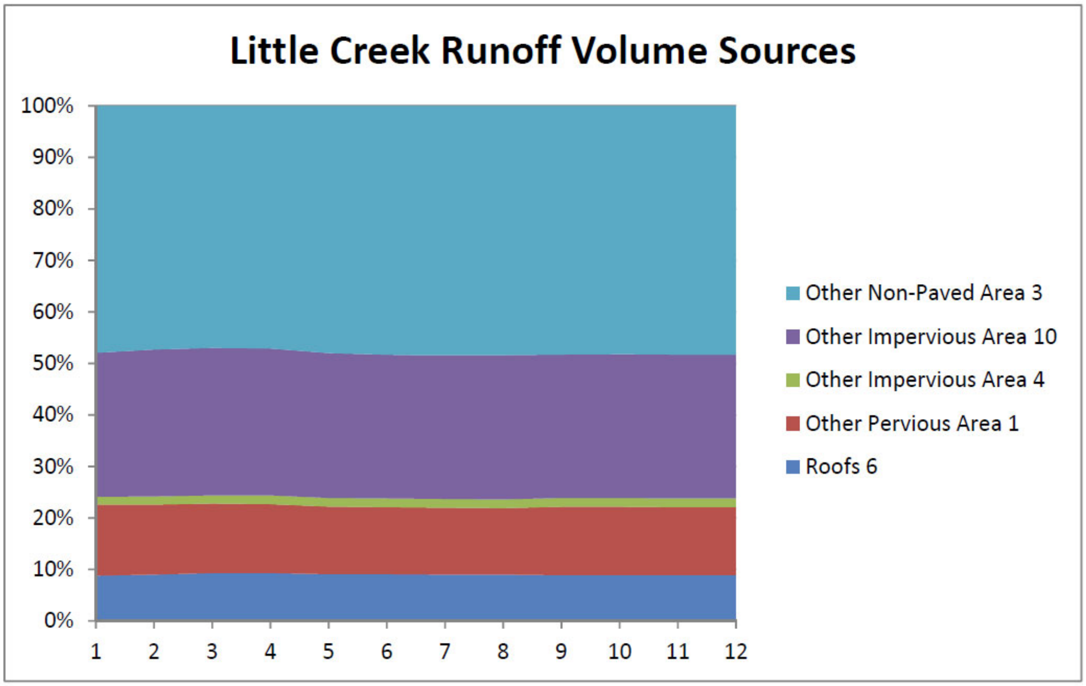
Land Use Development Characteristics for St Juliennes OF 40 & 41 (continued)

100 ONPA12 - Moderate laydown unpaved - drains to soil	6.74
101 ONPA12 - Moderate laydown unpaved - drains to vegetation	0
102 ONPA13 - Heavy laydown unpaved - drains to soil	0
103 ONPA13 - Heavy laydown unpaved - drains to vegetation	0
Total Area (acres)	25.52

Pg 127



Pg 129



Eppakayala, V.K. Performance Evaluation of Stormwater Treatment Controls at an Industrial Site. Ph.D. Dissertation. Department of Civil, Construction, and Environmental Engineering. The University of Alabama. Tuscaloosa, AL. 240 pgs. 2015.

Pg 135. 3.3.8 Infiltration Pond Characteristics
Field infiltration tests were conducted at six different locations in the pond to determine the dry pond infiltration characteristics. Turf-Tec infiltrometers were used to measure the infiltration rates in the dry pond (Figure 3-41). Infiltration tests were conducted using three infiltrometers placed within about 1m from each other to measure the variability of infiltration rates in close proximity. Water was added to the inner ring and allowed to overflow to fill up the outer ring. The decrease in the water level in the inner ring was measured for a period of 1 to 2 hours until a constant infiltration rate was observed. Additional water was added as the water level in the inner ring dropped to less than an inch of the ground surface to maintain continuous pooling of water. The infiltration rate was calculated as the rate of decline of the water level in the inner chamber. The rate of infiltration depends on several factors including hydraulic conductivity, soil structure, rain intensity, chemical nature of soils, depth to groundwater , etc. (Horton et al 1940, Chow et al 1998).

Pg 147. The test site is a heavy industrial facility located in the southeastern United States. The facility is approximately 21 acres in size, mostly covered with concrete, roofs, and severely compacted soils.

Pg 152. The soils in the dry pond showed moderate to high infiltration capacities. Variations of the final infiltration rates were observed in the infiltrometers placed about within a meter from each other and at different locations. This spatial variability in the dry pond was loosely correlated with the water path through the pond. Higher infiltration rates were observed at Locations 1, 3 (located towards pond side slopes) and 5 (outlet location of the pond). The dry pond system was not completely saturated during the infiltration tests and the measured infiltration rates only indicated the more favorable surface conditions. However, the pond infiltration rates were still high, and confirmed by runoff water losses monitored during actual rain conditions. In contrast, an infiltration test was attempted on the site’s surface soils, but the compaction was extreme and no infiltration was observed.