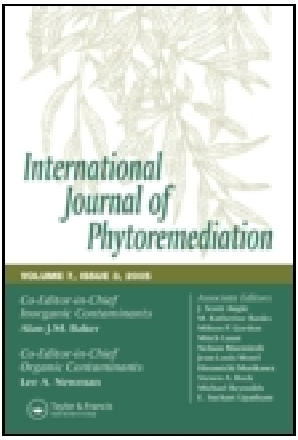

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SUSPENDED SOLIDS IN AND TURBIDITY OF RUNOFF FROM GREEN ROOFS

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Green roof technology is used to reduce the quantity of stormwater runoff, but questions remain regarding its impact on quality. This study analyzed the total suspended solids (TSS) in and the turbidity of runoff from green roof growth media mixed with composted pine bark in an indoor pot study. The results showed that there were elevated levels of TSS and turbidity in the runoff that decreased over time for all growth media. Both TSS and turbidity are affected by the type of growth media. Lava and haydite had higher mean TSS and mean turbidity than arkalyte and bottom ash. Vegetation reduced the mean turbidity and mean TSS of the first flush by an average of 53% and 63%, respectively, but generally had no statistically significant effect thereafter. The results indicate that the media, rather than the vegetation, has a greater effect on TSS and turbidity in the runoff. In areas with stringent water quality regulations for stormwater runoff from developed sites, media selection may be an important consideration. It may also be necessary in these regions to ensure that the roof is planted prior to receiving rainfall to minimize the first flush effect and that any irrigation does not result in runoff.

KEY WORDS: green roof, vegetated roof, turbidity, suspended solids, stormwater, water quality

INTRODUCTION

Green roofs are roofs that include vegetation by design. They use specific growth media that is lighter than topsoil, better drained, primarily inorganic, and capable of supporting good plant growth. Green roofs have been used since ancient times, but more recently, they have been widely reconsidered as a technique to reduce urban nonpoint source pollution and save energy. Nonpoint source pollution is a problem worldwide. It is the United States' largest water quality problem because it comes from many diffuse sources (USEPA 2010b).

Currently, green roofs' primary private benefits are considered to be increased roof longevity, offsetting impervious surface fees through reduced stormwater runoff, and decreased building energy consumption. They are also considered to have social benefits in urban areas, such as decreasing the urban heat island effect, reducing the stormwater

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runoff impact on sewer systems (particularly combined systems), and improving air quality. One study conducted to quantitatively integrate the range of stormwater, energy, and air pollution benefits of green roofs showed that the net present value (NPV) of an extensive green roof system was between 20.3% and 25.2% less than the NPV for a conventional roof over 40 years (Clark et al. 2008). Many studies have been conducted on the capabilities of green roofs to reduce the quantity of stormwater runoff (e.g., Carter and Rasmussen 2006; DeNardo et al. 2003; Mentens et al. 2006; Forrester 2007; Villarreal 2007; Woods et al. 2008; Richter et al. 2009; Richter 2010). The reduction varies, but for small rainfall events little or no runoff will occur. For storms of greater intensity and duration, a vegetated roof can significantly delay and reduce the runoff peak flow that would otherwise occur when using conventional roof design.

Less work has been done evaluating the quality of the stormwater runoff from green roofs. Because a green roof is a living system for which fertilizer is used, there are concerns about the nutrient load (nitrogen and/or phosphorus) of the runoff. Therefore, most studies related to runoff quality have focused on nutrients (e.g., Wu et al. 1998; Monterusso et al. 2004; VanWoert et al. 2005b; Hathaway et al. 2007; Moran et al. 2008). Woods (2010) found that the nitrate in the runoff from model built-in-place green roofs of various depths ranged from 3.0 ppm to 70.3 ppm over a 15-month period. The nitrate concentration from control roofs consistently remained below 4.0 ppm during the same time period, indicating that green roofs could impact water quality in terms of nitrate concentration. The growth media may also leach contaminants, such as heavy metals, which has been studied to a limited extent (e.g., Berndtsson et al. 2006; Alsup et al. 2010). Alsup et al. (2010) found in a pot leaching study of various growth media that they "would not likely be sources of Cr, Cu, Fe, Ni, or Zn" but that they "may be potential sources of Cd and Pb." However, heterogeneity in the media was a factor in their results.

Increasingly, turbidity and suspended solids levels in stormwater runoff are being regulated (Table 1). Suspended solids are defined as the particles that will not pass through a 2-micron filter. Total suspended solids (TSS) include clay particles, silt, fine organic debris, and other particulate matter that remain in suspension. Elevated concentrations of suspended solids affect the clarity of the water. In addition to causing a potential aesthetic concern, higher concentrations result in less light passing through water, which reduces the photosynthesis of aquatic plants, which in turn impacts the dissolved oxygen level and the aquatic life depending on the plants as a food source. Higher concentrations of suspended solids can also lead to rapid heating of the water, which might adversely affect aquatic life that has been adapted to a lower temperature (USEPA 1997). In addition, suspended solids can sorb toxins, such as heavy metals and pesticides, which readily cling to the particles' surfaces (Petavy et al. 2009; Voice and Weber 1983).

Turbidity specifically measures the clarity of the water. It is related to the scattering of light by suspended particles that cause water to have a cloudy appearance. Turbidity is an optical property of water that can be measured by a turbidity meter, or Nephelometer, as the intensity of light scattered at one or more angles to an incident beam of light (USEPA 2003a). Turbidity is mainly caused by suspended matter or impurities (such as clay, silt, and organic and inorganic matter). Excessive turbidity is aesthetically unappealing and could damage aquatic biodiversity. Even though turbidity is not a direct indicator of health risk, several studies had shown a strong relationship between removal of turbidity and removal of protozoa (USEPA 1999).

Therefore, due to the potential problems caused by suspended solids and turbidity and the subsequent increasing level of regulation of their levels in the environment, it is

Table 1 Examples of TSS and turbidity regulations

Location	Description	Regulated Level		Source
		TSS (mg/L)	Turbidity (NTU)	
Arizona, U.S.	Lakes with human contact		25	USEPA 2003b
	Cold water fishery		10	
Capital Regional District, Vancouver Island, CAN.	Discharges of prohibited waste, which includes colored water, into the municipal drainage system or a water course	75	50	CRD 2007
Delaware, Maryland, New Jersey, Pennsylvania, U.S.	Proposed developments in Coastal Zone Management area	Average 80% removal		Balascio and Lucas 2009
Florida, U.S.	Increase above natural background conditions		29	USEPA 2003b
Florida, U.S.	Proposed developments impacting surface waters designated as Outstanding Florida Waters	Reduced by 80% or 95%		Poulos 2009
Iowa, U.S.	Increase above natural background conditions		25	USEPA 2003b
London, Ontario, CAN.	Stormwater discharges into a storm sewer	15		Council of the City of London 2010
City of Gold Coast, Queensland, AUS.	Operational (post-construction) phase	80% removal		City of Gold Coast 2007
Queensland, AUS	Operational (post-construction) phase	75–85%[A]		Queensland 2009

[A] Reduction in mean annual loads from unmitigated development dependent on location.

important to evaluate the potential for green roofs to contribute to increasing suspended solids and turbidity levels in stormwater runoff. To this end, several hypotheses were tested. One, there will be elevated suspended solids and turbidity levels in the runoff from green roof media. Two, the levels will decrease over time. Three, the levels will vary with the type of media. And four, vegetation will reduce the level of suspended solids and turbidity in the runoff.

MATERIALS AND METHODS

Many kinds of green roof growth media are available. The four used in this study were arkalyte (clay heated to 1000°C), bottom ash (burned coal from a coal-fired power plant), haydite (shale or slate heated to 1000°C), and lava (volcanic rock). Most commercial green roof mixes contain either arkalyte or haydite in some proportion. Lava is an alternative to these heat-expanded aggregates and is often available in markets without haydite and arkalyte. Bottom ash is widely available from coal-fired power plants and is a potential alternative media. Alsup et al. (2010) studied the bottom ash used in this study and found that it slightly exceeded U.S. EPA recommended Water Quality Criteria for lead (~100–175 μg/L versus 65 μg/L) and cadmium (~3–4 μg/L versus 2 μg/L).

Figure 1 shows the average cumulative size distribution for each growth media based on the ASTM D-422 dry sieve analysis on three samples of each blended media (80% by volume inorganic media and 20% by volume composted pine bark). While similar overall, there are differences among the media. In particular, lava has a larger percentage of smaller particles, and bottom ash has a smaller percentage of mid-sized particles. Table 2 shows the results of a wet sieve analysis – washing each sieve until the water ran clear and then drying and reweighing. Results for all media except lava are based on a standard 1-hour drying time at 105°C. Because lava retained a greater amount of water, it was dried for a total of 4 hours. After each hour, it was weighed, and when the weights were similar at 4 hours, the test was stopped. As shown in Table 2, lava had the largest amount of fine particles, which is supported by the amount of visible dust associated with it. Lava also had the largest variation in results. The latter is likely due to its large water-holding capacity and the fact that it is the only growth media that has not undergone anthropogenic heat processing.

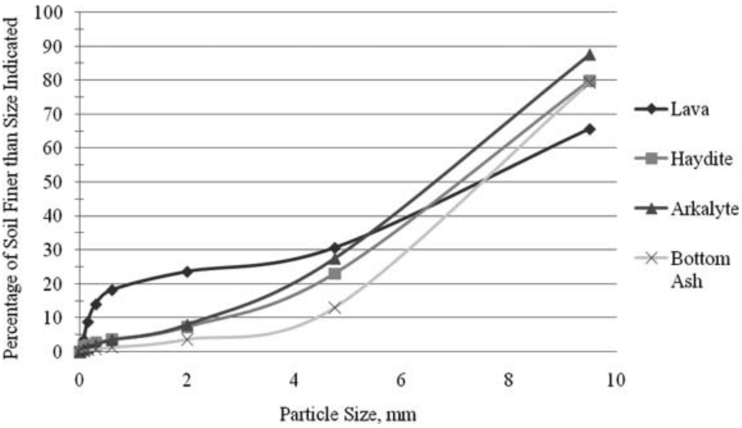

Figure 1 Cumulative growth media size distribution.

Table 2 Fines removed during wet sieve analysis of blended growth media

Blended Growth Media	Avg. Fines Removed[A] (g)	Std. Dev. (g)
Arkalyte	4.91	1.14
Bottom Ash	6.07	0.41
Haydite	6.70	0.52
Lava	40.25	11.23

[A] Fines are defined as particles smaller than 0.075 mm.

Screen material widely used in green roof construction to protect roof drains from clogging was placed in the bottom of 40 15-cm diameter pots prior to filling with the media to keep the media from flowing out of the drain holes. After blending with 20% by volume composted pine bark to provide a source of organics, each media was placed in five plastic pots to a depth of 10 cm and in five pots to a depth of approximately 5 cm. The latter pots were all planted with a mixed plug of five sedum species (*Sedum sexangulare, S. reflexum/rupestre, S. kamtschaticum, S. album, and S. spurium*) in October 2009 and filled with the blended media to a depth of 10 cm. The 72-count plugs were grown in a standard nursery propagation soil with a maximum dry growing volume of 71.9 cm^3. Because some soil was lost during planting, the plugs were estimated to occupy less than 5% of the total volume. Plants averaged 6 cm in diameter at planting. (Diameter measurements were made by averaging the measurement of the longest axis and the perpendicular axis of each plant. Diameters were used to calculate coverage directly based on the work of Forrester (2007).) Excess soil was not removed prior to planting in the pots to replicate conditions on green roof installations that use plugs. The plants were given 0.5 g of fertilizer (Nature Safe 5-6-6 Fine) at approximately 2 months and again at 2.5 months after planting. The planted pots are referred to as vegetated. The five pots of each media that were left unplanted are referred to as nonvegetated.

To control the amount and frequency of watering, the pots were placed in the Environmental Engineering Laboratory in the Engineering Building at Southern Illinois University Edwardsville located in Edwardsville, Illinois, USA in a completely randomized design. The room was kept at approximately 20°C. Because natural light was unavailable, three banks of four fluorescent bulbs each provided light for the plants 15 hours per day from planting in October 2009 through March 2010. The two middle bulbs in each bank were grow lights; the other two in each bank were regular fluorescent bulbs. The planted pots were placed so that the media surfaces were approximately 10 cm under the bulbs. The light intensity provided to the plants was measured as approximately 10% of the average full sun (noon) strength for the region and was deemed adequate to provide slow growth.

Initial experiments indicated that distilled water provided TSS and turbidity results closer to the region's rain water. Therefore, distilled water was used in all experiments. Based on the work of VanWoert et al. (2005a) and the recommendation of the nursery that supplied the plants, each pot was watered at approximately 15-day intervals. A shower head was used to deliver the water to each pot for a constant time of 2 minutes and a flow volume of 1 liter. Runoff samples were collected in 2-liter glass beakers beneath the pots and then transferred to 1-liter plastic bottles. They were tested immediately after collection for TSS and turbidity according to standard procedures described in APHA, AWWA, WEF (1998) (SM 2540 D and 2130 B, respectively). The first watering event used fresh media; subsequent watering events used the same media (i.e., the media was not replaced during the study). Runoff samples were collected at each watering event, beginning approximately 2 weeks after planting.

Two statistical analyses were used to evaluate the data. Differences between media were analyzed in SAS (v. 9.1) using a one-way ANOVA in a completely randomized design followed by a Tukey's post-hoc test to rank differences at an alpha level of 0.05. Differences between the vegetated and nonvegetated media were analyzed using the t-test at a significance level of 0.05. In addition, a power analysis was conducted using Minitab 16 Statistical Software.

RESULTS AND DISCUSSION

The power analysis for the comparison of the growth media indicated that for the majority of the watering events the power was high. For the turbidity results from the vegetated pots, the power ranged from 0.78 to 1.0, with an average of 0.98. Only one watering event, the fifth, was below 0.97. For the TSS results from the vegetated pots, the power ranged from 0.66 to 1.0, with an average of 0.94. Only two watering events, the second and fifth, were below 0.92. For the turbidity results from the nonvegetated pots, the power ranged from 0.92 to 1.0, with an average of 0.99. Only one watering event, the tenth, was below 0.98. For the TSS results from the nonvegetated pots, the power ranged from 0.63 to 1.0, with an average of 0.81. There were five watering events below 0.80. Therefore, on the whole, the results presented below can be considered accurate.

The power analysis for the comparison of the vegetated and nonvegetated pots indicated a large amount of variation in the power with most results having low power. For turbidity, the power ranged from 0.05 to 1.0, with the average ranging from 0.24 (haydite) to 0.60 (arkalyte). For TSS, the power ranged from 0.05 to 1.0, with the average ranging from 0.18 (haydite) to 0.43 (both arkalyte and bottom ash). Despite this difficulty, the results presented below provide useful comparative data.

Selected results from 15 watering events on vegetated pots and 11 watering events on nonvegetated pots are presented in Figures 2 to 7. Different letters indicate statistically different data at an alpha level of 0.05 based on the ANOVA analysis. As shown in Figures 2 and 3, the mean turbidity and mean TSS show slightly different initial results for

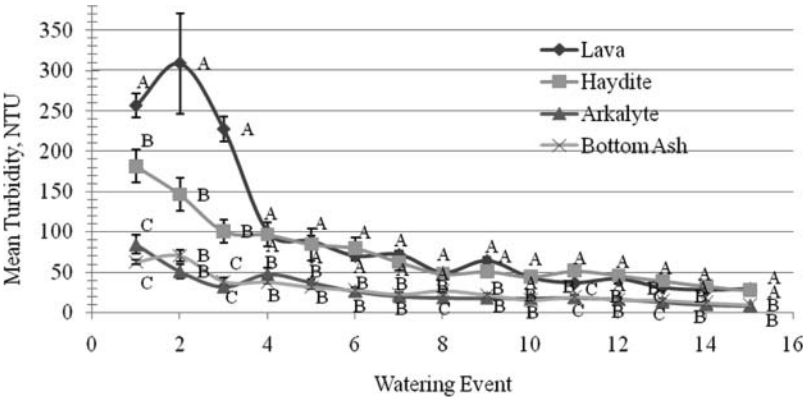

Figure 2 Mean turbidity in vegetated pots versus watering event. Letters that are the same indicate no statistical difference in a Tukey's post-hoc test to rank differences at an alpha level of 0.05. Bars indicate ±1 standard error.

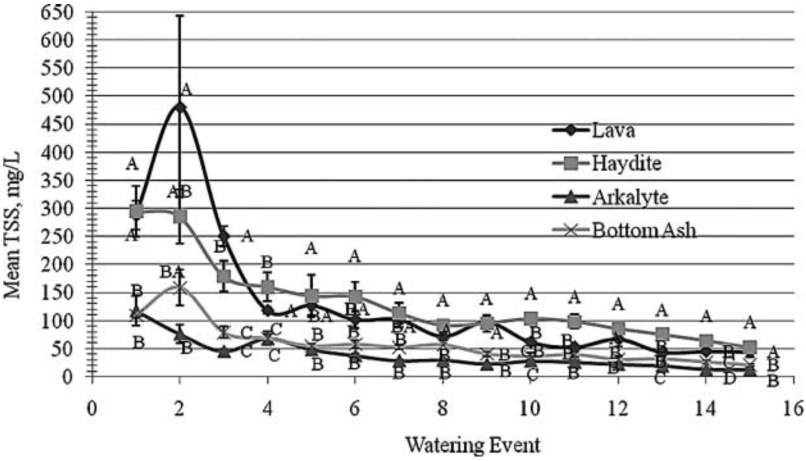

Figure 3 Mean TSS in vegetated pots versus watering event. Letters that are the same indicate no statistical difference in a Tukey's post-hoc test to rank differences at an alpha level of 0.05. Bars indicate ±1 standard error.

the vegetated pots, but they follow the same gradual downward trend. Similarly, Figures 4 and 5 show that both the mean turbidity and mean TSS from nonvegetated pots show a steep decline followed by a gradual leveling.

In general lava and haydite had the highest mean turbidity and mean TSS in both vegetated and nonvegetated pots while arkalyte and bottom ash had the lowest mean turbidity and mean TSS. Bottom ash consistently had the lowest initial mean turbidity and mean TSS value while arkalyte consistently had the lowest final value (Table 3). Haydite generally had the highest initial value while lava generally had the highest final value (Table 3). However, the differences between the initial and final values decreased over the watering events, i.e., the data converged. For example, the maximum difference in the mean turbidities in the vegetated pots dropped from 194 NTU to 21 NTU between the first and fifteenth watering events.

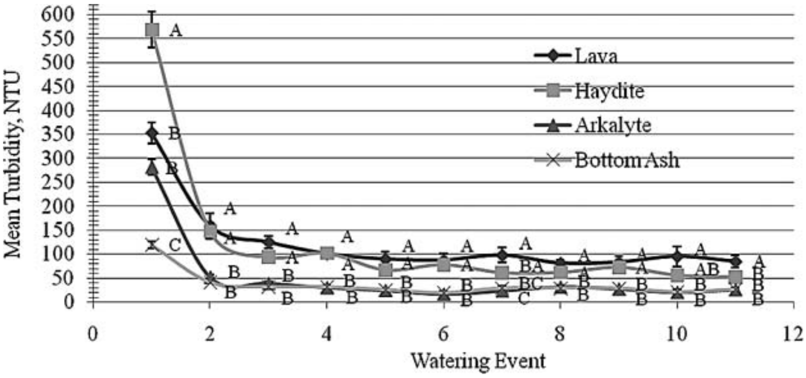

Figure 4 Mean turbidity for nonvegetated pots versus watering event. Letters that are the same indicate no statistical difference in a Tukey's post-hoc test to rank differences at an alpha level of 0.05. Bars indicate ±1 standard error.

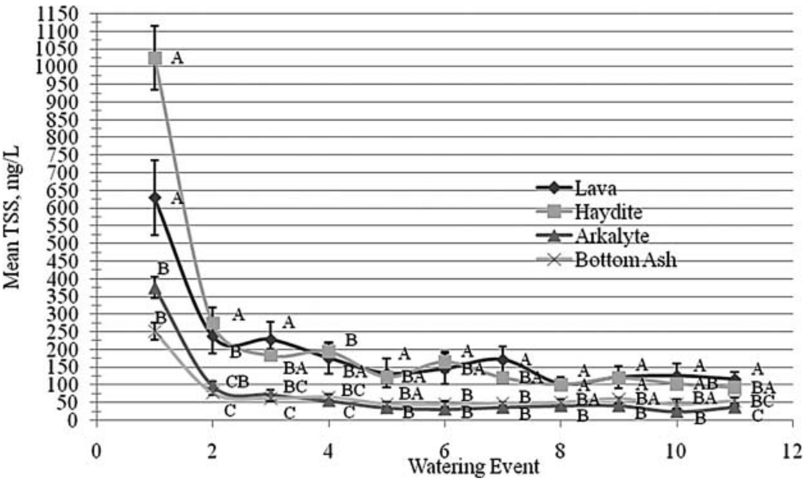

Figure 5 Mean TSS for nonvegetated pots for different watering events. Letters that are the same indicate no statistical difference in a Tukey's post-hoc test to rank differences at an alpha level of 0.05. Bars indicate ±1 standard error.

Figures 6 and 7 show the effect of the vegetation on the mean TSS of lava and arkalyte, respectively. Results for mean TSS from haydite are similar to the results for arkalyte (i.e., both curves descend); results for mean TSS from bottom ash are similar to the results for lava (i.e., the vegetated curve increases at the second watering event while all other points decrease). The effect of the vegetation is generally statistically different only in the first watering event, in which the TSS from the nonvegetated pots was between 2.2 times (lava) to 3.5 times (haydite) higher than from the vegetated pots. The reduction in mean TSS during the first flush ranged from 54% to 71%. The average reduction was 63%. The reduction in mean turbidity during the first flush had a wider range—from 27% to 71%. The average was 53%.

Even though the TSS from the vegetated lava (Figure 6) and bottom ash increased rather than decreased during the second watering event, the result is not statistically significant. Therefore, the data indicate that the vegetation and/or plug were able to reduce the mean TSS of the first flush but generally had no statistically significant effect thereafter.

Table 3 Initial and final mean TSS and mean turbidity values$^{A, B}$

	Turbidity				TSS			
	Vegetated		Non-Vegetated		Vegetated		Non-Vegetated	
Growth Media	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Arkalyte	84	*8*	282	*26*	119	*13*	377	*38*
Bottom Ash	*63*	10	*119*	27	*110*	21	*253*	56
Haydite	181	27	**568**	52	**295**	**53**	**1026**	94
Lava	**256**	**29**	353	**85**	288	45	631	**117**

[A] Final is 15 watering events for vegetated pots and 11 watering events for nonvegetated pots.

[B] Italics indicate the lowest value. Bold indicates the highest value.

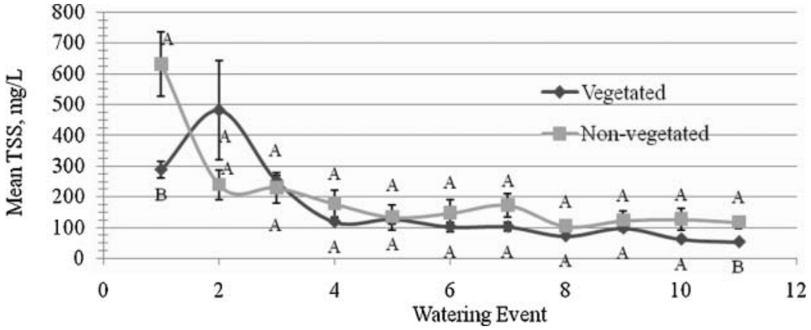

Figure 6 Mean TSS comparison between vegetated and non-vegetated blended lava growth medium. Letters that are the same indicate no statistical difference in a two-tailed t-test at a significance level of 0.05. Bars indicate ±1 standard error.

The results for mean turbidity from all four media are similar to the results for TSS except from the second watering event for bottom ash, in which the vegetated turbidity (70.4 NTU) was statistically larger than the nonvegetated turbidity (41.4 NTU). The peaks in the vegetated lava and bottom ash could be caused by the plug delaying the solids transport or, conversely, the soil mixture in the plug taking until the second watering event to be transported through the media. However, the effect appears to be negligible, not only because it is not statistically significant except in one case but because the vegetated results from the later watering events closely track the nonvegetated results.

The plants grew steadily during the experiment, as shown in Figures 8 and 9. Similar to Lucas (2009), the plants in lava performed better, possibly due to its higher water retention capacity. Surprisingly, even though the coverage of the plants in haydite was similar to the coverage in arkalyte and bottom ash (Figure 9), the mean TSS and turbidity in the runoff was statistically different than arkalyte and bottom ash and statistically the same as lava (Figures 2 and 3). This result implies that the media, rather than the vegetation, had a greater effect on TSS and turbidity.

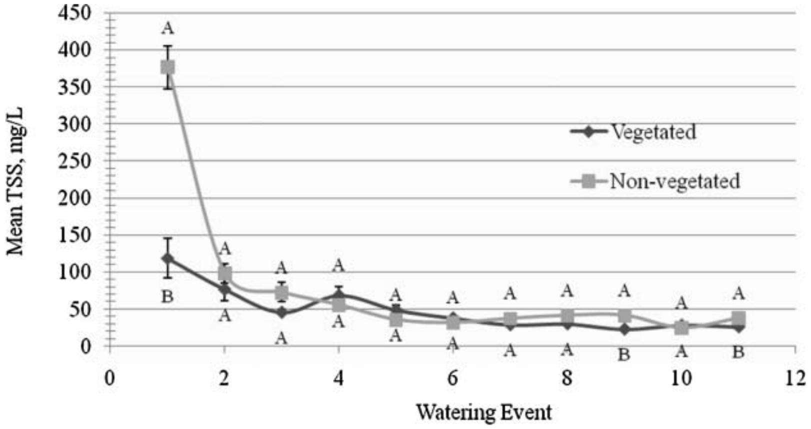

Figure 7 Mean TSS comparison between vegetated and non-vegetated blended arkalyte growth medium. Letters that are the same indicate no statistical difference in a two-tailed t-test at a significance level of 0.05. Bars indicate ±1 standard error.

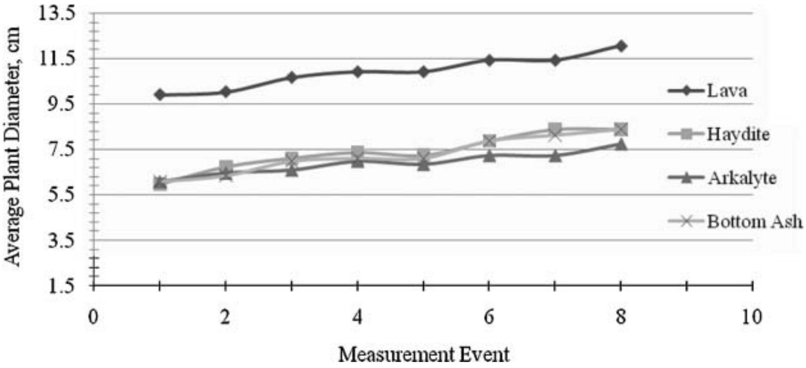

Figure 8 Average plant diameter over time.

In general, all results show a steep decline in mean turbidity after the first flush and a continued slight decline thereafter (Figures 2 and 4). The results are mixed regarding meeting regulated levels (Table 1). Arkalyte and bottom ash met the Vancouver Island, Canada 50 NTU limit by the third watering event, but lava and haydite did not meet it until the eighth watering event. Arkalyte and bottom ash met limits below 30 NTU (Table 1) by the sixth watering event; however, lava and haydite levels were still above 30 NTU until the fourteenth and fifteenth watering event respectively. Of potential concern are the high levels of the initial mean turbidity of all nonvegetated media. Except for bottom ash, they exceeded 280 NTU, which is the U.S. EPA's construction site standard (USEPA 2010a). However, subsequent data were below this level, and the presence of vegetation kept all the mean turbidity levels except for the second watering event below 280 NTU.

Similar to the results for turbidity, in general all results show a steep decline in mean TSS after the first flush followed by a continued slight decline (Figures 3 and 5). However, the TSS levels tended to remain considerably higher than regulated levels (Table 1). Vegetated haydite was still above 50 mg/L at the fifteenth watering event. By the thirteenth watering event, the TSS from vegetated lava was below 50 mg/L. By the ninth watering event, vegetated bottom ash was below 50 mg/L. By the fifth watering event, vegetated arkalyte was below 50 mg/L and was about 25 mg/L by the ninth watering event. For the nonvegetated media, arkalyte and bottom ash were below 50 mg/L by the fifth

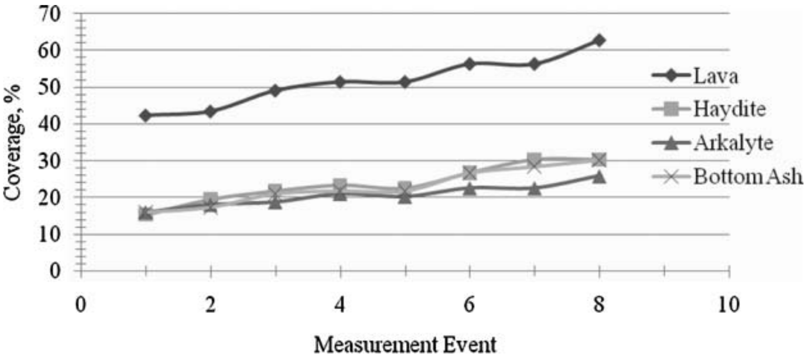

Figure 9 Average plant coverage over time.

Table 4 Reported TSS concentrations from nonvegetated roofs

Roof Type(s)	Location	TSS (mg/L)	Source
Galvanized iron	Toowoomba, QLD, Aus.	Median = 10 Range = 3–200	Brodie 2005
Aluminum, concrete, glass	Shanghai, China	Mean = 11–21	Wang and Li 2009
Unspecified	Paris, France	Mean = 29	Gromaire et al. 1999
Unspecified	Beijing, China	Mean = 121	Yufen et al. 2008
Unspecified	Tuscaloosa, AL, US	Range = ∼0–150	Morquecho 2005

watering event, but lava and haydite were still above 90 mg/L at the fifteenth watering event.

Morquecho (2005) reported turbidity levels of runoff from standard roofs (i.e., non-green roofs) ranging from approximately 2 to 22 NTU. By the seventh watering event, the mean turbidity in the runoff from vegetated arkalyte and bottom ash were approximately 22 NTU. By the fifteenth watering event, the mean turbidity in the runoff from vegetated haydite and lava were still above 25 NTU. Similarly, the mean TSS from vegetated lava and haydite were always above smaller values of TSS reported in the literature for standard roofs (e.g., 29 mg/L, Table 4). However, the mean TSS from the vegetated arkalyte and bottom ash were always below higher values of TSS reported in the literature for standard roofs (e.g., 150 to 200 mg/L, Table 4). Otherwise, at some point during watering events, the values became similar.

To investigate the possibility that differences or lack of differences in concentration data were a byproduct of differences in runoff volume due to differences in water retention capability, the mass of suspended solids in the runoff was analyzed for later watering events (Figures 10 and 11). The results are similar to the concentration data for nonvegetated pots (Figure 5 versus 11). The results for vegetated pots are similar in that lava and haydite lose greater quantities of suspended solids than arkalyte and bottom ash (Figure 3 versus 10).

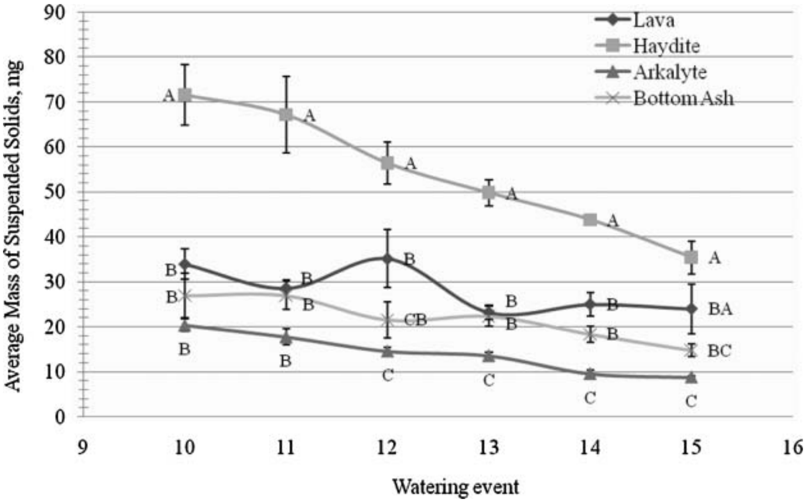

Figure 10 Average mass of suspended solids in vegetated pots. Letters that are the same indicate no statistical difference in a two-tailed t-test at a significance level of 0.05. Bars indicate ±1 standard error.

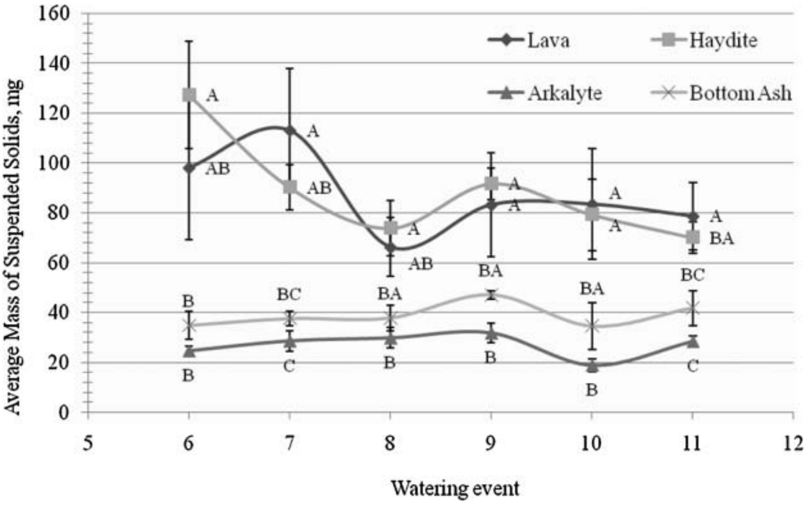

Figure 11 Average mass of suspended solids in non-vegetated pots. Letters that are the same indicate no statistical difference in a two-tailed t-test at a significance level of 0.05. Bars indicate ±1 standard error.

However, there are also some interesting differences. Vegetated haydite loses statistically more mass than vegetated lava versus the concentrations being statistically the same (Figure 10 versus 3) and the lava having more fines (Figure 1 and Table 2). Similarly, vegetated arkalyte loses statistically less mass than vegetated bottom ash versus the concentrations being statistically the same (Figure 10 versus 3). The mass loss from vegetated lava and vegetated bottom ash are statistically the same throughout the study period versus the concentrations being statistically different (Figure 10 versus 3). These results indicate that the differences between growth media can be partially explained by differences in water retention capacity and, thus, pore size. However, it is likely that differences in intraparticle porosity are also a factor. For example, the more open lava particles are likely able to capture a larger mass of fines released from the plugs than the smoother haydite particles are able to capture.

CONCLUSIONS

Most particles that cause the turbidity and TSS in the first watering event were from the dust flushed from the growing media or from pine bark particles mixed with the media, which can explain the high initial turbidity and suspended solids concentrations. While the vegetation significantly reduces this initial TSS and turbidity for all growth media, it generally has no significant effect thereafter despite slow but steady plant growth. However, both TSS and turbidity for all growth media decrease over time, indicating that the growth media, rather than the vegetation, has a greater effect on TSS and turbidity in the runoff.

The mean TSS and mean turbidity levels in runoff from 10-cm vegetated green roofs appear to be generally of the same magnitude as the runoff from standard roofing material. Thus, they could be expected to have similar effects on water clarity downstream. However, the level of TSS and turbidity is affected by the type of growth media. The different results between growth media indicated that, after 15 watering events, vegetated pots of lava and haydite have higher TSS and turbidity than vegetated pots of arkalyte and bottom ash. The results are similar for nonvegetated pots through 11 watering events. Therefore, for areas with stringent water quality regulations for stormwater runoff from developed sites, media selection may be an important consideration. For other areas, the consideration of turbidity and TSS from the media will be of minor importance.

If necessary, growth media could be rinsed prior to use to remove the first flush effect from occurring on the roof. However, there are important sustainability considerations to consider if implementing this scheme—e.g., water use and material and energy use in treating the rinse water. One way to minimize the first flush effect is to ensure that the roof is planted prior to rainfall and that any irrigation does not result in runoff.

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