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Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut

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ABSTRACT

This study compared the quality and quantity of stormwater runoff from replicated asphalt, permeable paver, and crushed-stone driveways. Rainfall was measured on-site and runoff was recorded using tipping buckets. Flow-weighted composite runoff samples were analyzed weekly for total suspended solids, total Kjeldahl nitrogen, nitrate-nitrogen, ammonia–nitrogen, total phosphorus (TP), zinc, lead, and copper. Infiltration rate was determined on each driveway annually. Repeated measures analysis of variance indicated that stormwater runoff was significantly different among each driveway type; the order of decreasing runoff was asphalt > paver > stone. Average infiltration rates were 0, 11.2 and 9.0 cm/h for asphalt, paver, and crushed stone driveways, respectively. Both paver and crushed stone driveways reduced stormwater runoff as compared to asphalt driveways. Runoff from paver driveways contained significantly lower concentrations of all pollutants measured than runoff from asphalt driveways. However, runoff from crushed stone driveways was similar in concentrations to runoff from asphalt driveways, except for TP concentrations, which were lower in runoff from crushed stone driveways than runoff from asphalt driveways. The mass export of measured pollutants followed the relative differences in stormwater runoff, rather than differences in concentrations.

1. Introduction

Surface water quality is negatively impacted by urban development due to pollutant loads in stormwater runoff (Brabec et al., 2002; Klein, 1979) and increases in runoff peaks and volumes (Leopold, 1968). According to the 1997 USDA—National Resources Inventory, developed land (urban, built-up, and rural transportation land) has increased by 34% since 1982 and is increasing at the rate of 0.7 million ha/y (USDA-NRCS, 2000). One major urban land use is residential subdivisions. The quality of urban runoff from residential areas is similar to other urban land use types, according to the Nationwide Urban Runoff Program (USEPA, 1983b). Key source areas vary by pollutant within residential areas. For example, lawns appear to have the highest runoff concentration of phosphorus and total Kjeldahl nitrogen (TKN) while streets have high runoff concentrations of total suspended solids (TSS) and many metals (Bannerman et al., 1993; Steuer et al., 1997). These studies show that residential roof runoff usually has low pollutant concentrations, but commercial roofs can be high in metals.

One potential focus for nonpoint source pollution mitigation in residential developments is reduction of driveway runoff. Driveway runoff is moderate in concentrations of solids, nutrients, metals, and PAHs among urban source areas (Bannerman et al., 1993; Steuer et al., 1997). Modeling by

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Bannerman et al. (1993) indicated that in residential watersheds 21% of total runoff comes from driveways as compared to 7% from lawns, though driveways represented only 5% of the area in that study. Steuer et al. (1997) modeled that 10% of basin runoff came from driveways even though they comprised 4% of the basin area. It follows that decreasing driveway runoff can appreciably decrease nonpoint source pollution from residential developments.

Not much is known about runoff from different driveway types. Steuer et al. (1997) monitored one asphalt driveway and two cement driveways but did not compare them. Bannerman et al. (1993) reported concentrations of suspended solids, phosphorus, and cadmium, copper, lead, and zinc in runoff from only asphalt driveways. Nitrogen concentrations and discharge were not monitored. Studies have been conducted on runoff from alternative paving surfaces used in roads and parking lots. For example, studies of pavers (Brattebo and Booth, 2003; Booth and Leavitt, 1999; James and Thompson, 1997; Pratt et al., 1995), and porous asphalt (Legret and Colandini, 1999; Rushton, 2001) have shown that, compared to asphalt surfaces, pavers reduce the runoff amount and concentrations of metals in infiltrated water (Brattebo and Booth, 2003) and runoff (James and Thompson, 1997), and porous pavement reduces metals in runoff (Legret and Colandini, 1999). These studies have not included nutrients in runoff and have not evaluated crushed stone driveways, which are common in New England. Rushton (2001) did analyze nutrients in stormwater runoff from porous asphalt but the results were confounded by the presence of swales in her study. It is important to study the impact of alternative paving materials on nutrients in stormwater runoff due to estuary and lake impairments caused by eutrophication in New England (Frink, 1991). The purpose of this study was to compare driveway stormwater runoff quality and quantity for the alternatives of asphalt, infiltrating pavers, or crushed stone surfaces.

2. Materials and methods

2.1. *Study area*

Study driveways were located in Waterford, CT, in a residential neighborhood that is part of the Jordan Cove Urban Watershed Project (Phillips et al., 2003). Normal annual rainfall was 1 238 mm in Groton, CT, 12 km from the study site (NOAA, 2001, 2002). Precipitation during the 22-month-study was 14.8% below normal. There were 13 weeks with no precipitation, and an additional 6 weeks with less than 1 mm of precipitation. An analysis of 104 storms at this site indicates that the median rainfall intensity was 9 mm/h and the median duration was 210 min (Hood, 2005). About 90% of storms were less than 29 mm/h intensity and 645 min duration. The average monthly temperature, measured in Groton, CT, fluctuated from −18.5 to 23.5 °C during the study (NOAA, 2001, 2002). Soils within the study area were originally mapped as Canton, an extremely stony fine sandy loam with 15–35% slopes, and Woodbridge fine sandy loam, with 0–3% slopes (Crouch, 1983). Following development, the soils are mainly Udorthents–Urban land complex.

Two replicates each of asphalt, concrete paver, and crushed stone driveways were monitored for stormwater runoff quality and quantity. Replicates were numbered 1 and 2 for each driveway type. Five of the driveways were shared and one was for a single home (Fig. 1). Driveway watershed areas were calculated using as-built maps and field measurements, and ranged from 7 to 730 m^2. The percent of land cover type in each driveway watershed varied and included driveway, lawn and landscaped areas, roofs, and steps (Table 1). Roofs were covered with fiberglass–asphalt shingles and gutters were aluminum.

2.2. *Methods*

Asphalt driveways were constructed from rolled, hot mix, bituminous concrete, 5 cm thick placed over compacted subsoil. Paver driveways used UNI EcoStone® (115 by 230 mm) interlocking concrete permeable pavement (UNI-GROUP USA Palm Beach Gardens, FL). Pavers were hand installed over 5 cm compacted and screeded coarse sand on top of 15 cm processed gravel. Drainage voids comprised 12% of the surface area and were filled with 3–6 mm peastone. Crushed stone driveways were comprised of 1.2 cm stone, 7.5 cm thick over compacted sand. Monitoring equipment was installed as each driveway was completed, resulting in unequal sampling periods at each driveway. The final driveway was completed in June 2002, beginning 12 months during which all six sites were monitored.

A concrete trench drain (ABT® Inc., Troutman, NC) located at the down slope end of each driveway collected overland flow. Flow volume was measured with a calibrated tipping bucket and mechanical counter located in a sump. A flow splitter was adjusted to collect sufficient sample for analysis without overfilling sample containers. The amount of flow collected varied by storm and site but averaged 0.0007% of total flow. Pre-acidified bottles were used for analysis of nutrients (sulfuric acid) and metals (nitric acid), while non-acidified bottles were used for suspended solids analysis. This study focused solely on overland flow, there was no collection of water that infiltrated through the pavers or crushed stone. Precipitation was monitored on-site using a heated, tipping bucket rain gauge. On-site precipitation was used to develop rainfall–runoff relationships, but rainfall departure was calculated using precipitation measurements made at the Groton CT NCDC station (NOAA, 2001, 2002). Composite stormwater samples were analyzed weekly for nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), TKN and total phosphorus (TP) with a Lachat QuikChem® AE flow injection analyzer (USEPA, 1983a). Un-acidified samples were analyzed gravimetrically for TSS (USEPA, 1983a). Total copper, lead and zinc were determined on monthly composite unfiltered samples using a Perkin Elmer Elan 6000 inductively coupled plasma-mass spectrometer (ICP-MS) and USEPA method 200.8 (USEPA, 1991). Samples were collected and analyzed following a USEPA approved Quality Assurance Project Plan (Clausen, 2000). Sample duplicates and spikes were performed every 20 samples and check standards were analyzed every ten samples with a ±10% acceptance criteria.

Infiltration rates were measured on asphalt and paver driveways annually using a 14.7 cm PVC single ring infiltrometer (Bouwer, 1986); a Mariotte column (Constanz and Murphy, 1987) was used to maintain a constant ponding depth of 1 cm in the ring. The ring was sealed to the driveway using a weight, weather stripping, and removable putty, which

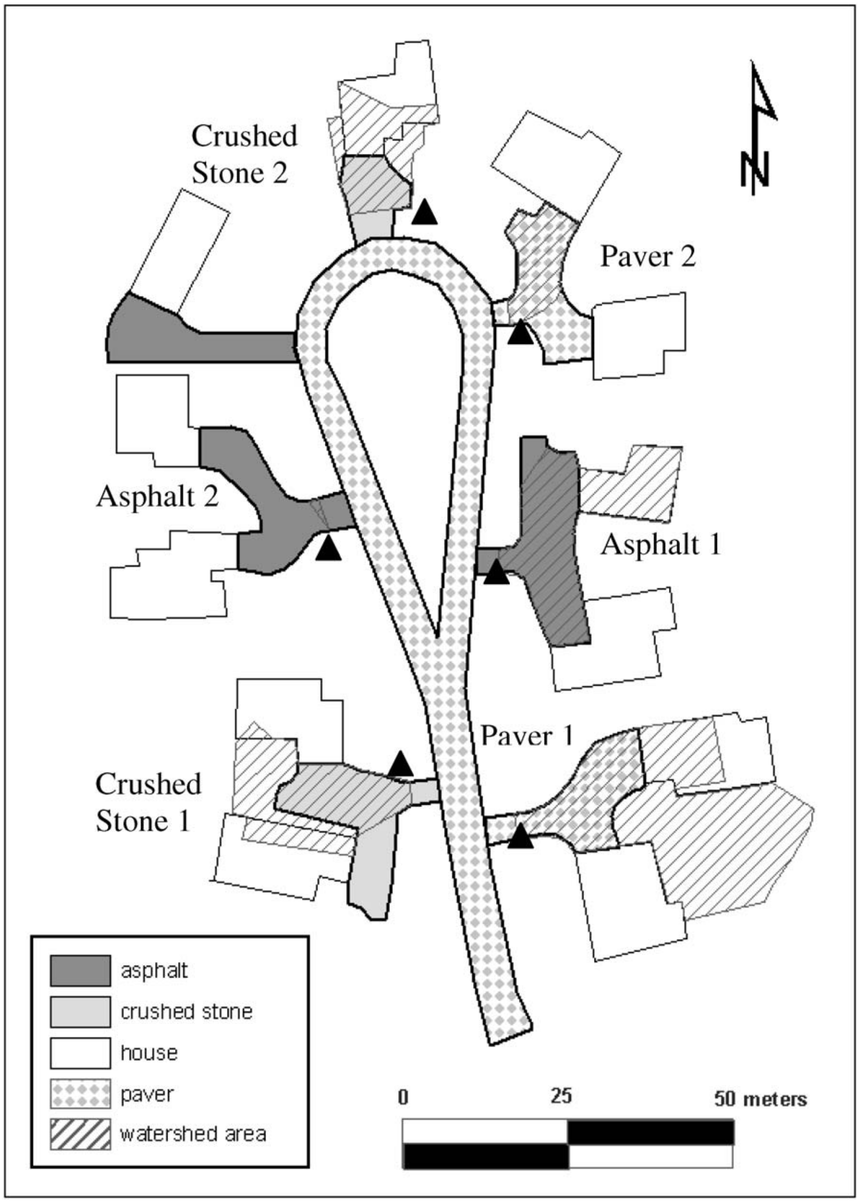

Fig. 1 – Project area site map including driveway type, monitoring locations (▲), and watershed areas (hatched).

Table 1 – Watershed characteristics for the six study driveway sites in Waterford, CT

Land cover	(Type)					
	Asphalt 1	Asphalt 2	Paver 1	Paver 2	Crushed stone 1	Crushed stone 2
Driveway (%)	56	100	22	100	53	37
Turf/landscaped (%)	0	0	63	0	27	13
Roof or steps (%)	44	0	15	0	20	50
Total area (m^2)	390	7	730	80	300	150
Slope (%)	3.3	3.2	4.4	4.7	2.6	4.5

prevented water from leaking out of the ring. A 14.7 cm metal ring was pounded 2.5 cm into the subbase material for the crushed stone driveways. Each infiltration test was conducted until infiltration rates reached equilibrium, which could take up to 2.5 h for one test, so that initial moisture content of the driveway material prior to testing did not impact test results. Data presented are the average final infiltration rates of three tests per driveway in 2002 and two tests per driveway in 2003. These standard methods of measuring infiltration were designed for soils but are less ideal for these driveway surfaces. Porosity of the crushed stone was determined by collecting a measured volume of stone from each crushed stone driveway, re-compacting it to its original volume in the lab, and adding a measured volume of water to the sample. A flowing infiltration test was conducted in 2003. A metered-perforated hose was placed across the driveway 5 m upslope from the trench drain. The rate of application was determined by trial-and-error as sufficient flow to provide measurable overland flow in the trench drain and was 51 and 8 cm/h for the paver and crushed stone driveways, respectively. Infiltration was calculated as volume applied minus volume of runoff per unit time. This method of measuring infiltration would be similar to the rainfall simulator approach in that a larger surface area (116–1373 m^2) was included in the test.

Concentration and runoff data were statistically analyzed using SAS version 8.0 software (SAS Institute Inc., 2001). Data were found to be log-normally distributed, therefore, statistical tests were performed on log-transformed data. Means presented are the anti-log of the transformed data. A repeated measures, analysis of variance was used to test for the overall difference among treatments. Seasons were used as the repeated measure. Means were separated using Tukey–Kramer least-squares differences. Relationships between weekly rainfall and runoff depth, pooled for each driveway type, were examined using linear regressions. To evaluate the effect of non-uniform land uses in each watershed on the results, runoff and concentration data were adjusted by multiplying by the proportion of lawn area to roof area. This adjustment factor was selected to account for varying infiltration rates among land covers. For example, most precipitation on a roof would drain to the driveway, but only a portion of the precipitation on the lawn would contribute runoff to a driveway. Both adjusted and unadjusted data were analyzed, although results presented are for only unadjusted data.

Annual pollutant mass export was calculated from concentration and flow data for March 2002, 2003. Export was calculated weekly as

$$\frac{VC}{A \times 10^8}$$

where V is the runoff volume in L, C the pollutant concentration in mg/L, A the watershed area in ha, and 10^8 is to convert mg to kg. Data presented are weekly export summed over the year March 2002 through March 2003 to yield export in kg/ha/yr. Data used were from the asphalt 1, paver, and crushed stone 1 driveways. The asphalt 2 and crushed stone 2 driveways were not included in export calculations due to missing runoff volume data from equipment malfunctions.

3. Results and discussion

3.1. *Runoff depth*

Runoff from the asphalt driveways was significantly greater than from the paver driveways, which in turn was greater than from the crushed stone driveways (Table 2). The reduction in runoff from asphalt to paver surface was 72% and to crushed stone was 98%. These results did not change when runoff, adjusted for the grass/roof ratio, was compared among driveway types (data not shown). There were no seasonal differences in runoff depth among driveway types from the repeated measures analysis. These results were consistent with findings from other paver research. Pratt et al. (1995) measured paver runoff to be from 37% to 47% of rainfall. James and Thompson (1997) reported that while runoff from asphalt surfaces equaled 100% of rainfall, paver runoff equaled 38–61% of rainfall, depending on the thickness of the base course. We observed paver runoff to be 40% of precipitation. Booth and Leavitt (1999) observed runoff from turfstone as <1% of total rainfall near Seattle, Washington. Their runoff was much less than what was observed for the pavers used in this study, but was close to runoff measured for crushed stone driveways.

Infiltration tests indicated that greater infiltration would be expected in the paver driveways than the crushed stone

Table 2 – Geometric mean ($\pm s$) pollutant concentration in stormwater runoff from asphalt, paver, and crushed stone driveways, Waterford, CT

Variable	n	Asphalt	Paver	Crushed stone
Runoff (mm)	70	1.8a ($\pm$1.0)	0.5b ($\pm$0.8)	0.04c ($\pm$0.2)
TSS (mg/L)	52	47.8a ($\pm$330.6)	15.8b ($\pm$45.3)	33.7a ($\pm$247.3)
NO_3-N (mg/L)	51	0.6a ($\pm$0.9)	0.3b ($\pm$1.2)	0.3ab ($\pm$0.4)
NH_3-N (mg/L)	51	0.18a ($\pm$0.36)	0.05b ($\pm$0.14)	0.11a ($\pm$0.24)
TKN (mg/L)	52	8.0a ($\pm$2.5)	0.7b ($\pm$0.9)	1.6ab ($\pm$2.3)
TP (mg/L)	52	0.244a ($\pm$0.288)	0.162b ($\pm$0.279)	0.155b ($\pm$0.502)
Cu (μg/L)	12	17a ($\pm$36)	6b ($\pm$5)	16a ($\pm$338)
Pb (μg/L)	12	6a ($\pm$24)	2b ($\pm$1)	3ab ($\pm$10)
Zn (μg/L)	12	87a ($\pm$519)	25b ($\pm$25)	57ab ($\pm$210)

Within each variable, means followed by the same letter are not significantly different at $\alpha = 0.06$.

driveways (Table 3). There was no infiltration in the asphalt driveways. Flowing infiltration test results were similar to the single ring tests except for the crushed stone driveway, where flowing infiltration was lower than single ring infiltration (Table 3). Multiple infiltration ring tests were performed over all areas of the driveways, while flowing infiltration tests were conducted only 5 m from the trench drain at the entrance to the driveway. This portion of the driveway showed more wear and compaction after routine use than the rest of the crushed stone surface. Compaction would naturally lower infiltration rates. Infiltration rates measured in this study for paver and crushed stone driveways would be considered "moderately rapid" (Novotny, 2003).

The flowing infiltration tests demonstrated differences in runoff response for the driveway types. For example, on the asphalt driveway it took one minute for the flow to travel the 5 m from the perforated hose to the discharge point in the trench drain. For the crushed stone and paver driveways discharge did not occur for 20 min after the application of water. In the paver and crushed stone driveways, the volume of available pore space determines the lag time from the start of precipitation until runoff begins. Once pore spaces are filled, runoff volume is controlled by precipitation intensity and infiltration rate.

Runoff from each driveway type was significantly related to precipitation (Fig. 2). Regression slopes follow the relative differences observed in runoff from each driveway type. R^2 values for paver ($F = 38.0$, $p<0.0001$) and crushed stone driveways ($F = 34.5$, $p<0.0001$) may be lower than for the asphalt driveways ($F = 158.7$, $p<0.0001$) due to variable infiltration rates at different storm intensities on crushed stone and paver driveways, while the asphalt driveways had no infiltration, and rainfall matched runoff more closely. Several outliers occurred for the paver 2 driveway (Fig. 2) whose watershed is 100% paver (Table 1). These outliers were not related to time of year. It is likely that antecedent conditions influenced the amount of runoff for these points. As Rushton (2001) observed, pervious paving is most effective for small and low-intensity storms. Pratt et al. (1995) observed runoff from pavers to be related to rainfall with R^2 values ranging from 0.80 to 0.86. These coefficients were higher than we observed, but some of our watersheds contained lawn and roof areas.

Table 3 – Mean (±s) infiltration rates from asphalt, paver, and crushed stone driveways

Test and Year	Asphalt (cm/h)	Paver (cm/h)	Crushed stone (cm/h)
Single ring 2002	0	11.8±9.5	11.3±3.1
Single ring 2003	0	10.5±5.9	9.7±7.8
Flowing 2003	0	11.4	6

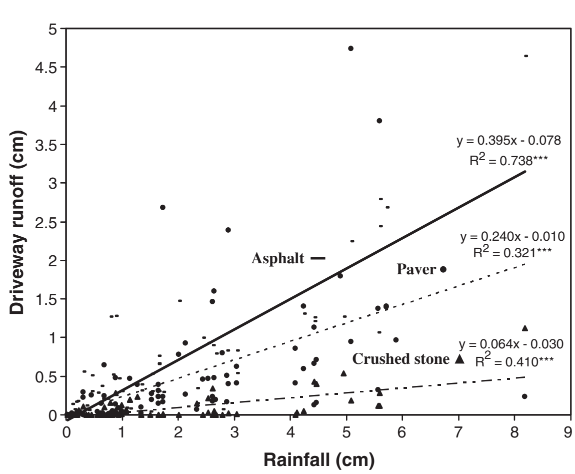

Fig. 2 – Rainfall–runoff relationships for the three driveway types. * Indicates significance at $p<0.0001$.**

3.2. *Concentration*

Runoff from paver driveways contained significantly lower concentrations of measured pollutants than runoff from the asphalt driveways (Table 2). However, crushed stone driveway runoff pollutant concentrations were similar to asphalt concentrations, except for lower TP concentrations in crushed stone driveway runoff. In addition, TSS, NH_3-N, and Cu concentrations in crushed stone runoff were higher than in paver runoff. Asphalt runoff had a statistically higher TKN concentration than crushed stone runoff in the summer, even though this difference was lost when comparing concentrations for all pooled time periods. Most of the nitrogen observed in runoff was in the organic form (Table 2). NO_3-N concentrations in runoff from the asphalt driveways averaged near the median NO_3-N of 0.65 mg/L from 2003 precipitation at the National Atmospheric Deposition Program site in Abington, CT (NADP, 2003). These results did not change when concentrations, adjusted for the grass/roof ratio, were compared among driveway types (data not shown). Results also did not change when the data was truncated to the final 12 months of the study, to exclude the period when only three driveways were being monitored.

TSS concentrations in driveway runoff (Table 2) observed in this study were lower than the 100 mg/L event mean concentration reported for urban runoff in the NURP study (USEPA, 1983b), and the 300 mg/L for asphalt driveways reported by Bannerman et al. (1993). Paver TSS concentrations were significantly lower in the fall (4.0 mg/L) than any other season (25.2 mg/L). Crushed stone TSS concentrations were significantly higher in the summer (111 mg/L) than in other seasons (23.3 mg/L). Direct sanding was not observed on any study driveways, which might explain lower values observed in this study.

Bannerman et al. (1993) identified driveways as a critical source area for phosphorus in residential watersheds. While TP concentrations in runoff from asphalt driveways were lower in this study than in Bannerman's study, 0.24 mg/L as compared to 1.16 mg/L, they were similar to Rushton's (2001) findings of 0.11 mg/L TP in asphalt runoff.

Metals runoff concentrations were similar to what has been reported in other studies for asphalt and paver driveways, but these studies are not entirely comparable. For example, Booth and Leavitt (1999) report only leachate concentrations, and the Rushton (2001) site also included swales. Overall, Pb concentrations reported in this study were lower than runoff concentrations reported in other studies. Runoff from asphalt and crushed stone driveways had Cu concentrations above USEPA (1999) freshwater aquatic toxicity thresholds of 13 (acute) and 9 μg/L (chronic). Pb and Zn concentrations in runoff from all driveways were lower than the acute aquatic toxicity threshold of 65 and 120 μg/L, respectively (USEPA, 1999).

3.3. *Export*

Mass export was calculated weekly and then data were summed to give total yearly export. Other studies have reported export per storm or per group of storms, but that was not possible for this study as runoff samples were collected weekly and were composites of all storms during that week. As expected, the mass export of all constituents in runoff from asphalt driveways was greater than that from paver driveways, which was greater than the export from crushed stone driveways (Table 4). Crushed stone driveways had the lowest export due to the low runoff volumes. James and Thompson (1997) also reported that TSS, NO_3, NH_3, TKN, Cu, Pb, and Zn export in runoff was greater from an asphalt parking lot than from an Eco-stone® paver parking lot in Guelph, Canada.

4. Conclusions

Of the three pavement types, asphalt driveways were consistently highest in runoff volume, and pollutant loads. Paver driveway runoff had significantly lower concentrations of pollutants than did runoff from asphalt and crushed stone driveways. Surprisingly, concentrations of pollutants in runoff from crushed stone driveways were not different than in runoff from asphalt driveways. Infiltration rates at both the paver and crushed stone driveways declined somewhat over the course of the study, though they were still greater than the zero infiltration measured on the asphalt driveways. This decrease is likely due to fine particles clogging the openings in the pavers and the soil surface at the stone-subsurface interface, which is expected. Even with decreased infiltration, the use of concrete pavers or crushed stone is preferable over the traditional asphalt material for control of nonpoint source pollution. The role and mechanisms of nutrient and metals retention by concrete pavers deserves further investigation.

Table 4 – Annual pollutant export from asphalt, paver, and crushed stone driveways, Waterford, CT

	Asphalt (kg/ha/yr)	Paver (kg/ha/yr)	Crushed stone (kg/ha/yr)
TSS	230.10	23.10	9.60
NO_3-N	1.78	1.25	0.15
NH_3-N	0.65	0.12	0.03
TKN	13.06	1.08	0.47
TP	0.81	0.25	0.04

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