Differences in Surface Water Quality Draining Four Road Surface Types in the Southern Appalachians

Barton D. Clinton *and* **James M. Vose,** *USDA Forest Service, Coweeta Hydrologic Laboratory, 3160 Coweeta Lab Road, Otto, NC 28763.*

ABSTRACT: *Improved and unimproved roads can be the primary source of stream sediment in forested watersheds. We assessed differences in production of total suspended solids (TSS; ppm) from four road surface conditions in a Southern Appalachian watershed: (1) a 2-yr-old paved surface (P), (2) an improved gravel surface with controlled drainage and routine maintenance (RG), (3) an improved gravel surface with erosion and sediment control structures installed and routine maintenance (IG), and (4) an unimproved poorly maintained gravel surface (UG). Variation was high among and within road surface types. The P surface generated the least amount of TSS, which was comparable to control sites, while the UG surface generated the most. The P surface produced significantly less TSS than the UG surface, but not less than the IG and RG surfaces. Variation among road surface types was related to TSS travel distance below the road, precipitation amount, time of year, and the existence of functioning erosion and sediment control structures. TSS decreased with travel distance (P = –81% over 38.5 m, IG = -30% over 30.5 m, RG = –89% over 39.4 m, and UG = –22% over 28.1 m). Also in this study we assessed the delivery of total petroleum hydrocarbons (TPH; ppm) from the P surface and found concentrations of < 0.5 ppm, which are well below published USEPA and NC DENR TPH standards for sediment. Paving is an attractive option for reducing maintenance costs and sediment production and transport; however, levels of TPH from freshly applied asphalt are unknown. South. J. Appl. For. 27(2):100–106.*

Key Words: Forest roads, sediment, overland flow, water quality, Chattooga River.

Roads affect the movement of water and sediment through landscapes and are often a major source of soil erosion in forested watersheds (Patric 1976, Van Lear et al. 1995, Luce and Black 2001). Sediment derived from forest roads may be detrimental to many terrestrial and aquatic organisms, and research has shown negative correlations between road density and fish stocks (Lee et al. 1997, Thompson and Lee 2000). In both the public and private sectors there has been a resurgence of interest in how forest roads affect stream water quality. Natural resource managers have been under considerable pressure from public and private organizations, as well as regulatory agencies, to minimize the degradation of terrestrial and aquatic resources caused by management activities. For example, the 11th Circuit Court of Appeals ruling temporarily suspended all ground-disturbing activities on the forest pending the outcome of a lawsuit filed against the Chattahoochee National Forest over effects of sediment on sensitive aquatic species (R. Ellis, Chattahoochee National Forest personal comm., 5/2002). Resource managers need more information on the effectiveness of management practices that reduce or minimize sediment production and delivery to aquatic ecosystems.

The effect of sediment derived from ground-disturbing activities on aquatic ecosystems is proportional to the distance sediment travels from its source. In addition, Swift (1986) found that sediment travel distance from unpaved road surfaces varies with slope steepness and drainage type (e.g., with and without outsloping and culverts), and ranges from <1 m (out-sloped without culvert) to near 100 m (culverts only). Swift (1984) demonstrated that increased vegetative cover on soil disturbance associated with roads reduced sediment production. Similarly, Grace (2000) showed the effectiveness of various vegetative mixes in reducing soil

NOTE: B.D. Clinton can be contacted at (828) 524-2128 (ext. 124); Fax: (828) 524-6768; E-mail: bclinton@fs.fed.us. The authors thank Mike Crane, District Ranger Andrew-Pickens RD Sumter NF South Carolina, Dave Jensen, District Ranger Tallulah RD Chattahoochee NF Georgia, and Randy Fowler, Chattooga Large Scale Watershed Restoration Project Coordinator, and their staffs for providing logistical and informational support for this research. Thanks also to Stan Zarnoch for helpful advice on appropriate statistical analyses. This study was funded by the USDA Forest Service Region 8 Large-Scale Watershed Restoration Project. Manuscript received January 17, 2001, accepted June 19, 2002.

erosion from forest roadside slopes. Luce and Black (2001) observed that heavy traffic during rainfall or ditch maintenance will increase erosion and sediment yield. Other studies have identified unpaved roads as a primary source of sediment in forested watersheds. For example, in a forested watershed in the southeastern United States, Van Lear et al. (1995) estimated that over 80% of all sources of sediment were associated with unpaved roads.

Best Management Practices (BMPs) have resulted from small-scale studies of the movement of coarse and fine sediments from forest roads (Swift 1988). [Published state BMPs for South Carolina, North Carolina, and Georgia are available online at www.state.sc.us/forest/refbmp.htm, http://www.dfr.state.nc.us/managing/water_qual/bmp_menu.htm,and www.gfc.state.ga.us/Publications/RuralForestry/index.aspx, respectively.] Designs for forest roads in the southeastern United States have been developed at the Coweeta Hydrologic Laboratory (Hewlett and Douglass 1968) and are being implemented in a variety of terrain types (Cook and Hewlett 1979). Although the use of BMPs is always recommended for new road construction—and often mandated by local, state, or federal regulation—watersheds may contain a range of road conditions that require site-specific consideration. Forest roads may be poorly maintained, deeply rutted dirt construction; they may be highly maintained gravel or paved roads; or they may be somewhere in between. Because the costs of rehabilitating poorly constructed or barely maintained roads are high, land managers must prioritize maintenance and restoration efforts. Information on the amounts and movement of sediment generated from a full range of road surface conditions increasingly has become a consideration. Paving is often considered a viable option for reducing sediment and maintenance costs on heavy traffic areas. However, little is known about the effectiveness of paving in reducing sediment production and transport, and there are concerns about the fate of petroleum-based hydrocarbons generated from paved surfaces.

Our study objectives were to: (1) compare total suspended solids (TSS) production and movement across a range of road surface types, and (2) quantify the amount and movement of petroleum-based hydrocarbons from a paved surface. Study sites were located on the Chattooga River Watershed, which drains parts of North and South Carolina and Georgia. Increased traffic along improved and unimproved roads within the watershed has prompted concerns about the effects of road sediment on stream water quality.

Methods

Study Site

The Chattooga River watershed is approximately 73,000 ha, of which about 49,400 ha are National Forest System lands and includes the Chattooga Wild and Scenic River corridor, the Ellicott Rock Wilderness Area, the Overflow Creek Wilderness Study Area, the Warwoman Wildlife Management Area, and the Blue Valley Experimental Forest. Elevations range from 270 m mean sea level (MSL) to 1,500 m MSL, and the watershed receives approximately 2,030 mm of precipitation, annually. There are over 4,800 km of streams and 800 km of roads in the watershed. Most of the watershed lies within extreme northeast Georgia, but it includes parts of three Ranger Districts (RD) in National Forests (NF) in three states—Andrew-Pickens RD on the Sumter NF in South Carolina, the Highlands RD on the Nantahala NF in North Carolina, and the Tallulah RD on the Chattahoochee NF in Georgia.

Study Design

Four road surface types were identified for study: (1) a 2-yr-old paved surface (P), (2) a graveled road section receiving routine maintenance levels (routine gravel or "RG"), (3) a graveled road section receiving high maintenance and sediment control features (improved gravel or "IG"), and (4) an unimproved graveled road section (UG). Three of the road sections (P, RG, IG) are located along an 8 km segment of Burrels Ford Road in Georgia and South Carolina. The UG road section is located on Overflow Creek Road, which follows the West Fork of the Chattooga River in Georgia.

Drainage systems and road maintenance varied among road surface types. The paved road segment was 2 yr old when the study began. On the P surface, inside ditches, headwalls, and culverts with rip-rap on the downslope side of the road had been installed. No ditch maintenance or shoulder grading had been performed after the pavement was installed (Andrew-Pickens RD pers. comm., 6/20/01). The same drainage system was installed on the RG surface, but without rip-rap. Maintenance on the RG surface included grading four times per year with thin, spot applications of gravel (Andrew-Pickens, RD, pers. comm.). Drainage on the IG surface included out-sloping with vegetated road shoulders, diversions with vegetation and rip-rap, and broad-based dips. In addition, silt fences were installed along lengths of the IG road below drainage outlets, although in many locations they had failed due to improper installation and/or high volumes of water and sediment. Improvements on the IG surface were made 2 yr prior to this study and included reshaping (outsloping), installation of broad-based dips, addition of an average 20 cm of spec 5 (3 cm) stone, which was cut into the road surface with plows, and a 5 cm covering of crusher run. After the improvements were made, maintenance consisted of grading three times annually. Sediment control from the UG surface was intermittent. Much of the drainage from the UG surface occurred at low points in the road near stream crossings, where a substantial volume accumulated. The UG surface was graded once each year but no gravel was applied (Tallulah, RD, pers. comm., 6/2001).

We measured total suspended solids (TSS; ppm) at visually obvious runoff outlets using custom made overland flow collectors. Water and TSS moving over the soil surface were collected in stainless steel, rectangular shaped funnels (10 × 32 cm). An outlet at the bottom of each collector was connected to a 200 L container with a flexible polyvinyl chloride hose. A total of 55 collectors were installed along 12 transects, three on each of the four road types. Collectors were anchored to the slope with rebar to prevent movement caused by heavy flows during large storms and were spaced between the downhill edge of the road and the stream. Spacing generally increased with increasing slope, but

Table 1. Mean total length and percent slope for the overland flow transects (n = 3 per surface type), and average distance between collectors for each road surface type.

Surface type	Transect distance (m)	Slope (%)	Collector distance (m)
Paved Surface (P)	38.5	26.0	9.6
Improved Gravel (IG)	30.5	48.1	6.1
Routine Maintenance (RG)	39.4	24.9	7.9
Unimproved Gravel (UG)	28.1	34.0	6.5

actual sampler location was determined by visible sediment deposits observed on the sites, slope steepness, and proximity to streams. In addition, seven collectors were installed at locations (above and below the road) where no obvious signs of sediment movement were visible to represent background conditions. Table 1 reports average transect length, slope, and distance between collectors for each road surface type.

Overland flow samples were collected after storm events greater than 0.25 cm. Precipitation data were collected from a central location within the watershed, and from local National Oceanographic and Atmospheric Administration (NOAA) precipitation collection stations. After thoroughly mixing the contents of the 200 L container, we took a 1 L subsample from each. We analyzed subsamples for TSS from all road surfaces, and for TPH from the paved surface. In addition, we took grab samples from Kings Creek, a nearby tributary of the Chattooga River, to determine background levels of TPH in stream water. We collected TSS samples in 1,000 ml plastic containers, preserved them (refrigerated <7 days), and analyzed those samples in accordance with standard industry methods (American Public Health Association et al. 1985). Although TSS includes both inorganic and organic material, we surmised that most material detected in our samples was inorganic, because the road surface itself had been the primary source. Methods for handling and preserving TPH samples were in accordance with EPA SW846 (U.S. Environmental Protection Agency 1994). All samples were analyzed at the University of Georgia Pesticide and Hazardous Waste Lab in Athens, Georgia.

Statistical Analyses

We used a randomized block design—with rain events as blocks—to control for variation in TSS due to rainfall. Road surface types were used as fixed factors, and the three transects per road surface type were used as replicates. TSS comparisons were made between road surface types using PROC GLM (SAS Inst. 1985); LSMEANS (SAS Inst. 1985) was used to separate means. Significant differences were evaluated at the $\alpha = 0.10$ level. PROC REG and PROC GLM (SAS Inst. 1985) were used to examine the relationship between sediment travel distance and road surface type. For these tests, we evaluated significance levels at the $\alpha = 0.10$ level but adjusted them using the experiment-wise error term ($n = 4$). Response models for each road surface type were developed using PROC REG (SAS Institute 1985).

Results and Discussion

Total Suspended Solids

Sediment production measured as TSS differed considerably among road surface types (Table 2, Figure 1a). Averaged over all transects and distances in each road surface type, the P surface had the least amount of off-road TSS movement with a mean value of 153 ppm, followed by the IG (1,470 ppm), RG (1,983 ppm), and UG (3,201 ppm) surfaces (Table 2, Figure 1a). By comparison, TSS in the undisturbed reference locations had a mean value of 113 ppm. Hence, the unpaved road surfaces had TSS concentrations considerably greater than background levels, while the P surface was only slightly greater. The P surface was significantly different ($P < 0.1$) from the UG surface, but not from the RG or IG surfaces.

The overall means discussed above reflect the combined effects of both road surface type and physical characteristics of the forest floor (e.g., litter depth, coarse wood) and soils (stability and erodibility), and steepness of slope below the road surface. To determine the effects of road surface type alone, we analyzed separately the differences among samplers located nearest the road surface (Figure 1b). The statistical relationships and rankings differed slightly from the overall means (Figure 1a); TSS concentrations closest to the

Table 2. Mean values and ranges for Total Suspended Solids (TSS) by road surface type. Means are treatment means across sites and sampler locations for all collection dates. Within columns, means with the same superscript are not significantly different (α = 0.10). Values in parentheses are standard errors.

Surface type	TSS	Absolute range	Storm events Number	Storm events Mean	Storm events Max
	(ppm)	(ppm)		(cm)	(cm)
Paved (P)	152.7 a (116.4)	1.0–10,300.0	21	3.9	9.1
Improved Gravel (IG)	1,470.4 ab (469.7)	1.0–117,350.0	23	3.7	9.1
Routine Gravel (RG)	1,983.1 ab (373.7)	0–31,950.0	26	3.5	9.1
Unimproved Gravel (UG)	3,201.3 b (1,380.3)	6.0–71,680.0	25	4.1	9.1

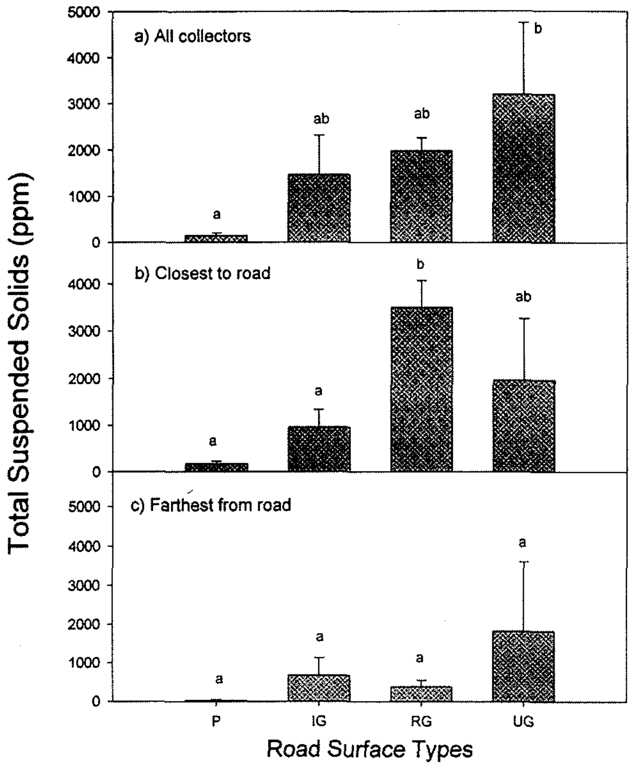

Figure 1. Comparison of total suspended solids (TSS) movement among road types by (a) mean TSS for all collectors, (b) mean TSS for collectors closest to the road, and (c) mean TSS for collectors closest to the stream. Error bars represent one standard error of the mean. Means with the same letter are not significantly *different.*

road ranked P<IG<UG<RG. In this analysis, TSS was significantly greater on the RG surface, compared with the P or IG surfaces, but was not different than the UG surface (Figure 1b). Clearly, paving, increased maintenance, and sediment control measures decreased the amount of TSS produced.

Because the delivery of road-generated sediment to surface waters is a primary concern, we also examined the spatial distribution of TSS along the transects. The paved surface had the lowest TSS concentrations throughout the length of transects (Figure 2a). The RG surface exhibited a consistent decrease in TSS with distance from the road (Figure 2c). The other road surfaces were highly variable; the greatest TSS concentrations sometimes were observed in the middle of a transect (e.g., Figure 2b). We attribute much of this variation to the storage and remobilization of road-generated sediment in mid-transect positions. For example, the UG surface had some of the highest observed concentrations of TSS at all transect positions (Figure 2d). This was primarily because of high concentrations of TSS generated from the road surface, combined with steep slopes below the road that prevented sediment entrapment. While the IG surface had the lowest concentrations from the unpaved surfaces (Table 2), the greatest TSS concentration for a given rain event occurred there. In part, this was due to failing sediment control devices. In areas where silt fences were installed, many had failed, and road-generated TSS traveled long distances below the road. For example, TSS was >500% higher below failed silt fences than in areas where the silt fences held. The third installation below the IG surface

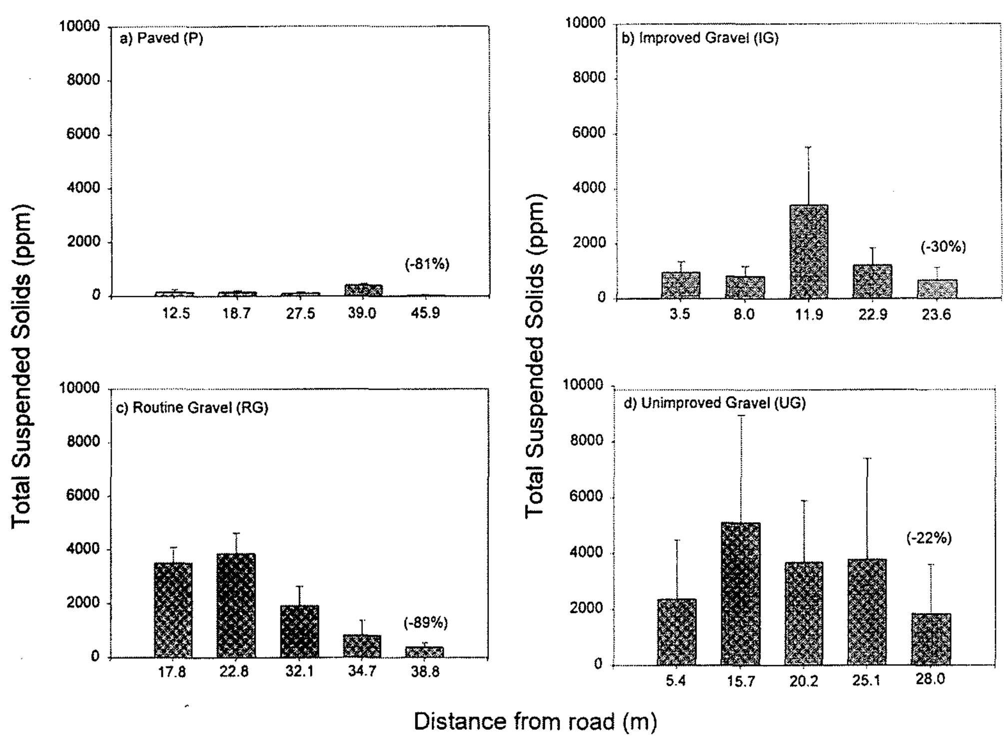

Figure 2. Comparison of total suspended solids (TSS) along transects for each road surface type. TSS values and distances (m) are means for each collector location within a road surface type ($n = 3$). Values in parentheses represent percent reduction in TSS from the closest to the farthest collector from the road. Error bars represent one standard error of the mean.

collected TSS from below a failed silt fence and consistently had higher TSS concentrations than other locations (Figure 2b). Sediment control measures on the IG included rip-rap that absorbed much of the energy from runoff—resulting in generally lower TSS concentrations from that surface type (Table 2 and Figure 2b).

In all cases, TSS was lowest in collectors nearest the stream, compared with collectors nearest the road (Figure 2), indicating entrapment of sediment generated from the road surface prior to stream delivery. Differences between near-road TSS and near-stream TSS ranged from 22% lower on the UG surface to 89% lower on the RG surface (Figure 2). The RG surface showed the greatest reduction in TSS along the transects. While TSS was reduced only 22% between the first and last collectors on the UG surface, it decreased 64% from the location with the greatest mean for the UG surface (location 2) to the last location. When analyzing TSS concentrations farthest from the road only, there were no significant differences among road surface types (Figure 1c). Still, mean TSS entering the stream from the UG road surface was near 2,000 ppm (Figure 2d). While there are no published standards for TSS in surface runoff, published standards for flow-independent nonpoint source turbidity in North Carolina stream waters (North Carolina Department of Environment and Natural Resources, Division of Water Quality, 2000) indicate values of 10 ppm for trout waters and 20 ppm for nontrout waters. These values often are exceeded in surface runoff entering streams from all surface types; however, surface runoff quickly is diluted by stream water, and the biological significance of this must be considered in the context of background levels of stream sediment and dilution potential. For example, although high TSS concentrations sometimes were observed near streams, TSS levels in Kings Creek during base-flow was 10 ppm, the upper bound for suspended sediment in trout waters.

We found a nonlinear relationship between TSS and distance from the road (Figure 3), with values low near the road, increasing between 15–20 m from the road, and declining to near zero at sample locations furthest from the road.

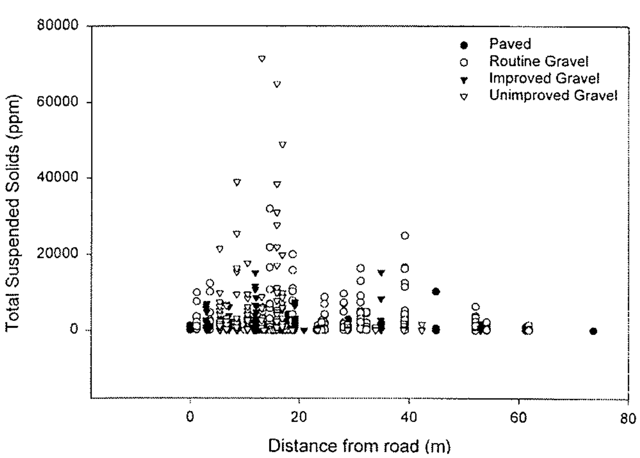

Figure 3. Plot of total suspended solids against distance (m) from road for each road surface type.

The regression model was defined as

$$Y = a + b(X),$$

where Y is the LOG_{10} of TSS, X is the TSS travel distance, and a and b are the intercept and slope, respectively. The regressions for each road surface type were significant ($P<0.0001$) with statistically significant differences in the slope and intercept parameters (Table 3). The rate of TSS movement was similar for distances below three of the four road surfaces (e.g., P = RG = IG < UG) as indicated by slopes of the regressions. The concentrations differed, particularly near the road, as indicated by the intercept terms. The ranks of intercepts for the four road types ($P < IG < RG = UG$) are reflected in the data in Figure 1b, as well.

To further illustrate differences in road types, we developed multiple linear regression models for each (Table 4). In general, the combination of distance from the road, precipitation amount, and Julian date explained the most variation in TSS. Surprisingly, terrain slope was not a significant regression parameter on any road surface. Swift (1986) demonstrated a weak, but generally positive relationship between terrain slope below the road and sediment travel distance across slopes varying from 0 to >80% at comparable sites in the Southern Appalachians. One possible explanation for the lack of a relationship in our study was that the range of slopes (i.e., 25 to 48%; Table 1) was too narrow to establish statistical significance. Our model representing the IG surface was weakest because of additional variation associated with the effects of both functioning and failed BMPs on TSS movement for that road surface. These regressions may prove useful in assessing the impact of current road conditions where sedimentation occurs in ephemeral or perennial watercourses. Although the R-squares are low, signs of the parameters for all models are logically consistent; i.e., TSS decreased with increasing distance from the road and increased with increasing precipitation. We interpret the significance of Julian date as a surrogate for intensity of vehicle activity (Luce and Black 2001), as road use increases substantially in the summer and fall due to recreation, fishing, and hunting (Andrew-Pickens Ranger District, unpublished data). Users applying these regressions should be mindful that they are case studies, and although the models serve to illustrate differences in road surface types as to their potential contribution of TSS, their predictive power should be considered low.

Table 3. Parameter estimates for the test for differences in slope and intercept for estimating Total Suspended Solids using distance from road as the independent variable. Statistics for the overall model are for intercept, r^2 = 0.57, P < 0.0001, and slope, r^2 = 0.43, P < 0.0001. Values of slope and intercept with the same superscript are not significantly different (α = 0.05).

Surface type	Slope	Intercept
Paved (P)	–0.02889 a	0.79447 a
Improved Gravel (IG)	–0.04818 a	2.12080 b
Routine Gravel (RG)	–0.04656 a	3.25326 c
Unimproved Gravel (UG)	–0.10636 b	3.71832 c

Table 4. Regression models and associated statistics for predicting Total Suspended Solids ($LOG_{10}TSS$) for the four road types. Parameters are D = distance below the road (m), P = total 24 hr precipitation (cm), JD = Julian Date.

Road surface	Regression model	R^2	F	P
Paved (P)	$Log_{10}TSS = -0.22724 - 0.03886(D) + 0.19638(P) + 0.00373(JD)$	0.18	15.46	<0.0001
Improved Gravel (IG)	$Log_{10}TSS = 1.65037 - 0.04755(D) + 0.11177(P)$	0.07	9.08	<0.0002
Routine Maintenance (RG)	$Log_{10}TSS = 2.32370 - 0.04645(D) + 0.083(P) + 0.0034(JD)$	0.15	16.43	<0.0001
Unimproved Gravel (UG)	$Log_{10}TSS = 2.62475 - 0.11202(D) + 0.24592(P) + 0.00199(JD)$	0.39	45.89	<0.0001

Total Petroleum Hydrocarbons

TPH was very low (< 0.5 ppm) in runoff samples taken from the P surface and was not detectible in runoff from the other nonpaved surfaces, or in Kings Creek, a nearby tributary of the Chattooga River. The P surface was 2 yr old when the study began, and although we did not record TPH values immediately after paving, these results suggest that beyond 2 yr, this type of paved surface is no longer a significant source of TPH. Petroleum hydrocarbons are more complex pollutants to standardize because of their many fates in natural systems, as well as their effects on terrestrial and aquatic ecosystems. For example, petroleum compounds may bind in the soil, biodegrade along their paths, enter the groundwater, or accumulate in detrital feeders and travel up the food chain. In general, their fates are bond strength and carbon-chain length dependent. The standard for TPH in sediment is 1,684 ppm (U.S. Environmental Protection Agency, Region 4 Supplemental Guidance to RAGS 1995), well above TPH levels observed in this study. Surface water quality standards are available for allophatic (2–25 ppm) and aromatic (32–118 ppb) hydrocarbons but not for TPH. The existence of legacy compounds in terrestrial or aquatic systems from fresh asphalt or from decades of vehicular traffic within a watershed is not known. Moreover, it is not known whether or not these hydrocarbons are allophatic, in which case measured TPH is well below surface water quality standards, or aromatic in which case they exceed published standards.

Conclusions and Implications

The amount of sediment movement from road surfaces is highly variable within and among surface types and is related to levels of maintenance and road drainage. Properly installed structures and maintenance practices substantially reduce sediment movement downslope from the road. Where measures to reduce sediment movement have failed or devices were not properly installed, there was some reduction in the amount of sediment with distance below the road, depending on the steepness of the downslope side of the road and the volume of water leaving the road at that point. The distance sediment travels below a road surface is related to the type of drainage system provided. Drainage that concentrates runoff and where no energy dissipating structures (e.g., rip-rap, silt-fences) are installed results in TSS concentrations high near the road but decrease with distance from the road. This has significant implications for water quality protection. For example, where runoff outlets of this type are optimally located, i.e., at the maximum distance from perennial or ephemeral streams, road drainage presents the least amount of risk for sedimentation. However, streams that are near runoff outlets of this type could be at risk. Hence, in order to prevent or reduce the distance traveled by sediment from road surfaces, it is crucial to ensure that drainage occurs in locations that are not adjacent to perennial or ephemeral water courses, and that the locations of outlets are at frequent enough intervals to keep water volumes at a minimum.

Observed levels of TPH were more than 300% below EPA and NCDENR Standards for TPH in sediment. However, the small concentrations of TPH found in paved surface runoff may continue to travel through the system. The information on TPH concentration that this study provides is a good indicator of what can be expected about the gross delivery of a suite of hydrocarbons for recently (within 2 yr) applied asphalt. The fates of various hydrocarbon compounds are dependent in large part on the size of the carbon molecule itself; the distribution of molecule size within the suite of all TPH molecules measured here is not known. Separation of these compounds is tedious and expensive but would, nonetheless, provide a more complete picture of TPH movement and dynamics. Additional studies are needed to more fully understand TPH dynamics, and the effects of petroleum hydrocarbons on ecosystem function.

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