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Changes to in-stream turbidity following construction of a forest road in a forested watershed in West Virginia

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**Changes to In-Stream Turbidity Following Construction of a Forest Road in
a Forested Watershed in West Virginia**

William Frank Sharp

**Thesis submitted to the
Davis College of Agriculture, Forestry & Consumer Sciences
at West Virginia University
in partial fulfillment of the requirements
for the degree of
Master of Science
in
Forestry**

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Abstract

Changes to In-Stream Turbidity Following Construction of a Forest Road in a Forested Watershed in West Virginia

by Will Sharp

In 1999, a study was initiated in two forested headwater channels to compare and contrast changes to in-stream suspended sediment and turbidity following the construction of a forest haul road. Turbidity (NTU), suspended sediment concentrations (SSC) (mg L^{-1}) and streamflow (L s^{-1}), were measured throughout May 2005. Both catchments are ephemeral/intermittent tributaries of the Left Fork of Clover Run in the Cheat River watershed. To exclude inputs of hillside sediment both catchments were continuously lined with silt fence from constructed gauging/sampling stations to the upper most portions of their drainage network. In July 2002, construction of a 0.93 km (0.58 mi) road (FS 973), encompassing 1.3 ha (3.3 ac) of the 32.7 ha (80.8 ac) treatment watershed, was initiated. FS 973 was completed in September 2003. Data were separated for comparison by road construction initiation (i.e. pretreatment and post-treatment), although, some analysis focused solely on the construction period independently. During the construction period, several tons of sediment were deposited in the stream channel. Following construction, the treatment watershed's stream turbidity, in relation to both watersheds pretreatment period and in respect to the reference watersheds post treatment period, increased significantly. While the highest turbidity value recorded in the treatment watershed (2352 Nephelometric turbidity units (NTU)) was 6.4 times larger than the highest turbidity sampled in the reference watershed, it was sampled during low streamflow ($<1.4 \text{ L s}^{-1}$ or $<0.05 \text{ ft}^3\text{s}^{-1}$ (CFS)). Fourteen post-treatment samples exceeded 100 NTU at discharges greater than 56.5 L s^{-1} (2.0 CFS) when the treatment watersheds average streamflow was 5.5 L s^{-1} (0.20 CFS). The reference watershed's samples stayed within expected ranges throughout the duration of this study. Turbidity increased significantly due to the construction of FS 973, specifically due to the prolonged period in a pioneered condition, construction of three culverted stream crossings, an inadequate cross-drain, and a constructed stream channel.

Dedication

The author wishes to thank family and friends.

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Introduction

Turbidity, the refractive index of a solution, is an indirect measure of in-stream suspended sediment concentrations (Anderson and Potts 1987). Although, turbidity can be affected by dissolved air, solution color, particle size and shape, and solution concentration, it often is a better predictor of in-stream suspended sediment concentrations than discharge (Anderson and Potts 1987).

Road construction and use are recognized as the primary sources of sediment production during forest operations (Hornbeck and Reinhart 1964). Roads accelerate erosion, affects run-off, and increases effective channel lengths in headwater watersheds (Reinhart 1964, Binkly and Brown 1993, Jones and Grant 1996, Wemple et al. 1996). One year after road construction in north central West Virginia, treatment watershed maximum turbidity exceeded maximum reference watershed turbidity by 3,700 JTU (Jackson turbidity units) (Hornbeck and Reinhart 1964). Turbidity increases were primarily attributed to the poorly located skid roads and skidding in streams (Kochenderfer and Hornbeck 1999).

Roads intercept subsurface flow and precipitation, which can accelerate the transfer of hillside water to stream channels (Reinhart 1964, Wemple et al. 1996). Some road sections have therefore been classified as channel extensions, that is, they drain intercepted precipitation and subsurface water directly into a stream channel. Channel lengths have increased up to 40 percent due to these road and stream linkages (Wemple et al. 1996). Eighty-eight percent of road run-off emptied into ephemeral/intermittent streams in western Washington and Oregon (Irvin and Sullivan unpublished data, as in Bilby et al. 1989). These processes can directly and indirectly affects the quality of streamflow by increasing sediment supply to-streams, increasing in-stream

sediment and turbidity, reducing channel storage, decreasing channel stability, and affect storm streamflow responses (Hornbeck and Reinhart 1964, Cornish 2001, Wemple et al. 1996).

Streams draining mountainous areas are constantly supplied with sediment from the surrounding hillsides. Morphological stability is dominated by sediment transport to supply ratios and episodic events (e.g. large storms). Stream sections with exposed bedrock indicate higher transport capacity than sections filled with colluvium (i.e. hillside delivered sediment). In addition, the channels with filled with more colluvium tend to be less stable morphologically (Montgomery and Buffington 1998). Streams that transport more sediment than supplied tend to become armored, that is, the interstitial spaces have less fine sediment, which leads to increased bed roughness and decreased average streamflow velocities, providing for increased transfer of heterogeneous sediment (Simons et al. 1963, Parker and Klingeman 1982). Channels filled with more colluvium tend to be less stable morphologically (Montgomery and Buffington 1998). Possible consequences include loss of pool density, increased average streamflow velocities and decreased channel roughness, thereby increasing the competence and capacity of a given streamflow (Lisle 1982).

The largest increases to in-stream suspended sediment and turbidity occurs during road construction and maintenance (Hornbeck and Reinhart 1964, Swift 1988). During and the following year after construction, streamflow becomes turbid more frequently, where more than fivefold increases in in-stream suspended sediment and turbidity can be common (Hornbeck and Reinhart 1964, Fredriksen 1970). Turbidity and sediment tend to decrease most rapidly within the first couple years post-treatment (Rice and Wallis 1962, Hornbeck and Reinhart 1964, Meaghan and Kidd 1972). After the first couple of years recovery rates decrease and elevated turbidity and sediment continue to persist for years (Hornbeck and Reinhart 1964).

The adverse effects caused by increasing in-stream sediment have initiated the use of better construction practices. For example, best management practices (BMPs) are mandated by the Clean Water Act 1977 and state law during forest operations. Water quality degradation following forest operations decreases with the use of the better construction practices (Kochenderfer and Hornbeck 1999). Although, these methods do decrease to-stream sediment transport, inadequate background sampling can mischaracterize BMP effectiveness (Edwards et al. 2004). Storm sampling is required to characterize sediment and turbidity in steep headwater stream channels, as variation between storm exports can be as large or larger than variation between annually exported sediment (Kochenderfer et al. 1997).

Turbidity is the primarily water quality parameter used to assess water quality in the East. “West Virginia water quality regulations permit no more than a 10 NTU increase from baseline conditions, specifically, “No point or non-point source to West Virginia's waters shall contribute a net load of suspended matter such that the turbidity exceeds 10 NTU's over background turbidity when the background is 50 NTU or less, or have more than a 10% increase in turbidity (plus 10 NTU minimum) when the background turbidity is more than 50 NTUs. This limitation shall apply to all earth disturbance activities and shall be determined by measuring stream quality directly above and below the area where drainage from such activity enters the affected stream. Any earth disturbing activity continuously or intermittently carried on by the same or associated persons on the same stream or tributary segment shall be allowed a single net loading increase.” (USEPA 2006).

Therefore, the objectives of this study were to: 1) describe turbidity before and after haul road construction, 2) determine if or when in-stream turbidity levels decreased after construction of a haul road in the treatment watershed, and 3) if possible, given the short pre and post treatment

periods, evaluate if recovery was linear, exponential, or if turbidity levels off at a level higher than pretreatment at some point in time.

Chapter 1: Literature Review

1.1 Sediment and Turbidity

Sediments in the stream channel are classified as either bedload or suspended sediment (Anderson 1970). Bedload particles have a particle diameter that prevents movement in suspension. Bedload particles are carried along the streambed through saltation (i.e., particles bouncing along the streambed). By contrast, suspended particles are small inorganic and organic particles that remain in suspension for extended periods. The duration in suspension depends upon available energy and particle properties (Guy 1978).

Turbidity, an indirect measure of suspended sediment concentrations, is a West Virginia State water quality parameter. Turbidity is usually a better predictor of suspended sediment concentrations (SSC) than streamflow and a better predictor of water clarity than SSC (Anderson and Potts 1987). Turbidity is a measure of water clarity (Anderson and Potts 1987), expressed currently in Nephelometric turbidity units (NTU), determined with a turbidimeter. In past studies, turbidity commonly was expressed in Jackson turbidity units (JTU), which are based on visual estimates of water clarity (Kochenderfer and Hornbeck 1999, Aubertin and Patric 1974). Both organic and inorganic particles contribute to turbidity. Streamflow turbidity will either increase or decrease as they increase or decrease in size and or number.

To transport suspended sediments, a stream must have enough energy to lift and move the particle. To continue carrying the particle, the stream must be able to overcome the inhibiting forces exerted upon the particle or it will settle back onto the streambed. The velocity and mass of water are the important factors in determining the kinetic energy (KE) of water:

$$KE = \frac{1}{2}(\text{mass} \times \text{velocity}^2)$$

Because the velocity term is squared in this equation, small increases in velocity result in relatively large increases in kinetic energy (Chang 2003).

A stream with substantial kinetic energy that is not carrying much sediment because of a lack of available sediment is referred to as “hungry water”; in other words, if sediment becomes available the water will have energy to detach and/or transport it. By contrast, if stream is carrying its maximum sediment load, some sediment must be deposited before more can be transported. Forest streams and watersheds that are largely undisturbed tend to be sediment-source limited; that is, even though stream water has the potential to carry more suspended sediment, the sediment supply is limited. Therefore, the stream does not carry its maximum potential load. Sediment limited streams typically reach peak sediment or turbidity levels before streamflow peaks, and they return to pre-storm conditions quickly (Stuart and Edwards 2006). Moderately to severely disturbed streams and watersheds, tend to be energy limited type relationships. Sediment concentrations and turbidity can increase proportionally with streamflow up to and after peak discharge and then return to baseline conditions more slowly than streamflow (Riedel et al. 2004).

1.2 In-stream Processes

A stream channel develops in dynamic equilibrium, working toward the efficient transfer of stream energy and sediment (Lane 1955). Sediment sizes and sediment volumes amounts stored in the channel and suspended in streamflow are functions of sediment supply and the transport capacity of different particles at different levels of streamflow (Shen and Li 1976). The transport capacity of sediment through a stream reach is a function of several stream parameters: width, depth, velocity, stream slope, channel roughness, concentration of sediment, size of sediment debris, and streamflow (Leopold et al. 1964). Sediment supply, streamflow, and channel

parameters are the dominant variables determining sediment transport through a channel (Leopold et al. 1964, Shen and Li 1976, Edwards et al. 2004).

Sediment transport can be separated into three in-stream components: initiation of transport, downstream transport, and deposition. The maximum size particle that a given streamflow can transport is the streamflow competence to lift and transport larger sediments. The total amount of sediment transported during a given streamflow is the streamflows capacity to transport more or less sediment (Gordon et al. 1992).

Streamflow at or near bankfull is the most efficient streamflow for transporting sediment (Leopold et al. 1964). The occurrence of bankfull streamflow varies between geographic areas. In meandering lowland channels bankfull streamflow generally occurs every 1.5 to 2 years (Leopold et al. 1964), while bankfull streamflows in mountainous streams is more variable and typically occurs less frequently (Lisle 1987, Nolan et al. 1987).

Sediment is commonly stored in-streams more than 10 times measured annual exports, typically due to long-term storage sites (Megahan 1982, Swanson and Lienkaemper 1978). Sediment can be stored for tens of years to millions of years in rivers (Reid 1982), although in steep headwater streams, storage is typically of shorter duration (Dietrich and Dune 1978). In a stream in the Pacific Northwest, approximately 50 percent of total exported sediment was estimated to have been derived from the stream channel (Anderson 1970). Cumulative sediment yield from sub-basins is often larger than the sediment yield if measured from the main channel further downstream (Guy 1978), which indicates the increase in channel storage downstream.

Large woody debris (LWD) can store large amounts of sediment in streams (Megahan 1982, Likens and Bilby 1982, Hart 2003). After measuring 17 sites in Oregon, Froehlich (1973) found larger woody debris averaged 30.6 Mg (33.6 tons) per 100 m (300 ft) of the stream channel.

Differences in channel morphology and sediment storage were observed in a stream that had 1.6 more LWD per 100 m (300 ft). In Tennessee, one logjam of 50 trees stored 1200 m^3 ($42,400 \text{ ft}^3$) of sediment (Hart 2003). In Idaho, Megahan (1982) found that about 15 years of an annual sediment yield were stored behind in-stream storage sites and that larger woody debris was one of the most important sediment storage sites. In West Virginia, organic matter made up 47 to 52 percent of the sediment deposited in long-term storage areas (Kochenderfer et al. 1987).

In western Washington, following large woody debris removal, one stream changed significantly after the first streamflow $6,485 \text{ L s}^{-1}$ ($229 \text{ ft}^3 \text{ sec}^{-1}$) even though higher flows occurred within 2 months. After removal of large woody debris average streambed elevation lowered 25.4 cm (10.0 in) from a fourth order stream, and one cross section lowered by 80 cm (30 in), and the overall number and volume of pools decreased (Bilby 1984).

Large amounts of fine sediment can be redistributed and added to streams when watersheds are disturbed (Lafayette and Callahan 1980). Fine sediment tends to fill the voids between larger substrate. When voids are filled with finer sediment, vertical water movement through streambed can be inhibited (Ratanavaraha 1998), increasing the transport potential of larger sediment (Lisle 1987). In addition, as smaller sediment fills pore spaces, channel roughness decreases, average velocities increase, and deposition velocities decrease (Simons et al. 1963) causing sediment transport to become more similar among particle size classes (Parker and Klingeman 1982, Andrews 1983). Channel roughness is a primary determinant of sediment transport, therefore, as streambed sediment become finer, pools will become shallower and steeper, and streamflow velocity for a given streamflow will increase, increasing the competence and capacity of a given streamflow (Lisle 1982).

1.3 Erosion from Forest Roads and Forest Operations

Roads are the primary sediment production sites in forested watersheds (Kochenderfer 1970, Brown and Krigier 1971, Reid and Dune 1984, Kreutzweiser and Capell 2001). Erosion rates from roads peak during construction (Swift 1984a, Kochenderfer and Helvey 1987) and decreases following construction. In a forest operation in Northwest California, roads did not exceed 4 percent of the total area, although were estimated to be the source of 40 percent of the total erosion (McCashion and Rice 1983). In West Virginia, Kochenderfer (1977) found road density to be approximately 5% to 8% of the area in nine logging sites.

Erosion rates from roads can differ significantly from closely related segments. In the East, measured erosion rates from roads have ranged from $4,200 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($4700 \text{ lb ac}^{-1} \text{ yr}^{-1}$) from broad based dips (Kochenderfer and Helvey 1987) to $1,250,000 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($1,400,000 \text{ lb ac}^{-1} \text{ yr}^{-1}$) around stream crossings (Swift 1978). Liberman and Hoover (1948) estimated $408 \text{ m}^3 \text{ km}^{-1}$ of soil loss on skid roads during a “loggers choice” high-grade harvest in western North Carolina. Most of the roads and trails were located in streams or adjacent to streams. Dry bulk density estimates from sediment deposits have ranged from 848 kg m^{-3} (Kochenderfer and Helvey 1984) in West Virginia to 989 kg m^{-3} in Oregon (Fredriksen 1970). The skidroad described above had the potential to deliver $140 - 170 \text{ kg m}^{-2}$ ($30 - 35 \text{ lb ft}^{-2}$) of sediment to the stream channel if the skid road width is assumed 2.4 m (8 ft).

Kochenderfer and Helvey (1987) reported that a 4-year annual sediment production average ranged from $10,600 \text{ kg ha}^{-1}$ ($12,700 \text{ lb ac}^{-1}$) from a 3-inch stone graveled road to $94,500 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($105,800 \text{ lb ac}^{-1}$) from an ungraveled road. Sediment production from the ungraveled road ranged from $28,000 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($31,400 \text{ lb ac}^{-1} \text{ yr}^{-1}$) to $160,800 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($180,100 \text{ lb ac}^{-1} \text{ yr}^{-1}$), compared to $4,200 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($4700 \text{ lb ac}^{-1} \text{ yr}^{-1}$) to $21,400 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($24,000 \text{ lb ac}^{-1} \text{ yr}^{-1}$) on the

graveled road. Road erosion rates differ significantly between the different surfaces applied and among individual years.

Swift (1984b) found surfaced and un-surfaced roads lost 18,100 kg ha⁻¹yr⁻¹ (20,200 lb ac⁻¹yr⁻¹) to 136,100 kg ha⁻¹yr⁻¹ (152,400 lb ac⁻¹yr⁻¹), respectively, in a 2-month period post construction. The large losses resulted from two large intense May storms. Approximately 76% of the 1981 soil loss occurred between May and November, and these relatively large episodic losses were the general trend for the study. Measured soil loss was the greatest during the growing season.

Road maintenance and use increases sediment loss from roads in both direct and interrelated indirect circumstances. Roadbed soil loss increases with traffic on unpaved roads (Kochenderfer and Helvey 1987, Swift 1984b). In Ontario Canada, Kreutzweiser and Capell (2001) found road maintenance increased fine sediment in average bedload estimates 4000 times higher than background levels, although, Grayson et al. (1993) found road segment sediment production increased 40 percent during use without maintenance.

Road location within a watershed can affect the amount of sediment that reaches a stream channel. Rainfall around stream crossings can transport sediment relatively easy to streams (Miller et al. 1997). Following road building in Dungog, Australia, the only statistically significant turbidity increase in streamflow was found from the stream with four culverted stream crossings (Cornish 2001). Eighty-eight percent of road run-off emptied into ephemeral/intermittent streams in western Washington and Oregon (Irvin and Sullivan unpublished data, as in Bilby et al. 1989).

Hillside storage typically transmits sediment to the stream channel (Lisle 1987) and hillside erosion does not even always reach a stream channel (Roberts and Church 1986, Benda and Dunne 1997, Roering et al., 1999, Cui et al., 2003). Hillside processes occur on a much longer

time scale than in-stream processes (Leopold et al. 1964). Several variables exist can speed up or slow down hillside delivery to streams. For example, Haupt (1959) found slope obstructions more important for determining sediment transport distance than slope. Parameter interactions (rainfall, elevation, slope, and aspect) make it difficult to isolate and quantify in-stream suspended sediment delivered from roads (Swanson and Fredrikson 1982).

1.4 Turbidity and In-stream Sediment

Hornbeck and Reinhart (1964) examined in-stream sediment and turbidity on four watersheds in West Virginia that received different harvests. Most of the sediment and turbidity increases were attributed to the poorly planned and located skid roads, the lack of water control on skid roads, skidding in streams, and the amount of timber harvested (Kochenderfer and Hornbeck 1999). During treatment, turbidity reached 56,000 JTU in the stream in which no watershed management occurred. The carefully managed watersheds highest turbidity reached 25 JTU and the control watersheds maximum turbidity reached 15 JTU (Hornbeck and Reinhart 1964). In addition, clearcut harvests that have excluded for road building, typically show no substantial increases to turbidity or suspended sediment (Likens et al. 1970, Fredriksen 1970, Brown and Krygier 1971)

Following a harvest in Pennsylvania, in which one watershed was clear cut and another was left undisturbed, the mean (196 ppm) and maximum (550 ppm) sediment concentration was significantly higher than the control watersheds (≤ 25 ppm) (Lynch et al. 1990). In North Carolina, maximum turbidity reached 3500 ppm while averaging 93.7 ppm post-treatment even though the control watersheds average turbidity stayed around 4.3 ppm (Lieberman and Hoover 1948).

The rate of recovery to background conditions following disturbance varies among many of the published studies. The first year maximum differed from second and third year by 4000 JTU

and 600 JTU respectively after a diameter-limit (Hornbeck and Reinhart 1964). Following road construction on erodable soil in Idaho, average sediment yields retained behind a sediment dam in an ephemeral drainage averaged $15,700 \text{ kg ha}^{-1}$ ($17,580 \text{ lb ac}^{-1}$) compared to a small amount in the reference watershed (Megahan and Kidd 1972). Eight years after road construction and harvest in Western Oregon, Fredriksen (1970) found the average treatment watershed sediment yield remained elevated ($27,600 \text{ kg ha}^{-1}$ ($30,900 \text{ lb ac}^{-1}$) when compared to the reference watershed (260 kg ha^{-1} (290 lb ac^{-1})).

In California, Rice and Wallis (1962) found a fivefold increase in sediment concentrations occurred in the first year following forest operations then returning to a twofold increase by the second year. Meaghan and Kidd (1972) found that that road related sediment was barely (2%) being exported after the second year post construction. Four years post-treatment sediment concentrations became similar between the treatment and control watersheds (Lynch and Corbett 1990).

Chapter 2: Methods

2.1 Study and Watershed Descriptions

In-stream suspended sediment, turbidity, and streamflow (i.e. stage and velocity) in two headwater streams were measured since 1999. Both streams are located within the Clover Run Watershed, Monongahela National Forest, north central West Virginia (Fig. 2.1). This design adopts the typical paired watershed design (e.g. reference and treatment watersheds) to evaluate the effects of road construction on water quality (i.e. turbidity and suspended sediment).

Monitoring stations (Fig. 2.2) were constructed in both watersheds to facilitate this study. The monitoring stations were constructed at the watersheds outlet to house automated samplers, which collected suspended sediment samples and stream stage and velocity measurements. Silt fences (Fig 2.3) around the active stream channels were installed in both watersheds, from the monitoring stations to the upper most portions of their drainage networks. In the beginning, the primary goal of this study was to measure to-stream sediment delivery, hence, the silt fence lining the stream channels, although, due to a number of events that led to a substantial amount of sediment being deposited in the stream channel, which is thoroughly described in a later section, the primary focus of this study shifted towards measuring changes to in-stream suspended sediment.

When measured from the stream monitoring stations, the treatment and reference watershed are 32.7 ha (80.8 ac) and 20.2 ha (49.9 ac) in area respectively (Table 2.1). The reference watershed is smaller because of an old road built before Forest Service ownership (1940's) was kept from crossing the stream channel above the gauging site. Although vehicles are nonexistent, 4-wheelers were used on the road to access the reference watershed (Edwards, P.J. Submitted). The road and stony portions of the hillsides indicate the reference watershed was

probably used for subsistence living (e.g. mountain farming and timbering) prior to Forest Service ownership. Probably like near by watersheds in the area (Lima et al. 1978). A small area of planted red pines (*Pinus resinosa*) indicates a reforestation project by the civilian conservation corps (CCC) probably occurred after Forest Service ownership. The treatment watershed, by contrast, exhibited no signs of anthropogenic disturbances (Edwards, P.J. Submitted), although, some level of timber harvest occurred prior to 1940.

Both watersheds are steep to moderately steep where slopes can exceed 80% (Table 2.1). This is typical of the headwater watersheds in this area (Fig 2.4). Hillside slopes average 42.6 percent and 38.7 percent in the treatment and reference watersheds respectively. The dominant aspects are east northeast and east in the treatment and reference watershed respectively. Both watersheds are underlain by the shale, siltstone, and sandstone of the Chemung geology (Losche and Beverage 1933). Depth to fractured bedrock from the soils surface tends to range from 0.5 m (20 in.) to 1.5 m (60 in.).

The soils, mapped in 1996 by the USDA Natural Resource Conservation Service, include Berks-Highsplint Association, Brownsville-Berks complex, Highsplint-Berks association, and Liadig channery silt loam (Soil 2004). These soils generally are considered moderately erodable. The soils acidity tends to increase with depth from slightly acid to strongly acid. Water infiltration is generally moderate to moderately rapid. Rock fragments range from 10 percent to 50 percent in the A-horizon, 15 percent to 75 percent in the B-horizon, and 35 percent to 90 percent in the C-horizon. The A-horizon tends to be a silty loam, which increases in clay content with depth. A layer of decaying leaves covers these soils (Losche and Beverage 1933, Soil 2004).

The vegetation in both watersheds is typical of northern hardwood forests, mixed mesophytic forests, and Oak-Hickory forest (Strausbaugh and Core 1978). Oaks (*Quercus* spp.),

black cherry (*Prunus serotina*), yellow poplar (*Liriodendron tulipifera*), american beech (*Fagus grandifolia*), maples (*Acer* spp.), and hickories (*Carya* spp.) are the dominant overstory tree species. The understory is comprised of witch hazel (*Hamamelis virginiana*), spicebush (*Lindera benzoin*), other associated species, and smaller overstory trees. The herbaceous layer is dominated by ferns (*Dryopteris* spp.), although, other species are typical, such as blueberries (*Vaccinium* spp.), greenbrier (*Smilax* spp.), club moss (*Lycopodium flabellaforme*) and herbaceous wild flowers.

Data from a weather station (1973-2004) located approximately 3.4 air kilometers away (operated by the US Forest Service's Northern Research Station), indicate the average precipitation for the area is approximately 161 cm yr⁻¹. The months of April through July generally receive the most precipitation, while September through November generally receives the least precipitation. The largest rainfall events are typically the result of tropical storms and hurricanes moving inland from the Atlantic Ocean. In addition, convective thunderstorms commonly produce intense periods of rainfall during the summer. Snowfall is common between November and March although can occur earlier or later. During the dormant season, a snow pack can remain on the ground for the majority of the winter or periodic rain-on-snow or fluctuating temperatures can produce intermittent ground coverings (Edwards, P.J. Submitted).

The hillsides include both flat benches and steep slopes. The upper most portions of the drainage divides typically forms bowl shapes. The surface areas of the streams (including ephemeral reaches) surveyed with a total station (unpublished data) are approximately 0.37 ha (0.93 ac) and 0.27 ha (0.66 ac) for the treatment and reference watersheds, respectively. The stream slopes are steep and average between 30 and 40 percent for individual segments (Fig. 2.5) (Bills 2005).

2.2 Field equipment, measurements, and sampling

Water samples have been collected and streamflow (i.e., stage and velocity) has been measured in the treatment and reference streams since 1999. Housing for stream gauging and sampling equipment (Fig. 2.2) was constructed in both watersheds near their mouths. Five-minute streamflow velocity and stage readings were recorded at both stations using an American Sigma 950 flow meter. Stream water samples were collected for turbidity analyses. Daily samples were collected with an American Sigma model 900s automatic sampler in each watershed. Stormflow samples were collected with an Isco model 2700 automatic sampler in each watershed. The Isco model 2700s were actuated using precipitation rather than stage and then sampled on pre-set time intervals following the first sample to obtain a better representation of sediment responses during storms (Edwards and Owens 1995). Funnels collected precipitation and transmitted it into PVC pipe that also held the actuator (Fig. 2.2).

In the treatment watershed, the stream reach used for gauging and sample collection had a bedrock bottom. The reference watershed's sampling reach originally had a cobble bottom, so to create a more stable control section, a PVC pipe cut was cut in half lengthwise and this was set in place in the middle of a stabilized control section constructed of native stone and concrete (Fig. 2.6). This half pipe was used to concentrate streamflow for stage and velocity readings. Water samples were collected from a pool below the outlet of the PVC pipe (Fig 2.7). During drier periods, the pool collected some sediment which resulted in some artificially elevated turbidity levels in samples collected during those periods (i.e., some of this settled sediment was collected during pumping by the automatic samplers). Most of these samples were identified as outliers and were removed from the data set by the Forest Service. Some large SSC samples in the reference watershed during Fall of 2004 were probably the result of the sampling environment and therefore

analysis was computed with and without these samples and was expressed in the result section. This problem did not exist for the treatment watershed because it had a bedrock streambed.

Stormflow sampling started November 2, 1999 and lasted until June 4, 2002 in both watersheds. One-hundred and fifty-three storms were sampled during pretreatment. Of these 70 were paired storms – that is, they were sampled on both the treatment and reference watershed. Stormflow sampling in the reference watershed started again on November 1, 2002 and lasted until April 30, 2005. Treatment watershed storm sampling started again on October 15, 2002 and lasted until April 30, 2005. One-hundred and thirty-four storms were sampled during post-treatment. Of these forty-two were paired storms. Samples were not collected from June 4, 2002 to October 15, 2002 for safety purposes during construction.

Stormflow sampling started November 2, 1999 and lasted until June 4, 2002 in both watersheds. Eighty-one and 72 storms were sampled in the reference and treatment watershed respectively. One-hundred and fifty-three storms were sampled during pretreatment. Of these 70 were paired storms. Stormflow sampling in the reference watershed started again on November 1, 2002 and lasted until April 30, 2005. Treatment watersheds storm sampling started again on October 15, 2002 and lasted until April 30, 2005. Sixty-five and 69 storms were sampled in the reference and treatment watershed respectively. One-hundred and thirty-four storms were sampled during post-treatment. Of these forty-two were paired storms. Samples were not collected from June 4, 2002 to October 15, 2002 for safety purposes during construction.

Stream velocity and stage measurements were made on 5-minute intervals since October 1, 1999. The velocity measurements from the American Sigma equipment were unstable and inaccurate, but the stage readings remained quite stable following calibration. Consequently, discharge was estimated from the stage measurements using Manning's equation in HEC-RAS

software (www.hec.usace.army.mil/software/hecras/). These calculations were made by the Forest Service. Stage < 2.0 cm (0.8 in) could not be measured accurately because of equipment limitations. Samples collected during these streamflows represented anywhere from 8 to 45 percent of the routine and storm samples during pre and post-treatment periods. These samples are referred to as samples collected when streamflow was below detection limits. Streamflow also could not be calculated when the streams were frozen or when samplers malfunctioned (Edwards, P.J. Submitted). Turbidity analysis relative to streamflow was nonexistent due to some large variations in streamflow regressions and peak streamflow comparisons. Streamflow is presented in liters per second (L s^{-1}).

2.3 Road Construction Activities

Road (FS 973) construction in the treatment watershed began July 8, 2002 and lasted throughout September 2003 (Fig. 2.8). FS 973 extended for 0.93 km (0.58 mi), encompassing 1.3 ha (3.3 ac) of the 32.7 ha (80.8 ac) treatment watershed. FS 973 extended for another 2.6 km (1.6 mi) after exiting the treatment watershed's drainage divide. Road construction is defined as the day heavy machinery began working within the treatment watershed to the day the haul road met BMP standards within the treatment watershed. Except for seeding, mulching, fertilizing, blowing hay, and installing a check dam on October 22, 2002 and May 7, 2003, road construction was ceased between October 15, 2002 and May 7, 2003 to avoid the winter months and the wet spring months. During FS 973 construction, three permanent culverts and two temporary culverts were used to form three stream crossings (Fig. 2.9). The fills over these crossings reached 9 m (30 ft). The first temporary culvert, later removed and replaced with the first permanent culvert, was used to proceed further into the watershed. The second temporary culvert was inadequately draining a steep tributary, therefore, it had to be removed. FS 973 construction was a slow process because

the fills over the culverts were large (i.e. up to 15 m (50 ft)), thus the fillslopes had to be meticulously constructed and compacted, some road cuts lead into large portions of bedrock that needed to be cut through and properly sloped, a culvert failed and had to be removed while the stream had to be diverted to another culverted stream crossing via a constructed rip-rap channel, and the treatment watershed was relatively remote and the number of trucks was limited, therefore, graveling the road became a very slow process.

By the end of July 2002, road construction consisted of constructing one temporary stream crossings, installing check dams in the stream channel around the first temporary culvert, and excavating and grading up the steep channel (i.e. the 2nd temporary culvert).

Towards the beginning of September 2002, the first temporary stream crossing was replaced with a permanent 60-inch diameter culvert, while the second and third stream crossings were constructed using a 48 and 38-inch permanent culverts respectively. To construct the first stream crossing a pad of soil was formed in the channel for the bulldozer to operate on while constructing the stream crossing (Fig 2.10). The pad stayed in the stream channel for approximately 7 days. Straw bales and check dams were placed around the culverts to trap sediment.

On September 16th 2002, 15 m (50 ft) past the 1st permanent stream culvert, a 2nd temporary culverted stream crossing was formed to drain a steep tributary (Fig 2.11). Although, the tributary had a small contributing area and was relatively dry throughout most of the time, during wet periods the stream would damage the road, therefore, a culvert had to be installed to divert the water to the fillslope side of the road.

In October 2002, excavation of the road had progressed beyond the watershed and the head wall on the first permanent culvert was being constructed. To facilitate headwall construction

another soil pad was formed in the stream crossing to support the machinery. The soil pad stayed in the channel for approximately 10 days. In addition, riprap (6" large native rock) was being placed along the fills slopes of the first stream crossing, and seeding and mulching were being placed where construction

FS 973 construction stopped from November 2002 to July 14 2003 except for seeding, mulching, fertilizing, and liming the fillslopes approximately up to the third stream crossing. Prior to May 2003, throughout that winter, FS 973 was left in a less resilient condition (i.e. inadequate use of BMPs) (Edwards, P.J. Submitted). The cutbanks still had to be sloped properly, surfacing still had to be applied, and some steep road segments were longer than allowed under West Virginia BMP guidelines (Edwards, P.J. Submitted).

In May 2003, a second check dam was installed below the first permanent culverted stream crossing. The fillslopes and cut slopes around every stream crossing were seeded, fertilized, limed, and then covered with chopped hay. In July 2003, cutbanks slope were graded to specifications up to the first culverted stream crossing.

In July 2003, the culverted stream crossing installed at the steep culvert, was found to be inadequate and then removed. The streamwater draining from culvert exited onto a steep, unconsolidated fillslope, removing an estimated 70 m³ of soil and destabilizing the road (three-dimensional survey using a total station) (Fig. 2.11) (Edwards, P.J. Submitted). A concrete and rock lined channel (i.e. 7-9" rock) was formed to maneuver the streamwater from this steep tributary channel above the first stream crossing (Fig. 2.12). In addition, in July 2003, surfacing (i.e. 7-9" rock) was applied around the fillslope where the culvert was removed, and gravel, seed, and mulch was applied to the road up to the 1st stream crossing.

By August 2003 and through the middle of September 2003, the cutbank slopes were properly sloped up to the third stream crossing, surface (4-inch limestone gravel) was applied to the road, seeding and mulch had been applied to the road, and the check dams were removed.

Significant sediment inputs to the stream channel only reached the channel directly where culverted stream crossings were formed. Typically, this was the result of deep fills and steep hillsides leading into and out of the stream crossings (Fig. 2.10) (Edwards, P.J. Submitted). The foundation of compacted soil formed in the stream channel above the first stream crossings to stabilize the track hoe during excavation and construction deposited a considerable amount of sediment directly in the stream channel (Edwards, P.J. Submitted). Even though the silt fence arrested a substantial portion of this sediment, there were times when significant amounts of sediment were released due to the silt fence being overtopped or knocked down (Edwards, P.J. Submitted).

Post-construction activities and occurrences and other related occurrences included initiation of forest harvesting in September 2004, road grading in January 2004, Hurricane Gordon in September 2000, Hurricane Isidore in September 2002, Hurricane Bill in August 2003, Hurricane Isabel in September 2003, Hurricane Francis in September 2004, Hurricane Ivan in September 2004, and Hurricane Jeanne in September 2004.

2.4 Turbidity

Water samples were processed for turbidity at the US Forest Service's Timber and Watershed Laboratory in Parsons, West Virginia. Turbidity, in nephelometric turbidity units (NTU), was determined using a Hach Ratio Turbidimeter, which was calibrated using formazin standards (Edwards, P.J. Submitted). The samples were first shaken to distribute the sediment throughout the bottle. A sub sample was then poured into a small glass tube. The sides were wiped free of

fingerprints and other dirt, and the glass tube was placed in the turbidimeter. After approximately 5 seconds, the turbidity value was recorded.

2.5 Suspended Sediment

After measuring turbidity, the sub-sample was poured back into the original bottle so suspended sediment concentrations could be calculated. Before measuring suspended sediment concentrations, the entire sample was weighted. The bottle, lid, and sample were weighed then subtracted from the known bottle and lid weight to obtain the weight and of the water/sediment sample. Each sample was filtered through one or more pre-dried and pre-weighted ashless GF/C glass microfiber filters using vacuum filtration. The bottles were rinsed several times, and each time the rinse water was filtered. The number of filters needed depended on the amount of sediment in the bottle. Although, most samples required only 1-3 filters, a few required 30 or more. All samples were then dried at 100 °C (212°F) for 2 hours then re-weighted. This weight minus the initial dry filter weight is the combination of the organic and inorganic material (g/L). The filters were then combusted in a muffle furnace for 1 hour at 550 °C (1022°F) and then re-weighted. This weight plus a 0.001 filter correction for filter loss during combustion, minus the initial dry filter weight, is the amount of inorganic material (g). The dry weight minus the combusted weight plus a 0.001 filter correction is the amount of organic material. These samples were determined using U.S. EPA method 160.2. All analysis involving suspended sediment concentrations used both organic and inorganic material.

2.6 Analysis

Statistical Analysis Systems (SAS 1988) was used to analyze these data. Nonparametric methods primarily were used because the data were not normally distributed. Wilcoxon signed-rank tests and median scores (Proc NONPAR1WAY) were used to transform the data to an ordinal

scale to make statistical conclusions about the location differences (higher lower or no difference (random)) between both watersheds' turbidity. Median scores were used to test for differences between watersheds turbidity.

The relationship between turbidity and SSC (TS ratio) was created to compare the turbidity of a sample to the suspended sediment concentration. This ratio compares two different types of water clarity measurements and samples between watersheds were of different volumes, therefore, any conclusions formed should be viewed with skepticism. However, sample volumes averaged by month and by storm were not significantly different between watersheds pretreatment and post-treatment periods. Parametric analyses were used on non-normal untransformed data in the form of regression analysis only. Log base 10 transformations were used to increase data normality and express changes to variability. Statistical significance were tested at 0.05 level.

Chapter 3: Results

3.1 Routine sampling

Twenty-three percent (1120) of the reference watershed's routine samples were collected during pretreatment. Twenty percent of these samples were sampled when streamflows were below the detection limit (2.0 cm) (Table 3.1). Pretreatment reference watershed routine samples averaged 4.0 NTU, with a standard deviation of 6.5 NTU (Table 3.2). Twenty-one samples exceeded 25 NTU and two samples exceeded 50 NTU (86 NTU and 96 NTU) (Fig. 3.1). Except for one sample, all other samples were sampled during relatively lower streamflows ($<0.60 \text{ L s}^{-1}$ ($<0.02 \text{ cfs}$)). The exception (96 NTU) was sampled during stormflow (108 L s^{-1} (3.8 cfs)) in March 2002.

Twenty-two percent (1019) of the treatment watershed routine samples were collected during pretreatment. Forty-five percent of these samples were sampled when streamflows were below the detection limit (Table 3.1).). Pretreatment treatment watershed routine samples averaged 1.7 NTU, with a standard deviation of 5.2 NTU (Table 3.2). Two samples exceeded 25 NTU (61 NTU and 147 NTU) (Fig. 3.1). Both samples were sampled during streamflow too low to measure.

Eleven percent (512) of the reference watershed samples were post-treatment routine samples. Thirteen percent of these samples occurred when streamflows were below the detection limit (Table 3.1). Pretreatment reference watershed stormflow samples averaged 9.0 NTU, with a 21.1 NTU standard deviation (Table 3.2). Forty samples exceeded 25 NTU. Thirty-five of the 40 samples occurred in the months of July, August, and September of 2004 (Fig 3.1). Twenty samples exceeded 50 NTU and three samples exceeded 100 NTU (102 NTU, 154 NTU, and 345 NTU). Fifty percent of the samples that were >25 NTU occurred during a streamflow below the

detection limit, including the three samples greater than 100 NTU. The three samples > 100 NTU fell within a 30-day period in August and September of 2004 (Fig 3.1).

The samples with higher turbidities that occurred in the fall of 2004 were unique events. These events could have been the result of uptake lines sampling deposited channel material or the result of several large storm events that occurred during the fall of 2004. Most of these samples occurred during streamflow that was below detection limits. If deleted from the data set, the sample average (4.4 NTU) decreased by more than half the original average (9.0 NTU) and the standard deviation (4.5 NTU) decreased 4.7 times from the original standard deviation (21.1 NTU). These samples represented fifteen percent of the posttreatment routine samples. These samples were excluded from analysis only when the graph or analysis specifically states “without fall 2004 samples”.

Ten percent (461) of the treatment watershed’s samples are post-treatment routine samples. Thirty percent of these turbidities occurred when streamflows were below the detection limit (Table 3.1). Pretreatment treatment watershed stormflow samples averaged 7.2 NTU, with a standard deviation of 12.1 NTU (Table 3.2). Fourteen samples exceeded 25 NTU, six exceeded 50 NTU, and three samples exceeded 100 NTU (107 NTU, 111 NTU, and 123 NTU) (Fig 3.1). Seven percent of the larger turbidities (>25 NTU) were sampled during streamflow too low to measure. Half of the larger turbidities (>25 NTU) were sampled during streamflow > 28 L s⁻¹ (1.0 cfs), including one sample that > 100 NTU.

Prior to treatment, the treatment watershed’s median and average routine turbidities were statistically lower than the reference watershed’s median and average routine turbidities (Table 3.2). After treatment, average routine turbidity between watersheds were no longer significantly different. The treatment watershed’s average routine turbidity became statistically greater than the

reference watershed's average if the fall 2004 samples from the reference watershed and paired treatment watershed samples were removed from the data set. The treatment watershed's median turbidity was statistically higher than the reference watershed's median turbidity.

During pretreatment, the linear regression relationship of turbidity between the treatment watershed (y variable) and reference watershed (x variable) routine turbidities had a statistically significant slope of 0.2 ($P < 0.01$), though the R^2 was only 0.03 (Fig. 3.2). After treatment, the slope increased to 1.4 and remained significant and the R^2 value increased slightly to 0.06. Fall 2004 samples were not used during this analysis. These turbidities were not normally distributed.

Routine samples were not collected during the majority of the treatment period. Turbidity was cumulated within watersheds (Fig. 3.3). Prior to treatment (October 1999 to July 2002), the treatment watershed's turbidities were 40 percent (slope = 0.4, $P < 0.01$) of the paired reference watershed's turbidities. This produced a 2371 NTU difference in cumulative turbidity values between watersheds. During treatment sampling (July 2003 to September 2003), the difference between paired turbidities decreased to 1509 NTU and as slope increased to 0.5 ($P < 0.01$). After treatment (September 2003 to May 2005), the difference between paired turbidities decreased to 1153 NTU and slope increased to 0.7 ($p < 0.01$). Fall of 2004 samples were not used during this analysis and these data were not normally distributed.

Streamflow was used to predict routine turbidity during pretreatment and posttreatment in both watersheds (Fig. 3.4). Both watershed's slopes were statistically significant before and after treatment however, R^2 values never exceeded 0.01. Large variations in routine turbidity during similar streamflows decreased correlations in both watersheds. In addition, seasonal changes to turbidity (Fig 3.5) reduced correlations in both watersheds. Turbidities were generally elevated May through September. $\log_{10}$ transformations did not increase the correlation between

streamflow and turbidity substantially. Fall of 2004 samples were not used during this analysis and these data were not normally distributed.

During pretreatment above average routine turbidities consistently occurred during lower-than-average streamflows and lower-than-average routine turbidities consistently occurred during above-average streamflows (Fig. 3.6, Fig.3.7). By contrast, average routine turbidity stayed essentially the same throughout the range of average post-treatment streamflows in the treatment watershed. Reference watershed routine turbidities sampled during the fall of 2004 were used to illustrate their occurrences during low streamflows in the reference watershed. Routine samples within the treatment watershed did not decrease like pretreatment values and post-treatment reference watershed routine samples.

Turbidity was used to predict suspended sediment concentrations (SSC) during pretreatment and post-treatment (Fig 3.8). All slopes were statistically significant within watersheds. The R^2 values between turbidity and SSC were higher than the R^2 values between streamflow and SSC. $\log_{10}$ transformations increased the R^2 between turbidity and SSC from 0.11 to 0.41 (Fig 3.9). No turbidity or suspended sediment concentration less than one were used in $\log_{10}$ transformations.

Reference watershed samples contained more sediment per turbidity value than the treatment watershed during pretreatment and post-treatment (Fig.3.10, Fig.3.11). The ratio between turbidity and suspended sediment concentrations (i.e. turbidity (NTU)/SSC (mg/L), the TS ratio) indicates that even though routine turbidities were statistically lower in the treatment watershed during pretreatment, the treatment watershed exhibited less sediment per turbidity value. The treatment and reference watershed's routine samples average and median TS ratio were not statistically different within watersheds classified by pretreatment and post-treatment periods

($P=0.32$, 0.26 , 0.81 , and 0.46 , respectively). During pretreatment, the treatment watershed's average and median TS ratio was statistically larger than the reference watershed's average and median TS ratio ($P<0.01$). After treatment, the treatment watershed's average TS ratio remained statistically larger than the reference watershed's TS ratio average ($P=0.03$), although the median values were not statistically different ($P=0.28$).

The largest turbidities consistently occurred during the summer months in both watersheds (Fig. 3.5). The treatment watershed's second year post-treatment May through September average (12.8 NTU) was 4.6 times the pretreatment level (2.8 NTU). The treatment watershed's third year post-treatment average (5.7 NTU) was twice the pretreatment level (2.8 NTU). The May through September average decreased 2.2 times from the second to third year post-treatment (Table 3.3).

After treatment, the treatment watershed's routine turbidities decreased toward pretreatment levels (Fig 3.12). Slope (-0.01) and intercept (11.3) were both statistically significant ($P<0.01$) and $R^2=0.43$. This equation yields, on average, a 3.7 NTU linear decrease per year from the intercept.

3.2 Storm sampling

Forty percent ($1,939$) of the reference watersheds samples were pretreatment stormflow samples. Twenty percent of these samples were sampled during streamflows below the detection limit (Table 3.1). Reference watershed samples during pretreatment averaged 4.5 NTU, with a standard deviation of 6.6 NTU (Table 3.2). Thirty-four samples exceeded 25 NTU and eight samples exceeded 50 NTU. The largest reference watershed turbidity occurred in August 2001 (106 NTU). Turbidities >25 NTU generally occurred below 6 L s^{-1} (0.2 cfs). Four occurred between 6 L s^{-1} and 28 L s^{-1} (0.2 and 1.0 cfs), and one (60 NTU) occurred at 160 L s^{-1} (5.8 cfs). Thirty-two percent of the turbidities >25 NTU were sampled during streamflows below the detection limit.

Thirty-five percent (1,661) of the treatment watersheds samples were pretreatment stormflow samples. Thirty-eight percent of these samples were sampled during streamflows below the detection limit (Table 3.1). Treatment watershed turbidities averaged 3.5 NTU, with a standard deviation of 13.8 NTU during pretreatment (Table 3.2). Twenty-seven samples exceeded 25 NTU, 11 samples exceeded 50 NTU, and five turbidities exceeded 100 NTU (120 NTU, 126 NTU, 185 NTU, 264 NTU, and 366 NTU). The largest pretreatment turbidity occurred in August 2000 (366 NTU). Four of the five turbidities that exceeded 100 NTU were sampled during streamflows below the detection limit. The other sample (120 NTU) was sampled in February 2000 at 48 L s^{-1} (1.7 cfs). Forty-eight percent of the largest turbidities ($>25 \text{ NTU}$) were sampled during streamflows below the detection limit.

Twenty-six percent (1,241) of the reference watershed's samples are post-treatment stormflow samples. Eight percent of these samples were sampled during streamflows below the detection limit (Table 3.1). Reference watersheds stormflow turbidities averaged 5.8 NTU, with a standard deviation of 8.1 NTU during post-treatment (Table 3.2). Thirty samples exceeded 25 NTU and 10 samples exceeded 50 NTU (Fig 3.4). The two highest samples (97 and 103 NTU) occurred in July 2003 and 2004, respectively. Twenty-seven percent of the turbidities $>25 \text{ NTU}$ were sampled during streamflows below the detection limit. Forty percent of the samples $> 50 \text{ NTU}$ were sampled during streamflows below the detection limit.

Thirty-three percent (1576) of the treatment watershed's samples are post-treatment storm samples. Nine percent of these samples were sampled during streamflows below the detection limit (Table 3.1). The treatment watershed's turbidities averaged 34.2 NTU, with a standard deviation of 109.7 NTU during post-treatment (Table 3.2). Three hundred and fifty-eight samples exceeded 25 NTU and 187 samples exceeded 50 NTU (Fig. 3.4). The majority (79 percent) of

turbidities > 50 NTU occurred in the months of May, June, July, August, and October. One hundred samples exceeded 100 NTU, 48 samples exceeded 200 NTU, 33 samples exceeded 300 NTU, and four samples exceeded 1000 NTU. The number of treatment watershed turbidities >25 NTU decreased with increased turbidity as a power function ($y(\text{\# of turbidities})=21165 (x (\text{NTU}))^{-1.2}$, $R^2= 0.97$). Eight percent of the turbidities >25 NTU, including seven samples greater than 100 NTU were sampled during streamflow below the detection limit. The percentage of samples sampled during streamflow below the detection limit (stage <2 cm) decreased by 12 and 29 percent in the reference and treatment watershed, respectively, from pretreatment to post-treatment percentages. The average of turbidity sampled during streamflow below the detection limit increased by 5 and 49 NTU in the reference and treatment watershed, respectively, from pretreatment to post-treatment levels (Table 3.1).

One hundred fifty-three storms were sampled during pretreatment, in which 70 were paired storms. The treatment watershed's average stormflow turbidity (3.5 NTU) was not statistically different ($P= 0.16$) than the reference watershed's average stormflow turbidity (4.4 NTU) for paired storms. The treatment watershed's median turbidity (2.1 NTU) for paired storms was statistically lower ($P=0.02$) than the reference watershed's median turbidity (3.8 NTU). Pretreatment median turbidities for paired storms were not statistically different between watersheds when turbidities sampled at streamflows lower than each individual watershed's average 5-minute streamflow average were deleted. The statistical differences between watershed's paired pretreatment median stormflow turbidities were the result of increased reference watershed turbidity during lower than average streamflow.

During pretreatment, the treatment watershed's average turbidity (6.8 NTU) during the rising limb of the hydrograph was not statistically ($P=0.08$) different than the reference watershed's

average rising stormflow turbidity (5.3 NTU) for paired storms. The average turbidity for the treatment watershed (1.8 NTU) falling limb of the hydrograph was statistically less turbid ($P<0.01$) than the reference watershed's average falling stormflow turbidity (3.4 NTU) for paired storms. The treatment watershed's median turbidities for both rising and falling limbs of the hydrograph were statistically less turbid than the reference watershed ($P<0.01$) paired storms.

One-hundred and thirty-five storms were sampled during post-treatment, of which, forty-two were paired. Post-treatment stormflow turbidities exceeded 100 NTU on the treatment watershed 100 times (Fig. 3.12, Fig 3.13) and exceeded 100 NTU on the reference watershed one time. The treatment watershed's average turbidity (33.2) was 5.4 times the reference watershed's average turbidity (6.2 NTU) ($P<0.01$). The largest recorded turbidity (2352 NTU) occurred at the beginning of a July 2003 storm. That storm's average turbidity was 133 NTU ($n=40$). Average stormflow turbidity exceeded 100 NTU four times post-treatment. The largest, 233 NTU, occurred in October 2002. For comparison, during pretreatment, the reference and treatment watershed's average stormflow exceeded 10 NTU 6 and 7 times, respectively.

During post-treatment, the treatment watershed's average turbidity (56.4 NTU) during the rising limb of the hydrograph was statistically ($P=0.01$) different from the reference watershed's average rising stormflow turbidity (7.2 NTU) for paired storms. The treatment watershed's average turbidity (24.3 NTU) during the falling limb of the hydrograph was statistically different than the reference watershed's (5.3 NTU) ($P<0.01$) average turbidity. The treatment watershed's median turbidity was statistically larger than the reference watershed's median turbidity during both rising and falling limbs ($P<0.01$) during post-treatment.

Prior to treatment, the treatment watershed's average stormflow turbidities were predicted from the reference watershed's average stormflow turbidities for paired storms (Fig 3.14). Slope

(0.8) was statistically significant ($P < 0.01$) and R^2 equaled 0.41. The treatment watersheds average stormflow turbidity for sixty-nine paired storms was approximately 80% of the reference watersheds average stormflow turbidity. After treatment, slope (4.0) remained statistically significant ($P < 0.01$) and R^2 equaled 0.16. These turbidities were not normally distributed.

Stormflow turbidity samples were relatively sparse throughout the treatment period (July 2002 to September 2003). Stormflow turbidities were averaged then cumulated during pretreatment to examine trends in treatment watershed's stormflow turbidities relative to the reference watershed's stormflow turbidities (Fig. 3.3). Prior to treatment, the treatment watershed's average streamflow turbidities were 80 percent (slope = 0.8, $P < 0.01$) of the paired reference watershed's average streamflow turbidities. This produced a 59 NTU difference in cumulative turbidity prior to construction. During treatment, slope (Slope = 2.5, $P < 0.01$) increased and the treatment watershed's cumulative turbidity increased 737 NTU above the reference watershed's cumulative turbidity. After treatment, slope increased (slope = 2.6, $P < 0.01$) and the treatment watershed's cumulative turbidity increased 951 NTU above the reference watershed's cumulative turbidity. These data were not normally distributed.

Streamflow was used to predict stormflow turbidity during pretreatment and post-treatment in both watersheds (Fig. 3.15). Both watersheds slopes were statistically significant before and after treatment ($P < 0.01$). R^2 values did not exceed 0.01. Large variations in stormflow turbidities during similar streamflows decreased correlations in both watersheds. In addition, seasonal changes to turbidity (Fig 3.5) could have influenced correlations in both watersheds. $\log_{10}$ transformations did not increase the correlation between streamflow and turbidity.

During pretreatment above-average stormflow turbidity consistently occurred during lower streamflows, and lower-than-average stormflow turbidity consistently occurred during above-

average streamflows (Fig. 3.6, Fig.3.7). By contrast, the average treatment watershed's stormflow turbidities were essentially 9 times their pretreatment average throughout every range of average streamflow. The elevated and consistent average stormflow turbidity during increasing average streamflow indicates a substantial increase in turbidity throughout all classes of streamflow after treatment in the treatment watershed.

Turbidity was used to predict suspended sediment concentrations (SSC) during pretreatment and post-treatment (Fig 3.16). Slopes were statistically significant within both watersheds. The R^2 values between turbidity and SSC were larger than the R^2 values between streamflow and SSC and ranged between 0.03 and 0.72. The largest correlation occurred in the treatment watershed post-treatment. Log_{10} transformations, used to reduce variation, increased parameter significance and improved correlation within watersheds (Fig 3.9). Log_{10} transformations increased R^2 values 30 to 40 percent above treatment watershed pretreatment values and reference watershed post-treatment values. The smallest increase (11 percent) occurred during post-treatment in the reference watershed. The largest variation occurred between two samples in the treatment watershed that differed by 7000 mg L^{-1} while maintaining essentially the same turbidity value.

Turbidity was used to predict suspended sediment concentrations (SSC) during pretreatment and post-treatment (Fig 3.16). Slopes were all statistically significant within watersheds. The R^2 values between turbidity and SSC were larger than the R^2 values between streamflow and SSC and ranged between 0.03 and 0.72. The largest correlation occurred in the treatment watershed after treatment. Log_{10} transformations, used to control variance, increased parameter significance and improved correlation between watersheds significantly (Fig 3.9). Log_{10} transformations increased R^2 values 30 to 40 percent above pretreatment and reference watershed

post-treatment levels. The smallest increase (11 percent) occurred during post-treatment in the reference watershed. The largest variation occurred between two samples in the treatment watershed that differed 7000 mg L^{-1} while maintaining essentially the same turbidity value.

Reference watershed samples contained more sediment relative to turbidity than the treatment watershed during pretreatment and post-treatment (Fig.3.10, Fig.3.11). The ratio between turbidity and suspended sediment concentrations (i.e. turbidity (NTU)/SSC (mg/L), the TS Ratio) indicates that even though stormflow turbidities tended to be lower in the treatment watershed during pretreatment, the treatment watershed exhibited higher turbidities relative to SSC. During pretreatment, the treatment watershed's average TS ratio was not statistically larger ($P=0.13$) than the reference watershed's average. The median TS ratio was statistically larger ($P<0.01$) than the reference watershed's and median TS ratio. After treatment, the treatment watershed's average TS ratio was statistically larger ($P<0.01$) than the reference watershed's average TS ratio. The treatment watershed's median TS ratio remained statistically larger ($P<0.01$).

Prior to road construction both the reference watershed and treatment watersheds' turbidities peaked prior to peak streamflow then receded to pre-storm turbidity quicker than streamflow (Fig 3.17). During post-treatment, the reference watershed's stormflow turbidities continued to peak prior to peak streamflow and recede quickly. By contrast, the treatment watersheds stormflow turbidities from October 2002 to May 2003 produced counterclockwise hysteresis (Fig 3.18) (Edwards, P.J Submitted). Peak turbidity occurred prior to peak streamflow then would remain elevated up to and after streamflow returned to low flow levels (Edwards, P.J Submitted).

After treatment, the treatment watershed's average stormflow turbidities declined toward pretreatment values. Slope (-0.06) and intercept (56.6) were both statistically significant ($P < 0.01$) and $R^2 = 0.12$. This equation yields, on average, a 21.9 NTU decrease per year from the intercept. A logarithmic decrease to average stormflow turbidity explained 5 percent more variation than a linear decrease.

Chapter 4: Discussion and Conclusions

No other studies have measured sediment dynamics in streams surrounded by silt fences. The sediment collected in the reference watershed's silt fence weighted anywhere between

67,241.5 g to 255,900 g yr⁻¹ (Hammons 2006, unpublished thesis). Storms to storm variation in exported sediment ranged anywhere from 15,000 times lower to 1.5 times larger than those sediment collections. Any significant in-stream modification to sediment supply, transport capacity, or channel structure due to the silt fence are either unknown, undetectable, or did not occur (Bills 2005).

A road was built in the reference watershed prior to 1930. The reference watershed was probably used for farming and timbering as other nearby watersheds (Lima et al. 1978). Studies have found in-stream changes resulting from early mountain farming and timbering decades later (Dils 1957). Portions of the reference watershed's hillsides are clustered with stone fragments and the stream channel tend to be storing more sediment than the treatment watershed. The reference watershed is probably still responding to disturbance, albeit not as prominent or rapid as a recent disturbance.

The reference watershed's storm and routine samples prior to construction were statistically more turbid than the treatment watershed's. The reference watershed's routine samples contained more sediment by weight relative to its turbidity index. Storm samples and TS ratios were similar between watersheds. The reference watershed produced less turbidity per sediment than the treatment watershed. This is probably the result of past disturbance in the reference watersheds (i.e. roads, farming, and timbering) as the reference watershed generally had larger median substrate than the treatment watershed (Bills 2005).

Substantial variation to streamflow occurred from pretreatment to post-treatment (Fig. 19, Fig. 20, and Fig. 21). Several studies have measured changes to streamflow following timber removal (Hornbeck et al. 1993, Jones and Grant 1996). Few studies have intensively measured streamflow changes due to road construction, therefore, streamflow responses due to road

construction are uncertain. Roads theoretically increase the efficiency of water transfer from hillsides to stream channels by intercepting subsurface streamflow and precipitation then directing the intercepted water directly to stream channels and/or in more concentrated levels onto the hillside below (Reinhart 1964, Wemple et al. 1996). Streamflows measurements and classes were not used rigorously to analyze turbidity because streamflow was modeled and deviated substantially from predicted values. For example, one predicted peak stormflow level differed between watersheds by 280 L s^{-1} (10 cfs) when the average streamflows were less than 28 L s^{-1} (1 cfs). The Forest Service employees who created the model would better suited to evaluate any changes to streamflow due to road construction, therefore any analysis that uses streamflow such as turbidity and streamflow relationships and/or SSC and streamflow relationships should be viewed with skepticism.

The results of this study demonstrated the effects of road construction on water quality. Several studies have identified roads as the primary source of to-stream sediment during forest operations and have identified road to stream interactions as the most problematic within the road network (Irvin and Sullivan unpublished data, in Bilby et al. 1989, Wemple et al. 1996). This study isolated most of the road network from the stream channel (e.g. silt fence), therefore, the majority of sediment that entered the treatment watershed's stream channel was the result of stream crossing construction. FS 973 occupies 4.1 percent of the treatment watershed and stream crossings occupy less than one percent of the treatment watershed.

Average and median turbidities for these watersheds were below 5 NTU during pretreatment. Turbidity is noticeable around 5 NTU (Strausberg 1983, in Edwards Submitted) therefore, these streams normally have clear water. Prior to treatment, the treatment watershed's

stream samples (2680) exceeded 25 NTU 29 times or 1 percent of the time and the reference watersheds samples (3059) exceeded 25 NTU 55 times or 2 percent of the time.

Maximum pretreatment turbidities were less than 400 NTU in both watersheds. They occurred during the largest storm events or during summer thunderstorms. Turbidities were elevated throughout the summer months during pretreatment. Stormflows that produced larger turbidities were relatively short-lived and storms samples overall produced clockwise hysteresis. Clockwise hysteresis is an indicator of a sediment supply limitation.

In July 2002 road construction was initiated within the treatment watershed. Very few samples were collected between July 2002 and July 2003, therefore, changes to in-stream turbidity during the 1st year post-treatment are unknown. Several studies site that the largest deviations to background levels occur within the first few months following disturbance (Hornbeck and Reinhart 1964, Fredriksen 1970), however, this may not be the case here as mitigation structures could have trapped and stored and disturbed sediment. However, sediment that does reach the stream channel during disturbances typically flushes quickly during the first couple of storms. In Oregon, sediment concentrations were measured 250 times expected levels during the first storm post-treatment, 9 times larger 2 months later, and remained elevated 2 to 3 times expected levels 2 years later (Fredriksen 1970). In West Virginia, average turbidity was 12.9 and 149.5 times larger during forest operations than first year after treatment from a clearcut and diameter limit harvest, respectively. Average turbidity was 38.0 and 6.0 times larger after the first year post-treatment than the second year post-treatment (Hornbeck and Reinhart 1964).

These samples were too few or occurred during insignificant times to provide an adequate account of turbidity during the first few storms post-treatment. However, if pretreatment values were increased to the same magnitude as in Hornbeck and Reinhart 1964 during treatment, then

average turbidity values could have been as high as 255 and 525 NTU for routine and storm samples respectively. These values would be deemed excessively high by all the past literature however, it does show the potential changes to both stormflow and routine during the first few storms during treatment.

The reference watershed stayed within normal background levels after treatment even though the treatment watershed's average and median turbidities were above 5 NTU. Fourteen percent of the turbidities exceeded 25 NTU in the treatment watershed. Elevated turbidities were the result of stream crossing construction. Areas in stream crossings were less than 1 percent of the treatment watershed using 10 m aerial photographs.

Maximum turbidity in the treatment watershed following treatment reached 2352 NTU and occurred during the initiation of a storm event. The treatment watershed's turbidities were less seasonally dependent, that is, the largest average monthly turbidity, occurred more so in late fall and during the winter months. The treatment watershed's stormflow turbidities were substantially elevated during the initiation of all storm events and is believed to be the result of precipitation impact remobilizing easily suspended channel sediment. Stormflows produced larger peak, average, and median turbidity values. Stormflow turbidities were relatively longer-lived and even maintained and increased after peak stormflow. Several storms produced counter-clockwise hysteresis towards the end of the 1st year post-treatment. Counter-clockwise hysteresis is an indicator of an energy limited situation and an abundance of sediment in the stream channel.

This study illustrates that significant increases to average turbidity during forest operations are not exclusively the result of similar increases to average SSC. For example, the treatment watershed routine and storm samples average SSC was 1.4 and 1.0 times the pretreatment levels post-treatment while average turbidity was 4.5 and 9.9 times the pretreatment levels post-

treatment, respectively. By comparison, the reference watershed routine and storm samples average SSC were 0.7 and 0.5 times the pretreatment levels post-treatment while average turbidity were 1.0 and 1.2 times the pretreatment levels post-treatment, respectively. SSC measurements are an inadequate indicator of water quality as decreases to water clarity were probably the result of smaller inorganic and organic sediment that weight less than average pretreatment sediments.

The TS ratio indicated that the treatment watersheds turbidities were significantly lower during pretreatment although less sediment per weight produced them. The reference watershed was transporting relatively more sediment with less turbidity. After treatment, the TS Ratio increased to 1.4 as the majority of turbidity values were larger then the SSC values. Towards the end of the post-treatment sampling period the TS ratio drops to around 0.5 as the majority of the turbidity values were half the SSC values. This indicates a considerable shift to sediment properties that influenced turbidity and SSC concentrations. The TS ratio went from the highest levels to the lowest levels relative to pretreatment levels in 2 years or by the 3rd year post-treatment. Although, turbidity is a better predictor of SSC than streamflow, the relationship between SSC and turbidity changed substantially between sample types, pretreatment and post-treatment periods, and levels of turbidity to warrant the use of several different regressional relationships.

Several studies have estimated the rate of water quality recovery after disturbance (Fredriksen 1970, Hornbeck and Reinhart 1964, Kochenderfer et al. 1997). In-stream turbidity values decreased during the second year post-treatment throughout the duration of this study. Routine turbidity probably decreased more so exponentially during the 1st year post-treatment, however, a linear decrease over time, from the start of post-treatment sampling (2nd year post-treatment) throughout the end of sampling (3rd year post-treatment), would best describe recovery

during this period. Linear regressions explained 12 and 43 percent of the variation to turbidity after treatment. These regression equations suggest the potential for turbidity to return to pretreatment levels about 3.5 year post-treatment. The decreasing rate of recovery and potential for residual sediment storage upstream suggests that recovery to pretreatment conditions could take even longer.

Prior to treatment, average daily rainfall was statistically significant predictor of average stormflow turbidity (Table 3.5). Average daily precipitation explained 11 and 38 percent of the variation to average stormflow turbidity during pretreatment. Average daily precipitations were not a statistically significant predictor of average stormflow turbidity during post-treatment. The relationship did not return to pretreatment values for the duration of this study. There was no statistical significance between the two parameters in the reference watershed.

Stream crossing have to be constructed with better soil conservation practices. This road extended throughout the treatment watershed before the crossings were finalized. Time study analysis may be useful to help contractors increase road production and efficiency while decreasing costs associated with road construction while increasing soil conservation. Although, these crossings are legally defined as non-point sources of pollution, this study illustrates that very specific points along the road network were mainly responsible for water quality degradation. Bridges should be used instead.

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Figure 2.1. The study area and delineated watersheds illustrating the general aspect of both watersheds.

Figure 2.2. A constructed monitoring station used to collect water samples and record streamflow velocity.

Figure 2.3. Example of the sediment fence that was lined around all stream channels in both watersheds. Picture was taken while standing on a stream crossing.

Figure 2.4. The elevation profile around the study area illustrates some of the major geographic formations within in the area.

Figure 2.5. Average stream slope segments of the main channel and selected tributaries (Bills 2005).

Figure 2.6. In-stream velocity sampling point constructed within the reference watershed. It was created with a half pipe of PVC, natural rocks and cement.

Figure 2.7. Constructed uptake area for suspended sediment collections in the reference watershed. Rocks were lined along the end of the pool to slow outflow and facilitate sample collection. This may have proved problematic due to increased deposition of sediment.

Figure 2.8. An aerial photo of the treatment watershed after haul road construction.

Figure 2.9. Aerial photo of treatment watershed that identifying culverts, the constructed stream channel, and the approximate dates of installation.

Figure 2.10. This photo illustrates the condition of the stream channel during the construction of a stream crossing (stream crossing #1). This figure shows a substantial amount of soil within the channel and the steep entry and exit.

Figure 2.11. The cross-drain discharged water eroded the steep fillslope in a short period. It was removed, and the channel above the road was concreted and rock lined so water could be directed above and into stream culvert #1.

Figure 2.12. This constructed riprap stream channel modification was constructed when cross-drain discharged water eroded the steep fillslope below.

Figure 3.1. Fluctuations in routine sampled turbidity over time. Samples were not collected during treatment. Fall of 2004 reference watershed samples were included to illustrate their uniqueness relative to treatment watershed samples.

Figure 3.2. The treatment watershed's paired routine turbidities (y) versus the reference watershed's (x) routine turbidities. Fall of 2004 samples and unpaired samples were not used. Paired samples were defined as samples occurring in both watersheds during the same day

Figure 3.3. The treatment watershed's cumulative turbidity (y) versus the reference watershed's cumulative turbidity (x) for paired routine and paired storm samples. Regression equations excluded fall of 2004 routine samples and used cumulative turbidity values.

Figure 3.4. Routine turbidities (y) verse their associated streamflows (x). Fall of 2004 routine samples were used to illustrate their occurrence during low streamflow. The elevated reference watershed slope relative to the treatment watershed is primarily due to larger turbidities sampled during lower streamflows.

Figure 3.5. Average monthly turbidity indicates elevated turbidity throughout the summer months during pretreatment and during the reference watershed's post-treatment samples. The bottom graph better illustrates the increase in treatment watershed's (x) average monthly turbidity relative to the reference watershed's. Reference watershed storm samples were used exclusively for the fall of 2004 turbidity samples.

Figure 3.6. Changes to routine and stormflow turbidities associated averaged discharge, 5-minute average discharge, and average routine and stormflow turbidity average throughout increasing discharge percentages (Q) during pretreatment. Turbidity was averaged relative to the samples associated streamflow level or discharge (Q).

Figure 3.7. Changes to routine and stormflow turbidities associated averaged discharge, 5-minute average discharge, and average routine and stormflow turbidity average throughout increasing discharge percentages (Q) during post-treatment. Turbidity was averaged relative to the samples associated streamflow level or discharge (Q).

Figure 3.8. Suspended sediment concentrations (y) verse routine turbidities (x). Samples from the fall of 2004 were not used. Three sample were removed from the graph but were used in regression relationships. These samples were around 10 to 15 NTU with SSC concentrations between 6000 and 9000 mg L⁻¹.

Figure 3.9. Transformed (Log₁₀) suspended sediment concentrations (y) verse transformed (Log₁₀) turbidities (x). Routine samples from the fall of 2004 were used. All SSC and turbidity samples <1 mg L⁻¹ and <1 NTU were not used.

Figure 3.10. The ratio between turbidity and SSC (i.e. turbidity (NTU)/SSC (mg L^{-1})), the TS ratio (x), is a dimensionless number that is used here to illustrate changes to turbidity relative to SSC in the reference watershed over time (y).

Figure 3.11. The ratio between turbidity and SSC (i.e. turbidity (NTU)/SSC (mg L^{-1})), the TS ratio (x), is a dimensionless number that is used here to illustrate changes to turbidity relative to SSC in the treatment watershed over time (y).

Figure 3.12. Treatment watershed's decrease to average monthly turbidity (Y axis) per day (X axis) and average stormflow turbidity (Y axis) per day (X axis).

Figure 3.13. Peak stormflow turbidities (x) before, during, and after treatment in both watersheds (Edwards, P.J. Submitted). Both paired and unpaired storm samples were used illustrate peak stormflow turbidity.

Figure 3.14. Post-treatment treatment watershed stormflow turbidities greater than 100 NTU and the streamflows at which they occurred.

Figure 3.15. Treatment watershed's (y) average stormflow turbidities versus the reference watershed's (x) average stormflow turbidities. Only paired storms were used.

Figure 3.16. Stormflow turbidities (y) (NTU) verses their associated streamflows (x) ($L s^{-1}$). The pretreatment turbidity scale was decreased by a factor of five compared to post-treatment regressions to better visualize pretreatment relationships. Large turbidities that occurred during low streamflow substantially reduced correlations between the two parameters.

Figure 3.17. Storm samples SSC (y) measurement verse the turbidity (x) measurement pretreatment is the top graph post-treatment is the bottom graph.

Figure 3.18. Example of a treatment watershed storm that produced clockwise hysteresis (Edwards, P.J. Submitted).

Figure 3.19. Example of treatment watershed storm that produced counter-clockwise hysteresis (Edwards, P.J. Submitted).

Figure 3.20. Monthly run-off from precipitation reference watershed.
 $\text{Runoff} = ((\text{ft}^3 \text{yr}^{-1} \text{ft}^{-2}) * (12 \text{in ft}^{-1})) * 2.54.$

Figure 3.21. Monthly run-off from precipitation treatment watershed.
 $\text{Runoff} = ((\text{ft}^3 \text{yr}^{-1} \text{ft}^{-2}) * (12 \text{in ft}^{-1})) * 2.54.$

Figure 3.22. Treatment watershed's (y) daily peak streamflow per area verses the reference watershed's (x) daily peak streamflow per area.

Table 2.1. Characteristics of the reference and treatment watersheds (Edwards, P.J. Submitted).

Characteristic	Reference	Treatment
Watershed size (ha)	20.2	32.7
Watershed aspect	E	ENE
Hillside steepness		
Range (% slope)	0.55-70.12	0.34-80.64
Mean (% slope)	38.7	42.6
% area in 30-50% slope class	52.5	40.7
% area in > 50% slope class	22.3	37.5
Stream length (m)	902	1325

Table 3.1. Nonparametric statistical tests between and within watersheds similar sample types collected during streamflow too low to measure.

Reference Watershed Samples	Percent Routine Samples	Routine Sample Average	Routine Sample Median	Percent Storm Samples	Storm Sample Average	Storm Sample Median
Pretreatment	20%	7.8 (a,1)	5.2 (a,1)	20%	6.4 (a,1)	7.7 (a,1)
Post-treatment	13%	25.0 (b,1)	5.6 (b,1)	8%	11.5 (b,1)	7.8 (b,1)
Treatment Watershed Samples	Percent Routine Samples	Routine Sample Average	Routine Sample Median	Percent Storm Samples	Storm Sample Average	Storm Sample Median
Pretreatment	45%	1.7 (a,2)	1.0 (a,2)	38%	4.0 (a,2)	1.2 (a,2)
Post-treatment	30%	6.1 (b,2)	4.8 (b,1)	9%	53.0 (b,2)	12.3 (b,2)

* Letters are used to denote statistical significance within watersheds, numerals are used to denote statistical significance between watersheds, and different numerals or letters indicate statistical differences between similar sample types.

Table 3.2. Nonparametric statistical tests between and within watersheds similar sample types.

	Samples	Watershed	n	Average (NTU)	StDev (NTU)	Median (NTU)	Ranks (NTU)
Pretreatment	All	Treatment	2680	2.8(a,1)	11.3	1.2(a,1)	2366(a,1)
		Reference	3059	4.3 (b,1)	6.6	2.5 (b,1)	3311(b,1)
	Routine	Treatment	1019	1.7 (a,1)	5.2	1.0 (a,1)	870 (a,1)
		Reference	1120	4.0 (b,1)	6.5	1.8 (b,1)	1251(b,1)
	Storms	Treatment	1661	3.5 (a,1)	13.8	1.4 (a,1)	1500(a,1)
		Reference	1939	4.5 (b,1)	6.6	2.9 (b,1)	2057(b,1)
Post-treatment	All	Treatment	2037	28.4 (a, 2)	97.2	7.7 (a, 2)	2304 (a, 2)
		Reference	1753	6.7 (b,2)	13.4	3.6 (b,2)	1419 (b,2)
	Routine	Treatment	461	7.2(a, 2)	12.1	4.6 (a, 2)	528 (a, 2)
		Reference	512	9.0(a, 2)	21.1	3.4 (b,2)	449 (b,2)
	Storms	Treatment	1576	34.6 (a, 2)	110.4	9.8 (a, 2)	1763 (a, 2)
		Reference	1241	5.7(b,2)	8.1	3.6(b,2)	960(b,2)

* Letters are used to denote statistical significance within watersheds, numerals are used to denote statistical significance between watersheds, and different numerals or letters indicate statistical differences between similar sample types.

Table 3.3. Changes to post-treatment May through September average turbidity relative to pretreatment May through September average turbidity.

May-September averages	Pretreatment	2 nd Year Post-Treatment	3 rd Year Post-Treatment
Treatment watershed	2.8 NTU	12.8 NTU	5.7 NTU
Increase from pretreatment average		4.6 times	2.0 times
Decrease from 2 nd Year Post-Treatment average			2.2 times

Table 3.4. Nonparametric statistical tests between and within watersheds suspended sediment concentrations (mg L⁻¹)

Reference Watershed	Average (mg/L)	Standard deviation (mg/L)	Median (mg/L)	Maximum (mg/L)
Pretreatment Routine Samples	50.1 (a,1)	375.8	4.5 (a,1)	8094.1
Pretreatment Storm Samples	27.0 (a,1)	134.1	7.6 (a,1)	3334.2
Post-treatment Routine Samples	39.5 (a,1)	145.8	7.1 (b,1)	1700.0
Post-treatment Storm Samples	14.1 (b,1)	46.6	6.1 (b,1)	1156.3
Treatment Watershed	Average (mg/L)	Standard deviation (mg/L)	Median (mg/L)	Maximum (mg/L)
Pretreatment Routine Samples	9.9 (a,2)	67.5	2.1 (a,2)	1733.3
Pretreatment Storm Samples	32.1 (a,1)	257.3	2.9 (a,2)	7390.0
Post-treatment Routine Samples	14.3 (a,2)	25.3	8.3 (b,2)	355.6
Post-treatment Storm Samples	33.7 (a,2)	114.1	10.4 (b,2)	2508.4

* Letters are used to denote statistical significance within watersheds, numerals are used to denote statistical significance between watersheds, and different numerals or letters indicate statistical differences between similar sample types.

Table 3.5. Treatment watershed regression analysis indicating average storm turbidity (NTU) resulting from average storm precipitation (cm) separated by years and treatment classes.

Period	Slope	P Value	Intercept	P Value	R ²	Average storm precipitation (cm)
2000	1.41	0.03	1.83	0.03	0.11	0.95
2001	1.47	0.05	1.97	<0.01	0.38	1.57
2003	1.86	0.72	30.13	0.01	<0.01	1.60
2004	-0.68	0.85	17.27	0.03	<0.01	1.67
Pretreatment	1.47	<0.01	2.03	0.01	0.13	1.20
Post-treatment	1.30	0.77	28.35	<0.01	<0.01	1.68