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Sources and ecological consequences of deposited and suspended sediments in small tributaries of the upper Elk River watershed, West Virginia

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**Sources and ecological consequences of deposited and suspended sediments in
small tributaries of the upper Elk River Watershed, West Virginia.**

Cynthia Louise Sanders

A Thesis submitted to:
Davis College of Agriculture, Forestry, and Consumer Sciences
At
West Virginia University

In partial fulfillment of the requirements for the degree of
Master of Science
In
Wildlife and Fisheries Resources

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Morgantown, West Virginia
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Abstract

Sources and ecological consequences of deposited and suspended sediments in small tributaries of the upper Elk River Watershed, West Virginia.

Cynthia Louise Sanders

Deposited and suspended sediments were sampled in small tributaries of the upper Elk River watershed to determine if differences exist in sediment transport and deposition based on land management activities of low disturbance, development, or timber harvesting. Brook trout (*Salvelinus fontinalis*) were sampled to determine if a negative relationship existed between populations and deposited or suspended sediments. There were no significant relationships in deposited sediments among land use yet timber harvest and developed lands had significantly higher transported sediments than low disturbance lands. There were no significant relationships between brook trout populations and deposited sediments. However, a slight negative relationship did exist between increasing suspended sediments and adult brook trout. High gradients in study tributaries likely resulted in low deposition of sediments while land management activities likely contributed to increasing suspended sediments. Best management practices and the Forest Stewardship Program may help to reduce sediments disturbed by timber harvesting.

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Chapter One

The Forest Stewardship Program and Forestry Best Management Practices In the United States and West Virginia

Abstract

The 1972 Federal Water Pollution Control Act and the 1987 Water Quality Act identified forest management practices as a non-point source of pollution. All states were federally mandated to implement water quality control programs based on federally accepted best management practices (BMPs). BMPs, such as streamside buffer strips, water control structures on roads, and rehabilitation of logging roads and landings, are designed to minimize the impact of timber harvesting on water quality. The Forest Stewardship Program is a financial and technical assistance program for non-industrial private forest (NIPF) landowners designed to encourage long-term management practices through use of forest management plans and BMPs when harvesting timber. A strong correlation exists between the use of professional foresters, like those involved with the FSP, and the use of West Virginia's BMPs. By reducing the impacts of timber harvesting on water quality, the impacts on native aquatic biota may also be reduced.

Introduction and Background

The 1972 Federal Water Pollution Control Act and the 1987 Water Quality Act identified forest management practices as a potential nonpoint source of water pollution (Martin and Hornbeck, 1994). Timber harvesting (and other forest management activities) can alter forest productivity, impact aquatic biota, cause stream eutrophication, and lessen the quality of drinking water (Lynch *et al.*, 1985). The stream parameters most disturbed by harvest practices are water temperature, turbidity and sediment levels, and nutrient concentrations (Corbett *et al.*, 1978; Lynch *et al.*, 1985). Forest landowners and managers should be aware of how certain land use practices impact a watershed and the biota it supports (Guimier, 1998).

The Clean Water Act requires all states to have water quality control programs based on federally accepted best management practices (BMPs) (Shaffer *et al.*, 1998). BMPs are designed to minimize the effects of timber harvesting, particularly erosion, on water quality (Arthur *et al.*, 1998; Shaffer *et al.*, 1998; Cornish, 2001). Some examples of BMPs include: streamside buffer strips, minimization of road construction impacts, use of water control structures on roads, removal of logging slash and treetops from streams, limiting disturbances to streams by excavation equipment, and the rehabilitation of all roads at the end of harvesting (Kochenderfer *et al.*, 1997; Arthur *et al.*, 1998; Martin *et al.*, 2000; Cornish, 2001). One method of assisting private landowners in implementing BMPs and forest management is the US Department of Agriculture's Forest Stewardship Program.

The Forest Stewardship Program (FSP) is a financial and technical assistance program designed to encourage long-term management practices on non-industrial

private forests (NIPF) (Egan *et al.*, 2001). The FSP mission is to assist NIPF owners in managing their land to achieve the forest management objectives that are unique to their properties, while recognizing the importance of maintaining or improving the health of these many NIPF acres for the benefit of society (Whipkey *et al.*, 2000). It is regulated on the national level by the USDA Forest Service (Egan *et al.*, 2001) and by individual states through a State Stewardship Coordinating Committee (WVDOF, 2001). Since its inception, the Forest Stewardship Program has made the technical assistance of private forest resource planners and consulting foresters more available to NIPF landowners (Whipkey *et al.*, 2000). Private forestry consultants and state service foresters can develop stewardship plans for the properties and also guide landowners through the application of the plans and the cost-sharing procedures (WVDOF, 2001). Studies in West Virginia have shown a significant interest in financial assistance and higher motivation to implement best management practices (BMPs) by the landowners when such assistance is available (Whipkey *et al.*, 2000).

Timber management is increasingly important in the state of West Virginia, where four-fifths of the state is forested (Whipkey *et al.*, 2000). Having close to 12 million acres in timber, West Virginia is the third most forested state in the U.S. (Whipkey *et al.*, 2000). Non-industrial private landowners control 83% of the timberland, having a population of roughly 260,000 persons with forested land (Birch, 1996; Whipkey *et al.*, 2000). The West Virginia Division of Forestry has roughly 600,000 acres currently listed in the Forest Stewardship Program (Provencer, 2004). Landowners enrolled in the FSP are more likely to use logging contracts and professional foresters during the harvests and sale of their timber (Egan *et al.*, 2001). A strong correlation has been shown between the

use of professionals in timber sales and the implementation of West Virginia's BMPs (Egan, 1999). These practices can affect hydrology, soil erosion, transport mechanisms, and chemical balance of water (Park *et al.*, 1994).

Best Management Practices

1. Road construction:

Logging roads, skid trails, and landings are major contributors to the addition of sedimentation into streams (Corbett *et al.*, 1978; Kochenderfer *et al.*, 1997; Cornish, 2001). These areas are the most vulnerable to erosion due to the removal of all vegetation in the construction of this road system. The removal of all vegetation exposes the greatest amount of mineral soil in timber operations. These road systems and landings create run-off channels that transport loose sediments via wind, wet weather, or even construction equipment. The primary source of erosion and of sediments reaching the stream via roads occurs at stream crossings (Martin and Hornbeck, 1994; Cornish, 2001).

There are several BMP guidelines that can be followed to reduce impacts of these practices. Culverts and diversionary tactics are two such examples. Skidding over ephemeral, intermittent, or perennial waters should not be allowed, unless the proper culverts or bridges are in place (Lynch *et al.*, 1985). Planning and construction of skid trails and logging roads away from streamside management zones can reduce sedimentation input from this practice (Lynch *et al.*, 1985; Kochenderfer *et al.*, 1997).

Diverting road runoff into a vegetated zone with high absorption can not only filter sediments but also keep excess groundwater from increasing normal flows.

The slope of the truck roads and skid trails can also help control the degree of erosion. The installation of water bars, broad-based dips, and other drainage devices greatly reduces the amount of soil erosion on these roads (Aubertin and Patric, 1974; Lynch *et al.*, 1985; Martin and Hornbeck, 1994; Arthur *et al.*, 1998). A water bar is a water diversion structure constructed of heavily packed dirt, 0.5 to 1.0 meter high. The downhill side of the water bar should be wider and divert run-off from the sloped loose soil of the road into forest soil where roots and organic matter can soak up the excess water. BMP guidelines specify distances between water bars, with intervals decreasing as the slope of the road increases. Broad-based dips are essentially trenches dug out of the road to trap water and divert it off into the forest. Once the harvesting operation is completed, all logging roads, skid trails, and landings should be retired and reseeded to prevent further sediment losses (Aubertin and Patric, 1974; Lynch *et al.*, 1985; Martin and Hornbeck, 1994; Arthur *et al.*, 1998).

2. Streamside management zones:

Streamside management zones (SMZ) are areas directly adjacent to ephemeral waters, perennial waters, and all other waters influenced by disturbance. The width of these buffer strips is determined by individual state requirements but should generally be a minimum of 30 meters wide on each side of the stream bank (Lynch *et al.*, 1985).

SMZs are an essential part of protecting the watershed from excessive sedimentation and pollution. These zones should consist of native, uncut vegetation in both the canopy and

the understory. Ideally, no logging practices should be carried out in these zones (Lynch *et al.*, 1985). Buffer strips can help protect stream banks from erosion by absorbing excess sub-surface water, thereby limiting the amount entering the stream (Arthur *et al.*, 1998). Without such interference, the excess water would increase the flow of the stream, which would cause greater agitation to the banks. Buffer strips provide a root system that helps maintain the soil and the stability of the bank (Arthur *et al.*, 1998). Trees provide woody debris and leaf litter that aid in maintaining dams in the stream (Martin and Hornbeck, 1994). Small woody debris dams provide habitat for fish and macroinvertebrates. Shade cast by streamside forests moderate temperatures and reduce drastic temperature fluctuations (Aubertin and Patric, 1974; Kochenderfer *et al.*, 1997), which is an important aspect of maintaining aquatic habitat, particularly in trout streams.

3. Logging debris:

Logging slash, treetops, and all other residual debris should be removed from the site if necessary and not be cast into streams (Lynch *et al.*, 1985; Martin and Hornbeck, 1994). Such woody debris can build up in the stream, push the water out of its channel, and cause additional erosion to the existing streambank. Additional erosion leads to increased turbidity and sediments in the water system. Excessive large woody debris dams can also decrease the flow of the water, cause increased surface area to build up behind it, and therefore raise the temperature of the water by exposing more water to solar radiation. (Lynch *et al.*, 1985)

4. Waste:

Waste materials should be properly handled and disposed of during logging operations to prevent pollutants from entering the stream via run-off or through the groundwater. Pesticides, herbicides, fertilizers, and other hazardous materials should not be handled, stored, applied, or disposed of in SMZs. Care should be taken to dispose of petroleum products when performing equipment maintenance in the harvesting area (Lynch *et al.*, 1985; Martin and Hornbeck, 1994). Human waste should also be disposed of properly (Martin and Hornbeck, 1994). Buffer strips in the SMZs can serve to filter these pollutants that reach the stream through excess water resulting from forestry practices.

Best Management practices specific to the state of West Virginia

The Logging Sediment Control Act, West Virginia Code 19-1b-7(g), is the primary state law that regulates erosion and soil movement into streams. The West Virginia Division of Forestry (WVDOF) regulates and enforces this law that relates to timber harvesting and best management practices. As of September 1992, the Logging Sediment Control Act requires any person conducting a logging operation, selling timber, or buying timber for resale to have a license issued by the WVDOF. The director is responsible for the development of standards and criteria for establishment of a regularly scheduled program of education, training and examination that all persons must successfully complete in order to be certified to supervise any timbering operation. Having this license also implies that the operator will protect environmental quality

through the use of BMPs. This law requires the loggers themselves to be certified in tree and equipment safety, first aid, and BMPs. Best management practices in West Virginia provide guidelines for road layout and construction, streamside management zones, and drainage measures. Any violations of this code or operation without license and/or certification can result in citations and civil penalties. (WVDOF, 2002)

1. Road construction:

All haul roads, skid roads, and landings should be constructed 30 meters away from perennial and intermittent streams and 8 meters away from ephemeral streams. Truck haul roads should have a grade of 10% or less. Water bars and cross drains should be maintained on a daily basis to ensure adequate drainage of the roads. Roads should cross as close to a right angle to the stream as possible and be graveled for 30 meters on either side. Culverts should be of the appropriate size to the stream so as not to impede water flow. Fords should occur minimally and only where bedrock makes up the streambed. Level areas with poor drainage capabilities should be avoided and operations should not be carried out in extreme weather.

Skid road construction should be laid out to allow for 60 meter spacing and grade should not exceed 15%, with the exception of short segments not exceeding 20%. Drainage measures should be installed every 30 meters and maintained daily. Culverts or bridges are required when a skid road crosses a stream and logs are not to be skidded through any stream. As with haul roads, right angles approaching a stream crossing are also recommended for skid roads.

Landings should be located in dry, firm areas, with adequate drainage for wet conditions. When servicing equipment on-site, proper waste disposal should be ensured. At the end of all harvesting operations, truck haul roads, skid trails, and landings should be immediately stabilized and reseeded to prevent further erosion. (WVDOF, 2002)

2. Streamside management zones:

The minimum width for a streamside management zone is 30 meters on perennial or intermittent streams and 8 meters on ephemeral streams. Equipment operation in this area should be limited to minimize disturbance and reseeded is required after any tree harvesting. Log landings should be located outside of this zone. However, if there is no other location available, reseeded and mulching should occur immediately after construction. Haul roads and skid roads should not be constructed within the streamside management zones except at stream crossings. Any roads built in the zone due to special circumstances should be graveled and reseeded after construction (WVDOF, 2002).

3. Logging debris:

Directional felling should be practiced to minimize stream impacts. Treetops should be pulled from the stream channel on all perennial and intermittent streams. Small logging debris can cause additional damage to the stream channel by increasing bank erosion and channel blockage. (WVDOF, 2002)

4. Waste:

When servicing equipment onsite, drain old oil and other automotive fluids into containers for proper disposal in accordance with solid waste disposal. All empty containers should be removed from the logging site and disposed of properly. (WVDOF, 2002)

Timber harvesting and streams

Increasing awareness of the links between the forest and the stream channel raises concerns that land use activities within a watershed can cause changes that may exceed the ability of aquatic biota to handle them (Sullivan *et al.*, 1987). Forestry practices can potentially alter sunlight, water temperature, sediments, nutrients, leaf litter inputs, woody debris, and channel structure – all of which influence habitat and nutritional resources of aquatic biota (Gregory *et al.*, 1987). The removal of the canopy may stimulate primary producers but the instability of instream sediments may result in the loss of aquatic vegetation. Microbes may benefit from increased nutrients and temperature but microorganisms may respond negatively to the decrease in detritus and reduced oxygen concentrations (Gregory *et al.*, 1987). Excessive sediments and decreased substrate stability may also negatively affect the abundance of aquatic insects. Insect communities often shift towards insects that drift, increasing the availability of prey for salmonids (Gregory *et al.*, 1987). However, these benefits may be negated if temperature and turbidity levels exceed the tolerance of these cold-water species, if spawning and rearing habitat become embedded with excess sediment, or if winter habitat is reduced (Gregory *et al.*, 1987).

Forest Stewardship Program and the Upper Elk Watershed

Originally, this project was funded by the USDA Forest Service to evaluate the success of the Forest Stewardship Program in the reduction of negative timber harvesting impacts on streams when compared to harvests by those not enrolled in the program. Unfortunately, due to the lack of recent FSP harvests (Figure 1), the project was modified to look at various land management activities and their impacts on headwater tributaries in the upper Elk River. The upper Elk River has been receiving heavy sedimentation due to timber harvesting, urban development, residential development, and agriculture. We decided to look at different types of land use and compare those with timber harvests to see if there were significant differences in the amount of sediment inputs into small tributaries that are potentially reproductive sites for brook trout and other aquatic biota.

Figure 1. West Virginia Division of Forestry data displays all recent harvests (2000-2003) and FSP enrollment (10 years or more) in the Upper Elk River watershed. Note: Only one FSP recent harvest occurs on a first- or second-order tributary in the upper Elk River and that is Laurel Run on the Back Fork of the Elk River.

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Chapter Two

Effects of land use on sedimentation processes and brook trout (*Salvelinus fontinalis*) populations in small tributaries of the Upper Elk River watershed

Abstract

Headwater trout streams in the Upper Elk River basin were selected using West Virginia Division of Forestry data to identify recent timber harvests and sampled for deposited sediments, suspended sediments, and brook trout. My objectives were: 1) to identify land use activities that result in the input of excessive fine sediments into the Elk River mainstem, and 2) relate brook trout population density to deposited and suspended sediment levels. Deposited sediment samples were collected from tributaries (N=21) of the Upper Elk watershed in fall of 2002. Brook trout were sampled in the fall of 2003. Water quality samples were collected, analyzed for total suspended solids (TSS), and turbidity measurements were taken at concurrent locations for the development of a basin-wide model relating turbidity to TSS.

Overall, deposited sediment levels in tributaries were low. However, timber harvested sites tended to possess higher percentages of deposited sediments in all critical size classes than either development or reference sites. Timber harvested sites also produced significantly higher average daily loads of suspended sediments, total suspended solid concentrations, and turbidity levels than reference sites but were not significantly different from development sites. Brook trout densities were not related to deposited sediments in any land use category but were negatively related to suspended

sediments in the timber harvesting sites. Brook trout densities were not related to pH, alkalinity, or calcium to hydrogen ionic ratios.

Based on these findings, I conclude that sediments are not being stored in the tributaries but significant amounts are being transported downstream as suspended load. There is some evidence that increased turbidity from timber harvest and development has a negative effect on brook trout populations residing in the small tributaries. In addition, it is likely that increased sediments being transported from the tributaries to the Elk River mainstem may negatively affect aquatic invertebrate production and fish communities downstream.

Best management practices designed for the forest industry could reduce the amount of sediments being disturbed by timber harvesting. The Forest Stewardship Program is a financial assistance program that encourages the use of BMPs. Increased enrollment in this program in the Upper Elk River watershed could lessen the impacts of sediments on trout populations in tributaries and mainstem reaches of the upper Elk River watershed.

Introduction and background

Humans have long been identified as an important geomorphic agent through processes such as road construction, housing construction, and mining (Hooke, 1999). Timber harvesting is another activity that does not disturb as much soil as construction or mining but can have a direct impact on forested streams and the watersheds they drain (Hooke, 1999). Stream channel morphology is directly related to sediment and water inputs to the channel (Sullivan *et al.*, 1987). Timber management can affect this by altering the amount of sediment or water entering the streams, thus changing the balance between sediment input and removal (Sullivan *et al.*, 1987). Sediment delivered to streams can be suspended and create turbid water, or deposited onto the streambed (Nerbonne and Vondracek, 2001). Although some sediment input is natural, excessive suspended and deposited sediments can have detrimental effects on stream biota (Waters, 1995).

It is important to identify how the stream morphology reacts when the sediment load increases in a gravel-bed stream. Excessive sediment loading that exceeds the stream transport capacity can result in channel bed aggradations, which leads to increased sediment storage (Montgomery and Buffington, 1998) and an increase in fine sediments (sand and smaller; Hausle and Coble, 1976) on the bed surface (Lisle and Hilton, 1992). Where these sediments are stored results in specific reactions from the channel itself and the biota that live there. Pools and riffles are two crucial stream habitat units that react to sediment load increases. Generally, riffles and pools are channel units that transport sediments at short-lived, high-velocity discharges (Milne, 1982). Increased sediment loads tend to result in the collection of fine sediments in pools (Lisle and Hilton, 1992),

the filling of interstitial space in the gravel bed, and the reduction in coarseness of the streambed (Montgomery and Buffington, 1998). During normal low flows in these habitat units, heavy sediment loads can build up and change the characteristics of depth, width, and even slope in these areas. Low flows also tend to transport excess sediments from the riffle units into the lower velocity zones of pool units (Lisle and Hilton, 1992).

Stream channels play a crucial role in transporting sediments from the headwaters to the oceans (Montgomery and Buffington, 1998), but they also serve as critical habitat for aquatic life. An increase in sediments into the fluvial system can greatly alter channel morphology and substrate size, resulting in poor fish habitat (Platts *et al.*, 1989). Brook trout (*Salvelinus fontinalis*), in particular, rely on riffles and pools in headwater streams for most of their life stages. Salmonids specifically are affected by changes in substrate size in spawning gravel and juvenile habitats (Platts *et al.*, 1989). Reproduction can be greatly reduced by heavy sediment inputs because spawning redds typically are located at the start of riffles (Shirazi and Seim, 1979; Platts *et al.*, 1989), where sediments can build up during increased sedimentation. When fine sediments (clay- to silt-sized particles) are being transported, some of the particles will infiltrate the clean, porous streambed gravel (Everest *et al.*, 1987). Fine sediment in spawning gravel inhibits the flow of water to the eggs and, in turn, reduces the amount of oxygen that is being delivered to, and traps waste produced by the embryos (Hausle and Coble, 1976). Should the egg survive to the larval stage, sediments built up in the gravel could prevent emergence. Small fish also use interstitial spaces in riffles for cover and escaping heavy flow for energy conservation. Slackwater pools on the edges of stream channels are rearing areas for juvenile fish (Rabeni and Jacobson, 1993). Sediment build-up in these smaller side pools

causes a decrease in depth in an already shallow environment, which in turn widens the pool and increases temperatures. Larger brook trout spend most of their life in deeper pools, foraging for food and seeking refuge from higher velocity currents (Flebbe and Dolloff, 1995; Logan, 2003). When pools start filling with excess sediments, the amount of habitat is reduced, as pools get shallower and broader. An increase in temperature is usually associated with a decrease in depth and an increase in width, which can be detrimental to trout.

Suspended solids, or turbidity, can also be detrimental to the health of stream fishes. Suspended sediments reduce light penetration and visual clarity (Barret *et al.*, 1992), increase physiological stress and susceptibility to disease (Reynolds *et al.*, 1989), and increase respiratory stress (Berg and Northcote, 1985). Brook trout in streams are typically drift feeders, occupying low velocity areas that are close to areas of swift velocity (Grant, 1990). Maintaining a low flow position enables the fish to minimize energy used to hold position and maximize access to invertebrate drift (Fausch, 1984). Sweka and Hartman (2001) found that increasing turbidity in an artificial stream containing brook trout caused the fish to switch from drift-feeding behavior to active foraging. Their results suggested turbidity could reduce growth through energy loss due to increased swimming activity. In a study on rainbow trout (*Oncorhynchus mykiss*) growth and sediment pulses, Shaw and Richardson (2001) found a negative relationship between growth rates and sediment pulse durations and concentrations. Using a severity of ill effect model, they were able to successfully predict a reduction in feeding rate and prey capture success for rainbow trout in their experiment.

The collection of fine substrate in riffles may also affect the population of aquatic insects that inhabit them, therefore, affecting the amount of prey available for feeding by fish (Shaw and Richardson, 2001; Shirazi *et al.*, 1979). Many benthic macroinvertebrate taxa require a streambed relatively free of fine sediment (Waters, 1995). Excessive deposited sediments can limit food resources and habitat of invertebrates by covering the substrate and filling interstitial spaces (Nerbonne and Vondracek, 2001). Studies by both Shaw and Richardson (2001) and Nerbonne and Vondracek (2001) showed a decrease in drift and benthic invertebrate abundance and richness with increased sediment loading. Scrapers are expected to decrease as algae and their rocks become embedded and filter feeders are expected to increase. Benthic and drift specialists were replaced with more generalists, omnivores, and burrowing taxa that prefer silt habitats (Nerbonne and Vondracek, 2001). Changes to the quantity and composition of invertebrates can directly influence the growth of resident fish (Shaw and Richardson, 2001).

Many other stream fishes besides brook trout can be negatively affected by an increase of sediments into the stream. Mottled sculpin (*Cottus bairdi*) typically inhabit coldwater streams and are often found concurrently with brook trout. They are riffle spawners and feed primarily on benthic invertebrates such as immature caddisflies, mayflies, stoneflies, and midges (Etnier and Starnes, 1993). Longnose dace (*Rhinichthys cataractae*) is a minnow that is frequently found in trout streams, is a clean gravel spawner, and also feeds on aquatic invertebrates such as mayfly, midge, and black fly larvae (Etnier and Starnes, 1993). Creek chubs (*Semotilus atromaculatus*) and central stonerollers (*Campostoma anomalum*) are also small stream inhabitants that spawn in riffles, over gravel substrate. Creek chub juveniles feed primarily on small aquatic

insects while the adults feed on larger invertebrates as well as larger prey items in the streams. Stonerollers may occasionally feed on aquatic insects but are more generalist feeders (Etnier and Starnes, 1993). Excessive sediment build-up that infiltrates gravel, saltates along the streambed, and decreases or alters the composition of aquatic invertebrates could negatively affect populations of all these species, not just brook trout, by loss of reproduction and/or prey. Many species can tolerate short exposures to poor conditions, but extended exposures usually lead to death or migration to better habitat (Sullivan *et al.*, 1987).

Other factors besides increased sedimentation and turbidity have been found to affect movement and survivorship of brook trout in headwater streams. Eastern North America is highly susceptible to acidification of stream waters due to acid rain deposition and poor buffering capacity of soils (Schindler, 1988). Studies in several small northeastern streams found reduced trout abundance in streams with a median pH of 5.0-5.2 (Baker *et al.*, 1996). Alkalinity helps to buffer the change in pH from increased acidity and minimum levels for brook trout are around 3 mg/L CaCO₃ (Mount *et al.*, 1988; Zurbuch *et al.*, 1996). Calcium to hydrogen ionic ratio is one more water chemistry parameter used to interpret buffering capacity and should be a minimum of 10 for acid sensitive fish (Menendez *et al.*, 1996).

The Elk River has the highest biodiversity of fish in West Virginia, with over 70 species of fish, including 18 species of darters and several species of madtoms (Stauffer *et al.*, 1995). The mainstem of the upper Elk River is considered to be one of the top trout streams in the state. The watershed is 90% forested and supports high quality timber stands of oak, yellow-poplar, ash, and cherry. The upper Elk section, specifically,

is primarily used for recreation and timber harvesting. Excess sedimentation as a result of land use activities is the primary pollutant that threatens the biota in this system. It has become enough of a concern that the USDA Forest Service and the West Virginia Division of Forestry, in cooperation with several watershed groups in the area, developed the Elk River Project to address the issues of siltation from logging roads, stream bank erosion, and the education of landowners and communities in the watershed. The timber industry has been important in this region for over 140 years and the future health of this region depends on the management of these forests (WVDEP, 1997).

This study examined the effects of sediment loads on tributaries of the Upper Elk River watershed, WV. My specific objectives were 1) to quantify variation in deposited and suspended sediment loads in streams of the upper Elk River basin and relate varying levels of sediment loads to natural watershed characteristics (e.g. gradient and valley shape) and human land use (e.g. forestry and residential development), and 2) to examine the relationship between varying levels of fine sediment loads and brook trout populations, especially as it relates to reproduction and juvenile recruitment.

Methods

Study Area

The Upper Elk River basin is located in Pocahontas, Randolph, and Webster counties in east central West Virginia (Figure 2). The basin area is 624 km², with an elevation range of 422 to 1,485 m. There are roughly 940 km of recognized streams in the watershed (at 1:24,000 scale), which does not include numerous unmapped intermittent and ephemeral streams.

Figure 2. Map of the Upper Elk River watershed in east central West Virginia, USA. Pocahontas, Randolph, and Webster counties are highlighted in red.

The three major bedrock types in the watershed are Mauch Chunk shale/sandstone, Pottsville sandstone, and Greenbrier limestone. The land cover is 72% hardwood forest, with the remaining 28% consisting of small proportions (i.e. <5% each) of pasture, shrublands, conifers, oaks, wetlands, row crop agriculture, and light urban development. Land use activities in the area consist of timber harvesting, residential development, agriculture, and recreation. Study streams in the upper region of the watershed were Big Spring Fork, Hawthorn Run, Old Field Fork, Crooked Fork,

Warwick Run, Laurel Run, Props Run, and one unnamed tributary in the headwater region of the Elk River (Figure 3). In the middle region, samples were taken from Upper Valley Fork, Mudlick Run, Valley Fork, Thayer Run, Hickory Lick Run (HLR), Hamrick Run, Mill Run, Big Run, Fisher Run, and Abb Run (Figure 4). The Back Fork of the Elk River enters the mainstem at Webster Springs and makes up the lower region of the study area. Sites on this branch of the Elk include Mill Run and Laurel Run (Figure 5). All streams were first or second order headwater tributaries to the mainstem of the upper Elk River and the Back Fork of the Elk River.

Study sites were selected within the Upper Elk River watershed across a range of varying stream gradient and human disturbance (timber harvest size and number, residential development, and low disturbance) (Table 1). Low disturbance sites were Crooked Fork, Hamrick Run, and the left fork of Hickory Lick Run (Lt F HLR). The residential development sites were Old Field Fork, Warwick Run, Big Spring Fork, Hawthorn Run, and Valley Fork. The harvested streams in this study were selected using West Virginia Division of Forestry data to identify non-industrial private forest (NIPF) land holdings and recent (2000-2003) harvests (Figure 6). Within timber harvest sites, I assigned a designation of light (L), moderate (M), or heavy (H) intensity depending on time since harvest, total number of acres harvested, and the total number of harvests within each study stream sub-watershed. Specifically, the light intensity class consisted of streams that were helicopter logged in 1999; the moderate intensity class consisted of streams that have one or two harvests since 2001; and the heavy intensity class consisted of streams harvested most recently, or those with three or more harvests on a single stream. Light harvest intensity sites (helicopter logging in 1999, no roads constructed)

were located on Laurel Run and Props Run on US Forest Service lands in the Monongahela National Forest. The moderate intensity sites were (number of harvests in basin in parentheses): Abb Run (1), Mudlick Run (1), Upper Valley Fork (1), Thayer Run (1), and Fisher Run (2). The heavy intensity sites were Laurel Run on the Back Fork (1: Forest Stewardship property and recent harvest), unnamed tributary of the Upper Elk (1), Mill Run (2), right fork of Hickory Lick Run (Rt F HLR, 3), Mill Run on the Back Fork (3), and Big Run (8).

Figure 3. Study streams within the headwater region of the Upper Elk River watershed are highlighted in blue. Old Field Fork, Warwick Run, Hawthorn Run, and Big Spring Fork are all in the development class. The U.S. Forest Service harvested Laurel Run and Props Run for timber as recently as 1999. The upper headwater region, Crooked Fork, is relatively undisturbed.

Figure 4. Study streams within the middle region of the Upper Elk River watershed are highlighted in blue. Abb Run, Fisher Run, Big Run, Mill Run, the right fork of Hickory Lick Run, Thayer Run, Mudlick Run, and Upper Valley Fork have had recent timber harvests in their respective watersheds. Hamrick Run and the left fork of Hickory Lick Run are considered low disturbance sites.

Figure 5. Study streams within the Back Fork of the Elk River watershed are highlighted in blue. Mill Run and Laurel Run have had recent timber harvests in their sub-watersheds. The harvest on Laurel Run was the only recent Forest Stewardship harvest on a first- or second-order tributary in the Upper Elk River watershed.

Table 1. Site characteristics of each study stream selected to evaluate sedimentation in the upper Elk River. In the description, each individual harvest acreage amount is a separate logging operation followed by the year it occurred.

Site	Basin Area (km)	Order	Elevation Range (m)	Gradient	Land Use	Harvest Intensity	Description
Crooked Fk	1.35	1	1246 - 1071	7.4	Reference	N/A	No recent timber harvests, no roads
Hamrick Run	2.46	1	1082 - 703	4.1	Reference	N/A	No recent timber harvests, one road
Lt F HLR	2.09	2	1083 - 691	6.6	Reference	N/A	No recent timber harvests, one road
Hawthorn Run	3.82	2	1147 - 941	3.1	Development	N/A	Golf Course
Old Field Fork	2.53	1	1079 - 938	3.1	Development	N/A	Residential, exposed soils
Upper Big Spring	4.47	1	1144 - 1060	3.2	Development	N/A	Construction of new road in 2002
Valley Fork	11.41	3	949 - 815	2.4	Development	N/A	Residential, construction
Warwick Run	3.76	2	1183 - 898	1.9	Development	N/A	Residential, agricultural, unpaved road
Laurel Run-USFS	7.58	2	1316 - 821	3.4	Timber	Light	Helicopter logging, no road construction, 1999
Props Run	3.48	2	1289 - 806	4.5	Timber	Light	Helicopter logging, 1999, mountain bike trail
Abb Run	3.83	2	964 - 691	4.1	Timber	Moderate	Harvested 20 acres, 2001
Fisher Run	1.62	2	978 - 597	6.2	Timber	Moderate	Harvested 202 acres, 2001; 70 acres, 2000
Mudlick Run	6.21	3	973 - 820	3.7	Timber	Moderate	Harvested 76 acres, 2000
Thayer Run	1.46	1	948 - 689	4.3	Timber	Moderate	Harvested 80 acres, 2001
Upper Valley Fork	2.79	2	943- 839	2.5	Timber	Moderate	Harvested 250 acres, 2001
Big Run	6.80	2	1076 - 646	4.9	Timber	Heavy	Harvested 235 acres, 2002; 225 acres, 2002; 65 acres, 2002; 228acres, 2001; 176 acres, 2001; 100 acres, 2001; 120 acres, 2000; 130 acres, 2000
Laurel Run-BFE	2.02	2	781 - 519	12.2	Timber	Heavy	Harvested 66 acres, 2002; Forest Stewardship Program participant
Mill Run	3.56	2	1031 - 657	3.9	Timber	Heavy	Harvested 50 acres, 2001; 225 acres 2001
Mill Run-BFE	3.92	2	833 - 472	5.2	Timber	Heavy	Harvested 20 acres, 2001; 75 acres, 2000; 40 acres 2000
Rt F HLR	3.28	1	947 - 691	4.6	Timber	Heavy	Harvested 400 acres, 2001; 10 acres, 2001; 90 acres, 2000
Unnamed Tributary	2.54	1	1122 - 795	6.5	Timber	Heavy	Harvested 2002

Figure 6. Circles represent recent NIPF timber harvests and their locations in the Upper Elk River watershed and the single FSP recent harvest on Laurel Run (Back Fork of the Elk) is represented by a star.

Deposited Sediment Sampling

In fall of 2002, deposited sediment samples were collected from study tributaries in the Upper Elk River watershed to quantify fine sediment levels (<2 mm; Curry and MacNeill, 2004) in the substrate and to relate findings to brook trout reproductive success in 2003. Ten sediment samples were collected from each study stream with a small shovel, 20 cm wide and 24 cm long (Grost *et al.*, 1991; Hakala, 2000). Each stream was sampled continuously upstream until ten locations of suitable spawning gravel were found. Qualifications for suitable spawning habitat were: depth between 5 and 25 cm, and substrate ranging from 4.0 to 30.0 mm in at least 7.0 cm of low velocity water (generally tails of pools; Hakala, 2000). Location for each sediment sample was selected randomly by assigning random numbers to each stream. Each third was then assigned a right, left, or center location in the stream. A designated pattern (right, center, left, center, etc.) was then followed upstream based on the initial location of spawning substrate. Gradient was measured using a clinometer. Valley shape, a measure of average slope of the basin, was determined using GIS (Wilson and Gallant, 2000).

To minimize operator bias due to manual sampling, all substrate components were removed from a pre-determined depth of 10 cm (average redd pocket depth of brook trout; Witzel and MacCrimmon, 1983; DeVries, 1997) and lifted slowly out of the water parallel to the streambed so as not to disturb the sample (Grost *et al.*, 1991). The substrate sample was allowed to drain briefly (Grost *et al.*, 1991) before placing it into a plastic bag for transport back to the lab where it was analyzed. Samples were dried in the lab at 70°C for 7 days. Once dried, each sample was sifted through Wentworth sieves in size increments of >32, 16, 8, 4, 2, 1, 0.5, 0.25, 0.125, 0.063 and <0.063 mm (Kaller,

2000). Each individual size class was then weighed to the nearest 0.1 g and its percentage of total weight of the substrate sample determined (Grost *et al.*, 1991; Kaller, 2000).

Fine sediments (<2 mm) can negatively impact organisms in aquatic systems by suspension in the water column, deposition on the substrate, and saltating along the gravel bed (Curry and MacNeill, 2004). Hakala (2000) studied sediment production in several central Appalachian streams and found two levels of sediment percentages detrimental to brook trout reproduction. Greater than 20% of spawning gravel composed of 1-0.063 mm diameter particles and greater than 0.6% composed of <0.063 mm diameter particles were found to inhibit reproduction (Hakala, 2000). In a study by Young *et al.* (1989), brook trout in a southeastern Wyoming stream were discovered excavating substrate during spawning, selectively removing sediments less than 1.70 mm in diameter. Platts *et al.* (1989) studied increased delivery of fine sediments and effects on salmon spawning and rearing habitat in the South Fork Salmon River, Idaho, and defined fine sediment as less than 4.75 mm in diameter. Increased amounts of fines at this size can infiltrate larger substrate and cause increased mortality to embryos and sac-fry prior to emergence (Phillips *et al.*, 1975). Based on these previous studies, I limited my analysis of deposited sediments to size classes <4 mm in diameter.

Suspended Sediment and Water Chemistry Sampling

Turbidity is directly related to concentrations of suspended sediments in streams (Beschta, 1996), and it provides an effective measure of suspended sediment loads. An important objective of my research was to quantify the relationship between turbidity and

total suspended solids (TSS) in the upper Elk River. Turbidity measurements and water samples were collected during various stream flow conditions, at random sites along the mainstem of the upper Elk River, and in each of the tributary sites from September 2003 to May 2004. Turbidity (nephelometric turbidity units, or NTUs) was measured with a YSI meter (± 0.1). One liter water samples were collected mid-stream and at a consistent rate from the surface to the bed and back to the surface (Beschta, 1996). Water samples were filtered through pre-weighed glass fiber filters (pore size: $0.7\mu\text{m}$). The filters were then dried at 105°C in an Isotemp oven for 24 hours and then weighed to the nearest ± 0.0001 mg (Beschta, 1996). By subtracting the original weight of the filter and adjusting for the amount of water filtered, the amount of total suspended solids (mg/L) was determined. Turbidity measurements also were taken with a concurrent discharge measurement in order to calculate TSS loads of each of the study tributaries. Discharge was taken at 60% depth using a flow staff and a digital flow meter, in ten equal cells in a cross-section of the stream (WVDEP, 2003).

Water quality parameters of pH, temperature, and specific conductivity were measured with a YSI meter during site selection in the summer, fish sampling in the fall, water quality sampling in late winter, and during flow measurements in late spring. Whole water samples also were taken from the thalweg of each study stream during the late winter. These samples were analyzed in the lab for alkalinity (mg/L CaCO_3) and calcium to hydrogen ionic ratio.

Fish Sampling

I used using backpack electrofishing gear and a three-pass depletion method to sample fish communities in the fall of 2003. Sampling was focused at this time to target brook trout spawning and juvenile recruitment. Juvenile recruitment was related to fine sediment levels collected in the previous fall. The length of each study reach was determined by multiplying the average stream width by forty, with a minimum length of 100 meters and a maximum of 300 meters. One person carried the backpack electrofishing unit with another individual following behind holding a backup net and a bucket for the length of the site while removing all fish for each individual pass. Block nets were used at the top and bottom of each site to ensure population closure. The trout were anesthetized with clove oil and measured for total length (mm) and weight (g). The anesthetized trout were then placed in live wells for recovery. All other fish were sorted to species, counted, collectively weighed (g), and then a maximum and minimum length (mm) range was noted for each species. No fish was returned to the stream until the entire length of the site had been sampled for three passes and all fish data had been recorded.

A length-frequency distribution was used to determine the length gap separating the age-0 from the age-1 fish. Applied pressure to the abdomen of all but age-0 fish allowed for in field identification of potentially spawning adults. Only those fish that supplied eggs or milt upon pressure, and those who had the depleted look of a post-spawn fish, were considered sexually mature.

Hypotheses and Statistical Methods

In this study, I sought to test two hypotheses regarding sedimentation and land use activities in the upper Elk River watershed: (i) timber harvesting areas discharge significantly greater amounts of deposited and suspended sediments into headwater streams relative to other land management activities, and (ii) brook trout reproduction and population structure is negatively affected by excess sedimentation in those same headwater streams.

An analysis of covariance test was used to examine the interactive effect of gradient and land use on deposited and suspended sediment concentrations. Initial analysis of covariance tests, followed by post-hoc pairwise t-tests, were used to identify significant effects within three deposited sediment size groupings: <4.0 , $1.0-0.063$, and <0.063 mm. Actual deposited sediment data were transformed into percents of total sample for statistical analysis. An analysis of variance test was also used to determine if significant differences in sediment production existed based on harvest intensity within the timber harvest land use category. Analysis of variance tests were used along with post hoc t-tests to determine if land use or intensity of harvest resulted in significant differences in turbidity.

Linear regression was used to test for relationships between young of the year (YOY), adult, and total brook trout density and the three critical size classes of deposited sediments, <4 , $1-0.063$, and <0.063 mm. Linear regression was also used to test for relationships between brook trout density and turbidity and TSS concentrations. Linear regression was also used to test brook trout density relationships with other parameters such as gradient, basin area, pH, alkalinity, and calcium to hydrogen ionic ratios.

Correlation statistics were used to test for a relationship between the presence of brook trout and exotic trout species.

All deposited sediment data, suspended sediment data, trout density data, and water chemistry data were log-transformed to approximate normality (Zar, 1996). Statistical analyses were performed on log-transformed data, whereas all figures and tables represent actual data. All statistical tests were performed at the 95% confidence level. However, due to the high variability in sediment production as a result of topography, I interpreted $p < 0.05$ as significant, $0.05 < p < 0.10$ as marginally significant and worthy of further consideration or discussion, and $p > 0.10$ as not significant.

Results

Deposited Sediment

Mean sample weight (g) of ten samples, mean sediment weight (g) for each size class, the sum of means for groupings 1-0.063 mm, and the sum of means for sediments <4 mm for each study stream are listed in Appendix I. Fine sediment proportions (<0.063 mm) were below the level of 0.6% of total sample weight deemed detrimental to brook trout in the study by Hakala (2000) in all of my study streams (Figure 7; percent data, Table 2). Although seven streams in the timber harvest category were above 20% in the 1-0.063 mm grouping of sediment proportions deemed critical by Hakala's study (Figure 8; percent data, Table 2), they did not exceed 20% by much and were very similar in composition to the reference category. Two streams in the reference category were very close to the subjective cut-off of 20% in this sediment size class.

Table 2. Percent composition for each size class in each study stream based on the raw data averages. Percents exceeding critical levels based on previous studies are highlighted. R= Reference, D= Development, and T= timber harvesting.

Stream	Land Use	Sediment Size Classes (mm) - Percent of total sample weight (g)													
		Total	>32	16.00	8.00	4.00	2.00	1.00	0.50	0.25	0.13	0.063	<0.063	1-0.063	<4.00
Crooked Fk	R	757.9	18.74	11.65	21.60	19.96	13.78	6.72	4.21	1.96	0.78	0.33	0.18	14.00	27.97
Hamrick Run	R	900.1	4.22	11.86	22.66	22.38	18.10	9.40	6.22	3.19	0.85	0.27	0.21	19.94	38.24
Hickory Lick Lt Fk	R	864.1	8.93	12.93	23.40	20.94	13.98	8.11	6.21	3.67	1.27	0.36	0.18	19.61	33.78
Average	R	840.7	10.19	12.16	22.59	21.16	15.39	8.15	5.61	2.99	0.97	0.32	0.19	18.04	33.62
Old Field Fork	D	789.0	11.12	21.00	27.05	20.86	11.55	5.10	2.15	0.63	0.26	0.14	0.13	8.28	19.96
Warwick Run	D	841.4	18.43	20.89	25.91	17.76	8.54	2.86	1.26	0.83	0.65	0.31	0.23	5.92	14.69
Upper Big Spring	D	821.5	12.38	28.66	25.00	12.11	5.97	3.56	3.65	3.88	1.30	0.30	0.15	12.69	18.80
Hawthorn Run	D	840.7	11.80	11.94	24.56	22.12	13.87	6.93	3.95	1.78	0.47	0.15	0.12	13.27	27.26
Valley Fork	D	830.5	15.84	19.12	27.24	18.58	8.76	3.59	2.98	3.34	1.84	0.56	0.26	12.31	21.33
Average	D	824.6	13.95	20.28	25.94	18.28	9.74	4.40	2.80	2.10	0.91	0.29	0.18	10.51	20.42
Laurel Run (USFS)	T	816.0	10.16	14.34	19.68	21.67	15.50	8.53	4.94	2.57	0.61	0.17	0.14	16.82	32.47
Props Run	T	833.8	5.01	15.03	24.54	20.33	13.64	8.58	6.97	4.35	1.07	0.27	0.16	21.22	35.02
Unnamed Trib	T	1065.2	10.59	12.02	20.24	16.98	15.49	10.30	8.75	4.10	1.01	0.30	0.20	24.47	40.16
Upper Valley Fork	T	677.7	4.65	10.46	27.29	22.99	14.34	7.41	5.69	4.35	1.67	0.45	0.25	19.58	34.17
Mudlick Run	T	821.6	5.70	15.93	24.91	19.07	12.26	7.46	4.52	5.43	3.35	0.89	0.39	21.65	34.31
Thayer Run	T	909.9	12.69	15.10	21.41	16.59	13.47	8.94	6.64	3.30	1.14	0.42	0.27	20.43	34.17
Hickory Lick Rt Fk	T	982.8	10.59	26.43	21.24	14.31	10.36	7.08	5.35	3.09	0.98	0.35	0.23	16.85	27.44
Fisher Run	T	894.6	18.55	7.02	22.22	19.32	12.79	7.28	5.25	4.58	2.04	0.55	0.34	19.70	32.84
Abb Run	T	730.7	2.29	15.31	30.37	23.48	12.90	6.78	4.64	2.91	0.81	0.23	0.17	15.37	28.44
Mill Run	T	722.1	2.79	11.44	24.18	24.80	17.16	8.53	5.09	3.13	1.70	0.75	0.38	19.20	36.75
Mill Run (BFE)	T	772.0	4.25	12.58	22.48	21.12	15.65	9.94	7.22	4.26	1.64	0.48	0.34	23.53	39.52
Laurel Run (BFE)	T	791.8	2.30	14.41	17.23	23.12	18.07	8.92	5.17	5.97	3.15	0.96	0.56	24.18	42.81
Big Run	T	918.7	16.57	16.88	16.06	14.88	12.37	8.61	7.15	5.06	1.62	0.44	0.27	22.88	35.51
Average	T	841.3	8.61	14.56	22.19	19.55	14.06	8.38	6.04	4.09	1.58	0.47	0.28	20.55	34.89

Figure 7. Fine sediment (<0.063 mm) production by stream and by land use type (bars represent standard error). The timber harvest sites increase in harvest intensity from left to right.

Figure 8. Critical sediment (1-0.063 mm) production by stream and by land use type (bars represent standard error). The timber harvest sites increase in harvest intensity from left to right.

Average percent composition of sediment <0.063 mm was 0.19% in the reference class, 0.18% in the development class, and 0.29% in the timber harvest class (Figure 9). Timber harvested lands had significantly higher percent composition of sediments <0.063 mm than developed lands ($F = 5.52$, d.f. = 1, 18, $p = 0.03$). There were no significant differences in fine sediment deposition among timber and reference sites ($p > 0.10$) or among reference and development ($p > 0.10$). Average percent composition of sediment ranging from 1–0.063 mm was 18.0% for the reference class, 10.5% for the development class, and 20.5% for the timber management class (Figure 10). Timber harvested lands had significantly higher percent composition of sediments 1–0.063 mm than developed lands ($F = 38.65$, d.f. = 1, 18, $p < 0.001$). Reference sites had greater percent of sediments 1–0.063 mm than developed lands ($F = 12.91$, d.f. = 1, 18, $p = 0.002$), but there were no differences among timber and reference sites ($p > 0.10$). Average percent composition of sediments <4 mm was 33.6% for the reference class, 20.4% for the development class, and 34.9% for the timber management class (Figure 11). Timber harvested lands had significantly higher percent composition of <4 mm sediments than developed lands ($F = 44.77$, d.f. = 1, 18, $p < 0.001$). Reference sites had greater percent of sediments <4 mm than developed lands ($F = 19.45$, d.f. = 1, 18, $p < 0.001$), but there were no differences among timber and reference sites ($p > 0.10$).

Figure 9. Mean percent composition ($\pm$ standard error) of deposited sediments (<0.063 mm diameter) in tributaries draining watersheds of varying land use. Similar letters above columns indicate no significant difference ($p>0.10$).

Figure 10. Mean percent composition ($\pm$ standard error) of deposited sediments (1-0.063 mm diameter) in tributaries draining watersheds of varying land use. Similar letters above columns indicate no significant difference ($p>0.10$).

Figure 11. Mean percent composition ($\pm$ standard error) of deposited sediments (<4 mm diameter) in tributaries draining watersheds of varying land use. Similar letters above columns indicate no significant difference ($p>0.10$).

Deposited Sediment and Gradient

The analysis of covariance test for interactive effects of gradient and land use on deposited sediments resulted in significant influences in the three sediment critical size classes (Figures 12, 13, and 14; Table 3) and post hoc comparisons of the means using Scheffe's test revealed where this effect was the strongest. In all critical sediment size classes, land use by itself and gradient by land use interaction had significant influences on sediment deposition in the study tributaries. Gradient alone had no significant effect (Table 3). The finding of no significant effect of land use on percent composition of <0.063 mm size fraction may be due to a high rate of transport of this size class as suspended load from high gradient tributaries.

I observed significant differences in all three critical size classes between timber and development (<0.063 mm: $F= 3.93$, d.f.= 1, 15, $p= 0.07$; 1-0.063 mm: $F= 8.78$, d.f.= 1, 15, $p= 0.009$; <4.0 mm: $F= 7.38$, d.f.= 1, 15, $p= 0.02$). Average percent composition in the timber harvest class was 1.5 times greater in <0.063 mm sediments and two times greater in 1-0.063 mm sediments than in the development class (Figure 15). Marginally significant differences were found in deposited sediments <4 mm ($F= 3.36$, d.f.= 1, 15, $p= 0.09$) between timber management sites and reference sites but not in the 1-0.063 or <0.063 mm size classes ($p>0.10$). Average percent composition was slightly higher in the timber harvest sites than in the reference sites for this size class (Figure 16). Comparisons of development sites and reference sites yielded significant differences among size classes of 1-0.063 mm ($F= 7.45$, d.f.= 1, 15, $p= 0.02$) and <4 mm ($F= 9.98$, d.f.= 1, 15, $p= 0.007$) but no difference in <0.063 mm sediments ($p>0.10$). Average percent composition in reference sites was almost twice as great in 1-0.063 mm sediments and 1.5 times greater in <4 mm sediments than in development sites for these sediment size classes (Figure 17).

Figure 12. Relationship between gradient and % composition of <0.063 mm size fraction of deposited sediment as a function of land use.

Figure 13. Relationship between gradient and 1.0 to 0.063 mm % composition of deposited sediments as a function of land use.

Figure 14. Relationship between gradient and <4.0 mm % composition of deposited sediments as a function of land use.

Table 3. Analyses of covariance tests on gradient by land use interaction reveal significant effects in all deposited sediment size classes.

Size Class	D.F.	F Value	P Value
<0.063 mm	5,15	3.11	0.04
Land Use	2,15	2.02	0.17
Gradient	1,15	0.97	0.34
Land Use*Gradient	2,15	3.14	0.07
1-0.063 mm	5,15	12.39	<0.001
Land Use	2,15	5.73	0.01
Gradient	1,15	1.67	0.22
Land Use*Gradient	2,15	3.10	0.08
<4.0 mm	5,15	14.8	<0.001
Land Use	2,15	6.16	0.01
Gradient	1,15	0.68	0.42
Land Use*Gradient	2,15	3.42	0.06

Figure 15. Average percent composition ($\pm$ standard error) of the <0.063 , $1-0.063$, and <4 mm sediment size classes in timber harvest and development sites. Timber harvest sites increase with intensity from left to right. Rt F HLR is the right fork of Hickory Lick Run.

Figure 16. Average percent composition ($\pm$ standard error) of the <4 mm sediment size class is higher in timber harvest sites than in reference sites. Lt F HLR is the left fork and Rt F HLR is the right fork of Hickory Lick Run.

Figure 17. Average percent composition ($\pm$ standard error) of the 1-0.063 and <4 mm sediment size classes in reference and development sites. Lt F HLR is the left fork of Hickory Lick Run.

Deposited Sediment and Valley Shape

The analysis of variance test to identify valley shape differences by land use resulted in an overall p value of 0.09 ($F = 2.77$, d.f. = 2,18) so I sub-divided the analysis with a land use contrast statement. This analysis detected marginally significant differences in percent slope between development and reference sites ($F = 3.08$, d.f. = 1,18, $p = 0.097$) and significant differences between development and timber sites ($F = 5.09$, d.f. = 1,18, $p = 0.04$). Timber and reference sites showed no significant differences ($p > 0.10$) and both had higher average valley slopes than development sites. Using an analysis of covariance, I tested for a valley shape and land use interaction on deposited sediments (<4, 1-0.063, and <0.063 mm). I found an overall model effect for the size classes of <4 and 1-0.063 mm but no interaction effect or valley shape effect and no significant effect at all in the <0.063 mm class (Table 4). The finding of no significance in the <0.063 mm class was probably due to the fact that this size class is most influenced by discharge than other topographical factors. Based on this analysis, timber and reference sites had steeper valley slopes (i.e. greater sources of upland sediment) than development sites.

Table 4. In the 1-0.063 and <4 mm sediment size classes, the overall model is significant but there is no land use/valley shape interactive effect.

Size Class	D.F.	F Value	P Value
<0.063 mm	5,15	1.30	0.32
Land Use	2,15	0.65	0.54
Valley Shape	1,15	0.02	0.88
Land Use*Valley Shape	2,15	0.41	0.67
1-0.063 mm	5,15	8.50	<0.001
Land Use	2,15	2.55	0.11
Valley Shape	1,15	2.07	0.17
Land Use*Valley Shape	2,15	1.60	0.24
<4.0 mm	5,15	10.38	<0.001
Land Use	2,15	3.14	0.07
Valley Shape	1,15	1.96	0.18
Land Use*Valley Shape	2,15	1.91	0.18

Deposited Sediment and Harvest Intensity

Using harvest intensity as the independent variable and each sediment class as the dependent variable, I tested for significant differences in deposited sediment based on harvest intensity within the timber harvest land use (Figure 18). There were no significant differences in the <4 mm ($F= 1.24$, d.f.= 2,10, $p= 0.33$) or in the 1-0.063 mm size class among harvest intensities ($F= 1.19$, d.f.= 2,10, $p= 0.34$). There were marginally significant differences in the <0.063 mm size class ($F= 3.62$, d.f.= 2,10, $p= 0.07$) with most occurring between the light and heavy intensity of harvest ($F= 7.16$, d.f.= 1,10, $p= 0.02$) and between moderate to light intensity of harvest ($F= 4.63$, d.f.= 1,10, $p= 0.06$). Heavy intensity and moderate intensity had average <0.063 mm percents twice as great as light intensity. There were no significant differences between moderate intensity and heavy intensity ($F= 0.40$, d.f.= 1,10, $p= 0.54$).

Figure 18. Percentage of the <0.063 mm sediment size class as a reflection of timber harvest intensity. Harvest intensity is based on time since harvest, total acres harvested, and total number of harvests within each study stream sub-watershed.

Suspended Sediment

Turbidity

Turbidity measurements ranged from 0.1 to 70.0 NTUs in tributaries across all land use types, from 1.0 to 107.5 NTUs in the mainstem and Back Fork, and reached a high of 550 NTUs on one occasion in the right fork of Hickory Lick Run. The observation of 550 NTUs was deemed an outlier due to the rarity of the event and therefore was not included in any further analysis. The turbidity measurements and the corresponding TSS data were used to develop turbidity-TSS curves for the tributaries, the mainstem, and the Back Fork of the upper Elk River. The similarity of these three

turbidity curves is displayed in Figure 19. Consequently, we pooled the entire data set and constructed a model applicable to all water bodies in the Upper Elk watershed ($TSS = 0.78(\text{turbidity}) + 3.24$, $R^2 = 0.92$).

Figure 19. Turbidity curves from the tributaries, mainstem, and Back Fork of the upper Elk River are combined to demonstrate the close relationship between total suspended solids and turbidity found in all three of the study area components.

The range of turbidity in the reference sites was 0.1 to 11.4 NTUs; the development sites ranged from 0.1 to 34.5 NTUs; and the timber harvest sites ranged from 0.1 to 70 NTUs (Figure 20). Average turbidity for the reference streams was 3.2 NTUs, 6.9 NTUs for the development streams, and 10.2 NTUs for the timber harvested streams. There was an overall marginally significant difference in mean turbidity ($F = 2.93$, d.f. = 2,18, $p = 0.08$) among land use types. Contrast statements demonstrated no significant differences between timber harvest and development sites ($F = 0.80$, d.f. = 1,18,

$p = 0.38$) or reference and development sites ($F = 2.12$, $d.f. = 1, 18$, $p = 0.16$) but yielded a p value of 0.03 ($F = 5.73$, $d.f. = 1, 18$) for timber harvest versus reference sites. Timber harvest sites had an average turbidity almost three times as great as average turbidity in reference sites.

Figure 20. Average ($\pm$ standard error) turbidity (NTU) measured at each study stream as a function of land use. Timber harvest sites increase with harvest intensity from left to right.

Turbidity and Harvest Intensity

With harvest intensity as the independent variable and turbidity as the dependent variable, I found that significant differences in suspended sediment transport existed based on harvest intensity within the timber harvest land use (Figure 21; $F = 24.45$, $d.f. = 2, 10$, $p < 0.001$). Heavy intensity had an average turbidity almost twice as great as moderate intensity ($F = 12.25$, $d.f. = 1, 10$, $p = 0.006$) and six times greater than light intensity ($F = 47.33$, $d.f. = 1, 10$, $p < 0.001$). Moderate intensity average turbidity was three times as high as average turbidity in light intensity ($F = 17.47$, $d.f. = 1, 10$, $p = 0.002$).

Figure 21. Average turbidity ($\pm$ standard error bars) for each stream sorted by harvest intensity.

Total Suspended Solid Concentrations

The range of TSS concentrations in the reference sites was 4.3 to 6.0 mg/L; the development sites ranged from 4.7 to 10.1 mg/L; and the timber harvest sites ranged from 3.8 to 18.1 mg/L (Figure 22). There was an overall difference in TSS concentrations among land use types ($F= 3.16$, $d.f.= 2,18$, $p= 0.07$). Contrast statements demonstrated marginally significant differences between timber harvest sites and development sites ($F= 3.31$, $d.f.= 1,18$, $p= 0.09$) and significant differences between timber and reference sites ($F= 4.42$, $d.f.= 1,18$, $p= 0.05$) but no significant differences were found between development and reference sites ($F= .28$, $d.f.= 1,18$, $p= 0.60$). TSS concentrations in

timber harvest sites averaged 1.5 times greater than in development sites and almost twice as great as TSS concentrations in reference sites.

Figure 22. Average total suspended solid (TSS) concentrations as a variation of land use. Bars represent standard error.

Total Suspended Solid Concentration and Harvest Intensity

I also tested for significant differences in TSS concentrations using harvest intensity as the independent variable and average TSS as the dependent variable (Figure 23). Heavily harvested sites had marginally significant higher average suspended solid concentrations than moderately harvested sites ($F= 4.70$, d.f.= 1,10, $p= 0.06$) and significantly higher than lightly harvested sites ($F= 22.71$, d.f.= 1,10, $p<0.001$). Moderate intensity sites were also significantly higher in TSS concentrations than the light intensity sites ($F= 9.5$, d.f.= 1,10, $p= 0.01$). Heavy intensity sites averaged 1.25

times greater than moderate intensity sites and almost 2.5 times greater than light intensity sites in TSS concentrations.

Figure 23. Average total suspended solid (TSS) concentrations with increasing harvest intensity.

Daily Sediment Load

Total sediment loads per day were calculated using average discharge and average TSS concentrations for each study stream and ranged between 25 and 423 kg/day for the months of March through May 2004. Average load per day for this time period was the lowest in the reference sites at 45 kg/day, the middle class was the development group at 114 kg/day, and the timber harvested sites recorded the highest average sediment load at 153 kg/day. It is important to remember that total sediment load is influenced by discharge and can be misinterpreted. In Figure 24, Valley Fork, Big Run, and the right fork of Hickory Lick are the three streams carrying the greatest sediment load but not all

three have the highest discharge. Laurel Run (USFS) has a greater discharge but is carrying less sediment load due to lower overall TSS concentration. Laurel Run on the Back Fork is the opposite, having the second highest TSS concentration but transporting less than 100 kg/day due to a very low average discharge. Because of this, we looked at the relationship between total concentrations of suspended solids (TSS; mg/L) and total daily load (Figure 25).

Using an average TSS concentration from the reference sites and the light intensity of harvest sites and discharge from each actual study stream, I calculated the additional sediment load resulting from moderate and heavy intensity of harvest (Figure 26). Moderately harvested sites input an additional average of 53 kg/day and heavy intensity inputs an additional average of 120 kg/day over reference and light intensity harvest sites into the mainstem of the upper Elk River and the Back Fork of the Elk.

Figure 24. Sediment load relationship with discharge of a stream. Red points denote development sites, blue points denote reference sites, and green points denote timber harvest sites.

Figure 25. Sediment load relationship with total suspended solid concentration. Red points denote development sites, blue points denote reference sites, and green points denote timber harvest sites.

Figure 26. The difference between load calculated with observed TSS concentrations and discharge for each study stream and load calculated using the average TSS concentration for reference and light intensity of harvest (expected). The letter preceding the stream name indicates classification, R-reference, L-light intensity, M-moderate intensity, and H-heavy intensity.

Water Chemistry

Outside of suspended sediments, water quality in the upper Elk River tends to be very good due to the lack of industrial effluent or heavy coal mining that other rivers in the state experience and the water quality test results support this. Average pH ranged from 6.57 in Hamrick Run and Mill Run of the Back Fork to 7.42 in Warwick Run (Figure 27). Alkalinity (mg/l CaCO_3) ranged from 2.96 in Abb Run to 18 in Warwick Run (Figure 28). Calcium: Hydrogen ratios ranged from 4:1 in the left fork of Hickory Lick Run to 376:1 in Warwick Run (Figure 29).

Figure 27. Average pH (taken from summer, fall, winter, and spring measurements) of all study streams, $\pm$ standard error. The letter preceding each stream name represents land use.

Figure 28. The range of alkalinity (mg/L CaCO₃) in the study tributaries of the upper Elk. The letter preceding each stream name represents land use.

Figure 29. Calcium to hydrogen ratios for each study stream. The letter preceding each stream name represents land use.

Brook Trout Populations

Brook trout were found in twelve (57%) of the twenty-one study streams (Figure 30). Age-0 trout were found in nine of the study streams and sexually mature adults were found in seven of the study streams. All species sampled in the study streams are listed in Table 5. Brook trout density ranged from 0 to 0.014 young of the year (YOY) fish per square meter and 0 to 0.054 total fish per square meter.

Figure 30. Location of brook trout highlighted in red, among the twenty-one study streams, highlighted in blue.

Table 5. Different species found in each stream sampled in this study are listed below. Streams with brook trout are highlighted. R = Reference, D = Development, and T = Timber harvesting.

Stream	Basin Area (km ²)	Species Present											
		Land Use	BKT	RBT	BNT	BND	CSR	CRC	FTD	GSF	LND	MOS	NHS
Crooked Fork	1.35	R	X									X	
Lt F HLR	2.09	R			X								
Hamrick Run	2.46	R											
Upper Big Spring	4.47	D	X			X					X	X	
Hawthorn Run	3.82	D	X	X		X	X	X			X	X	
Old Field Fork	2.53	D				X		X					
Warwick Run	3.76	D				X	X	X	X	X		X	
Valley Fork	11.41	D	X	X	X	X						X	
Laurel Run (USFS)	7.58	T	X	X	X	X					X	X	
Props Run	3.48	T	X	X		X		X				X	
Unnamed Tributary	2.54	T											
Upper Valley Fork	2.79	T	X									X	
Mudlick Run	6.21	T	X			X						X	
Thayer Run	1.46	T	X		X							X	
Rt F HLR	3.28	T			X							X	
Mill Run	3.56	T	X										
Big Run	6.8	T			X	X		X			X	X	X
Fisher Run	1.62	T			X								
Abb Run	3.83	T	X		X			X					
Mill Run (BFE)	3.92	T	X										
Laurel Run (BFE)	2.02	T											

BKT – brook trout (*Salvelinus fontinalis*)
BND – blacknose dace (*Rhinichthys atratulus*)
BNT – brown trout (*Salmo trutta*)
CRC – creek chub (*Semotilus atromaculatus*)
CSR – central stoneroller (*Campostoma anomalum*)
FTD – fantail darter (*Etheostoma flabellare*)
GSF – green sunfish (*Lepomis cyanellus*)
LND – longnose dace (*Rhinichthys cataractae*)
MOS – mottled sculpin (*Cottus bairdi*)
NHS – northern hogsucker (*Hypentilium nigricans*)
RBT – rainbow trout (*Oncorhynchus mykiss*)

There were no significant relationships between YOY, adult, or total brook trout densities and deposited sediments <0.063, 1-0.063, or <4 mm (Table 6). There also were no significant relationships between YOY brook trout density and turbidity ($F = 1.90$, d.f.= 1,19, $p = 0.18$). However, there was a significant negative relationship between adult brook trout density and turbidity (Figure 31; $F = 8.96$, d.f.= 1,19, $p = 0.008$) but a low R^2 ($= 0.32$). The relationships of brook trout biomass were similar to those of densities. I found a marginally significant negative effect of turbidity on biomass (Figure 32; $F = 3.76$, d.f.= 1, 19, $p = 0.07$) but a low R^2 ($= 0.16$).

Because of the strong relationship between turbidity and TSS, relationships between TSS and brook trout mirror those of turbidity. The relationship between TSS and YOY brook trout was not significant ($F = 1.52$, d.f.= 1,19, $p = 0.23$) but there was a significant negative relationship between TSS and adult density (Figure 33; $F = 8.91$, d.f.= 1,19, $p = 0.008$, $R^2 = 0.32$). The analysis of brook trout biomass and TSS concentration was similar to that of turbidity. Significant differences were found between biomass and increasing suspended solids (Figure 34; $F = 4.91$, d.f.= 1,19, $p = 0.039$; $R^2 = 0.20$).

Table 6. Linear regression statistics for brook trout density versus <0.063, 1-0.063, and <4 mm size classes of deposited sediments.

	D.F.	F Value	P Value
<0.063 mm			
YOY Density	1,19	0.17	0.69
Adult Density	1,19	2.94	0.10
Total Density	1,19	1.97	0.18
1-0.063 mm			
YOY Density	1,19	0.20	0.66
Adult Density	1,19	0.00	0.95
Total Density	1,19	0.01	0.91
<4.0 mm			
YOY Density	1,19	0.23	0.68
Adult Density	1,19	0.04	0.85
Total Density	1,19	0.00	0.97

Figure 31. There was a negative relationship between adult brook trout density and increased turbidity within the study sites.

Figure 32. There was a negative relationship between brook trout biomass and increased turbidity within the study sites.

Figure 33. There is a negative relationship between adult brook trout density and TSS concentrations in the study sites.

Figure 34. There is a slightly negative relationship between brook trout biomass and increasing TSS concentrations in the study sites.

Using linear regression, I detected no significant relationship between total, adult, or young of the year brook trout density with topographical characteristics of gradient, basin area, or valley shape (Table 7) or with the abiotic factors of pH, alkalinity (mg/L CaCO_3), or calcium to hydrogen ionic ratio (Table 8). There were no significant relationships between brook trout biomass and gradient, basin area, valley shape, pH, alkalinity, or calcium to hydrogen ionic ratio ($p > 0.10$). There was no relationship evident between the presence of brook trout and rainbow trout ($p > 0.10$) or between the presence of brook trout and brown trout ($p > 0.10$). Figure 35 illustrates which types of trout were found in each of the study streams.

Table 7. Linear regression statistics on brook trout densities versus gradient, basin area, and valley shape of all study streams.

	D.F.	F Value	P Value
Gradient			
YOY Density	1,19	1.80	0.20
Adult Density	1,19	0.35	0.56
Total Density	1,19	0.86	0.36
Basin Area			
YOY Density	1,19	0.23	0.64
Adult Density	1,19	2.11	0.16
Total Density	1,19	1.54	0.23
Valley Shape			
YOY Density	1,19	0.06	0.95
Adult Density	1,19	0.05	0.83
Total Density	1,19	0.02	0.89

Table 8. Linear regression statistics on brook trout densities versus pH, alkalinity, and calcium: hydrogen ionic ratio in all study streams.

	D.F.	F Value	P Value
pH			
YOY Density	1,19	0.92	0.35
Adult Density	1,19	0.32	0.58
Total Density	1,19	2.17	0.35
Alkalinity			
YOY Density	1,19	2.54	0.13
Adult Density	1,19	1.02	0.33
Total Density	1,19	1.80	0.20
Calcium:Hydrogen			
YOY Density	1,19	2.59	0.12
Adult Density	1,19	0.63	0.44
Total Density	1,19	1.38	0.25

Figure 35. Three species of trout were collected in the upper Elk River basin and are presented above with the corresponding streams. Only Laurel Run of USFS land sustained all three species and several streams did not sustain any trout. Streams are grouped by land use and timber harvests increase in intensity from left to right.

Discussion

The first research objective in this study was to quantify variation in deposited and suspended sediment loads in streams of the upper Elk River basin and relate varying levels of sediment loads to natural watershed characteristics (e.g. gradient, valley shape) and human land use (e.g. forestry and residential development). Timber harvest sites, on average, significantly exceeded development sites in all deposited critical sediment size classes. Reference sites on average had higher percentages of deposited sediments than development sites. This may be directly related to upland sources of sediments (i.e. valley shape) as timber and reference stream valleys were more confined than

development stream valleys. Development tends to occur in the low valleys and floodplains where the ground is more stable (Van Rompaey, 2002). Mountains and ridgelines that are too steep for safe development are either harvested for timber or left untouched in this area (i.e. reference sites in this study). This is evident by the significant differences in average valley slope between development and both timber and reference sites in this study. The development sites were also located in a karst region of the watershed. The nature of limestone soils to break down into fine silts and clays allows for the increased transportation of sediments due to small size rather than the deposition. Lacroix *et al.* (2000) found that 70% of suspended matter in a karst system is derived from the dissolution of chalk and the other 30% was attributed to the suspension of limey clays. The sandstone soils of the rest of the region tend to be heavier and less susceptible to transport than finer sediments. This could be an explanation for lower deposited sediments in developed sites than in timber and reference sites. Although overall deposited sediment levels were low, timber harvest sites did have the highest percentages in the majority of all size classes of the land use practices in this study. This finding is supported by studies in California (Burns, 1972), British Columbia (Scrivener and Brownlee, 1982), Alaska (Sheridan *et al.*, 1984), and Idaho (Platts *et al.*, 1989) that found increases in fine sediments after logging, with elevated levels persisting as long as five years after the operation.

Turbidity levels were significantly higher in the timber harvest and development sites than in the reference sites potentially indicating greater soil disturbances upstream. Timber sites had similar valley shape to that of reference sites but average turbidity was almost three times greater. This indicates greater contribution of sediments to the

mainstem from timber harvest lands and developed lands than from reference streams. Several studies from Oregon have reported an increase in suspended solids after logging occurs (Anderson, 1971; Brown and Krygier, 1971; Swanson and Dyrness, 1975; Cornish, 2001). Again, it is important to note that development sites were located in a region where soils consist primarily of silts and clays that tend to be picked up and transported at lower velocities than other soil types, leading to higher turbidity than may be attributed to land management activities. Within the timber harvest sites, more recent harvesting and individual stream basins with multiple harvests predictably had greater turbidity than older sites logged with no road construction. This finding of low turbidity in the light intensity and increased turbidity in the moderate and high intensity is supported by findings from Cornish (2001) that roads increase turbidity in logging operations.

Total suspended solid concentrations and total daily loads were considerably higher in the timber harvest and development class than in the reference class, also indicating increased erosion and sediment input from upstream disturbance. Martin *et al.* (2000) studied timber harvests and reference lands in New Hampshire and found increased amounts of sediment load on harvested lands when compared with uncut reference lands. Timber harvesting also had higher TSS concentrations and average daily loads than development, but tends to occur on steeper slopes with greater upland sources of sediment so it would be difficult to ascertain the increase coming directly from land management.

My second objective was to examine the relationship between varying levels of fine sediment loads and brook trout populations, especially as it relates to reproduction

and juvenile recruitment. Seven streams exceeded the 20% composition of sediments 1-0.063 mm in diameter deemed critical to brook trout populations (Hakala, 2000).

Because only timber harvested sites exceeded this amount, this finding suggests that increased erosion may be occurring upstream as a result of logging practices. All study streams had lower percent fines (<0.063 mm) than the level also deemed detrimental to brook trout by Hakala (2000). Based on comparisons of brook trout density and deposited sediments of detrimental size classes, I found no overall evidence to suggest that the sedimentation in the tributaries of the upper Elk River watershed is negatively affecting brook trout reproduction or distribution. Previous studies have shown excessive fine sediment delivery to impede salmonid reproduction (Hausle and Coble, 1976; Shirazi and Seim, 1979; Everest *et al.*, 1987; Platts *et al.*, 1989; Hartman and Scrivener, 1990; Crisp, 1993; Curry and MacNeill, 2004). However, the lack of significant levels in sediments in this study is likely a result of the high-gradient stream channels and the increased mobility of silt- and clay-sized particles at any flow (Sullivan *et al.*, 1987). Stream gradients less than 2% are conducive to sediment deposition (Ikeda, 1975; Florsheim, 1985), and the range of gradients in this study was 1.9-12.2%. Development streams had the lowest gradients as a whole with Warwick Run (gradient = 1.9), and all other streams in this study have average gradients exceeding 2%. Fine sediments (<0.063 mm) can be transported at lower velocities, resulting in greater flushing rates and sediment levels that may not be indicative of management practices upstream.

In contrast, I did observe a significant negative effect of increased turbidity on brook trout populations. Brook trout density and biomass declined as turbidity increased in the study sites. The reduction of density as a function of increased turbidity is similar

to the findings of Berube and Levesque (1998) of a reduction in number and biomass of brook trout in lakes disturbed by logging when compared to lakes undisturbed in Quebec, Canada. Sigler *et al.* (1984) found that juveniles are more susceptible to moderate levels of turbidity, resulting in a reduction in growth and increased avoidance. Swenson (1978) also found partial avoidance of turbidity by lake trout in both western Lake Superior and in a laboratory setting. Studies by Barret *et al.* (1992) and Vinyard and Yuan (1996) demonstrated a reduction in foraging success of trout with increased levels of turbidity. Sweka and Hartman (2001) found a reduction in growth rates of brook trout as a result of switching from drift feeding to active foraging in turbid water, an energetically costly switch. Although we did not directly measure growth in this study, these studies may support a reduction in biomass as a result of higher levels of turbidity.

There was no correlation between the presence of brook trout and other wild salmonids, but I believe this may not be a clear distinction. Fausch and White (1981) found brown trout excluded brook trout from preferred resting positions, a critical and scarce resource. The most significant effect was the increased tendency of brook trout to remain inactive on the streambed in the presence of brown trout. DeWald and Wilzbach (1992) also found that brown trout shifted the distribution of and decreased the frequency of initiated aggressive interactions by brook trout. The presence of rainbow trout was also found to negatively influence the distribution of brook trout in streams of the southern Appalachians (Larson and Moore, 1985). In this study, the rainbow trout occurred in streams containing brook trout but their distribution in the drainage was more sporadic than brown trout. Laurel Run on USFS lands had high numbers of brook trout,

brown trout, and rainbow trout, potentially altering the analysis, while all other streams in the study area had one species or the other and little overlap of all three.

Water quality in the upper Elk River was well suited for brook trout with all streams having an average pH above 6.0 (Johnson *et al.* 1987; Welsh and Perry, 1997). Alkalinity was within the range sufficient to support brook trout used by biologists in treating acidic streams (Mount, *et al.*, 1988; Zurbuch, *et al.*, 1996). Four streams were below the recommended calcium to hydrogen ionic ratio of 10 (Menendez, *et al.*, 1996) and three out of those four streams maintained trout (two of which contained brook trout). The one stream below this ratio with no fish also had a 3-meter waterfall about 20 meters from its confluence with the mainstem. Because the water parameters of the tributaries in this study meet the requirements of brook trout, it stands to reason that there would be no significant relationships between brook trout density and pH, alkalinity, or calcium to hydrogen ionic ratios.

No single factor is capable of explaining fish production patterns so it is difficult to say what may be influencing brook trout in these study streams. Fish populations may be food limited during certain parts of the year and habitat limited during others (Gregory *et al.*, 1987). Limiting factors may change according to the age structure of the population as well as the environment (Sarneckchia and Bergersen, 1987). Movement patterns may depend on water quality, spawning, prey availability, and/or suitable habitat (Logan, 2003). This study did not examine aquatic insect availability and distribution or habitat assessment, factors that could very well be determining presence or absence in these upper Elk River tributaries.

Overall, it appears that timber harvesting does increase the amount of sediments found in and transported by streams in the upper Elk River watershed. Development streams are transporting significant amounts of suspended solids to the mainstem but not storing significant amounts of sediments in the streambed. Reference streams had similar percentages of deposited sediments compared to the other land uses, though no stream during the period of the study exceeded the critical limits set for brook trout production, but turbidity levels indicate low suspended sediment transport. It is unclear how much variation in sediment deposition and transport is related to changes in gradient and valley slope but we do know that environmental factors play a role (Everest *et al.*, 1987).

It also appears that the factors controlling brook trout distribution and reproduction are weakly related to land use management at this time. Increased timber harvesting resulted in increased turbidity levels, which can drive down the density and biomass of brook trout (with a lot of unexplained variation from other environmental factors). Perhaps this is because brook trout spawn in smaller, high-gradient tributaries that tend to transport sediment rather than store it. The tributaries in this study appear to be transporting the majority of sediments into the mainstem where brook trout are not common spawners. Increases in the transportation of sediments from the tributaries to the mainstem may cause a reduction in the quality of the environment within the larger river (Simons, 1975). Instability of instream sediments as a result of increased load may result in the loss of aquatic vegetation (Gregory *et al.*, 1987). Increased sediments also saltate along the bottom, scraping or covering primary production. Microbes may flourish in the warmer, more nutrient rich water but microorganisms may decline due to decreased detritus and decreased oxygen level (Gregory *et al.*, 1987). Insect communities

tend to shift towards drifting, benefiting salmonids, but these benefits may be negated if temperatures increase and spawning and rearing habitat become embedded with sediments (Gregory *et al.*, 1987). It is apparent that increased transportation of sediments into the mainstem could negatively impact aesthetics, mainstream benthic spawners, aquatic insects, primary production, or aquatic vegetation.

The turbidity curves generated for the tributaries, mainstem, and back fork of the Elk River will hopefully aid future monitoring of total sediment loads for the watershed. By taking a turbidity reading, it will allow for the estimation of suspended solid concentrations when actual TSS samples have not been collected. Together with flow measurements, researchers or river monitors will be able to calculate sediment loads at that time. Scatter associated with the curve reflects the high degree of variability in sediment sources, rainfall intensities, and other environmental factors (Beschta, 1996).

The Forest Stewardship Program (FSP) can help reduce the impacts of sedimentation as a result of timber harvesting in a watershed such as the upper Elk River. The FSP is designed to encourage long-term forest management by non-industrial private forest landowners (Egan *et al.*, 2001) while understanding the benefits of maintaining the health of these forests for society (Whipkey *et al.*, 2000). Participation in the Forest Stewardship program is not as high as it could be in the upper Elk River watershed, given that out of the 145 recent harvests, only three were FSP participants. However, in a study by Provencer (2004) on forest road systems in central West Virginia, best management practice compliance was found to be significantly lower on harvested FSP properties than on harvested non-FSP properties, indicating that simply encouraging enrollment to the program may not reduce the amount of sediments resulting from harvest activities.

Increased efforts to reduce soil disturbance (i.e. better planning of road construction) need to be encouraged and made financially feasible. Kochenderfer *et al.* (1997) found that BMPs can be effective in minimizing impacts to soil and water resources in West Virginia when followed. Increased monitoring of BMP compliance in the area by the Division of Forestry may also help ensure that everything legally required to minimize logging impacts is being done. Setting total maximum daily load limits on sediments for tributaries in the upper Elk River watershed may be the only way to reduce sediment input to the mainstem.

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Appendix I: Sediment data by study stream

Table 9. Average weight of sediment samples per study stream, sorted into size class by diameter (mm). Land use activities are separated by reference (R), development (D), and Timber harvesting (T).

			Sediment Size Classes (mm) - Weight (g)												
	Land Use	Total	>32	16.00	8.00	4.00	2.00	1.00	0.50	0.25	0.125	0.063	<0.063	1-0.063	<4.00
Crooked Fk	R	757.9	142.0	88.3	163.7	151.3	104.5	50.9	31.9	14.9	5.9	2.5	1.40	106.13	211.99
Hamrick Run	R	900.1	38.0	106.8	204.0	201.5	162.9	84.6	56.0	28.7	7.7	2.4	1.85	179.46	344.20
Lt Fk HLR	R	864.1	77.1	111.8	202.2	181.0	120.8	70.1	53.6	31.7	10.9	3.1	1.54	169.47	291.85
Average	R	840.7	85.7	102.3	189.9	177.9	129.4	68.5	47.2	25.1	8.2	2.7	1.60	151.69	282.68
Old Field Fork	D	789.0	87.7	165.7	213.4	164.6	91.2	40.2	17.0	5.0	2.0	1.1	1.00	65.32	157.48
Warwick Run	D	841.4	155.1	175.8	218.0	149.5	71.9	24.0	10.6	7.0	5.5	2.7	1.92	49.81	123.59
Upper Big Spring	D	821.5	101.7	235.4	205.3	99.5	49.0	29.2	30.0	31.9	10.7	2.4	1.21	104.24	154.46
Hawthorn Run	D	840.7	99.2	100.4	206.5	186.0	116.6	58.2	33.2	15.0	4.0	1.2	0.98	111.59	229.15
Valley Fork	D	830.5	131.5	158.8	226.2	154.3	72.8	29.8	24.7	27.7	15.3	4.7	2.18	102.20	177.16
Average	D	824.6	115.0	167.2	213.9	150.8	80.3	36.3	23.1	17.3	7.5	2.4	1.46	86.63	168.37
Laurel Run (USFS)	T	816.0	82.9	117.0	160.6	176.9	126.5	69.6	40.3	21.0	5.0	1.4	1.14	137.28	264.92
Props Run	T	833.8	41.7	125.3	204.6	169.5	113.7	71.5	58.1	36.2	8.9	2.2	1.32	176.97	292.02
Unnamed Trib	T	1065.2	112.9	128.0	215.6	180.9	165.0	109.7	93.2	43.7	10.8	3.2	2.12	260.65	427.81
Upper Valley Fk	T	677.7	31.5	70.9	184.9	155.8	97.2	50.2	38.6	29.5	11.4	3.0	1.72	132.68	231.57
Mudlick Run	T	821.6	46.8	130.8	204.7	156.7	100.8	61.3	37.2	44.7	27.5	7.3	3.22	177.90	281.87
Thayer Run	T	909.9	115.5	137.4	194.8	151.0	122.5	81.3	60.4	30.0	10.3	3.8	2.42	185.93	310.88
Hickory Lick Rt Fk	T	982.8	104.1	259.7	208.7	140.6	101.8	69.6	52.5	30.4	9.6	3.5	2.25	165.65	269.67
Fisher Run	T	894.6	166.0	62.8	198.8	172.9	114.5	65.1	47.0	41.0	18.2	4.9	3.06	176.24	293.76
Abb Run	T	730.7	16.7	111.9	222.0	171.6	94.3	49.5	33.9	21.2	6.0	1.7	1.25	112.30	207.84
Mill Run (Rt 219)	T	722.1	20.2	82.6	174.6	179.1	123.9	61.6	36.8	22.6	12.3	5.4	2.77	138.66	265.35
Mill Run (BFE)	T	772.0	32.8	97.1	173.6	163.0	120.8	76.8	55.7	32.9	12.7	3.7	2.61	181.68	305.07
Laurel Run (BFE)	T	791.8	18.3	114.1	136.4	183.1	143.1	70.7	41.0	47.3	25.0	7.6	4.44	191.43	338.97
Big Run (Rt 219)	T	918.7	152.2	155.1	147.5	136.7	113.6	79.1	65.7	46.5	14.9	4.1	2.51	210.16	326.27
Average	T	841.3	72.4	122.5	186.7	164.4	118.3	70.5	50.8	34.4	13.3	4.0	2.37	172.89	293.54

Appendix II: Analyses with only streams containing brook trout

Studies have shown that salmonids can be negatively impacted by increased deposited (Hausle and Coble, 1976; Shirazi and Seim, 1979; Everest *et al.*, 1987; Platts *et al.*, 1989; Hartman and Scrivener, 1990; Crisp, 1993; Curry and MacNeill, 2004) and suspended sediments (Swenson, 1976; Sigler *et al.*, 1984; Barret *et al.*, 1992; Vinyard and Yuan, 1996; Berube and Levesque, 1998; Sweka and Hartman, 2001). It has also been found that brook trout presence can be dependent on water quality, prey availability, and suitability of habitat (Gregory *et al.*, 1987; Logan, 2003). Due to the variability in factors that determine brook trout presence or absence, I ran a complete analysis on density data from only those streams in which brook trout were found.

Brook trout densities were statistically significant in both suspended sediment and water quality parameters. Total brook trout densities were negatively related to turbidity and total suspended solid concentrations (Figure 36; A and B). There were significant negative relationships between pH, alkalinity, and calcium to hydrogen ionic ratio (Figure 37; A, B, and C). There were no significant relationships between total density and gradient, basin area, valley shape, deposited sediments (<0.063 , $1-0.063$, <4 mm), or average daily load ($p>0.10$).

Adult brook trout density relationships were similar to those of total brook trout densities. There were significantly negative relationships in adult density versus turbidity and versus TSS concentrations (Figure 38, A and B). There were significant negative relationships between adult density and pH and calcium to hydrogen ionic ratio (Figure 39; A and B). There were no significant relationships between adult density and

deposited sediments (<0.063, 1-0.063, <4 mm), average daily load, gradient, basin area, valley shape, or alkalinity ($p>0.10$).

Young of year densities appeared to be affected by only water quality in this analysis. YOY densities were not significantly related to turbidity, TSS concentrations, average daily load, deposited sediments (<0.063, <4 mm), gradient, basin area, valley shape, or alkalinity ($p>0.10$). However, YOY densities were negatively related to increasing pH and increasing calcium to hydrogen ionic ratio (Figure 40, A and B). Surprisingly, YOY densities displayed a very weak yet positive relationship with increasing 1-0.063 mm sediments (Figure 41).

The relationships between total and adult densities versus turbidity and TSS concentrations are similar to those found among all streams. The positive relationship between YOY brook trout and 1-0.063 mm deposited sediment percentages is likely a result of a high flow year increasing the flushing rate of sediments in high gradient streams. The negative relationships between density and increased pH, alkalinity, and C: H are statistically significant but not biologically significant. The ranges of pH, alkalinity, and C: H in these study streams are well within the ranges of brook trout requirements (Johnson *et al.*, 1987; Mount, *et al.*, 1988; Menendez, *et al.*, 1996; Zurbuch, *et al.*, 1996; Welsh and Perry, 1997).

Figure 36. There is negative relationship between total brook trout density and increasing turbidity (A; $F= 5.13$, d.f.=1,10, $p= 0.05$) and increasing TSS (B; $F= 4.72$, d.f.= 1,10, $p= 0.06$) in streams that contain brook trout.

Figure 37. There is a negative relationship between total brook trout density and increasing pH (A; $F = 7.79$, d.f. = 1,10, $p = 0.02$), increasing alkalinity (B; $F = 5.81$, d.f. = 1,10, $p = 0.04$), and increasing calcium to hydrogen ionic ratio (C; $F = 9.17$, d.f. = 1,10, $p = 0.01$).

Figure 38. There is a significant negative relationship between adult brook trout density and increasing turbidity (A; $F= 7.64$, d.f.= 1,9, $p= 0.02$) and increasing TSS concentration (B; $F= 7.35$, d.f.= 1,9, $p= 0.02$).

Figure 39. There is a marginally significant negative relationship between adult brook trout density and increasing pH (A; $F = 4.35$, d.f. = 1,9, $p = 0.07$) and increasing calcium to hydrogen ionic ratio (B; $F = 4.92$, d.f. = 1,9, $p = 0.05$).

Figure 40. There is a significant negative relationship between YOY brook trout density and increasing pH (A; $F = 4.38$, d.f. = 1,7, $p = 0.08$) and increasing calcium to hydrogen ionic ratio (B; $F = 5.97$, d.f. = 1,7, $p = 0.05$).

Figure 41. YOY brook trout density demonstrated a slightly positive relationship with increasing 1-0.063 mm % composition.

Appendix III: Additional graphs of brook trout relationships

Figure 42. Total brook trout density versus gradient (A), basin area (B), and valley shape (C).

Figure 43. Total brook trout density versus turbidity (A), TSS concentration (B), and average daily load (C).

Figure 44. Brook trout density versus deposited sediments.

Figure 45. Brook trout density versus pH (A), alkalinity (B), and calcium to hydrogen ionic ratio (C).

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