EVALUATION OF SAMPLING TECHNIQUES FOR MONITORING SUBSTRATE COMPOSITION AND CHANNEL DIMENSION CHANGES IN OUACHITA MOUNTAIN STREAMS

By

MICHAEL CRAIG SCHAUB

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Thesis Approved:

Thesis Advisor

Edwin L. Miller

William L. Fisher

Thomas C. Collins

Dean of the Graduate College

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CHAPTER I

INTRODUCTION

Background

Monitoring forest streams for changes in physical, chemical, and/or biological properties has become a major focus among regulatory and management agencies across the United States. The suitability of these properties for a particular beneficial use defines the quality of a water resource and, as such, has lent impetus to the development of legislation meant to prevent its degradation. The National Forest Management Act and the Clean Water Act currently require the USDA Forest Service and the States to maintain or improve water quality and its associated beneficial uses. Included in these requirements is the control of non-point source pollution. In this regard, the U.S. Environmental Protection Agency considers the implementation of Best Management Practices (BMP's) as the best option for meeting these objectives (Clingenpeel and Cochran 1992). After the development and initiation of these measures, however, some form of periodic stream monitoring is necessary to assess how effective given BMP's are in abating non-point source pollution and protecting water quality (Clingenpeel and Cochran 1992; Bevenger and King 1995).

Included among the major water quality concerns of forest managers are sedimentation in stream channels and increased streamflows that may result from timber management activities. In watersheds managed for timber production, streamflow modifications and increased sediment delivery to stream channels can occur as a result of runoff from unpaved forest roads and areas disturbed by timber harvest and site preparation activities. As knowledge about the combined effects of multiple land use activities on hydrological and erosional processes has grown, so has awareness of how such processes can, over space and time, cumulatively affect water quality and aquatic habitat. In general, two areas within a stream can be directly affected when erosional and hydrological processes are altered. First, fine sediment entering the water column can increase levels of suspended sediment, turbidity, and nutrient loading. Second, increased sedimentation and streamflow may affect channel morphology and the sizes of streambed material, or substrate, which are important factors for the survival of aquatic organisms.

Although channel morphology and substrate quality are not alluded to in the definition of water quality, their alteration can have indirect effects on the biological health of a stream. A stream's capacity to support a healthy biological communitiy, of course, is an important component when considering its overall quality as a water resource. With this in mind, a number of hydrologists, geomorphologists, and fisheries biologists have developed various methods for assessing stream channel and substrate changes arising from the cumulative impacts of land use activities such as forest management. Several of these monitoring methods will be the focus of this paper.

Definition of the Problem

The only monitoring program that considers substrate composition in Ouachita Mountain streams is the Basin Area Stream Survey (BASS). This survey is a comprehensive monitoring program that identifies and compares physical, chemical, and biological characteristics of streams to evaluate BMP effectiveness in the Ouachita National Forest (Clingenpeel and Cochran 1992). The substrate monitoring component of this survey has never been scrutinized vis-a-vis alternative sampling methods currently used in other regions. It is unknown whether the substrate sampling technique employed by the BASS method adequately characterizes the overall substrate composition or amount of fine sediment within a given stream reach or habitat. It is possible that other, more intensive, sampling schemes are more descript and sensitive to changes in substrate composition. However, it is also possible that equivalent results are attainable using any sampling procedure. Therefore, other sampling methods need to be evaluated and compared in order to assess their monitoring potential in Ouachita Mountain streams.

The BASS method also monitors changes in channel form which may arise because of altered flow and sediment delivery regimes by taking habitat length measurements and cross-sectional width and depth measurements at the midpoint of individual habitat units. From these measurements, habitat surface area and volume can be calculated. An alternative parameter for monitoring changes in channel dimensions can be calculated by taking the total width of a given channel cross-section and dividing it by the average or maximum depth of that cross-section. This dimensionless width-to-depth ratio can then be used as a reference index for assessing future channel alterations. However, this alternative parameter has never been utilized in the study area. Therefore, it is currently unknown how many cross-sections are needed to adequately describe the overall width-to-depth ratio of a given habitat.

Objectives

The specific objectives of this study are to:

1. Compare determinations of percent fines and median particle size among four substrate sampling procedures within habitats of two streams in the Ouachita Mountains.
2. Determine which substrate sampling procedure, if any, is best for monitoring substrate changes in the types of streams studied.
3. Compare width-to-depth ratios as derived from one, three, and ten cross-sectional measurements taken within each habitat.

CHAPTER II

LITERATURE REVIEW

Forest Management and Watershed Processes

Increased runoff and sediment delivery to stream channels in forested watersheds typically occurs as a result of timber harvest operations, site preparation activities, or via unpaved forest roads. Each of these aspects of forest management can individually or collectively contribute to changes in on-site conditions. Increases in the amount and rate of sediment and water movement can lead to alterations of downstream channel characteristics and aquatic habitats far removed from the originally affected site (Coats and Miller 1981; Ryan and Grant 1991). Although on-site effects of an individual land use may be considered negligible, the combined downstream effects of all land uses occurring in a watershed may be more problematic (Sidle and Sharpley 1991). Therefore, understanding how forest management can affect erosional and hydrological processes in a given watershed is an important first step in assessing cumulative effects.

Timber management activities can potentially modify the hydrologic behavior of a forested watershed in a variety of ways. Increased soil moisture, stormflows, and peak flows have primarily been attributed to the loss of vegetation and the associated reduction in evapotranspiration (Hewlett and Helvey 1970; Patric 1973; Harr et al. 1975; Patric 1980, Hewlett and Doss 1984; Blackburn et al. 1986). Bosch and Hewlett (1982) reviewed 94 watershed studies and found that, with the exception of only one experiment, none of them observed a reduction in water yields with reduced vegetative cover, or, conversely, increases in yields with increases in cover. Miller et al. (1988a) observed a 10cm increase in annual stormflow the first year following clearcutting on a small watershed in Arkansas., This increase was attributed to the reduction in evapotranspiration following vegetation removal. Increased surface runoff can also occur because of soil compaction and disturbance associated with skid trails, log decks, and mechanical site preparation (Gent et al. 1984; Blackburn et al. 1986). There are exceptions, however, as Miller (1984) observed a decrease in annual stormflow the first year following harvest on a small watershed in Oklahoma. Contour ripping, a form of site preparation applied after harvest, is suspected to have increased infiltration and the detention storage capacity of the affected soils. Roads and roadside ditches can act as conduits for runoff thereby increasing streamflows as observed in Oregon (Harr et al 1975; Lyons and Beschta 1983) and Idaho (King and Tennyson 1984).

Sediment loss is also a problem in timber managed watersheds. Soil erosion can occur by the detachment of soil particles by raindrops or overland flow, by mass movements on steep slopes, such as debris flows, or by the erosion of stream channel banks. Each of these erosional mechanisms can be aggravated by timber management activities (Brown and Binkley 1994). The loss of vegetative cover as a result of timber harvests tends to weaken the stability of soils by increasing soil moisture and reducing root strength (Brown and Binkley 1994). Additionally, soil compaction and disturbance caused by machinery used in harvest and site preparation operations enhances the erosive potential of overland flow. Several studies in the mid-south have shown temporary increases in soil loss from harvested and mechanically prepared sites (Beasley 1979; Miller 1984; Blackburn et al. 1986, Miller et al. 1988b). In each case, soil erosion diminished within a year or two as the sites were revegetated.

Forest roads can be an additional source of sediment in actively managed watersheds. Erosion of the roadbed, roadside ditches, and cut and fill slopes can increase sediment losses (Swift 1984; Miller et al. 1985). In the Ouachita Mountains of Oklahoma, the slopes of roads and the extent of area contributing runoff to the road-ditch system are important factors controlling the amount of road erosion and sediment loss (Vowell 1985). Studies conducted on streams in Oregon (Brown and Krygier 1971; Beschta 1978; Harr and Fredriksen 1988) and northern California (Rice et al. 1979) have shown increases in suspended sediment because of the combined effects of clearcutting, road construction, and slash burning. Increased levels of fine sediment in streambed substrates have also been correlated with logging operations and forest roads in Wyoming (Eaglin and Hubert 1993) and Idaho (Platts et al. 1989). In most of these cases, the number of stream crossings and/or the proximity of roads alongside stream channels greatly affected the amount of sediment observed in streams. Eaglin and Hubert (1993) observed that as the number of stream crossings increased in a watershed, the amount of fine sediment deposited in the stream channel increased. In the southeastern United States, unpaved road surfaces accounted for 80.2% of all observable sediment sources contributing fine sediment to the Chattooga River of Georgia and South Carolina (Van Lear et al. 1995). Patric (1976) believes forest roads deserve special attention as they are “unquestionably” the most important source of soil erosion in managed forests of the eastern United States.

Cumulative Effects on Stream Communities

An important effect of forest management on streams is the reduction of stream habitat complexity (Bisson et al. 1992). Pools, riffles, bed material, and channel banks are important elements that provide morphological complexity to streams (Beschta and Platts 1986). Pools and riffles differ by hydraulic conditions and substrate types and provide critical habitat to fish during different stages of their life cycles (Lisle 1982). In most cases, substrate refers to the mineral material of a stream on which aquatic organisms reside. Substrate particle sizes not only affect flow resistance and bed stability but also determine the quality of habitat for benthic macroinvertebrates, the amount of cover for some larval fish, and the suitability of the streambed as a fish spawning medium (Beschta and Platts 1986; MacDonald et al. 1991). Stable streambanks provide cover for stream organisms and support riparian vegetation which also benefits biotic diversity by providing shade, nutrients, and woody debris to streams (MacDonald et al. 1991). Various studies have shown correlations between stream habitat complexity (e.g. substrate complexity) and the diversity of fish species and other stream organisms (Gorman and Karr 1978). Increased water and sediment delivery to stream channels has the potential for modifying these morphological elements and lowering the biotic diversity of streams.

Flow modification can potentially simplify stream channels and habitats when a stream's capacity to carry a given amount of bed material is increased, resulting in increased scouring of the streambed. Increased peak flows can cause downcutting of stream channels, reduce habitat heterogeneity, remove habitat forming features such as large woody debris, and enhance streambank erosion (MacDonald et al. 1991). Increased flows can also enhance streambed movement which can potentially dislodge and crush benthic organisms and developing fish (Burns 1972).

Increased sedimentation in streams occurs when the amount of sediment entering a stream exceeds that stream's capacity to transport it downstream as bedload or in suspension. This can result in channel simplification and habitat loss by causing channel aggradation in which pools fill with sediment and riffles are scoured (Lisle 1982; Jackson and Beschta 1984; Lisle and Hilton 1992). An experimental introduction of sand to a stream in Michigan eliminated pools resulting in a "continuous run" as opposed to the natural sequence of pools and riffles (Alexander and Hansen 1986). As sediment accumulates in the deeper portions of a stream channel, streamflow typically becomes shallower as it spreads out across the channel. To compensate for this wider area of flow, an unconstrained stream channel will often become wider as its streambanks are laterally eroded (Lisle 1982; Grant 1988). This not only introduces increased amounts of sediment directly from the streambank, it can also result in reduced stream shading, nutrient availability, and sediment retention because of the loss of riparian vegetation. In such cases, increased solar radiation and shallower water depths may increase water temperatures, resulting in a reduction of species intolerant to temperature fluctuations (MacDonald et al. 1991).

Sediment accumulation not only simplifies overall channel structure and morphology, but on a smaller scale, it also degrades habitat within the streambed itself. Basically, this occurs when fine sediment clogs the interstitial spaces between streambed particles. Interstitial spaces, or void spaces between larger streambed stones, provide habitat for a variety of aquatic organisms at various stages of development.

Most benthic invertebrates require a course substrate because it provides abundant protective cover and maximizes microscopic plant growth, which is an important food source (Cordone and Kelly 1961). Therefore, one of the major factors leading to benthic invertebrate population declines is the loss of interstitial space because of streambed sedimentation (Chutter 1969; Chapman and McLeod 1987). In North Carolina, Tebo (1955) observed a significant reduction in the standing crop of benthic organisms in an area impacted by sediment from nearby forest roads and skid trails. Soon thereafter, benthic invertebrate numbers rebounded following a flood that removed the accumulated sediment and re-exposed the underlying rubble and gravel substrate.

The principal effects of sedimentation on fish communities include a reduction in food availability (i.e. benthic invertebrates) and a disruption of natural reproduction (Cordone and Kelly 1961). In Missouri, Berkman and Rabeni (1987) found that species belonging to the same feeding and reproductive guilds responded equally to increased sedimentation. They observed declines in those reproductive guilds requiring clean gravels for spawning. Feeding guilds dependent on benthic organisms as a food supply were likewise reduced as such food sources declined because of sedimentation. Extensive sedimentation reduces cover for young fish, entraps pre-emergent fish, and reduces the amount of intergravel dissolved oxygen necessary for egg development (Chapman and McLeod 1987; MacDonald et al. 1991). In some cases, the survival rates of eggs and alevins can rapidly decline because of sedimentation (Alexander and Hansen 1986).

Various warmwater stream studies have shown only temporary changes in benthic invertebrate (Adams and Maughan 1988; Matlock and Maughan 1988) and stream fish (Rutherford et al. 1992) assemblages because of the combined effects of forest management. Other work conducted in similar climates has shown no discernible effects on aquatic biota due to clear-cutting, especially when such clearcuts were properly conducted to minimize stream disturbance (Boschung and O'Neil 1981). However, it should be noted that the short-term effects of forest management activities, when sustained over long time periods, may override the resiliency of stream ecosystems and their ability to recover from temporary perturbations (Burns 1972; Rutherford et al. 1992).

Substrate Sampling Techniques

Monitoring substrate composition most often involves the measurement of substrate particle sizes. A variety of sampling techniques can be used to determine the particle size distribution within a given area of the streambed. These techniques can be placed into two general categories: volumetric sampling and areal sampling (Muir 1969; Gomez 1983). Volumetric sampling involves the collection of a given volume of substrate particles from the surface and/or subsurface of the streambed for particle size analysis.

Areal sampling involves the measurement of particle sizes over a given area at the bed surface. Both volumetric and areal sampling are typically limited to use in shallow, wadable streams.

A number of devices have been used to collect volumetric substrate samples. McNeil and Ahnell (1964) designed an excavated core sampler that has been widely used by fisheries biologists in substrate assessments. A coring device is driven to a given depth and then excavated by hand until empty. The excavated material is then preserved for sieve analysis. This technique is somewhat limited because it is biased against large particles that do not fit within the coring device, surface and subsurface differences in particle size cannot be delineated because of extensive mixing, fine sediment that becomes suspended is lost, it cannot be used if substrates are so large or cemented that the coring device cannot be driven to the required depth (Platts et al. 1983).

Freeze-core samplers have also been developed for use in substrate characterization (Walkotten 1976; Everest et al. 1980). These devices use a cryogenic medium to effectively freeze and remove streambed sediments at given depths. Such devices are advantageous when analyzing the stratification of substrate sizes with depth. However, in addition to being labor and equipment intensive, freeze-cores are difficult to collect in streams with large or cemented substrates and cannot be obtained in areas that are not submerged under water (Platts et al. 1983; Hudson 1994).

Researchers have also used a standard shovel for taking bulk samples of stream substrates. Grost et al. (1991) compared excavated core samples, single probe freeze-core samples, and shovel samples taken from small streams in Wyoming. They observed no significant differences in substrate composition between excavated core samples and shovel samples. The composition of freeze-core samples, however, were significantly different than both the excavated core samples and shovel samples. Other studies have shown freeze-core samples to differ most from the actual composition of test substrates when compared to excavated core and shovel samples (Grost et al. 1991). Accordingly, Grost et al. (1991) suggested that a shovel would serve as a "viable alternative" to other sampling devices when sampling shallow streams as shovels are inexpensive and require less sampling time and effort. It should be noted, however, that all of these sampling devices are somewhat limited for use in stream reaches consisting of large substrates.

Another volumetric sampling device is the Whitlock-Vibert box. This device consists of a small, perforated box filled with gravel of a known size. It is placed in cavities dug in the substrate with its top flush to the streambed surface. Over time, the box is allowed to fill with fine sediment bedload. At the end of a given time period, the box is retrieved and analyzed for the percentage of fine sediment that deposited within the test gravels. Obviously, this device is useful only when monitoring changes in the fine sediment fraction of the substrate (Hudson 1994). Whitlock-Vibert box samples have been shown to compare favorably with other coring techniques when the characterization of fine sediment was of concern (Wesche et al. 1989).

Areal sampling has often been conducted by photographic analyses or by visual assessments of the substrate types found within a streambed, such as boulder, cobble, gravel, and fine sediment, and their relative coverage of the streambed (Chapman and McLeod 1987). The Instream Flow Incremental Methodology (IFIM) (Bovee 1982) uses a system in which the predominant particle sizes and degree of embeddedness are visually estimated and assigned ranks according to size and embeddedness characteristics, the sum of which constitutes a single substrate score for the area being evaluated (Chapman and McLeod 1987). Embeddedness refers to the degree to which coarse particles are surrounded or buried by finer particles (MacDonald et al 1991). Visual estimates are advantageous in that they are easy to perform and do not require the manual collection of samples for sieve analysis. However, different operators often interpret particle sizes differently which introduces bias to such estimates (Hudson 1994). Therefore, obtaining reproducible results between operators and over time may be difficult, thereby affecting the "comparibility of data among studies" (Kondolf and Li 1992). Platts et al. (1983) found year-to-year accuracy and precision of particle size estimates rated fair to poor, especially for smaller particle sizes such as cobble, gravel, and fine sediment. This was attributed to the difficulty of delineating size categories when particle diameters lay at either end of their respective size spectrums. In a comparison of various substrate sampling methods, Hudson (1994) found that visual survey methods produced "subjective, vague, and inconclusive" information in comparison to more systematic, quantitative methods. She suggested visual estimates be used in basic habitat analyses only. In a study of various fish habitat inventory parameters, Overton et al. (1993) visually estimated the percent cover of each substrate type found within a given habitat type and then verified this estimate on every fifth habitat type sampled using a more systematic areal sampling technique known as the pebble count.

The pebble count technique was developed as a systematic way to determine the relative coverage of a streambed by substrate particles of various sizes (Wolman 1954). The Wolman pebble count procedure is conducted by establishing a grid system over the area that is to be characterized. Each grid point represents 1/100th of the entire study area. For example, the grid system may be established by stretching ten parallel, equidistant tapes across the study area along each of which ten equidistant samples are taken as the operator traverses along each tape. Samples are taken by reaching down with the index finger to the streambed below the tip of the operator's boot. The index finger should be extended and the eyes averted or closed so as to assure randomness of selection (Wolman 1954; Leopold 1970). The first particle touched by the index finger is picked up and its intermediate axis, defined as neither the longest nor shortest axis, is measured. This measurement is then tallied in the appropriate numerical size class and the stone is returned to the stream. Although the types of grade scales used in substrate characterization studies vary, the Wentworth scale, or modifications thereof, is most often used (Table 1). This process is repeated at each of the 100 grid points until 100 pebbles have been measured. From this data, a cumulative size distribution curve can be drawn for use in deriving various statistical parameters (Wolman 1954).

Much like visual estimates, pebble counts are less difficult to use in coarse bedded streams and provide more representative samples of the area under investigation than volumetric sampling methods (Wolman 1954). Results obtained by their use have also been shown to be reproducible and comparable among different studies conducted by different operators (Wolman 1954; Hey and Thorne 1983; Mosley and Tindale 1985).

Table 1

WENTWORTH GRADE SCALES FOR PARTICLE SIZE

Class	mm
Very large boulder	4096 -- 2048
Large boulder	2048 -- 1024
Medium boulder	1024 -- 512
Small boulder	512 -- 256
Large cobble	256 -- 128
Small cobble	128 -- 64
Very coarse gravel	64 -- 32
Coarse gravel	32 -- 16
Medium gravel	16 -- 8
Fine gravel	8 -- 4
Very fine gravel	4 -- 2
Sand, silt, clay	< 2

Assuming operators are properly trained in the pebble count technique, results are most reproducible among different operators when sample sizes are limited to less than 100 pebbles (Hey and Thorne 1983). Kondolf and Li (1992) compared pebble counts and visual estimates in the determination of surface particle size distributions. They found that visual estimates exaggerated differences among stream areas that exhibit similar bed material characteristics. Because of the reproducibility of pebble counts, they suggested that this technique be adapted and applied in IFIM studies. Other authors suggest the use of pebble count procedures when monitoring land management activities that can potentially contribute significant amounts of sediment to streams, such as timber harvests or forest road construction (Potyondy and Hardy 1994; Bevenger and King 1995).

The major disadvantage of using pebble counts is that operators are typically biased towards the selection of large particle sizes as the probability of touching a pebble increases as its surface area increases (Leopold 1970). Thus, it is very important that operators not look at the streambed during the selection process and that a fixed point on the index finger, such as a corner of the fingernail, be used to select particles for measurement (Kondolf and Li 1992; Potyondy and Hardy 1994). Also, pebble counts cannot be used to delineate between particles generally less than 2 to 4mm; these particles are typically categorized simply as <2mm, <4mm, or "fines" (Wolman 1954; Leopold 1970; Kondolf and Li 1992). In general, surface sampling techniques are limited because they only describe particle sizes at the bed surface, which is often deficient in fine sediment when compared to the subsurface (Kondolf and Li 1992). If the bed surface is extensively covered by fine sediment, this may indicate that excessive sedimentation is occurring throughout the bed deposit or that fine sediment is being deposited above a stable gravel bed that prevents the filtering of fines to the subsurface (Kondolf 1995).

Measures of Substrate Composition

Particle size data obtained using volumetric and areal sampling techniques can be used to plot cumulative size distribution curves. Volumetric sampling yields size class frequency by weight data; areal sampling yields size class frequency by number data (Muir 1969). From these curves, a number of measures can be derived which describe substrate composition.

One type of measure widely used is the percentage of substrate particles less than a given size by weight, volume, or number. This measure is often referred to as "percent fines". Many studies vary in their definition of percent fines because the sediment size that can significantly alter substrate composition and habitat suitability varies from one region to another. Reference particle sizes that delineate percent fines have ranged from 0.75mm to 8mm (Potyondy and Hardy 1994).

Other types of measures incorporate the entire particle size distribution as opposed to only the fine fraction. Those that express the central tendency of particle size distributions include the geometric mean, arithmetic mean, and the median particle size. Sorting coefficients are used to express the variance of particle sizes in a deposit. The fredle index and the modified fredle index incorporate both the central tendency of the distribution and the variance of particle sizes.

Platts et al. (1979) and Shirazi and Seim (1981) concluded that the geometric mean provides a "more complete description of total sediment composition" than does percent fines and is, therefore, more appropriate for use in the evaluation of spawning gravel composition. However, despite its high correlation with fish embryo survival, Beschta (1982) debated its use when assessing changes in substrate composition arising from land use activities within a watershed. He found a more direct correlation between percent fines and both embryo survival and substrate composition changes. To obtain a more complete description of textural composition, Beschta (1982) suggested using a modified version of the fredle index (Lotspeich and Everest 1981) which combines a measure of central tendency with a measure of sorting. The median particle size (D_{50}) is a measure of central tendency seldom used by fisheries biologists but suitable for use as an indicator of framework particle size (Kondolf 1995). This and other percentile values, as derived from the cumulative size frequency curve, are also useful when evaluating the flow resistance or bed material transport potential of streambed deposits (Mosley and Tindale 1985).

Young et al. (1991) compared 15 measures of substrate composition to examine their relationship with both survival-to-emergence of salmonids and known changes in substrate composition. They concluded that the "way in which stream substrates are disturbed may dictate the most appropriate measure of substrate composition". Deep scour events that alter the proportion of many substrate sizes may warrant the use of a measure of central tendency so that changes in the overall size framework can be detected (Young et al. 1991). Hydrologic events that introduce large amounts of fine sediment to the stream channel may require the use of a percent fines measure since the fine sediment portion of the size distribution will be most affected (Young et al. 1991).

Monitoring Channel Changes

Increased flows tend to increase channel widths and depths while increased sediment availability can enhance channel widening and decrease channel depth (Beschta and Platts 1986). In general, the effects of increased sediment delivery and streamside land use activities on channel morphology are greater than the effects of increased flows caused by land management practices (Beschta and Platts 1986). A number of studies have shown increased channel widths and decreased channel depths with channel aggradation (Lisle 1982; Lyons and Beschta 1983) and reductions in large organic debris availability (Dose and Roper 1994). In order to determine whether a stream channel is becoming wider, deeper, or both, a consistent monitoring system that is sensitive to temporal changes in channel geometry is needed.

In some cases, changes in channel width can be detected using aerial photographs of openings in riparian canopy cover (Grant 1988; Ryan and Grant 1991). Other measures or indices quantify aspects of habitat units (pools, riffles, etc.) such as type, sequence, number, average depth, maximum depth, residual depth, surface area, volume, and/or thalweg profile (MacDonald et al. 1991, Clingenpeel 1994). An alternative measure, the width-to-depth ratio, is determined from width and depth data as measured at channel cross-sections.

The width-to-depth ratio is a dimensionless index based on the width and average depth of the wetted channel (discharge dependent) or the entire bankfull channel (geomorphically dependent) (Ontario Ministry of Natural Resources 1994; Overton et al. 1995). This index indicates morphological changes arising from alterations in "the relative balance between the sediment load and the sediment transport capacity" (MacDonald et al. 1991; Overton et al. 1995). An increase in the width-to-depth ratio may indicate lateral bank erosion; decreasing width-to-depth ratios may indicate channel degradation or, possibly, a return to normal conditions following an aggradational event (MacDonald et al. 1991).

CHAPTER III

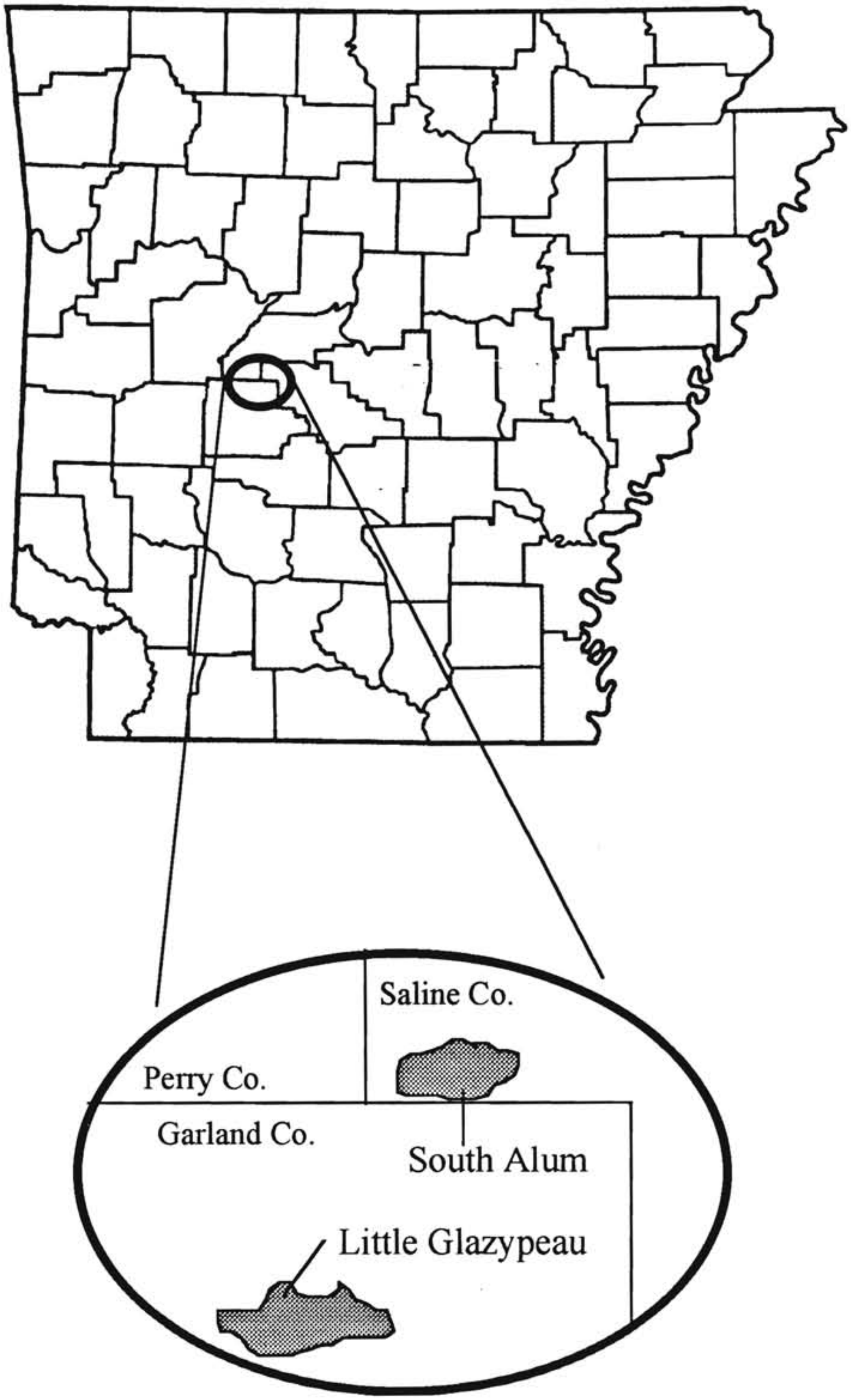
METHODS AND MATERIALS

Study Areas

The streams chosen for this study are second to third order headwater streams located in the Ouachita Mountains of central Arkansas. Flow in these streams is typically perennial although in lower order, upstream reaches flow becomes intermittent during the drier months of the year. Soils in the region are derived from east-west trending formations of uplifted, folded and faulted sandstone, shale, quartzite and slate. Although the soils occurring in the watersheds of these streams belong to the same soil association (Sandlick), soil types as they occur in or near stream channels vary between the two sites (Dewit and Steinbrenner 1981).

South Alum Creek is located in Saline County, Arkansas. It is 6.7 km long and drains a 1580 ha watershed in the Ouachita National Forest. Its watershed has not been actively managed for timber production in several decades. It is currently administered as an experimental forest by the U.S. Forest Service. The soils in this watershed are well drained, sloping to steep fertile soils with a stony loam surface and clay loam to clay

Figure 1: Location of study watersheds.



subsoil (Robinson 1964). Stream deposits consist of stony mixed alluvium. Nearby upland soils consist primarily of Tate stony loam and Wickham stony loam with slopes ranging from 3 to 20 percent. Stone content in such soils, defined as those pieces of rock between 250mm and 610mm in diameter, ranges from 2 to 70 percent (Robinson 1964).

Little Glazypeau Creek is situated to the southwest of South Alum Creek in Garland County, Arkansas. It is 7.7 km in length and drains a watershed area of approximately 1740 ha. The entire watershed is located on lands owned and actively managed by Weyerhaeuser Company. Soils occurring in proximity to the stream are primarily deep, moderately well-drained, and loamy to medium in texture. Underlying substratum, observable along streambanks and in channels, consists of water-washed sandstone and shale gravels and occasionally, shale bedrock (Dewit and Steinbrenner 1981).

Sampling Procedures

A map wheel was used to determine the total length of each stream from 1:24,000 scale USGS topographic maps. Each stream was divided into nine equal sections. Starting at the outlet of the watershed and moving upstream, the first reach of four consecutive habitats encountered within each section was selected for sampling. Sampling was restricted to only those habitats that had adequate flow so as to be properly identifiable, and to only those habitats that were shallow enough to be waded. Due to the lack of flow in upstream areas and to increase the number of habitats sampled, an extra reach of four consecutive habitats was sampled within some sections of both streams. On a second order tributary of Little Glazypeau Creek, three additional reaches were also sampled.

Habitat types are often placed into one of three broad categories based on water depth: pools, runs, and riffles. These three classes can then be broken down further based on gradient, water surface agitation, water velocity, position in the channel, and/or scour characteristics (McCain et al. 1990). In our case, we broadly identified habitats by visual inspection based on water depth, water velocity, and gradient. Deep, low gradient habitats with slow moving water were identified as pools. Shallow, moderate to high gradient habitats with faster moving water were identified in the field as riffles, runs, and step runs. These were later classified more broadly as fastwater habitats.

Each habitat was flagged and identified in the field by section number, habitat number, and habitat type. The length of each habitat was measured to the nearest meter. Each habitat was divided into 10 equally spaced transects. At each transect, a flag was placed at the estimated bankfull flow height of the active channel. Bankfull flow heights were estimated based on changes in vegetation, grade, and/or soil characteristics. Bankfull flow is the flow that is large enough to completely fill the channel. On average, it has a return interval of 1.5 years and is the dominant channel shaping event (Platts et al. 1983). Extending from this point on the streambank, a measuring tape was stretched across the channel, perpendicularly to the direction of flow, to the bankfull stage on the opposite bank. The tape was held level during all width and depth measurements.

Channel widths were measured to the nearest 0.1 meter. Channel depths were measured to the nearest 0.01 meter at a minimum of ten points across each transect. Such measurements were taken at breaks in depth across the cross-sectional profile. A channel width-to-average depth ratio was calculated for each of the ten transects within each habitat. The ratio calculated for the midpoint transect, the average ratio calculated from all ten transects, and the average ratio calculated from three transects (midpoint and two habitat endpoint transects) could then be compared among one another.

Pebble counts were conducted by an operator who, while wading the stream channel, would reach down to the streambed with his eyes closed or averted and select the first particle touched by his index finger. The intermediate axis, or width, of each selected particle was measured and classified into the appropriate size class of the modified Wentworth scale. This scale differs from the original Wentworth scale in that size classes differ by a factor of $\sqrt{2}$ (2, 2.8, 4, 5.6, 8, 11.3, 16, etc.). Particles were placed into the size class that represented the upper limit of the interval within which the measured diameter occurred. For example, if the intermediate diameter of a stone fell between 11.3mm and 16mm, it was placed into the 16mm size class. Following measurement, each particle was returned to the streambed. This procedure was repeated until the desired number of particles had been collected and measured.

The Wolman pebble count technique (Wolman 1954) was conducted by sampling ten streambed particles along each of the ten pre-established transects per habitat (Figure 2). Each particle was collected from ten equidistant points along each transect while traversing from the left bank to the right bank. A total of 100 particles were measured per

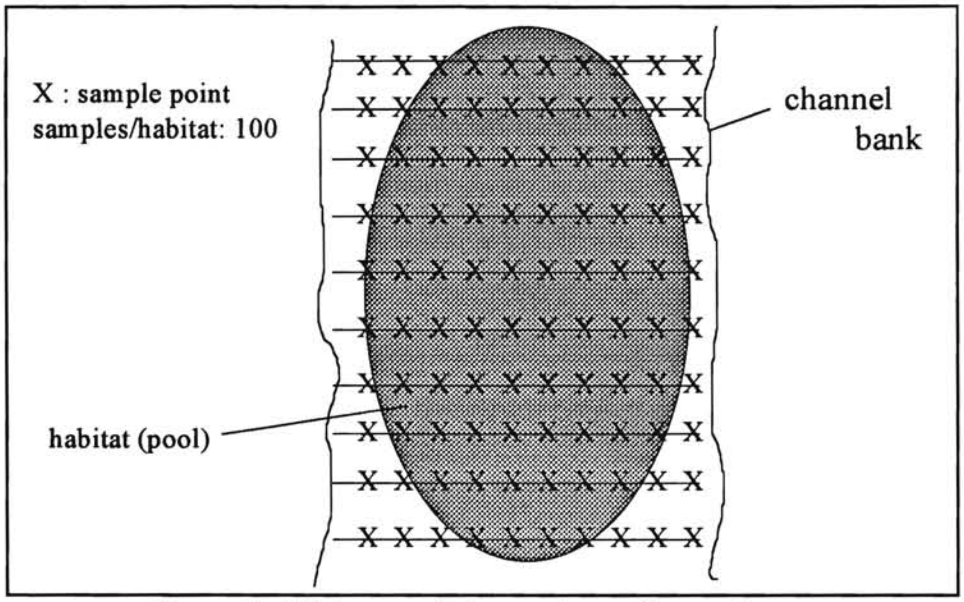


Figure 2: Wolman pebble count sampling pattern

habitat. The size of each particle sampled represented the particle size covering 1% of the total habitat area.

The BASS pebble count procedure (Clingenpeel 1994) is much the same as the

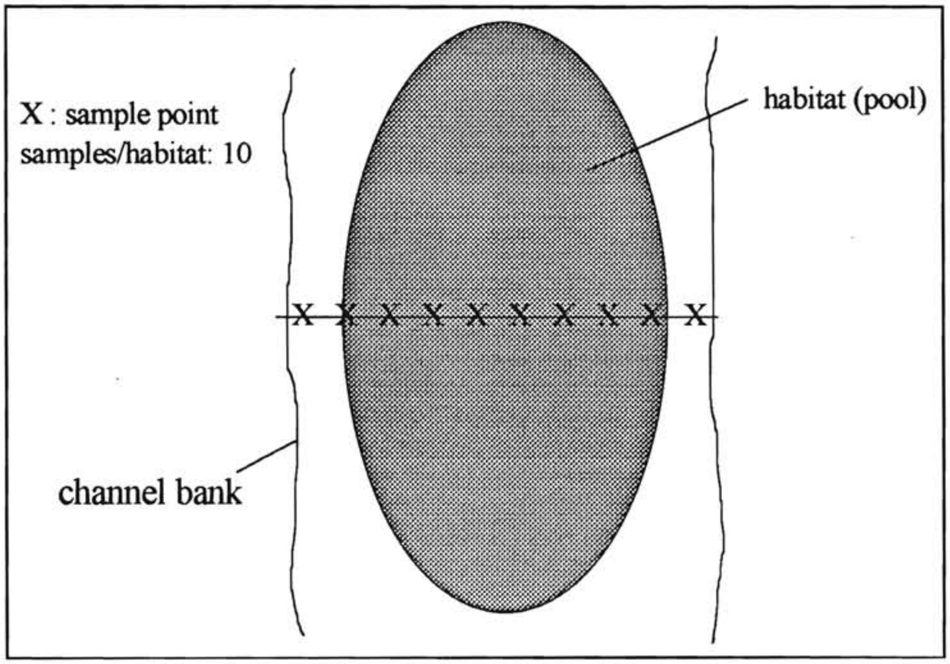


Figure 3: BASS pebble count sampling pattern

Wolman procedure except that not as many samples are required. Ten particles were sampled along a single midpoint transect (Figure 3). The size of each particle sampled represented the particle size covering 10% of the total habitat area.

The zig-zag pebble count procedure used in this study was a modified version of the procedure described by Bevenger and King (1995). For each reach of four habitats, the individual habitat lengths were summed and then divided into ten equally spaced segments. Starting at the beginning of the first habitat and moving upstream, a measuring tape was stretched diagonally across each segment from the left bank to the right bank. These diagonals were stretched back and forth across all ten segments resulting in a zig-zag sampling pattern across the entire four habitat reach (Figure 4). Along each diagonal, ten streambed particles were sampled and measured, resulting in a total sample size of 100 particles per reach. The number of particle sizes measured in each habitat was noted as sampling proceeded upstream from one habitat to the next. The number of particles sampled per habitat depended on the relative length of a given habitat to the entire length of the reach. For example, if a habitat was 20m in length and occurred in a 100m reach, two diagonals would be stretched across the habitat and twenty particles would be sampled.

Bulk sampling was conducted using a standard sharpshooter shovel. Only two habitats from every other reach were sampled using this method. A total of 12 habitats were sampled per stream. Across each habitat, five parallel, equally spaced transects were stretched from bankfull to bankfull (Figure 5). At equally spaced points along each transect, six substrate samples were taken from the streambed, placed in bags, and

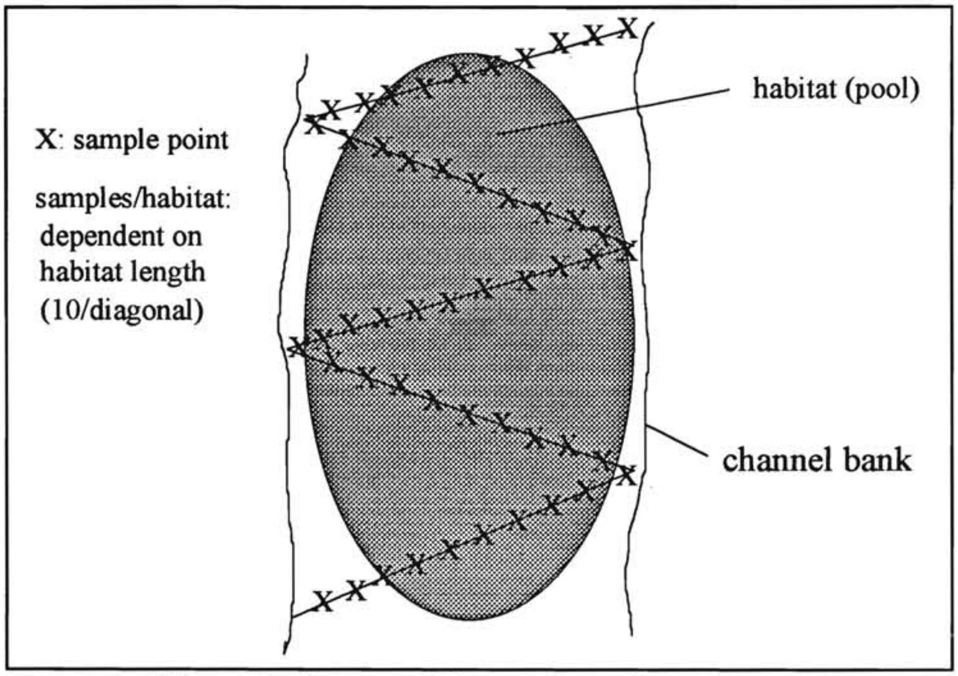


Figure 4: Zig-zag pebble count sampling pattern

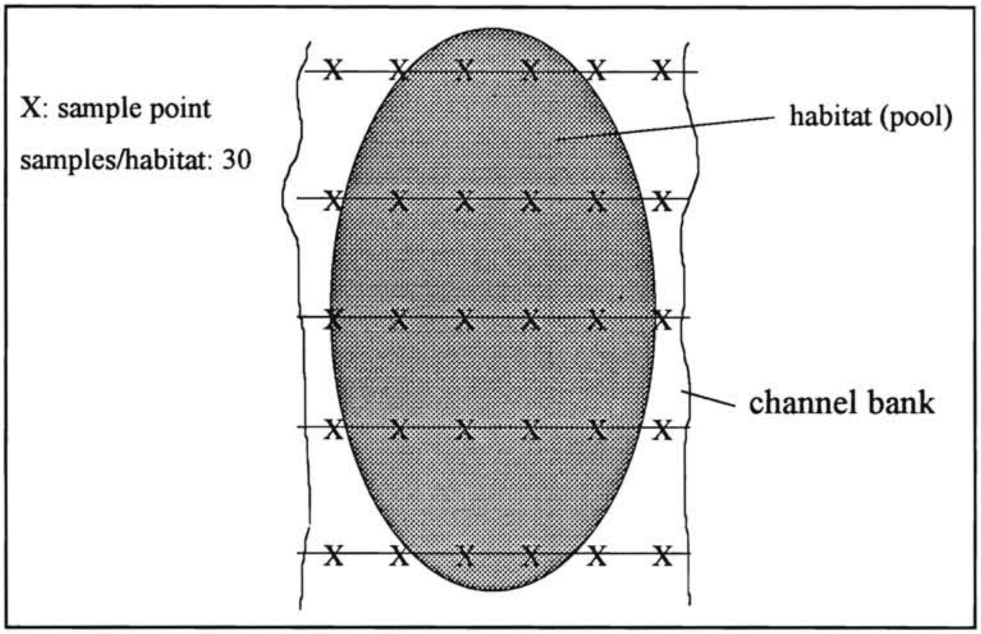


Figure 5: Bulk sampling points

transported to the laboratory for sieve analysis. A total of 30 samples were taken from each habitat. At each sampling location, the operator avoided bias by averting his eyes and randomly spiking the shovel into the streambed at arm's length. A sample was then taken from the point where the shovel landed. An effort was made to obtain, to the maximum extent feasible, equal sized bulk samples from a depth of 10 to 12cm. Sample sizes varied with the proportion of large particles in the sample. If the operator spiked the shovel in an area consisting primarily of bedrock or large boulders exceeding 128mm, a bulk sample could not be taken and the area was simply noted as containing no fine sediment.

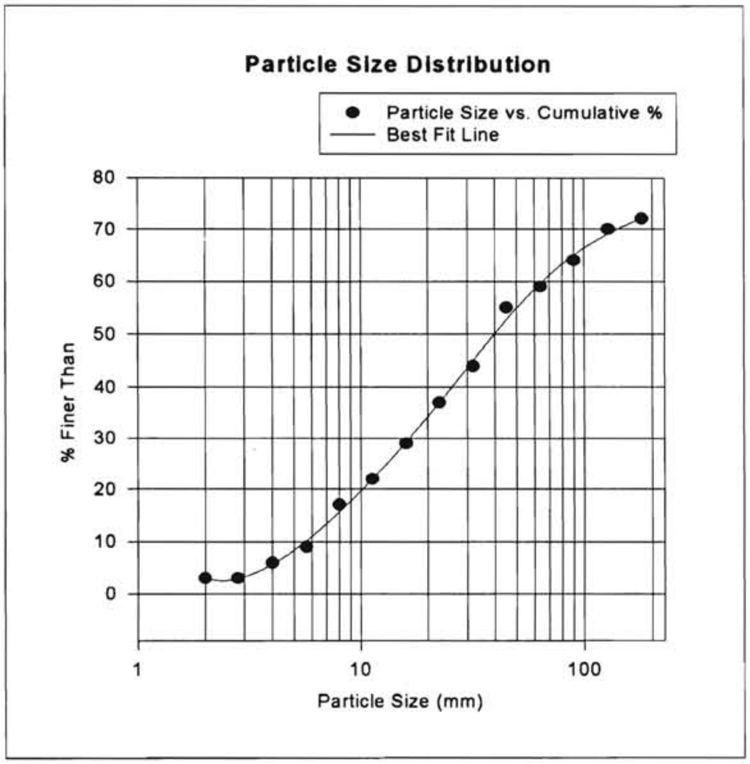
Derivation of Substrate Measures

Data from the pebble count procedures was used to determine the percentage of fine sediment less than 2mm covering the bed surface and to derive the median particle size within each habitat. A cumulative size frequency table for each habitat was constructed from pebble count data. This table shows the number of stones falling within each size class and the cumulative percentage of particles less than each successive size class limit (Table 2). The percentage of streambed particles falling within the 2mm size class was considered fine sediment. Size classes and cumulative frequency data derived from this table was then plotted on a semi-logarithmic graph using SigmaPlot graphing software (Tilling et al. 1994) (Figure 6). A "best-fit" line was regressed through these points from which the 50th percentile value (D_{50}), or median particle size, could be extrapolated.

Table 2
Cumulative Size Frequency Table

Class	*Frequency*	*Cumulative %*
2	3	3.00%
2.8	0	3.00%
4	3	6.00%
5.7	3	9.00%
8	8	17.00%
11.3	5	22.00%
16	7	29.00%
22.6	8	37.00%
32	7	44.00%
45	11	55.00%
64	4	59.00%
90	5	64.00%
128	6	70.00%
180	2	72.00%
>180	28	100.00%

Figure 6: Cumulative Size Frequency Curve



Bulk samples were taken to the laboratory and analyzed for the percentage of fine sediment (<2mm) by weight. Each sample was dried, weighed, and sieved through standard A.S.T.M sieves to separate the larger substrates from finer particles. The measured weight of fine sediment was then divided by the total sample weight to get a value of "percent fines". These values were averaged over all 30 samples to determine the composite amount of fine sediment occurring in each habitat.

Statistical Analyses

Using stream habitats as experimental units, width-to-average depth ratio (WDR) and particle size distribution data obtained by each sampling method were tested for normality using a univariate procedure (Shapiro-Wilk test) in SAS (SAS 1990). Analysis of variance (ANOVA) was then used to test the following hypotheses:

1) H_0: D_{50}(Wolman) = D_{50}(BASS) = D_{50}(Zig-zag)
2) H_0: %fines(Wolman) = %fines(BASS) = %fines(Zig-zag)
3) H_0: %fines(Wolman) = %fines(BASS) = %fines(Zig-zag) = %fines(Shovel)
4) H_0: WDR(1 transect) = WDR(3 transects) = WDR(10 transects)

Since most data was found not to be normally distributed, analysis of variance was applied on ranks for all comparisons. This application is equivalent to the non-parametric Kruskal-Wallis test (SAS 1990). The Fisher's Least Significant Difference (LSD) Procedure was then used to differentiate between significantly different sample means obtained among the various sampling methods.

CHAPTER IV

RESULTS AND DISCUSSION

Substrate Composition Measurements

The first comparison of substrate sampling techniques was among the three pebble count procedures. Experimental units included 56 habitats on Little Glazypeau Creek and 48 habitats on South Alum Creek. The analysis of variance applied to the ranked values of both D_{50} and percent fines revealed no significant interaction between habitat type (pool and fastwater) and sampling procedure across both streams and within each stream (Table 3). Therefore, methods were tested for differences across all habitat types. Significant differences were observed among sampling methods for both D_{50} and percent fines across both streams as well as within each stream (Table 3).

Table 3: Significance levels of interaction and treatment terms for variables D_{50} and percent fines (3 method comparison)

	Median Particle Size (D_{50})		**Percent Fines**	
	Habitat-method interaction *p* value	Method *p* value	Habitat-method interaction *p* value	Method *p* value
Both streams	0.48	0.0001*	0.24	0.0001*
Little Glazypeau	0.54	0.0001*	0.56	0.0152*
South Alum	0.71	0.0001*	0.33	0.0001*

* statistically significant (α=0.05)

Across all habitats of both streams and within each stream the mean D_{50} value as measured by the zig-zag sampling method was significantly larger than the D_{50} values obtained using the Wolman and BASS methods. No significant differences in D_{50} were observed between the Wolman and BASS methods among or within streams (Tables 4-6). The three methods were more variable across and within streams when measuring percent

Table 4: LSD test results for variable D_{50} across both streams (3 method comparison).

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (mm)	N
Zig Zag	A	190.18	58.39	103
BASS	B	138.34	42.28	102
Wolman	B	136.5	42.51	104

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 5: LSD test results for variable D_{50} within Little Glazypeau Creek (3 method comparison)

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (mm)	N
Zig Zag	A	110.17	47.77	56
BASS	B	74.77	29.07	55
Wolman	B	66.89	26.00	56

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 6: LSD test results for variable D_{50} within South Alum Creek.
(3 method comparison)

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (mm)	N
Zig Zag	A	84.14	71.04	47
Wolman	B	67.17	61.77	48
BASS	B	63.29	57.75	47

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

fines. All methods were significantly different from one another when measuring percent fines across all habitats of both streams (Table 7). On habitats within Little Glazypeau Creek, the BASS and Wolman methods estimated similar amounts of fine sediment, both of which were significantly greater than the amount estimated by the zig-zag procedure (Table 8). Within South Alum Creek, the zig-zag and BASS methods estimated similar amounts of fine sediment, although both estimated significantly less than the amount estimated by the Wolman procedure (Table 9).

Table 7: LSD test results for variable percent fines across both streams.
(3 method comparison)

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (%)	N
Wolman	A	178.98	6.21	104
BASS	B	154.42	6.26	104
Zig Zag	C	136.1	4.56	104

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 8: LSD test results for variable percent fines within Little Glazypeau Creek. (3 method comparison).

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (%)	N
Wolman	A	90.94	8.20	56
BASS	A	89.96	8.75	56
Zig Zag	B	72.61	6.33	56

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 9: LSD test results for variable percent fines within South Alum Creek. (3 method comparison)

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (%)	N
Wolman	A	89.57	3.90	48
BASS	B	64.18	3.35	48
Zig Zag	B	63.75	2.49	48

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

The next comparison of substrate sampling methods was among the three pebble count techniques and the bulk sampling procedure. Only twelve habitats per stream were used as experimental units for this comparison due to the smaller number of habitats sampled with a shovel. No conversion of results obtained by bulk sieve analysis was necessary in order to compare bulk-by-weight data to frequency-by-number data produced by pebble counts (Kellerhals and Bray 1970). ANOVA was applied to ranked values of percent fines. No significant interaction between habitat type and sampling procedure was observed (Table 10). Methods were then tested for significance across all habitat types. Significant differences were observed among sampling methods across habitats of both streams and within South Alum Creek. There was no significant difference between the four sampling techniques within Little Glazypeau Creek (Tables 10 & 12).

Table 10: Significance levels of interaction and treatment terms for variable percent fines. (4 method comparison)

	Percent Fines	
	Habitat-method interaction *p* value	Method *p* value
Both streams	0.81	0.0185*
Little Glazypeau	0.33	0.5845
South Alum	0.47	0.0065*

* statistically significant (α = 0.05)

Table 11: LSD test results for variable percent fines across both streams. (4 method comparison)

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (%)	N
Bulk	A	55.46	7.40	24
Wolman	A	53.10	6.33	24
BASS	A B	48.38	6.29	24
Zig Zag	B	37.06	4.46	24

* means of ranks with the same letter are not significantly different (α = 0.05)
** not used in LSD test

Across all habitats of both streams and within South Alum Creek, the zig-zag pebble count method estimated significantly less fine sediment than did the bulk and Wolman sampling methods. Differences between the bulk, Wolman, and BASS sampling methods were statistically insignificant (Table 11 & 13)

Table 12: LSD test results for variable percent fines within Little Glazypeau Creek. (4 method comparison)

Method	T Grouping*	Mean of ranks	Arithmetic Mean** (%)	N
Bulk	A	26.67	9.37	12
BASS	A	25.79	7.5	12
Wolman	A	24.96	7.58	12
Zig Zag	A	20.58	6.04	12

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 13: LSD test results for variable percent fines within South Alum Creek (4 method comparison)

Method	T Grouping*		Mean of ranks	Arithmetic Mean** (%)	N
Bulk	A		30.00	5.428	12
Wolman	A		28.25	5.08	12
BASS	A	B	22.96	5.08	12
Zig Zag		B	16.79	2.87	12

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

These results indicate that operators conducting the zig-zag substrate sampling procedure consistently missed small particles occurring in the streambed. Mean values of D_{50} and percent fines as measured by the zig-zag procedure were larger and smaller, respectively, compared to alternative methods. Operator error is a possible reason for this discrepancy as one of the operators conducting the zig-zag procedure at various times during the sampling period did not at any time perform either the BASS or Wolman pebble counts. However, this operator was trained properly in the pebble count technique, had prior experience in its use on previous projects, and seemed to perform it as consistently as other operators. Assuming this was the case, previous experimental work by Wolman (1954) and Hey and Thorne (1983) would predict that, for the sample sizes taken (<100 pebbles/habitat), operator error would be minimal.

A more likely explanation involves sampling frequency along streambanks. From the starting point of each diagonal, the operator would pace 1/10th the length of the diagonal before selecting a stream pebble. The tenth pebble was always selected at the end of the diagonal on the opposite bank. Therefore, at each intersection of diagonals along the bank, only one pebble was selected. In a 20m habitat, two diagonals would be used and only 2 out of 20 pebbles selected along those diagonals would be selected from bankside areas. Likewise, 2 out of 10 pebbles selected along the midpoint transect (BASS procedure) and 20 out of 100 pebbles selected along ten transects (Wolman procedure) would be selected from bankside areas. Fine particles were generally more evident along banks as opposed to mid-channel areas, likely because of sloughing of bankside soils into the streambed and reduced flow velocities. Assuming that fine sediment existed along both streambanks of a habitat 20m in length, the zig-zag procedure may produce a percent fines value of only 10% while the other two procedures would produce a value of 20%. The lack of small particles detected by the zig-zag sampling pattern causes a shift in the particle size distribution toward large particle sizes resulting in larger D_{50} values.

In terms of areal sampling, an early assumption in this study was that the Wolman and zig-zag methods would detect a significantly greater amount of fine material than did the BASS procedure, particularly in pools. In northwestern California, Lisle (1982) observed that shallow pool areas downstream of pool "deeps" acted as in-channel depositional sites for fine sediment. Since the BASS method is conducted at the midpoint of every habitat, it was assumed that BASS would not account for fine sediment occurring in other depositional sites along the longitudinal profile of each habitat, particulary in pool tails. The alternative pebble count methods would seem to be more advantageous in this regard. However, the comparison among the three pebble count methods in this study showed otherwise.

Across both streams and within each stream, the BASS and Wolman methods were statistically similar in the measurement of D_{50}. Both methods consistently produced smaller D_{50} values than did the zig-zag method. This indicates the inclusion of more small particles by the BASS and Wolman methods. Despite statistical differences among measurements of percent fines when comparing the three methods across and within streams, the differences among arithmetic means were quite minor in practical terms. Among the three pebble count methods, the measured percentage of fine sediment ranged from 4.6-6.3% across both streams (Table 7), 6.3-8.8% within Little Glazypeau Creek

(Table 8), and 2.5-3.9% within South Alum Creek (Table 9). Arithmetic means were most similar among the BASS and Wolman methods.

The similarity among the Wolman and BASS methods seems to indicate that substrate composition varies little along the longitudinal profile of individual habitats in the two study streams. The distribution of particle sizes measured at the midpoint of each habitat closely matched particle size distributions derived from particle size measurements taken at 100 points throughout each habitat. Substrate composition seemed to vary most along bankside areas where small particles were more evident. As discussed previously, this may explain why the zig-zag sampling pattern produced slightly different values than did the Wolman and BASS sampling patterns.

Bulk samples were collected with the intention of examining the fine sediment content of streambed surface and subsurface deposits, via frequency-by-weight analysis, and comparing the findings to frequency-by-number data obtained by the three pebble count methods. Bulk sieve analysis results are theoretically equivalent to pebble count results given that deposits are homogeneous with depth (Hey and Thorne 1983). Any differences in size distributions between the two sampling techniques may be attributable to differences in particle size distributions between the surface layer and underlying deposits (Kellerhals and Bray 1970). Initially, it was presumed that bulk sampling would detect greater amounts of fine sediment than pebble count methods because of its reduced bias against the selection of small particle sizes and because shovel samples consisted of at least partially subsurface particles. Gomez (1983) compared two areal sampling techniques to shovel sampling and observed that the median particle size was significantly smaller when substrate was sampled volumetrically because of the inclusion of subsurface particles in the sample. Fine particles are often winnowed from surface layers by streamflow which results in a surface armour layer that is deficient in fine particles in relation to the subsurface (Gordon et al. 1994; Kondolf 1995).

The average percentage of fine sediment estimated by bulk sampling in this study was only slightly higher than the amounts measured by the three pebble count procedures within both streams. The only statistically significant difference among methods was between bulk sampling and the zig-zag method on South Alum Creek. The lack of any real differences among these methods indicates that, on average, the amount of fine sediment occurring in the study streams is homogeneous from the surface down to the depth sampled. It is possible that greater amounts of fine sediment exist at depths below that which was sampled in this study. The proportion of fine sediment occurring in a bulk sample often varies with the depth to which the sample is taken (Muir 1969).

Overall, neither of these streams were heavily laden with sediment over continuous reaches. Directly downstream from low water crossings and roadside drainage ditches on Little Glazypeau Creek, heavier sedimentation was more obvious although the effects became less apparent within short distances downstream from the affected area. Heavy sedimentation was also detected in two pools on South Alum Creek where cattle trailing through the stream had eroded streambanks. These effects were also somewhat isolated. Streamflow at the time of sampling was likely too low to adequately transport these sediments downstream. These sediment sources may be too minor to affect a large number of reaches within either stream.

Considering the substrate characteristics as they existed at the time of sampling, the practical significance of any differences among the four sampling methods was relatively minor. The only possible exception was in the measurement of median particle size (D_{50}) in which the zig zag method produced much larger values within both streams than did the alternative pebble count methods. When examining the mean percentages of fine sediment detected by each method, no one method had a distinct advantage over all other sampling methods in accounting for fine sediment. If cost was of concern to a monitoring agency, the zig-zag and BASS pebble count methods would be preferrable for use due to the reduced time and effort required to perform them. Of these two methods, the BASS sampling pattern compared most favorably with the more intensive Wolman and bulk sampling procedures when measuring D_{50} and percent fines within both streams. It also required fewer samples per habitat than did the zig-zag method. With this in mind, the BASS method would be preferrable for monitoring purposes. If the BASS method results do not accurately reflect the perceived spatial variability of substrates within a given habitat, such as might be seen in exceedingly long habitat units, a more intensive sampling method, such as the Wolman procedure, may be needed.

Width-to-Depth Ratio Measurements

Analysis of variance was applied to ranks of width-to-depth ratio (WDR) values. Significant interaction between habitat type and measurement method (1, 3, and 10 cross-sections) occurred across both streams and within Little Glazypeau Creek. Methods were tested for significance within each habitat type at these two levels. No significant interaction between habitat and method was detected within South Alum Creek. Methods were tested for significance across all habitats in this stream (Table 14).

Table 14: Significance levels of interaction and treatment terms for variable WDR.

	Habitat-method interaction *p* value	Method (across all habitats) *p* value	Method (fastwater) *p* value	Method (pool) *p* value
Both streams	0.0024*	.	0.0019*	0.0001*
Little Glazypeau	0.0028*	.	0.0047*	0.0001*
South Alum	0.0617	0.0001*	.	.

* statistically significant ($\alpha = 0.05$)

Significant differences were observed among methods within each habitat type across both streams and within Little Glazypeau Creek (Table 14). In all fastwater habitats across both streams and within Little Glazypeau Creek, there was no significant difference between the 3 and 10 cross-section measurements of WDR. Both produced significantly larger values than the single midpoint cross-section (Tables 15 & 17). In all pools across both streams and within Little Glazypeau Creek, all cross-section measurements of WDR were significantly different from one another (Tables 16 & 18). Across all habitats within South Alum Creek, a significant difference was observed among the three cross-section measurements (Table 14). All cross-section measurements were observed to be significantly different from one another in this stream (Table 19).

In all comparisons, the WDR measured by one cross-section at the midpoint of each habitat was always smaller than the WDR's averaged from 3 and 10 cross-sections

Table 15: LSD test results for variable WDR within fastwater habitats of both streams.

Method (# cross-sections)	T Grouping*	Mean of ranks	Arithmetic Mean**	N
Three	A	186.32	17.80	54
Ten	A	174.40	17.17	54
One	B	157.52	16.59	54

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 16: LSD test results for variable WDR within pool habitats of both streams.

Method (# cross-sections)	T Grouping*	Mean of ranks	Arithmetic Mean**	N
Three	A	174.17	16.66	50
Ten	B	145.74	15.05	50
One	C	96.95	12.69	50

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 17: LSD test results for variable WDR within fastwater habitats of Little Glazypeau

Method (# cross-sections)	T Grouping*	Mean of ranks	Arithmetic Mean**	N
Three	A	103.93	18.58	30
Ten	A	99.48	18.17	30
One	B	87.27	17.14	30

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 18: LSD test results for variable WDR within pool habitats of Little Glazypeau.

Method (# cross-sections)	T Grouping*	Mean of ranks	Arithmetic Mean**	N
Three	A	89.58	16.70	26
Ten	B	75.10	15.10	26
One	C	45.92	12.81	26

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

Table 19: LSD test results for variable WDR within all habitats of South Alum Creek.

Method (# cross-sections)	T Grouping*	Mean of ranks	Arithmetic Mean**	N
Three	A	84.22	16.72	48
Ten	B	72.25	15.46	48
One	C	61.03	14.24	48

* means of ranks with the same letter are not significantly different ($\alpha = 0.05$)
** not used in LSD test

per habitat. Because channel widths were generally constant within each habitat, this was likely due to greater depths occurring at the midpoint areas of pools and/or step runs. Step runs were the primary habitat type within the larger habitat classification known as "fastwater". The three cross-section method was conducted by taking width-depth ratio measurements at the two endpoints and the midpoint of each habitat. The two endpoint measurements were typically in shallow areas while the midpoint area was deeper, especially in pools. The use of two endpoint measurements tended to raise WDR values.

The average WDR measured in this manner was always larger than WDR's derived from 1 and 10 cross-sections. The average WDR among the 10 cross-section measurements was likely the intermediate value because it incorporated a more equivalent number of measurements from both deep and shallow areas along the longitudinal profile of each habitat.

The only difference among the three cross-sectional WDR survey methods not observed to be statistically significant was between the 3 and 10 cross-section determinations in fastwater habitats of Little Glazypeau Creek. When evaluating the arithmetic mean WDR for each method from a practical standpoint, all differences between WDR measurements appear minor despite the observed statistical significance. Differences among methods in each habitat type, especially in fastwater habitats, were quite small (Table 20).

Table 20: Raw WDR means as measured by each method within habitats of each stream.

	South Alum			L. Glazypeau		
	1 X-sec.	3 X-sec.	10 X-sec	1 X-sec.	3 X-sec.	10 X-sec
Pools	12.57	16.62	15.00	12.81	16.70	15.10
Fastwater	15.91	16.82	15.92	17.40	18.59	18.17

Differences among methods were slightly more pronounced in pools because of more variable depths along the channel profile. For monitoring purposes, one channel cross-section per habitat would probably be sufficient to detect changes in channel widths or depths over time because the magnitude of differences among methods in this study was negligible in practical terms.

CHAPTER V

CONCLUSIONS

Substrate Monitoring Techniques

Four substrate sampling techniques were compared on two streams in the Ouachita Mountains. Pool and fastwater habitats within each stream were the experimental units to which each method was applied. Three pebble count methods, each differing by sampling pattern and frequency, and one bulk sampling method were compared. The median particle size (D_{50}) was compared among the three pebble count methods. The percentage of fine sediment occurring within each habitat was compared among all methods. The methods differed similarly for both measured variables across all habitat types.

The BASS, Wolman, and bulk sampling techniques estimated substrate composition similarly across all comparisons. The zig-zag procedure consistently gave larger D_{50} values and smaller percent fines values than did other sampling methods. This was likely due to the reduced sampling frequency by the zig-zag procedure along streambanks where finer particles were most evident. Differences in percent fines as measured among the four sampling methods were much less striking than previously expected. Although statistical differences were observed, the magnitude of those differences were of minor consequence. Since the Wolman, zig-zag, and bulk sampling patterns covered greater areas along the longitudinal profile of each habitat and bulk samples partially incorporated subsurface deposits, it was expected that these methods would perhaps estimate greater amounts of fine material than did the BASS method which was conducted along a single midpoint transect. This study's findings indicate otherwise.

The Wolman method is assumed to give the best estimate of substrate composition among all pebble count procedures because pebble size measurements are made at 100 points throughout the extent of each habitat. The similarity of the BASS method to the Wolman method in the measurement of D_{50} supports the use of BASS in describing the overall framework size of substrates. The comparability of BASS to all other methods when measuring percent fines also supports its use when fine sediment is of concern. Among methods, the BASS method also required the least time and effort to conduct. Overall, the results of this study indicate that the BASS sampling procedure is adequate in characterizing substrates in the types of streams studied. For monitoring purposes, it would likely be preferrable over other, more intensive, sampling methods because of cost efficiency.

It should be noted that the streams surveyed in this study were not heavily impacted over their entire lengths. It is possible that substrate composition in a severely impacted stream would exhibit greater spatial variability within habitat units, such as by increased sedimentation in pool tails. In such cases, the BASS method may not detect this increased variability. Further study is needed in order to assess the comparability of these four methods in heavily impacted streams. The ability of each method to detect changes in substrate composition over time also warrants further investigation.

Width-to-Depth Ratios

Channel width-to-average depth ratios were calculated and averaged over 1, 3, and 10 cross-sections per habitat. In most cases, differences among the three methods of measuring the width-to-depth ratio in a given habitat were statistically significant. From a practical standpoint, these differences were minor for monitoring purposes. Channel widths changed little within most habitats. Width-to-depth ratios varied with the number of cross-sections measured in deep versus shallow channel areas. Differences among the methods were more pronounced in pools than in fastwater habitats because of more variable depths within pools.

The number of cross-sections to be used in monitoring width-to-depth ratios depends on how sensitive the monitoring program needs to be. Monitoring small-scale changes in channel widths and/or depths may require numerous cross-sections per habitat or reach. If information about more broad-scale changes in widths and depths affecting several kilometers of a stream is needed, only one cross-section per habitat or every other habitat may be sufficient.

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APPENDIX I:
PEBBLE COUNT DATA

Pebble Count Data - Little Glazypeau Creek

Reach#	Habitat#	Habitat Type	Method	D50 (mm)	%fines
A	1	Pool	Wolman	168	5
A	1	Pool	Bass	58	10
A	1	Pool	ZigZag	200	2.63
A	2	Fastwater	Wolman	33	3
A	2	Fastwater	Bass	44	0
A	2	Fastwater	ZigZag	89	0
A	3	Pool	Wolman	26	6
A	3	Pool	Bass	46	10
A	3	Pool	ZigZag	54	0
A	4	Fastwater	Wolman	40	3
A	4	Fastwater	Bass	39	10
A	4	Fastwater	ZigZag	110	0
0	1	Fastwater	Wolman	27	7
0	1	Fastwater	Bass	.	0
0	1	Fastwater	ZigZag	107	2.38
0	2	Pool	Wolman	29	10
0	2	Pool	Bass	21	10
0	2	Pool	ZigZag	22	8.57
0	3	Fastwater	Wolman	22	8
0	3	Fastwater	Bass	27	10
0	3	Fastwater	ZigZag	47	7.69
0	4	Pool	Wolman	23	6
0	4	Pool	Bass	16	10
0	4	Pool	ZigZag	110	0
1	1	Fastwater	Wolman	16	9
1	1	Fastwater	Bass	15	10
1	1	Fastwater	ZigZag	27	0
1	2	Pool	Wolman	13	17
1	2	Pool	Bass	14	10
1	2	Pool	ZigZag	15	15.56
1	3	Fastwater	Wolman	16	9
1	3	Fastwater	Bass	26	0
1	3	Fastwater	ZigZag	59	0
1	4	Pool	Wolman	19	12
1	4	Pool	Bass	18	20
1	4	Pool	ZigZag	88	12
2	1	Fastwater	Wolman	20	9
2	1	Fastwater	Bass	34	10
2	1	Fastwater	ZigZag	42	5.56
2	2	Pool	Wolman	14	11
2	2	Pool	Bass	10	10
2	2	Pool	ZigZag	17	8.33
2	3	Fastwater	Wolman	16	6
2	3	Fastwater	Bass	25	10
2	3	Fastwater	ZigZag	48	0
2	4	Pool	Wolman	17	10
2	4	Pool	Bass	16	20
2	4	Pool	ZigZag	33	6.67

Pebble Count Data - Little Glazypeau - cont'd

Reach#	Habitat#	Habitat Type	Method	D50 (mm)	%fines
3	1	Pool	Wolman	22	23
3	1	Pool	Bass	30	30
3	1	Pool	ZigZag	30	20
3	2	Fastwater	Wolman	25	7
3	2	Fastwater	Bass	34	0
3	2	Fastwater	ZigZag	66	0
3	3	Pool	Wolman	26	9
3	3	Pool	Bass	26	10
3	3	Pool	ZigZag	35	20
3	4	Fastwater	Wolman	25	6
3	4	Fastwater	Bass	37	0
3	4	Fastwater	ZigZag	61	5.71
4	1	Fastwater	Wolman	25	5
4	1	Fastwater	Bass	29	0
4	1	Fastwater	ZigZag	47	9.09
4	2	Pool	Wolman	32	12
4	2	Pool	Bass	56	20
4	2	Pool	ZigZag	40	25
4	3	Fastwater	Wolman	39	5
4	3	Fastwater	Bass	21	0
4	3	Fastwater	ZigZag	29	10
4	4	Pool	Wolman	15	23
4	4	Pool	Bass	5	50
4	4	Pool	ZigZag	10	12.12
5	1	Fastwater	Wolman	25	1
5	1	Fastwater	Bass	29	0
5	1	Fastwater	ZigZag	34	0
5	2	Pool	Wolman	22	8
5	2	Pool	Bass	17	10
5	2	Pool	ZigZag	37	6.67
5	3	Fastwater	Wolman	16	3
5	3	Fastwater	Bass	18	0
5	3	Fastwater	ZigZag	34	12.5
5	4	Pool	Wolman	15	11
5	4	Pool	Bass	10	20
5	4	Pool	ZigZag	26	16.67
6	1	Fastwater	Wolman	10	12
6	1	Fastwater	Bass	14	10
6	1	Fastwater	ZigZag	14	9.09
6	2	Pool	Wolman	13	14
6	2	Pool	Bass	11	20
6	2	Pool	ZigZag	12	11.67
6	3	Fastwater	Wolman	19	8
6	3	Fastwater	Bass	18	10
6	3	Fastwater	ZigZag	54	0
6	4	Pool	Wolman	19	6
6	4	Pool	Bass	12	0
6	4	Pool	ZigZag	19	15.79

Pebble Count Data - Little Glazypeau - cont'd

Reach#	Habitat#	Habitat Type	Method	D50 (mm)	%fines
7	1	Fastwater	Wolman	16	11
7	1	Fastwater	Bass	21	0
7	1	Fastwater	ZigZag	26	6.9
7	2	Pool	Wolman	17	15
7	2	Pool	Bass	21	10
7	2	Pool	ZigZag	19	10.71
7	3	Fastwater	Wolman	25	7
7	3	Fastwater	Bass	33	10
7	3	Fastwater	ZigZag	44	0
7	4	Pool	Wolman	17	8
7	4	Pool	Bass	7	10
7	4	Pool	ZigZag	16	9.52
8	1	Fastwater	Wolman	21	10
8	1	Fastwater	Bass	19	10
8	1	Fastwater	ZigZag	31	14.29
8	2	Fastwater	Wolman	17	10
8	2	Fastwater	Bass	26	0
8	2	Fastwater	ZigZag	11	8.7
8	3	Pool	Wolman	12	6
8	3	Pool	Bass	9	10
8	3	Pool	ZigZag	14	15.38
8	4	Fastwater	Wolman	35	7
8	4	Fastwater	Bass	33	0
8	4	Fastwater	ZigZag	26	4.17
9	1	Fastwater	Wolman	44	5
9	1	Fastwater	Bass	12	10
9	1	Fastwater	ZigZag	45	0
9	2	Pool	Wolman	16	7
9	2	Pool	Bass	136	10
9	2	Pool	ZigZag	64	4
9	3	Fastwater	Wolman	51	6
9	3	Fastwater	Bass	23	10
9	3	Fastwater	ZigZag	45	4
9	4	Fastwater	Wolman	30	5
9	4	Fastwater	Bass	38	10
9	4	Fastwater	ZigZag	16	5.56
Trib 1	1	Fastwater	Wolman	30	11
Trib 1	1	Fastwater	Bass	47	10
Trib 1	1	Fastwater	ZigZag	102	4.35
Trib 1	2	Pool	Wolman	27	7
Trib 1	2	Pool	Bass	32	20
Trib 1	2	Pool	ZigZag	36	0
Trib 1	3	Fastwater	Wolman	25	1
Trib 1	3	Fastwater	Bass	25	0
Trib 1	3	Fastwater	ZigZag	32	5.13
Trib 1	4	Pool	Wolman	21	8
Trib 1	4	Pool	Bass	37	0
Trib 1	4	Pool	ZigZag	93	0

Pebble Count Data - Little Glazypeau - cont'd

Reach#	Habitat#	Habitat Type	Method	D50 (mm)	%fines
Trib 2	1	Fastwater	Wolman	21	5
Trib 2	1	Fastwater	Bass	20	0
Trib 2	1	Fastwater	ZigZag	64	0
Trib 2	2	Pool	Wolman	22	9
Trib 2	2	Pool	Bass	29	0
Trib 2	2	Pool	ZigZag	43	3.45
Trib 2	3	Fastwater	Wolman	24	8
Trib 2	3	Fastwater	Bass	23	10
Trib 2	3	Fastwater	ZigZag	51	2.78
Trib 2	4	Pool	Wolman	26	9
Trib 2	4	Pool	Bass	26	10
Trib 2	4	Pool	ZigZag	29	0
Trib 3	1	Fastwater	Wolman	25	6
Trib 3	1	Fastwater	Bass	16	20
Trib 3	1	Fastwater	ZigZag	47	5.88
Trib 3	2	Pool	Wolman	33	7
Trib 3	2	Pool	Bass	114	0
Trib 3	2	Pool	ZigZag	92	0
Trib 3	3	Fastwater	Wolman	28	3
Trib 3	3	Fastwater	Bass	42	0
Trib 3	3	Fastwater	ZigZag	73	0
Trib 3	4	Pool	Wolman	26	4
Trib 3	4	Pool	Bass	34	0
Trib 3	4	Pool	ZigZag	40	6.06

Pebble Count Data - South Alum Creek

Reach#	Habitat #	Habitat Type	Method	D50 (mm)	%fines
0	1	Pool	Wolman	68	6
0	1	Pool	Bass	54	10
0	1	Pool	ZigZag	106	3.85
0	2	Fastwater	Wolman	66	6
0	2	Fastwater	Bass	61	10
0	2	Fastwater	ZigZag	83	3
0	3	Pool	Wolman	75	5
0	3	Pool	Bass	94	0
0	3	Pool	ZigZag	76	6.67
0	4	Fastwater	Wolman	66	4
0	4	Fastwater	Bass	68	0
0	4	Fastwater	ZigZag	75	0
1	1	Pool	Wolman	56	6
1	1	Pool	Bass	63	20
1	1	Pool	ZigZag	85	0
1	2	Fastwater	Wolman	82	0
1	2	Fastwater	Bass	65	0
1	2	Fastwater	ZigZag	151	0
1	3	Fastwater	Wolman	72	2
1	3	Fastwater	Bass	37	0
1	3	Fastwater	ZigZag	79	0
1	4	Pool	Wolman	39	2
1	4	Pool	Bass	70	0
1	4	Pool	ZigZag	43	0
2	1	Fastwater	Wolman	54	0
2	1	Fastwater	Bass	67	0
2	1	Fastwater	ZigZag	63	0
2	2	Pool	Wolman	71	0
2	2	Pool	Bass	84	0
2	2	Pool	ZigZag	92	0
2	3	Pool	Wolman	65	4
2	3	Pool	Bass	56	10
2	3	Pool	ZigZag	86	0
2	4	Fastwater	Wolman	75	1
2	4	Fastwater	Bass	104	0
2	4	Fastwater	ZigZag	37	0
2A	1	Pool	Wolman	59	10
2A	1	Pool	Bass	44	10
2A	1	Pool	ZigZag	60	8.33
2A	2	Fastwater	Wolman	50	6
2A	2	Fastwater	Bass	54	0
2A	2	Fastwater	ZigZag	65	4.17
2A	3	Pool	Wolman	52	10
2A	3	Pool	Bass	27	10
2A	3	Pool	ZigZag	60	0
2A	4	Fastwater	Wolman	58	8
2A	4	Fastwater	Bass	65	10
2A	4	Fastwater	ZigZag	58	5.88

Pebble Count Data - South Alum Creek - cont'd

Reach#	Habitat #	Habitat Type	Method	D50 (mm)	%fines
3	1	Fastwater	Wolman	40	2
3	1	Fastwater	Bass	44	0
3	1	Fastwater	ZigZag	55	0
3	2	Fastwater	Wolman	136	0
3	2	Fastwater	Bass	136	0
3	2	Fastwater	ZigZag	83	0
3	3	Pool	Wolman	59	6
3	3	Pool	Bass	80	0
3	3	Pool	ZigZag	68	0
3	4	Fastwater	Wolman	45	2
3	4	Fastwater	Bass	25	0
3	4	Fastwater	ZigZag	58	0
4	1	Pool	Wolman	35	1
4	1	Pool	Bass	45	0
4	1	Pool	ZigZag	64	4.17
4	2	Fastwater	Wolman	50	3
4	2	Fastwater	Bass	48	0
4	2	Fastwater	ZigZag	56	0
4	3	Pool	Wolman	92	0
4	3	Pool	Bass	65	0
4	3	Pool	ZigZag	58	0
4	4	Fastwater	Wolman	91	1
4	4	Fastwater	Bass	65	0
4	4	Fastwater	ZigZag	80	0
5	1	Pool	Wolman	58	1
5	1	Pool	Bass	79	0
5	1	Pool	ZigZag	68	0
5	2	Fastwater	Wolman	46	5
5	2	Fastwater	Bass	43	0
5	2	Fastwater	ZigZag	67	0
5	3	Fastwater	Wolman	72	3
5	3	Fastwater	Bass	71	0
5	3	Fastwater	ZigZag	146	0
5	4	Pool	Wolman	178	3
5	4	Pool	Bass	.	0
5	4	Pool	ZigZag	.	3.03
5A	1	Pool	Wolman	59	4
5A	1	Pool	Bass	52	1
5A	1	Pool	ZigZag	108	0
5A	2	Fastwater	Wolman	66	4
5A	2	Fastwater	Bass	83	0
5A	2	Fastwater	ZigZag	110	0
5A	3	Pool	Wolman	71	0
5A	3	Pool	Bass	89	0
5A	3	Pool	ZigZag	104	6.98
5A	4	Fastwater	Wolman	57	1
5A	4	Fastwater	Bass	36	0
5A	4	Fastwater	ZigZag	65	3.45

Pebble Count Data - South Alum Creek - cont'd

Reach#	Habitat #	Habitat Type	Method	D50 (mm)	%fines
6	1	Pool	Wolman	103	1
6	1	Pool	Bass	106	0
6	1	Pool	ZigZag	82	0
6	2	Fastwater	Wolman	141	1
6	2	Fastwater	Bass	131	0
6	2	Fastwater	ZigZag	89	0
6	3	Pool	Wolman	94	4
6	3	Pool	Bass	73	10
6	3	Pool	ZigZag	106	3.23
6	4	Fastwater	Wolman	103	2
6	4	Fastwater	Bass	103	0
6	4	Fastwater	ZigZag	79	0
7	1	Pool	Wolman	36	5
7	1	Pool	Bass	27	10
7	1	Pool	ZigZag	50	4
7	2	Fastwater	Wolman	33	5
7	2	Fastwater	Bass	21	10
7	2	Fastwater	ZigZag	36	0
7	3	Pool	Wolman	19	6
7	3	Pool	Bass	11	0
7	3	Pool	ZigZag	30	8.7
7	4	Pool	Wolman	29	5
7	4	Pool	Bass	44	0
7	4	Pool	ZigZag	36	9.09
8	1	Pool	Wolman	40	6
8	1	Pool	Bass	55	0
8	1	Pool	ZigZag	48	4
8	2	Fastwater	Wolman	29	7
8	2	Fastwater	Bass	26	0
8	2	Fastwater	ZigZag	40	0
8	3	Pool	Wolman	30	5
8	3	Pool	Bass	30	0
8	3	Pool	ZigZag	38	5
8	4	Fastwater	Wolman	27	3
8	4	Fastwater	Bass	20	10
8	4	Fastwater	ZigZag	56	2.94
9	1	Pool	Wolman	34	7
9	1	Pool	Bass	26	10
9	1	Pool	ZigZag	70	6.67
9	2	Fastwater	Wolman	31	8
9	2	Fastwater	Bass	36	10
9	2	Fastwater	ZigZag	91	0
9	3	Pool	Wolman	24	14
9	3	Pool	Bass	13	20
9	3	Pool	ZigZag	49	20.59
9	4	Fastwater	Wolman	29	2
9	4	Fastwater	Bass	18	0
9	4	Fastwater	ZigZag	30	5.88

APPENDIX II:
BULK SAMPLE DATA

Bulk Sample Data - Little Glazypeau Creek

Reach#	Habitat#	Habitat Type	Method	% fines
A	1	Pool	Bulk	6.6
A	2	Fastwater	Bulk	3.76
1	3	Fastwater	Bulk	6.4
1	4	Pool	Bulk	8.5
3	2	Fastwater	Bulk	9.53
3	3	Pool	Bulk	5.63
5	2	Pool	Bulk	19.37
5	3	Fastwater	Bulk	7.6
7	2	Pool	Bulk	21.63
7	3	Fastwater	Bulk	15.53
9	2	Pool	Bulk	5.6
9	3	Fastwater	Bulk	2.23

Bulk Sample Data - South Alum Creek

Reach#	Habitat#	Habitat Type	Method	% fines
1	3	Fastwater	Bulk	1.07
1	4	Pool	Bulk	12.9
2A	3	Pool	Bulk	5.9
2A	4	Fastwater	Bulk	4.53
4	3	Pool	Bulk	2.77
4	4	Fastwater	Bulk	2.4
5A	1	Pool	Bulk	3.27
5A	2	Fastwater	Bulk	3.6
8	3	Pool	Bulk	6.6
8	4	Fastwater	Bulk	3.63
9	2	Fastwater	Bulk	4.87
9	3	Pool	Bulk	13.6

APPENDIX III:
WIDTH-TO-DEPTH RATIO DATA

Width-to-Depth Ratio Data - Little Glazypeau Creek

Reach#	Habitat#	Habitat Type	# Cross-sections	W/D Ratio
A	1	Pool	Ten	16.55
A	1	Pool	One	11.17
A	1	Pool	Three	20.38
A	2	Fastwater	Ten	23.11
A	2	Fastwater	One	19.84
A	2	Fastwater	Three	21.39
A	3	Pool	Ten	19.67
A	3	Pool	One	19.72
A	3	Pool	Three	22.32
A	4	Fastwater	Ten	20.30
A	4	Fastwater	One	15.84
A	4	Fastwater	Three	17.06
0	1	Fastwater	Ten	24.79
0	1	Fastwater	One	21.52
0	1	Fastwater	Three	29.75
0	2	Pool	Ten	18.76
0	2	Pool	One	14.78
0	2	Pool	Three	22.37
0	3	Fastwater	Ten	17.07
0	3	Fastwater	One	18.93
0	3	Fastwater	Three	19.34
0	4	Pool	Ten	13.88
0	4	Pool	One	11.04
0	4	Pool	Three	16.46
1	1	Fastwater	Ten	20.44
1	1	Fastwater	One	20.65
1	1	Fastwater	Three	21.31
1	2	Pool	Ten	16.40
1	2	Pool	One	12.37
1	2	Pool	Three	16.49
1	3	Fastwater	Ten	22.66
1	3	Fastwater	One	20.9
1	3	Fastwater	Three	22.58
1	4	Pool	Ten	15.29
1	4	Pool	One	11.17
1	4	Pool	Three	15.91
2	1	Fastwater	Ten	17.96
2	1	Fastwater	One	13.02
2	1	Fastwater	Three	16.7
2	2	Pool	Ten	16.45
2	2	Pool	One	12.6
2	2	Pool	Three	17.31
2	3	Fastwater	Ten	23.72
2	3	Fastwater	One	23
2	3	Fastwater	Three	24.15
2	4	Pool	Ten	16.08
2	4	Pool	One	10.7
2	4	Pool	Three	20.94

Width-to-Depth Ratio Data - Little Glazypeau - cont'd

Reach#	Habitat#	Habitat Type	# Cross-sections	W/D Ratio
3	1	Pool	Ten	14.16
3	1	Pool	One	15.25
3	1	Pool	Three	13.66
3	2	Fastwater	Ten	18.34
3	2	Fastwater	One	17.26
3	2	Fastwater	Three	17.46
3	3	Pool	Ten	11.91
3	3	Pool	One	10.1
3	3	Pool	Three	13.77
3	4	Fastwater	Ten	12.64
3	4	Fastwater	One	8.35
3	4	Fastwater	Three	12.66
4	1	Fastwater	Ten	14.42
4	1	Fastwater	One	17.03
4	1	Fastwater	Three	17.79
4	2	Pool	Ten	12.26
4	2	Pool	One	10.37
4	2	Pool	Three	14.14
4	3	Fastwater	Ten	22.97
4	3	Fastwater	One	30.52
4	3	Fastwater	Three	21.6
4	4	Pool	Ten	17.41
4	4	Pool	One	22.49
4	4	Pool	Three	16.63
5	1	Fastwater	Ten	24.59
5	1	Fastwater	One	14.5
5	1	Fastwater	Three	26.44
5	2	Pool	Ten	12.97
5	2	Pool	One	11.2
5	2	Pool	Three	16.12
5	3	Fastwater	Ten	13.64
5	3	Fastwater	One	10.88
5	3	Fastwater	Three	16.81
5	4	Pool	Ten	20.54
5	4	Pool	One	12.57
5	4	Pool	Three	22.33
6	1	Fastwater	Ten	32.45
6	1	Fastwater	One	34.67
6	1	Fastwater	Three	31.35
6	2	Pool	Ten	20.21
6	2	Pool	One	15.54
6	2	Pool	Three	26.22
6	3	Fastwater	Ten	31.51
6	3	Fastwater	One	26.35
6	3	Fastwater	Three	27.56
6	4	Pool	Ten	17.94
6	4	Pool	One	16.78
6	4	Pool	Three	16.32

Width-to-Depth Ratio Data - Little Glazypeau - cont'd

Reach#	Habitat#	Habitat Type	# Cross-sections	W/D Ratio
7	1	Fastwater	Ten	16.24
7	1	Fastwater	One	15.84
7	1	Fastwater	Three	16.49
7	2	Pool	Ten	16.62
7	2	Pool	One	13.16
7	2	Pool	Three	21.34
7	3	Fastwater	Ten	25.41
7	3	Fastwater	One	25
7	3	Fastwater	Three	28.71
7	4	Pool	Ten	12.71
7	4	Pool	One	7
7	4	Pool	Three	13.56
8	1	Fastwater	Ten	6.67
8	1	Fastwater	One	7.2
8	1	Fastwater	Three	7.29
8	2	Fastwater	Ten	12.63
8	2	Fastwater	One	10.48
8	2	Fastwater	Three	13.99
8	3	Pool	Ten	15.49
8	3	Pool	One	14.35
8	3	Pool	Three	15.98
8	4	Fastwater	Ten	10.06
8	4	Fastwater	One	11.04
8	4	Fastwater	Three	12.15
9	1	Fastwater	Ten	16.35
9	1	Fastwater	One	21.95
9	1	Fastwater	Three	16.25
9	2	Pool	Ten	11.77
9	2	Pool	One	11.56
9	2	Pool	Three	11.45
9	3	Fastwater	Ten	12.87
9	3	Fastwater	One	10.31
9	3	Fastwater	Three	10.92
9	4	Fastwater	Ten	11.83
9	4	Fastwater	One	9.94
9	4	Fastwater	Three	11.54
Trib. 1	1	Fastwater	Ten	15.91
Trib. 1	1	Fastwater	One	13.94
Trib. 1	1	Fastwater	Three	16.68
Trib. 1	2	Pool	Ten	16.22
Trib. 1	2	Pool	One	14.88
Trib. 1	2	Pool	Three	15.96
Trib. 1	3	Fastwater	Ten	16.38
Trib. 1	3	Fastwater	One	14.02
Trib. 1	3	Fastwater	Three	21.18
Trib. 1	4	Fastwater	Ten	12.55
Trib. 1	4	Pool	One	11.35
Trib. 1	4	Pool	Three	13.75

Width-to-Depth Ratio Data - Little Glazypeau - cont'd

Reach#	Habitat#	Habitat Type	# Cross-sections	W/D Ratio
Trib. 2	1	Fastwater	Ten	12.56
Trib. 2	1	Fastwater	One	12.62
Trib. 2	1	Fastwater	Three	12.92
Trib. 2	2	Pool	Ten	10.78
Trib. 2	2	Pool	One	10.03
Trib. 2	2	Pool	Three	10.87
Trib. 2	3	Fastwater	Ten	11.76
Trib. 2	3	Fastwater	One	12.4
Trib. 2	3	Fastwater	Three	11.27
Trib. 2	4	Pool	Ten	11.49
Trib. 2	4	Pool	One	10.24
Trib. 2	4	Pool	Three	10.85
Trib. 3	1	Fastwater	Ten	17.79
Trib. 3	1	Fastwater	One	19.75
Trib. 3	1	Fastwater	Three	16.43
Trib. 3	2	Pool	Ten	13.70
Trib. 3	2	Pool	One	12.64
Trib. 3	2	Pool	Three	16.1
Trib. 3	3	Fastwater	Ten	17.94
Trib. 3	3	Fastwater	One	16.55
Trib. 3	3	Fastwater	Three	17.69
Trib. 3	4	Pool	Ten	10.85
Trib. 3	4	Pool	One	10
Trib. 3	4	Pool	Three	12.87

Width-to-Depth Ratio Data - South Alum Creek

Reach#	Habitat#	Habitat Type	# Cross-sections	W/D ratio:
0	1	Pool	Ten	13.48
0	1	Pool	One	10.95
0	1	Pool	Three	16.13
0	2	Fastwater	Ten	14.15
0	2	Fastwater	One	15
0	2	Fastwater	Three	12.48
0	3	Pool	Ten	11.98
0	3	Pool	One	11.07
0	3	Pool	Three	12.37
0	4	Fastwater	Ten	10.55
0	4	Fastwater	One	8.72
0	4	Fastwater	Three	10.42
1	1	Pool	Ten	22.85
1	1	Pool	One	22.13
1	1	Pool	Three	24.73
1	2	Fastwater	Ten	27.48
1	2	Fastwater	One	37.89
1	2	Fastwater	Three	29.5
1	3	Fastwater	Ten	16.13
1	3	Fastwater	One	12.6
1	3	Fastwater	Three	15.29
1	4	Pool	Ten	19.73
1	4	Pool	One	14.84
1	4	Pool	Three	19.24
2	1	Fastwater	Ten	17.58
2	1	Fastwater	One	13.61
2	1	Fastwater	Three	19.29
2	2	Pool	Ten	25.74
2	2	Pool	One	19.55
2	2	Pool	Three	29.74
2	3	Pool	Ten	20.95
2	3	Pool	One	17
2	3	Pool	Three	22.32
2	4	Fastwater	Ten	18.29
2	4	Fastwater	One	17.32
2	4	Fastwater	Three	16.59
2A	1	Pool	Ten	15.61
2A	1	Pool	One	12.32
2A	1	Pool	Three	15.93
2A	2	Fastwater	Ten	23.95
2A	2	Fastwater	One	16.7
2A	2	Fastwater	Three	27.02
2A	3	Pool	Ten	15.68
2A	3	Pool	One	16.32
2A	3	Pool	Three	19.01
2A	4	Fastwater	Ten	18.09
2A	4	Fastwater	One	13.68
2A	4	Fastwater	Three	17.89

Width-to-Depth Ratio Data - South Alum - cont'd

Reach#	Habitat#	Habitat Type	# Cross-sections	W/D ratio:
3	1	Fastwater	Ten	11.34
3	1	Fastwater	One	12.61
3	1	Fastwater	Three	11.35
3	2	Fastwater	Ten	16.17
3	2	Fastwater	One	22.37
3	2	Fastwater	Three	17.46
3	3	Pool	Ten	13.35
3	3	Pool	One	12.48
3	3	Pool	Three	16.33
3	4	Fastwater	Ten	10.57
3	4	Fastwater	One	10.19
3	4	Fastwater	Three	11.2
4	1	Pool	Ten	19.92
4	1	Pool	One	15.68
4	1	Pool	Three	22.34
4	2	Fastwater	Ten	18.43
4	2	Fastwater	One	17.65
4	2	Fastwater	Three	16.78
4	3	Pool	Ten	10.05
4	3	Pool	One	8.22
4	3	Pool	Three	10.99
4	4	Fastwater	Ten	10.91
4	4	Fastwater	One	10.6
4	4	Fastwater	Three	15.95
5	1	Pool	Ten	18.27
5	1	Pool	One	19.47
5	1	Pool	Three	20.31
5	2	Fastwater	Ten	12.11
5	2	Fastwater	One	13.85
5	2	Fastwater	Three	15.52
5	3	Fastwater	Ten	19.65
5	3	Fastwater	One	20.79
5	3	Fastwater	Three	20.57
5	4	Pool	Ten	11.54
5	4	Pool	One	16.2
5	4	Pool	Three	14.54
5A	1	Pool	Ten	12.47
5A	1	Pool	One	7.61
5A	1	Pool	Three	13.67
5A	2	Fastwater	Ten	14.43
5A	2	Fastwater	One	18.9
5A	2	Fastwater	Three	15.08
5A	3	Pool	Ten	12.75
5A	3	Pool	One	4.43
5A	3	Pool	Three	11.67
5A	4	Fastwater	Ten	11.66
5A	4	Fastwater	One	12.27
5A	4	Fastwater	Three	12.41

Width-to-Depth Ratio Data - South Alum - cont'd

Reach#	Habitat#	Habitat Type	# Cross-sections	W/D ratio:
6	1	Pool	Ten	11.16
6	1	Pool	One	10.59
6	1	Pool	Three	12.05
6	2	Fastwater	Ten	13.38
6	2	Fastwater	One	12.81
6	2	Fastwater	Three	13.9
6	3	Pool	Ten	10.87
6	3	Pool	One	7.08
6	3	Pool	Three	10.8
6	4	Fastwater	Ten	13.04
6	4	Fastwater	One	11.7
6	4	Fastwater	Three	12.31
7	1	Pool	Ten	11.67
7	1	Pool	One	13.24
7	1	Pool	Three	13.56
7	2	Fastwater	Ten	15.00
7	2	Fastwater	One	13.25
7	2	Fastwater	Three	14.87
7	3	Pool	Ten	18.31
7	3	Pool	One	14.46
7	3	Pool	Three	20.21
7	4	Pool	Ten	16.40
7	4	Pool	One	11.17
7	4	Pool	Three	18.7
8	1	Pool	Ten	12.80
8	1	Pool	One	7.88
8	1	Pool	Three	14.6
8	2	Fastwater	Ten	11.53
8	2	Fastwater	One	11.19
8	2	Fastwater	Three	16.61
8	3	Pool	Ten	12.42
8	3	Pool	One	8.79
8	3	Pool	Three	12.94
8	4	Fastwater	Ten	13.72
8	4	Fastwater	One	11.07
8	4	Fastwater	Three	14.3
9	1	Pool	Ten	9.17
9	1	Pool	One	6.5
9	1	Pool	Three	11.94
9	2	Fastwater	Ten	11.90
9	2	Fastwater	One	13.16
9	2	Fastwater	Three	13.63
9	3	Pool	Ten	12.74
9	3	Pool	One	13.7
9	3	Pool	Three	14.65
9	4	Fastwater	Ten	31.98
9	4	Fastwater	One	33.85
9	4	Fastwater	Three	33.36

VITA

Michael Craig Schaub

Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF SAMPLING TECHNIQUES FOR MONITORING SUBSTRATE COMPOSITION AND CHANNEL DIMENSION CHANGES IN OUACHITA MOUNTAIN STREAMS

Major Field: Environmental Science

Biographical:

Personal Data: Born in Fort Worth, Texas, on September 20, 1969, the son of John W. and Linda M. Schaub.

Education: Graduated from Burleson High School, Burleson, Texas in May 1988; received Bachelor of Science degree in Environmental Science from Texas Christian University, Fort Worth, Texas in December 1992. Completed the requirements for the Master of Science degree with a major in Environmental Science at Oklahoma State University in July 1996.

Professional Memberships: American Water Resources Association