Particle Size Distribution Analysis of a Mining-Impacted Gravel-Bed Stream in Ohio Using a Hybrid Sediment Sampling Technique

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ABSTRACT

As part of a risk assessment study of the Leading Creek Watershed in Ohio, a prior Virginia Tech researcher collected pavement and subpavement sediment samples at 17 sites using the hybrid areal sampling technique with a clay adhesive. The watershed, which is heavily impacted by mining and agricultural activities, suffers from low pH, high concentrations of metals and sediment in the water column, and excessively silted streambeds. The current work presents the results of the particle size analyses performed on the hybrid samples in the context of evaluating the effectiveness of the technique itself and as a tool in future watershed/ecological studies, as well as examining possible relationships between siltation and indicators of ecological health in Leading Creek. By combining clay grid and adhesive sampling methods, the hybrid technique consistently achieved an effective particle size sampling range of 0.05 mm (1.97×10^{-3} in) to over 300 mm (11.8 in), thereby reducing the common problem of truncation. However, the overlap of the clay adhesive and natural sediment distributions and atypical sediment loading from surrounding abandoned and reclaimed mine lands obscured expected trends such as downstream fining and hindered the analysis of materials finer than 0.125 mm (4.93×10^{-3} in). Volumetric conversion of areal samples using the Modified Cube Model with a traditional exponent of –1 for clay was complicated by the large amount of fines in the

Leading Creek samples. Further investigation into a more appropriate conversion technique for the evaluation of fine sediment samples is warranted.

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TABLE OF CONTENTS

ABSTRACT ii

ACKNOWLEDGEMENTS iv

TABLE OF CONTENTS v

LIST OF TABLES vii

LIST OF FIGURES vii

INTRODUCTION 1

LITERATURE REVIEW 3
- Introduction 3
- Characteristics of Gravel-Bed Streams 3
  - Gravel-Bed Layers 3
  - Pavement Layer Properties 4
  - Subpavement Layer Properties 6
  - Sediment Texture 6
  - Downstream Fining 6
- Accumulation of Fines 7
- Gravel-Bed Stream Sampling 9
  - Importance of Particle Size Analysis 9
  - Truncation 10
- Gravel-Bed Stream Sampling Techniques 11
  - Areal Sampling 12
  - Grid Sampling 14
  - Transect Sampling 17
- Sample Conversion 17
- Hybrid Sampling Technique 20
- Other Sampling Considerations 23

JOURNAL ARTICLE 25

INTRODUCTION 25
- Gravel-Bed Stream Sampling 25
- Sediment Sampling and the Hybrid Method 27
- Objectives and Approach 30
- Background on Leading Creek Watershed 31

MATERIALS AND METHODS 34
- Sampling Using the Hybrid Approach 34
- Particle Size Analysis 40
- Pure Adhesive Characterization 43

Calculation of Hybrid Particle Size Distributions 45

RESULTS **47**
Assessment of the Hybrid Method... 47
Sample Truncation 47
Accounting for Adhesive Contribution.. 48
Volumetric Conversion 49
Combining Grid and Areal Samples 52
Leading Creek Hybrid Sample Analysis.. 54
Analysis of Sediment Texture and Ecological and Land-Use Parameters 60

DISCUSSION **65**

CONCLUSIONS **68**

REFERENCES.. **70**

APPENDIX.. **73**

VITA.. **86**

LIST OF TABLES

JOURNAL ARTICLE

Table 1. Leading Creek ecological data....61

Table 2. Leading Creek land-use data....61

Table 3. R-values from Pearson correlation analysis....63

APPENDIX

Table A1. Adhesive, grid, and hybrid distributions for Leading Creek sampling stations....74

Table A2. Match point ratios for hybrid pavement samples....78

Table A3. Summary of particle size statistics for Leading Creek hybrid samples....79

LIST OF FIGURES

LITERATURE REVIEW

Figure 1. Illustration of gravel-bed layers....4

JOURNAL ARTICLE

Figure 1. Leading Creek Watershed bare soil and abandoned strip mine locations. (Ph.D. dissertation by Justin Babendreier, 2000. Used with permission.)...32

Figure 2. Leading Creek hybrid sampling site locations. (Ph.D. dissertation by Justin Babendreier, 2000. Used with permission.)....35

Figure 3. Leading Creek mainstem daily average flowrates prior to hybrid sampling, measured at gage station LCS5B. (Ph.D. dissertation by Justin Babendreier, 2000. Used with permission.)....36

Figure 4. Gravelometer used during hybrid grid sampling. 38

Figure 5. Method of analysis for each particle size range....41

Figure 6. Adhesive Sample Analysis Procedure....44

Figure 7. Grid, areal, and hybrid particle size distributions for typical pavement sample T25PAV....48

Figure 8. Effect of varying correction exponent on areal distributions for pavement

sample LCS1. 51

Figure 9. Effect of varying correction exponent on D_{50} values for pavement sample LCS1 52

Figure 10. Match point ratios for diameters common to areal and grid samples 53

Figure 11. Pavement and subpavement distributions for sampling sites T58, LCS4, and LCS7 (51.1 km, 36.2 km, and 17.3 km from confluence with Ohio River, respectively 55

Figure 12. Comparison of pavement and subpavement D_{10} and D_{50} values (n=17) 56

Figure 13. Comparison of Leading Creek bed slope profile and change in subpavement D_{50} values. 58

Figure 14. Pavement and subpavement distributions for sites not associated with a tributary confluence 59

Figure 15. Armor ratios for D_{10}, D_{50}, and D_{90} statistics (n=17) 64

APPENDIX

Figure A1. Pure adhesive distributions obtained from wet sieve tests...........................80

Figure A2. Comparison of pavement and subpavement D15 values (n=17) 81

Figure A3. Comparison of pavement and subpavement D35 values (n=17) 81

Figure A4. Comparison of pavement and subpavement D65 values (n=17) 82

Figure A5. Comparison of pavement and subpavement D85 values (n=17) 82

Figure A6. Comparison of pavement and subpavement D90 values (n=17) 83

Figure A7. Comparison of percentage of material coarser than 10 mm for pavement and subpavement samples (n=17)..83

Figure A8. Comparison of percentage of material finer than 2 mm for pavement and subpavement samples (n=17)..84

Figure A9. Comparison of percentage of material finer than 0.125 mm for pavement and subpavement samples (n=17)...84

Figure A10. Pavement distributions for six Leading Creek tributary sites.......................85

Figure A11. Subpavement distributions for six Leading Creek tributary sites. 85

INTRODUCTION

Sampling the streambed of a river provides valuable information about the hydraulic and ecological characteristics present. Engineering calculations such as those relating to flood behavior and erosion potential are performed using estimators of streambed roughness, while measurements of siltation or embeddedness can be related to aquatic habitat quality.

Accurate streambed sampling is more difficult to perform in a gravel-bed stream than a sand-bed stream, in large part because of the wide range of particle sizes typically found in gravel-bed streams (Klingeman *et al*, 1993). Longitudinal and temporal variations in bed material composition can lead to sampling inconsistencies (Diplas, 1994). In addition, gravel-bed streams are typically made up of three layers, the pavement, subpavement, and underlying bed, each containing a distinct population of particles (Diplas and Sutherland, 1988; Diplas and Fripp, 1992; Fripp and Diplas, 1993). Because the pavement and subpavement layers can be correlated with different properties of a stream, generally the pavement with hydraulic characteristics and the subpavement with ecological parameters (Diplas and Fripp, 1992; Fripp and Diplas, 1993), it is often beneficial to isolate one or both of these layers during sampling. This requires sampling techniques that are conducive to layer isolation, in contrast to traditional bulk sampling, which simply removes a volume of bed material for analysis.

A hybrid sampling technique was developed by Dr. Panayiotis Diplas at Virginia Tech. The theory behind the hybrid sampling technique addresses two obstacles to accurately sampling a gravel-bed stream. First, it is an areal technique, making it capable of isolating the pavement or subpavement of a streambed. Second, it combines two established areal techniques, grid and adhesive sampling, in order to be able to sample a wider range of particle sizes present in a stream, alleviating the common problem of sampling truncation (Diplas and Fripp, 1992; Fripp and Diplas, 1993).

The potential of the hybrid method to obtain more accurate particle size distributions than previously possible makes it attractive for use in watershed monitoring programs, as well as regulatory programs. To date, the technique has been used primarily in limited academic applications and only to analyze materials larger than approximately 0.125 mm (4.93 x 10^{-3} in). More extensive use and analysis of the hybrid method is necessary so that practical applications and limitations can be determined.

During a multidisciplinary ecological risk assessment of Leading Creek watershed in Ohio performed by researchers at Virginia Tech, the hybrid method was used collect 17 pavement and 17 subpavement samples along the creek's mainstem. The watershed is heavily impacted by mining and agricultural activities, resulting in high levels of sedimentation and poor ecological quality (Cherry *et al*, 1999). The current work presents the resulting hybrid particle size distributions with the goal of examining the effectiveness of the technique in investigating fine materials (< 0.125 mm) in a gravel framework and their relationship with land-use and ecological parameters. An overall assessment of the technique throughout the sampling and analysis process was also performed.

LITERATURE REVIEW

Introduction

Gravel-bed streams are characterized by having a coarse surface layer and finer subsurface layer (Diplas, 1987) unlike sand-bed streams, for which grain size is uniform in the vertical direction. In addition, sand-bed streams have a very narrow range of particle sizes and can consequently be described with a single particle diameter statistic such as D_{50} (Diplas, 1987). Gravel-bed streams can be comprised up of material ranging from clay sized particles to cobbles or boulders. Thus, more rigorous particle size analysis is required in order to characterize such a wide range of grain sizes. Because accurate measurements of grain size statistics such as D_{50} or D_{90} require knowledge of the entire particle size distribution, it is important that all grain sizes present in a gravel-bed stream be representatively sampled (Fripp and Diplas, 1993). Traditional sampling techniques are generally biased toward the description of either large or small grain fractions, making it difficult to accurately characterize gravel-bed streams.

Characteristics of Gravel-Bed Streams

Gravel-Bed Layers

The bed surface of a gravel-bed stream is typically composed of three distinct layers. The uppermost layer, commonly termed the pavement or armor layer, contains a high percentage of coarse particles. The thickness of the pavement layer is approximately equal its D_{90} (Diplas, 1992 and 1994). Directly beneath the pavement is the subpavement layer, which is about twice its D_{90} grain size in thickness (Diplas, 1991). The particles that make up this stratum are generally smaller that those in the pavement, with the ratio of the median size of pavement to subpavement particles commonly falling between 2.0 and 2.5 (Parker, 1980). In addition, it is common for the subpavement to collect a significant amount of fine material that is able to penetrate through spaces between pavement particles. The bed below the subpavement, which does not have a predetermined thickness (Diplas and Fripp, 1992), is typically composed of material similar in size to subpavement particles, but with fewer fines (Church *et al*, 1987). Figure 1 depicts the typical composition of gravel-bed layers.

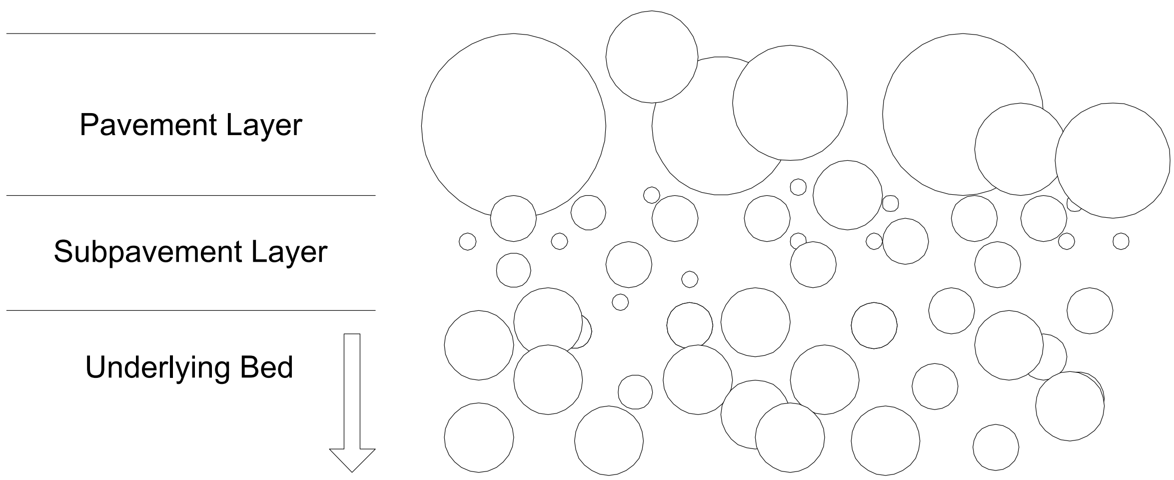


Figure 1. Illustration of gravel-bed layers.

Pavement Layer Properties

Because the pavement and subpavement layers in a gravel-bed stream are each composed of a distinct population of particles, it is important that the layers be analyzed separately. Layer isolation during gravel-bed sampling is also essential because each correlates to different properties of a stream (Fripp and Diplas, 1993). The pavement layer of a gravel-bed stream is closely linked to its hydraulic characteristics. Estimates of D_{90} and D_{50} are often used in calculations of channel roughness and stability, respectively (Fripp and Diplas, 1993), which influence the behavior of the stream during flood events.

Flow depth, bridge pier scour, and erosion potential calculations are also made using information about the surface layer. However, because the pavement layer is approximately only one grain in thickness, it is often difficult, but immensely important that it be isolated and analyzed discretely.

Many have hypothesized about the reason for the existence of a pavement layer, as well as about the processes that cause its formation. Parker and Klingeman (1982) surmised that the armor layer of a gravel-bed stream serves as a bed-load transport regulator. At low shear stresses, which are common for gravel-bed rivers, fine grains are more easily moved than coarse grains. However, a greater number of coarse grains at the surface will counteract this by increasing the chances of transport and providing spaces for finer grains to be sheltered from the flow. Because sand-bed streams typically have higher shear stresses, for which the difference in fine and coarse grain mobility is minimal, they do not form a pavement layer.

Little *et al* (1976) described the way in which a stream becomes armored under constant flow conditions. They stated that as finer, more mobile particles are washed away, the rate of sediment transport decreases because less remaining material is movable. Eventually, the sediment transport rate will approach zero, resulting in an armored surface. Thus, the formation of a pavement layer creates a more stable channel by reducing erosion. Little *et al* (1976) also presented an empirical technique to determine, for a given sediment distribution and flow properties, if a streambed will form an armor layer. The technique can also determine the D_{50} and standard deviation of the resulting particle distribution.

Subpavement Layer Properties

The composition of the subpavement layer of a gravel-bed stream is intimately connected to the ability of the stream to serve as a spawning ground for fish and habitat for benthic communities (Waters, 1995). Generally, the clogging of pore spaces by excess fines in this layer affects the abundance and diversity of the organisms that inhabit or breed within it by limiting hiding spaces and reducing oxygen content (Waters, 1995). Consequently, the percentage of fine material present has been quantified for use in ecological research (Fripp and Diplas, 1993) or for regulatory control over the quality of spawning grounds (Adams and Beschta, 1980). An accurate subpavement particle size distribution can also be used to predict bedload transport rates (Diplas, 1987).

Sediment Texture

The coarse particles in a gravel-bed stream are often referred to as the framework, while the voids between them are generally filled with much finer sediment, termed the matrix (Church *et al*, 1987). The relative proportion of each determines whether the gravel-bed is classified as framework- or matrix-supported, with matrix-supported gravels being composed of over 30% fine material (Church *et al*, 1987). Framework-supported gravels typically exhibit pronounced pavement and subpavement layers, while matrix-supported beds are more uniform with depth. In addition, a framework-supported bed will accumulate fine or matrix material during low flows and periodically purge these fines during high flows (Adams and Beschta, 1980).

Downstream Fining

Another characteristic of gravel-bed rivers is the phenomenon of downstream fining, wherein the percentage of fine particles composing the bed material increases as one moves downstream (Church and Kellerhals, 1978). Church and Kellerhals (1978) listed two mechanisms that contribute to the process, namely abrasion and selective transport of different sizes and lithologies. They presented the following relationship first introduced by Sternberg (1875) to describe downstream fining:

$$W = W_0 \exp(-a_w x) \quad (1)$$

where W is the weight of a representative bed particle, such as D_{50}, at some distance x downstream from an arbitrary starting point ($W=W_0$ where $x=0$), and a_w is the 'coefficient of weight diminution'. Church and Kellerhals (1978) found it difficult to characterize the degree of downstream fining through sampling, however, as the inherent variability in gravel-bed sampling frequently overwhelms the subtle change in bed composition due to downstream fining. In addition, the exponential trend is often interrupted by the introduction of coarse sediment via tributaries, as well as by variations in bed material lithology and stream power (Church and Kellerhals, 1978).

Accumulation of Fines

According to Diplas and Parker (1992), the accumulation of fine material in gravel-bed streams is one of the most significant results of nonpoint source pollution. Large amounts of fine sediment are often introduced into gravel-bed streams via erosion from nearby mining, forestry, construction, and agricultural activities (Diplas and Parker, 1992; Waters, 1995). Once excess fines enter a waterway, they change the structure of the gravel bed by settling into pores or sealing them off (Diplas and Parker, 1992). Accumulation of fines also affects the bed's roughness and bedload transport rate.

The introduction of excess fines into a gravel-bed stream has adverse affects on organisms that live and reproduce in the streambed (Diplas and Parker, 1992). One significant example is the resulting interference with successful fish spawning, which commonly takes place within the pool and riffle systems of gravel-bed streams (Diplas, 1994). Because sediment tends to accumulate in areas of lower velocity such as pools, desirable spawning sites can quickly become clogged. A silted bed also cannot provide adequate shelter and hiding spaces for young, vulnerable fish, resulting in increased predation. In extreme cases, sedimentation can cause reductions in water depth or the complete loss of pools, thereby limiting the carrying capacity of the stream for fish (Waters, 1995).

Siltation of gravel-bed streams also adversely affects benthic macroinvertebrate communities, which in turn limits fish productivity. Waters (1995) reported that there is a positive relationship between benthos abundance and substrate particle size, with a heterogeneous mixture of gravel, pebbles, and cobbles providing the most desirable habitat. Overly silty or mucky beds can also lead to a change in insect species composition, reducing those readily available to fish, namely Ephemeroptera, Plecoptera, and Trichoptera (EPT) species, and increasing species richness towards unavailable burrowing organisms (Waters, 1995).

Diplas (1994) studied the conditions under which fines are deposited and removed from gravel-bed streams. The addition of fines to the matrix material of a streambed is reported to typically only occur above a depth referred to as the seal depth. The thickness of the deposited fine sediment or seal thickness has been found to be a function of the framework composition, with thicknesses typically ranging from 2 to 3 times the framework D_{90} (Diplas, 1994; Lisle, 1989). Diplas (1994) reported that deposited fines can be lifted out of the pavement layer with relatively moderate flows. However, flood-scale flows causing significant bedload motion were required to remove fines from the deeper subpavement. Thus, the ecological impacts of excess fines can be persistent and difficult to reverse between major flood events.

Gravel-Bed Stream Sampling

Importance of Particle Size Analysis

Accurate descriptions of pavement and subpavment size distributions are essential for understanding the hydraulics and ecology of a gravel-bed stream. Other river characteristics such as bedload transport rate, sediment budget, and habitat description are also directly related to a bed's particle size distribution (Wohl *et al*, 1996). In addition, distinguishing the boundaries of and characterizing sediment deposits can provide a better understanding of local bedload motion (Crowder and Diplas, 1997). Accurate gravel-bed sampling can be an important component of successful channel monitoring programs (Wohl *et al*, 1996). Thus, sampling techniques capable of identifying changes in bed composition due to environmental factors or remediation efforts are essential.

There are many obstacles to accurate gravel-bed sampling. Fripp and Diplas (1993) cited large natural spatial and temporal variations in bed composition as two such complications. Spatial variations can be classified as longitudinal, e.g., downstream fining and homogeneous sediment deposits, or vertical due to the presence of an armor layer. Temporal variations are primarily the result of floods and human activities causing streambed siltation. In addition, because the range of grain sizes in a gravel-bed river can exceed four orders of magnitude, it is difficult to accurately sample all size fractions, especially when using only a single method of measurement (Church *et al*, 1987). Other sampling issues cited by Kellerhals and Bray (1971) include wide bimodal size distributions (i.e. large amounts of material in the sand and gravel range with a lower percentage in between the two) and the use of sampling procedures that are not volumetrically equivalent.

Kellerhals and Bray (1971) also addressed the confusion caused by a lack of sampling standardization. They listed five primary steps for sampling, analyzing, and describing fluvial gravels, and emphasized that complication arises because each step can be performed using several accepted methods. The first step is the selection of site and sampling time, which can in itself introduce a high degree of bias due to the existence of spatial and temporal variations. The second step is to choose the method of sample collection. Most techniques are not able to consistently sample all size fractions in proportion to their presence in the stream (Fripp and Diplas, 1993), and as a result many particle size distributions are truncated at either the upper or lower size fractions. Third, a method of grain size classification must be selected, with variations including the use of square mesh sieves, direct measurement of the b-axis with calipers, and diameter assignment based on a sphere of equal volume. The first two options are almost exclusively used and return little variation in results (Kellerhals and Bray, 1971). Step four in the process is to calculate the percentage of the sample that falls into each chosen particle size interval. The frequency can be based on total sample weight, volume, or number of stones collected. Finally, step five is the presentation of results, which is most commonly in the form of a cumulative distribution function.

Truncation

Fripp and Diplas (1993) discussed the significance of failing to sample the entire particle size range of a gravel-bed stream. They asserted that truncation not only results in a loss of information about the truncated material, but also leads to an inaccurate, distorted particle size distribution. Thus, statistics that are based on the particle size distribution such as D_{50} and D_{90} may not accurately describe the sampled bed. Furthermore, because the amount of distortion is dependent on a frequently unknown amount of missing material, truncated samples cannot be accurately compared among themselves. In some instances the percentage of truncated material is known and the bias of the distribution can be corrected. However, the shape of the entire distribution is still dependent on the shape of the truncated distribution, and can therefore not be recovered.

Gravel-Bed Stream Sampling Techniques

There are two main categories of gravel-bed sampling; volumetric and surface sampling (Diplas and Sutherland, 1988). Volumetric or bulk sampling is considered to be the traditional or standard sampling procedure (Diplas and Sutherland, 1988). It was described by Diplas and Sutherland (1988) as "the removal of a predetermined volume of bed material, sieve analysis, and interpretation of the results in terms of a frequency distribution by weight." In order to prevent bias toward the sampling of smaller particles, the volume of a bulk sample should be large enough to be independent of the individual particle sizes (Diplas and Sutherland, 1988). Volumetric sampling is most appropriate for sand-bed stream analysis or for sampling the material beneath the subpavement layer of a gravel-bed stream (Fripp, 1991).

Because bulk sampling cannot isolate bed material that is only one grain thick, it is not conducive to the study of pavement or subpavement layers (Marion and Fraccarollo, 1997; Diplas and Sutherland, 1988). For this type of analysis, surface oriented sampling techniques must be employed. Surface sampling can be broken down into three main categories; areal, grid, and transect (Diplas and Sutherland, 1988).

Areal Sampling

An areal technique samples all grains in a predetermined area that are exposed to a river's flow (Diplas and Sutherland, 1988). One way it can be accomplished is by photographing an area and visually analyzing the photo to classify grain sizes. An areal sample can also be obtained by spray-painting an area and collecting only those rocks that have been colored. This technique can introduce bias through the addition of mass to the particles and by truncating smaller particles during hand collection (Fripp, 1991). Paint can also flow into voids, causing material in the second layer to be sampled as well (Fripp, 1991). Wilcock and Stull (1989) addressed the problem of truncation during sample collection by adding magnetite to the paint. The painted particles could then be lifted from the bed with the use of a strong magnet.

Areal sampling can also be performed by using an adhesive to remove a layer of particles from the bed. Diplas and Sutherland (1988) stated that this method is the most consistent technique available. It involves pouring or pressing an adhesive such as wax, clay, epoxy resins, soap grease or tape onto the surface of a gravel bed and lifting out the layer of adhered particles. The sample is separated from the adhesive in the lab and analyzed by sieving.

Fripp and Diplas (1993) stated that clay and wax are the most commonly used adhesives. Advantages of clay include that it is readily available, easy to use, and provides repeatable results for those size fractions outside the particle distribution of the clay used. A clay adhesive sample is typically collected by spreading a layer of ordinary potter's clay onto a paddle or piston-like device and firmly pressing it onto the bed surface. Unlike wax, clay can be used to collect samples from a dry bed or under up to one meter of water, making it much more versatile (Fripp and Diplas, 1993). For analysis of size fractions > 0.125 mm (4.93 x 10^{-3} in), sample recovery involves simply washing away the clay with tap water (Fripp, 1991).

Adhesive sampling with wax is more complicated in that it requires that the wax be melted before use. The molten wax is then poured into an open frame on a dry bed surface and allowed to harden, thereby retaining the surface layer of particles (Fripp, 1991). The wax must then be remelted in the lab in order to recover the sample material. Although sampling with wax is more time consuming than other adhesives, it has the advantage of not disturbing the particles during sampling (Fripp, 1991). However, an important drawback to using wax is its tendency to flow into voids created by larger particles in the surface layer, thereby lifting out fine grains in the underlying layer. This leads to over-sampling of fine grains and an inaccurately described surface layer (Diplas and Sutherland, 1988).

Diplas and Fripp (1992) observed that the adhesive strength of clay is too low to consistently sample particles greater than 40 mm (1.6 in) in diameter. An upper size limit of 40 mm was also estimated for areal sampling using wax (Diplas and Sutherland, 1988). Thus, the larger size range of an adhesive areal sample is truncated and therefore biased. Consequently, adhesive sampling alone is most appropriate for streambeds and deposits containing predominately finer material (Diplas and Fripp, 1992).

Adhesive sampling is also more ideal for characterization of the subpavement layer of a streambed, which is primarily made up of material less than 40 mm in diameter (Fripp and Diplas, 1993). It was suggested by Fripp and Diplas (1993) that the subpavement can be easily reached and isolated by first removing the pavement layer with an areal clay sample and subsequently sampling the subpavement with the same technique (Fripp and Diplas, 1993). Subpavement isolation is difficult to achieve using traditional freeze core sampling using liquid CO_2 or liquid nitrogen, as it is often difficult to separate the entire subpavement layer from the sample. In addition, freeze core sampling is more cumbersome and expensive than the adhesive technique (Fripp and Diplas, 1993).

Grid Sampling

Grid (or grid by number) sampling involves removing stones at specific points on the gravel bed by hand (Diplas and Fripp, 1992). These points are sometimes determined by laying a wire mesh grid over the bed surface or by measuring predetermined distances with a survey tape (Kellerhals and Bray, 1971). When using a grid, the grain lying directly below each grid point is sampled. If, however, a void lies under a grid point, it is accepted that the nearest grain to the void be removed (Diplas and Sutherland, 1988).

The most widely used variation of grid sampling was first presented by M. G. Wolman in 1954 and is known as the Wolman walk or pebble count. In this method, the sampler wades out into the stream and establishes a grid by pacing off a predetermined distance. After each set of paces, the sampler picks up the pebble lying beneath the big toe of his or her right boot (Wolman, 1954). Wolman recommended that the sampler's eyes be averted when picking up the stone to avoid bias. The intermediate axis of the sampled stone is then measured with a scale, such as a Wentworth scale showing only class limits (Wolman, 1954), or gravelometer, a template with openings comparable to large sieve sizes (Hey and Thorne, 1983). The process is repeated until the desired number of stones have been sampled and measured, with 100 stones being the generally accepted guideline. Because the accuracy of a statistic such as D_{50} is a function of the distribution to be sampled as well as the sample size, statistical methods can be used to calculate the number of stones that must be collected to achieve a desired level of accuracy (Diplas and Fripp, 1992). This is important particularly when small percentages of material must be accurately estimated.

Wolman (1954) cited several advantages of the pebble count method over areal and bulk sampling, including being more applicable to sampling very coarse materials and providing "a more representative sample of an entire reach of a stream." Wolman estimated that in order to obtain a single representative volumetric sample of a coarse gravel-bed reach, approximately 200 to 300 pounds (90 to 140 kg) of material would have to be removed. Sampling at this scale would be expensive and impractical. Thus, grid sampling is an effective alternative that can be carried out by a single operator with minimal equipment. However, because the technique is somewhat subjective in terms of grid layout, pacing technique, and pebble selection (Hey and Thorne, 1983), the possibility of operator error has been addressed by numerous researchers. Although Wolman found "no significant variation in results obtained from different operators", Hey and Thorne (1983) used ANOVA tests to conclude that sample sizes greater than 120 are sensitive to operator error. It was therefore suggested that one operator perform sample collection for large samples requiring a high level of accuracy. For situations when more than one operator must be used, a maximum sample size for a given level of accuracy should be established prior to sampling (Hey and Thorne, 1983). Similar conclusions were made by Wohl *et al* (1996), as they suggested the use of a single operator when monitoring changes in channel substrate over time or when comparing distributions between multiple streams.

Wolman (1954) cited the principal limitation of the pebble count method to be "the inability to measure accurately the fine particles." He reported a diameter of 2-4 mm (0.08-0.2 in) as the smallest pebble size that can be measured in the field. However, Diplas and Fripp (1992) observed during grid sampling of the New River in Virginia that particles with a sieve diameter of about 10 mm (0.4 in) were the smallest that could be collected with precision. In their 1993 paper, Fripp and Diplas stated that a sampler cannot distinguish particles that are smaller than the width of the index finger (typically 15 mm or 0.6 in). Thus, grid sampling results in particles smaller than about 10 to 15 mm being "drastically underrepresented" (Fripp and Diplas, 1993).

Several researchers have suggested ways to correct the sampling method's bias toward larger particles. Because the probability of touching a pebble during sampling is proportional its exposed area, Leopold (1970) proposed weighting the number of particles collected in each size class by a factor "inversely proportionate to the square of the diameter of the b-axis." Diplas and Lohani (1997) suggested that particles that are too small to be picked up by hand be noted in the sampler's data collection sheet, giving an estimate of the proportion of particles in the sampled reach that are smaller than a known size, such as 10 mm (0.4 in). They further suggested that an accurate distribution of the fine material be obtained through areal sampling. This combination of sampling techniques is the basis of the hybrid method introduced by Diplas and Fripp (1992) to eliminate sampling bias associated with truncation.

Transect Sampling

Not as widely used as grid sampling, transect or line sampling involves collecting all the grains lying along a predetermined line (Diplas and Sutherland, 1988). The resulting sample is analyzed as a frequency by weight or frequency by number (Fripp, 1991). This method, like grid sampling, is only appropriate for easily distinguishable, large particles (Diplas and Sutherland, 1988).

Sample Conversion

As mentioned above, particle size analysis of gravel-bed samples is generally in the form of a frequency distribution. For bulk or adhesive areal samples, the distribution is on a weight basis and is typically obtained through sieve analysis. Grid samples are analyzed in terms of frequency by number and transect samples in terms of frequency by weight or number (Diplas and Sutherland, 1988).

Because different surface sampling techniques tend to sample different grain size populations, it is often difficult to draw accurate conclusions or make comparisons based on surface sample distributions (Fripp and Diplas, 1993). In addition, the bias present in an areal sample analyzed as a frequency by weight is typically non-linear, as larger particles removed from a specific surface area will occupy more volume and weigh more than smaller particles taken from the same area (Fripp, 1991). Because of this non-uniform bias, an areal sample cannot be accurately compared to other areal samples (Fripp, 1991).

To be able to draw conclusions and make comparisons using surface sampling results, they must be converted to an equivalent volumetric basis (Fripp, 1991). Kellerhals and Bray (1971) presented the first conversion technique for this purpose.

They used a voidless cube model with three randomly packed grain sizes, each size composing one third of the total volume, to obtain the following formula:

$$p(V\text{-}W)_i = Cp(W\text{-}A)_i D_i^x \qquad (2)$$

Where $p(V\text{-}W)_i$ and $p(W\text{-}A)_i$ are the percentages of the size fraction i from volume-by-weight and area-by-weight techniques respectively, D_i is the geometric mean diameter for the size fraction between i and $i+1$ and C is a proportionality constant equal to:

$$C = \frac{1}{\sum p(W-A)_i D_i^x} \qquad (3)$$

The exponent, x, serves to correct the bias in the surface sample and is unique to the technique used. For areal samples, this bias is toward coarser grains due to the inability of the adhesive to pick up the fine grains that are shielded by larger particles and the relationship between particle size and weight. Kellerhals and Bray (1971) experimentally determined a value of –1 for x for wax areal sample conversion. However, Proffitt (1980) and Ettema (1984) found that an exponent of –1 overcorrects for the bias toward coarse grains when wax is used because it is able to flow into voids and lift out some fine particles. Thus, the Kellerhals and Bray (K-B) voidless cube model is invalid for wax sampling (Diplas and Sutherland, 1988; Marion and Fraccarollo, 1997). For the analysis of grain sizes larger than 0.125 mm (4.93×10^{-3} in), the K-B exponent of –1 was found to result in accurate conversions of samples obtained with void independent substances such as clay (Diplas and Fripp, 1992), tape (Diplas and Sutherland, 1988), and spray paint (Church *et al*, 1987).

The Kellerhals and Bray model was also used to examine the conversion of a grid by number sample to an equivalent volumetric sample. It was determined that both procedures yield the same results, and therefore, no conversion is needed (Kellerhals and

Bray, 1971). This finding has been confirmed through experiments by Proffitt (1980), Diplas and Sutherland (1988), and Church *et al* (1987). The inherent equivalence between the two procedures is due to the fact that the weighting factor for the relationship between frequency by number and frequency by weight cancels out the weighting factor used to convert the sample to a volumetric basis (Kellerhals and Bray, 1971)

Proffitt (1980) empirically determined a more appropriate exponent of –0.47 in equation (2) for wax sample conversion through sampling material with a known particle size distribution. However, he noted that the conversion technique is "very sensitive to sampling errors in the finer sizes as a result of the negative exponent." Thus, he suggested ignoring the finest 1% of an areal distribution before converting to an equivalent volumetric sample.

Diplas and Sutherland (1988) presented a modified cube model that accounts for porosity by considering the smallest particles in the K-B model to be voids. The model considers only two grain sizes, the smaller of which being the same size as the voids and the larger being twice the diameter of the smaller. The modification results in a porosity of 33.3%, which was reported to be typical for fluvial sediments. The conversion formula obtained from the modified model is:

$$p(V-W)_i = Cp(A-W)_i f_1(D_i) f_2(D_i) \quad (4)$$

Where $f_1(D_i)$ is equal to D_i^{-1} and accounts for the particles picked up from the uppermost layer. Those additional particles that are lifted from underlying layers due to the use of a void penetrating adhesive are accounted for in the $f_2(D_i)$ term, which is equal to $D_i^{(1-x)}$. Through simulated wax sampling using the model, Diplas and Sutherland (1988) obtained a value for the exponent, x, of –0.42. They also examined the effect of porosity on exponent estimation and determined that a porosity of 30%, which was said to possibly be more appropriate for irregularly shaped particles, results in an exponent in agreement with Proffitt's experimentally determined value of –0.47.

Hybrid Sampling Technique

Because particle sizes in a gravel-bed stream can range from silt to gravel (Fripp and Diplas, 1993), a grid or areal sample alone is often not capable of describing an entire grain size distribution. In response to this deficiency, Diplas and Fripp (1992) presented a hybrid sampling technique. The method statistically combines particle size distributions obtained from grid and areal samples taken from the same site, thereby utilizing the effective sampling range of both methods to obtain a complete, unbiased description of the bed surface. Diplas and Fripp utilized a potter's clay as an adhesive for their areal sampling technique. The overlapping sampling range (between approximately 10 and 40 mm or 0.4 to 1.6 in. in diameter) allows the two distributions to be equated at what is termed the match point and rescaled to create a single distribution.

Fripp and Diplas (1993) outlined the steps needed to utilize the hybrid technique. First, it was recommended that the minimum grid and areal sample sizes required to reach statistically significant conclusions be calculated. Petrie and Diplas (2000) introduced a multinomial technique for this purpose that determines sample size based upon confidence intervals about the entire distribution. The technique requires an initial survey of the sampling site in order to estimate the largest and smallest particle sizes present. The grain size percentile of interest (e.g. D_{50}), desired width of the confidence interval or error at that percentile, and number of sieve sizes to be used in the analysis are then specified for use in the following equation:

$$\chi^2_{\alpha/k,1} = \frac{nE^2}{(E+p)(1-E-p)} \tag{5}$$

where α is the confidence coefficient, k is the number of sieves, $\chi^2_{\alpha/k,1}$ is the upper (1-α/k)100 percentage point of the chi-square distribution with one degree of freedom, n is the sample size, p is the grain size percentage of interest and E is the allowable confidence interval at that grain size. Petrie and Diplas solved the equation for different values of α, n, p, and E to create a series of graphs to be used for sample size selection. Once grid sampling is performed, a transformation developed by Petrie and Diplas (2000) can be applied to the resulting distribution in order to estimate the areal or volumetric sample size necessary to match the accuracy of the grid sample.

Fripp and Diplas (1993) also presented a bionomial technique for estimating minimum sample size that was said to be more appropriate when only information about a specific grain size percentile is needed (Petrie and Diplas, 2000). The technique begins with the calculation of the number of particles, n, in a grid sample based on the required level of accuracy of the percentile of interest. The equation developed is as follows:

$$n = \frac{z^2_{(\alpha/2)}\, p(1-p)}{E^2} \tag{6}$$

where n is the sample size, $z^2_{(\alpha/2)}$ is the two-tailed z statistic from a normal distribution for a confidence interval of 100(1-α), p is the percentile of interest, and E is the error or accuracy of the estimate. Diplas and Fripp (1992) used a mathematical proof to determine the minimum area of an areal sample and volume of a bulk sample having the same accuracy as an associated grid sample of n stones. The area and volume expressions were found to be nD_n^2 and $2nD_n^3$, respectively, where D_n is the maximum grain size present. For an areal sample, a D_n of 40 mm is a reasonable approximation, as it is the largest particle consistently amenable to clay adhesive sampling (Diplas and Fripp, 1992).

Hey and Thorne (1983) developed a method of sample size calculation using a student's t-test. The expression is given as:

$$N = \left(\frac{ts}{d} \right)^2 \quad (7)$$

where N is the grid sample size, t is the value of the t-statistic for $n-1$ degrees of freedom at a given confidence level, n is the initial sample size, s is the sample standard deviation, and d is the desired level of accuracy. Because pre-analysis is required to determine the sample standard deviation, the technique is often not feasible (Fripp and Diplas, 1993).

The second proposed step in the hybrid sampling technique is to carry out grid sampling using the Wolman walk method (Fripp and Diplas, 1993). For each particle collected, the sieve diameter is recorded as the minimum opening in a gravelometer that the stone can pass. An areal sample is then used to collect finer particles within the study area. The exact location for areal sample collection is determined by performing a variation of the Wolman walk wherein the sampler paces off a predetermined distance and examines the bed directly under his or her right big toe. If the location contains particles that are predominately less than 40 mm (1.6 in) in size, a sample is taken. If not, the sampler continues to pace the grid. A piston device with a thin layer of potter's clay, as used in a study carried out by Fripp and Diplas (1993), can be used to lift the areal sample from the bed. In some cases, several areal samples must be collected to obtain the previously calculated minimum sample area.

Once grid and areal samples have been collected, the distributions from each must be combined to obtain the overall particle size distribution of the bed material (Fripp and

Diplas 1993). The areal distribution, which is obtained through sieve analysis of the combined areal sample, must first be converted to an equivalent volumetric distribution using the appropriate exponent for the adhesive material used. As discussed previously, the grid by number sample is already equivalent to a volumetric sample and needs no conversion. In order to combine the grid and converted areal distributions, the percentiles for the size fractions common to both distributions (typically between 15 mm and 40 mm) must be examined. A size fraction within this range for which the percentiles of each distribution are of similar proportion is then chosen as a match point. One sample distribution is adjusted to fit the other by multiplying each percentile in the first distribution by a factor equal to the ratio of the percentiles at the match point chosen. Thus, the distributions are made to be equivalent at the match point. Fripp and Diplas (1993) described the overall distribution to simply be the grid distribution for percentiles above the match point and the areal distribution for percentiles below the match point. Finally, a scaling factor is used so that sum of the total distribution's percentiles is equal to 100%.

Other Sampling Considerations

Several criteria should be considered when sampling a gravel-bed stream. Kellerhals and Bray (1971) stressed that the sampling method chosen should be able to obtain the correct population for the data desired. For example, a surface oriented technique should be employed for an investigation of fluvial processes. Kellerhals and Bray (1971) also noted that the efficiency of the sampling scheme chosen with respect to the data needed should be considered. Thus, a very large bulk sample should not be collected if the same information can be obtained from a 100 stone grid sample. Sample site selection also plays an important role in the results obtained. Thus, when samples are to be compared, a consistent portion of each reach should be selected so that changes in hydraulic properties do not bias results (Kellerhals *et al,* 1976). Finally, determining an adequate sample size prior to field-work can facilitate the accurate characterization of bed material (Church and Kellerhals, 1978; Diplas and Fripp, 1992; Petrie and Diplas, 2000).

JOURNAL ARTICLE

INTRODUCTION

Gravel-Bed Stream Sampling

The composition of streambed material greatly influences both hydraulic and ecological characteristics of a river. Thus, accurately describing this material is important for many engineering and biological applications. Obtaining complete and accurate particle size distributions for gravel-bed streams, however, can be exceedingly difficult. First, it is not uncommon for a gravel-bed stream to be composed of particles ranging from clay (<4 μm or 1.6×10^{-4} in) to cobbles or boulders (>256 mm or 10.1 in) (Klingeman *et al*, 1993). Thus, a single sampling technique is often not sufficient to accurately investigate these stream beds. Large temporal variations in bed material composition due to variations in bedload transport rates also contribute to sampling inconsistencies, as the fraction of matrix material (particles less than approximately 0.125 mm or 4.93×10^{-3} in) is largely dependent upon the elapsed time since a major flood event (Diplas, 1994). As a result, bed material monitoring over time can produce unreliable and misleading results. Likewise, the alternating bar structure of many gravel-bed streams makes the location of sample collection a significant variable. Finally, the characteristic vertical stratification of bed material in gravel-bed streams adds another dimension to sampling. In order to fully assess stream behavior and quality, it is often necessary to isolate the uppermost layer or pavement layer and/or the underlying subpavement layer.

Not only is each layer in a gravel-bed stream made up of a distinct distribution of particle sizes, but each also correlates to different properties of a stream. Because the pavement layer is in direct contact with the water flow, its composition influences the stream's hydraulic behavior. As a result, estimators of pavement layer quality are important for engineering calculations such as those related to flood behavior, erosion potential, and bridge and pier scour. The subpavement layer of a gravel-bed stream is an essential habitat for fish spawning and benthic communities, and both the amount and size of the sediment present can affect fish productivity (Waters, 1995). Excess fine material, which is often introduced into gravel-bed streams via erosion from nearby mining, forestry, construction, and agricultural activities, typically settles in the subpavement layer where it can have a choking effect (Diplas, 1994). As a result, biologists frequently study subpavement composition as an indicator of ecological health. For example, the amount of sediment finer than 1 mm (0.4 in) in diameter has been used as a measure of habitat quality and sedimentation impact during stream monitoring and risk assessment studies (Adams and Beschta, 1980). Some water-quality standards have incorporated limits on fine sediments in spawning gravels (Adams and Beschta, 1980). However, because of the temporal variations in fine sediment quantity, a consistent, repeatable method for sampling is needed. Typically, it is recommended that sampling be performed at low flow conditions when beds are most stable and easily accessed (Babendreier, 2000; Lisle, 1989). In addition, analyzing stream flow records several months up to bed sampling is recommended to help identify potential sources of variation (Babendreier, 2000). Perhaps most important, however, is the use of an unbiased sediment sampling technique that is appropriate for all particle sizes present in the streambed.

Sediment Sampling and the Hybrid Method

Traditional volumetric or bulk sampling is the only truly unbiased sampling technique available; however, it has two significant drawbacks. First, it is often infeasible for gravel-bed streams that contain very large gravel and boulders, as the sample size collected must be large enough to be independent of individual particle sizes. Thus, in some instances, a volumetric sample would have to weigh several hundred pounds to be unbiased (Wolman, 1954). Second, bulk sampling is unable to isolate pavement and subpavement layers in a gravel-bed stream and is therefore inappropriate for many engineering and biological applications (Diplas and Fripp, 1992; Hey and Thorne, 1983; Kellerhals and Bray, 1971; Marion and Fraccarollo, 1997). The alternative to volumetric sampling is to collect a layer of particles or areal sample and later convert the results to a common, unbiased volumetric basis.

Grid sampling is a commonly used areal sampling technique. The most simple variation, called the Wolman walk, requires a researcher to wade into a stream and remove by hand particles found at points on a grid. Although a wire mesh grid can be used, a pacing technique is often chosen for simplicity. At each set of paces, the sampler stops and picks up, with eyes averted, the particle directly under his or her toe and measures the particle size using calipers, a template, or other measuring device. The process is repeated until the sampler has collected a predetermined number of stones based on achieving a desired level of accuracy, typically around 100 stones. The results are then typically analyzed as a frequency distribution by number. The resulting distribution has been determined by numerous studies to be equivalent to that obtained by a volumetric sample (Church *et al*, 1987, Diplas and Sutherland, 1988; Kellerhals and Bray, 1971; Proffitt, 1980).

The primary disadvantage of grid sampling is that the smallest particle size that can be consistently sampled is limited by the size of the researcher's finger (typically 10-15 mm or 0.4 to 0.6 in) (Diplas and Fripp, 1992; Fripp and Diplas, 1993). Because truncating any portion of a particle size distribution results in a distortion of the entire remaining distribution, using only a grid sample to describe a bed that contains particles finer than 15 mm leads to biased and misleading results (Fripp and Diplas, 1993).

Other areal sampling techniques entail sampling all grains in a predetermined area of the bed. Spray-painting an area and collecting the colored particles is one such technique, but bias can occur by truncating smaller particles during hand collection or sampling material in the second layer that received paint (Fripp, 1991). Another frequently-used method is to lift out a layer of grains using an adhesive such as wax, clay, epoxy resins, or tape. Of these adhesives, wax and clay are the most effective and commonly used (Fripp and Diplas, 1993). Although desirable because it does not disturb sampled particles, disadvantages associated with wax include its inability to sample submerged beds and most importantly, its tendency to flow into pavement voids, thereby sampling fine grains in the underlying layer (Diplas and Sutherland, 1988). The handling of molten wax can also be a hazard for researchers. Clay is readily available, easy to use, and has been shown to provide repeatable results when used to collect materials larger in diameter than the largest particle present in the clay adhesive (Fripp and Diplas, 1993). It can be used to conveniently collect samples from both a dry bed or a bed under up to one meter of water (Fripp and Diplas, 1993). Typically, the clay is separated from the sample by wet sieving.

The adhesive strength of the clay or wax used to collect the sample determines the largest particle that can be accurately sampled (typically around 40 mm or 1.6 in). Consequently, adhesive sampling alone is most useful for deposits containing predominately fine material or for subpavement sampling (Diplas and Fripp, 1992).

Areal samples must be mathematically converted to an equivalent volumetric basis in order to make accurate comparisons between samples. This conversion process is complicated by the fact that the bias in an areal sample is not linear, but rather varies with grain size. Because larger particles occupy a larger volume than smaller particles for an equal surface area, areal distributions tend to be skewed toward the upper grain sizes (Fripp, 1991). The conversion model typically used is the following formula developed by Kellerhals and Bray (1971):

$$p(V-W)_i = Cp(W-A)_i D_i^x \quad (1)$$

where $p(V\text{-}W)_i$ and $p(W\text{-}A)_i$ are the percentages of the size fraction i from volume-by-weight and area-by-weight techniques, respectively, D_i is the geometric mean diameter for the size fraction between i and $i+1$, and C is a proportionality constant equal to:

$$C = \frac{1}{\sum p(W-A)_i Di^x} \quad (2)$$

The value of the exponent, x, is dependent on the sampling technique used. For wax areal sampling, a value of –0.47 is commonly used (Diplas and Sutherland, 1988; Proffitt, 1980), while –1 applies for clay samples (Diplas and Fripp, 1992). The smaller correction for wax samples results from the tendency of wax to pick up fine grains from underlying layers.

In order to avoid the inaccuracies associated with sample truncation, either at the upper or lower portion of the size range, a hybrid sampling technique can be used. The technique, which was first presented by Diplas and Fripp (1992), utilizes both grid and clay areal sampling to obtain a complete, unbiased particle size distribution. In addition, the hybrid method allows a pavement and subpavement sample to be sequentially collected, thus allowing for a more complete analysis of both hydraulic and ecological conditions in the stream. Because the technique requires minimal equipment, can be performed by a single operator, and can be used in both dry and wet streambeds, it is ideal for incorporation into watershed monitoring programs. In addition, the potential of the technique to obtain more accurate distributions than previously possible may in turn allow researchers to achieve more accurate engineering and ecological assessments.

Objectives and Approach

Researchers at Virginia Tech performed a multidisciplinary ecological risk assessment of Leading Creek watershed in Ohio. Among the work performed was measurements biodiversity, water and sediment chemistry and toxicity testing, habit surveys using USEPA and Ohio EPA methods, GIS land use and cover data collection, and flow and water quality modeling.

Hybrid sampling along Leading Creek's mainstem was performed by Dr. Justin Babendreier during the risk assessment in an attempt to validate its use for large-scale studies, particularly in cases where accurate sampling of very fine material is needed. As a continuation of his work, particle size analysis of the 17 pavement and 17 subpavement hybrid samples collected was performed for the present work in order to: (1) assess the overall effectiveness of the sample collection and data analysis methods, (2) examine relationships between the resulting particle size distributions and Leading Creek ecological and land-use data, particularly for materials finer than 0.125 mm (4.93 x 10^{-3} in); and (3) evaluate the potential of the technique as a tool in future regulatory and research oriented stream studies.

Background on Leading Creek Watershed

Leading Creek, located in southeastern Ohio, is part of the Ohio River Basin. The approximately 388 km^2 (150 mi^2) watershed contains a network of 61 first to fourth order tributaries, many of which are heavily impacted by abandoned strip mine land (ASML) and abandoned near-surface underground mine land (AUML), and active deep underground mines (Babendreier, 2000). In addition to coal mining, Leading Creek Watershed contains numerous urban, agricultural, and limestone quarry operations. As seen in Figure 1, bare soil areas, indicating agricultural and construction activities, are concentrated in the upper portion of the watershed, while abandoned mine lands are generally located in the middle and lower portions. As a result of these activities, the watershed suffers from low water pH, high concentrations of metals and sediment in the water column, and excessive inundation of streambeds by clay, silt, and sand (Cherry *et al*, 1999). These conditions in turn have adversely affected stream ecology in Leading Creek. In addition, the reduced carrying capacity of the stream has led to more frequent and severe flooding.

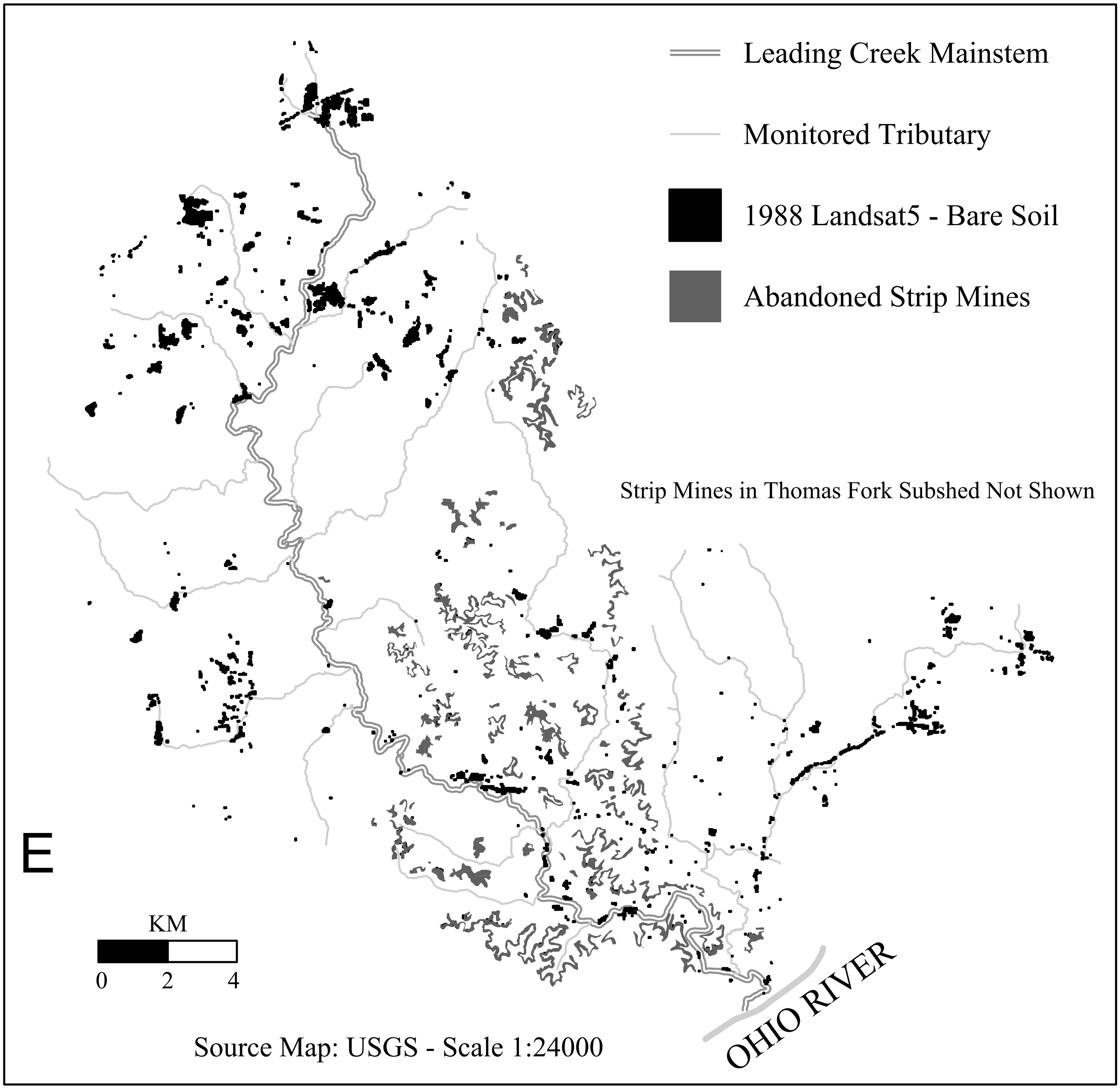


Figure 1. Leading Creek Watershed bare soil and abandoned strip mine locations. (Ph.D. dissertation by Justin Babendreier, 2000. Used with permission.)

In response to the degradation of Leading Creek, a multidisciplinary hydrologic-based ecological risk assessment of the watershed was performed by a group of Virginia

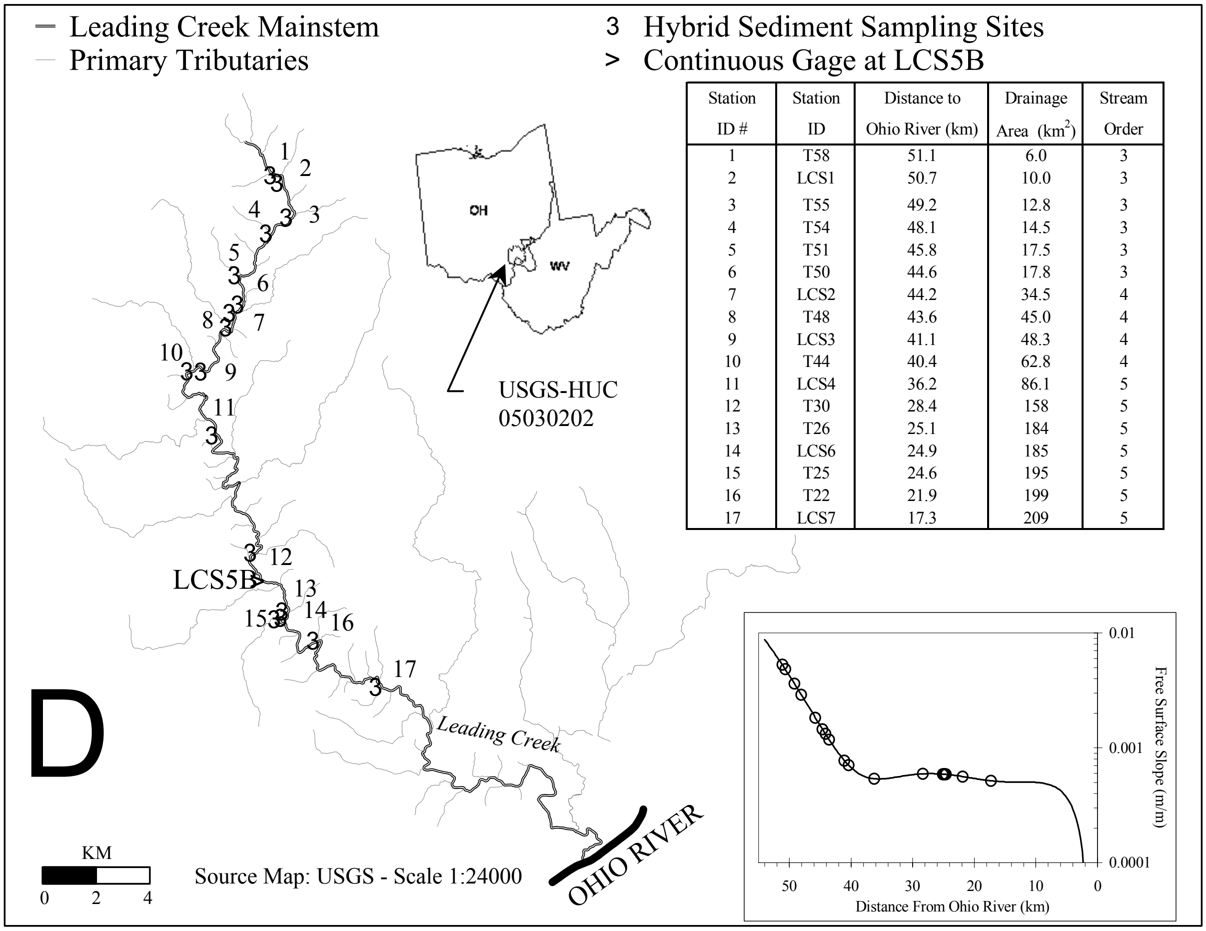
Tech scientists and engineers. One goal of the study was to gain a better understanding of the impacts of such commingled land uses on aquatic habitat, toxicity, and biodiversity. During the study, a wide range of biological and water quality parameters were monitored at 28 to 55 stream sites throughout the watershed. Three relatively unimpacted reference stream sites in two nearby watersheds were also monitored. Among the parameters evaluated were several indices of biodiversity and habitat quality.

The upper 75% of the Leading Creek mainstem is characterized as a gravel-bed stream. In this portion, the stream exhibits a weak pool-riffle configuration with alternating bars and tributary bars. At a distance of approximately 16 km (10 mi) from its confluence with the Ohio River, the mainstem streambed becomes more dominated by sands and finer materials, primarily due to natural sorting processes and the increasing dominance of strip mines and associated sedimentation. Throughout the Leading Creek watershed, human activities have contributed to high levels of sedimentation, which has significantly decreased the natural carrying capacity of the channel in some areas (Cherry *et al*, 1999). More frequent and severe floods have occurred in recent years as a result of this decreased capacity. In addition, sedimentation has impacted ecological health in the watershed by destroying aquatic habitat and reducing the transport of oxygen and nutrients into the streambed.

MATERIALS AND METHODS

Sampling Using the Hybrid Approach

As part of the Leading Creek risk assessment study, hybrid samples were collected by single operator, Dr. Justin Babendreier, at 17 sampling stations along the mainstem between the 12^{th} and 16^{th} of September, 1997. Hybrid sampling sites were located in an area between approximately 51 and 17 km (32 and 11 mi) from Leading Creek's confluence with the Ohio River. Each station was assigned a station ID, with general mainstem sites designated by the letters LCS and sites immediately downstream from a tributary confluence designated by a T-prefix. Figure 2 shows the location of each sampling station, as well as gauging station LCS5B, and summarizes the information associated with each site.



Station ID #	Station ID	Distance to Ohio River (km)	Drainage Area (km^2)	Stream Order
1	T58	51.1	6.0	3
2	LCS1	50.7	10.0	3
3	T55	49.2	12.8	3
4	T54	48.1	14.5	3
5	T51	45.8	17.5	3
6	T50	44.6	17.8	3
7	LCS2	44.2	34.5	4
8	T48	43.6	45.0	4
9	LCS3	41.1	48.3	4
10	T44	40.4	62.8	4
11	LCS4	36.2	86.1	5
12	T30	28.4	158	5
13	T26	25.1	184	5
14	LCS6	24.9	185	5
15	T25	24.6	195	5
16	T22	21.9	199	5
17	LCS7	17.3	209	5

Figure 2. Leading Creek hybrid sampling site locations.
(Ph.D. dissertation by Justin Babendreier, 2000. Used with permission.)

Relatively low-flow conditions existed at the time of sampling. However, the system incurred an approximate 100-year storm on March 1 of 1997 followed by several bankfull and near-bankfull events in the subsequent three weeks. The sampled stretch of Leading Creek was characterized by the sampler as having uniform flow (Babendreier, 2000). The flow record for the Leading Creek mainstem, normalized to the drainage area of the gauging site, is provided in Figure 3.

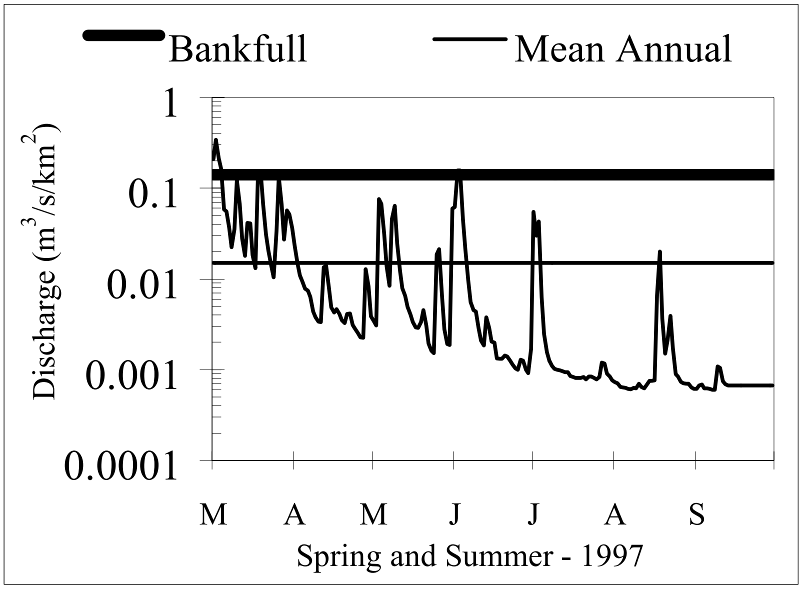


Figure 3. Leading Creek mainstem daily average flowrates prior to hybrid sampling, measured at gage station LCS5B. (Ph.D. dissertation by Justin Babendreier, 2000. Used with permission.)

Sampling zones at each station were selected based on the nearest downstream gravel bar below each sampling site. These gravel bars were typically associated with an alternating bar structure. The actual areas chosen for sampling represented the control structure (riffle bar area) for upstream pools (i.e. the turbulent zone of the standard pool-riffle configuration). The sampling zone covered the entire stream width (excluding bank toes) within the control structure. Reach lengths sampled ranged from 3 to 23 m (10 to 75 ft), while reach widths ranged from 2 to 14 m (0.6 to 47 ft), with most cross-sections between 6 to m (20 and 40 ft).

At each station, a grid sample was collected within the predetermined sampling zone in accordance with the technique developed by Wolman (1954). The sampler generally took 5 paces in one direction, bent down and with eyes averted, collected the stone nearest to his right big toe. He then turned left and repeated the process. The pacing technique was slightly altered around obstacles such as large boulders. One hundred to 150 pebbles were removed from the bed without replacement for each sample. Because the pacing distances and turns were not uniform, a random sampling was achieved.

Most pebbles were measured at the site with the use of a gravelometer, a plexi-glass sheet with openings corresponding to sieve diameters from 9.4 to 152.4 mm (0.37 to 6.0 in) (Figure 4). Pebbles that were larger than the largest opening in the gravelometer were measured at the site with a hand-tape measure by recording the diameter of all three ellipsoidal axes. Encountered only at site T20, boulders too large to sample in this manner (larger than approximately 0.66 m or 2.2 ft on the longest axis) were measured in place with a hand-tape measure by recording the diameter of all three ellipsoidal axes. Boulders measured in place were not resampled if encountered again. Except for immovable boulders, stones were continuously collected, and all were measured for size after sampling was completed.

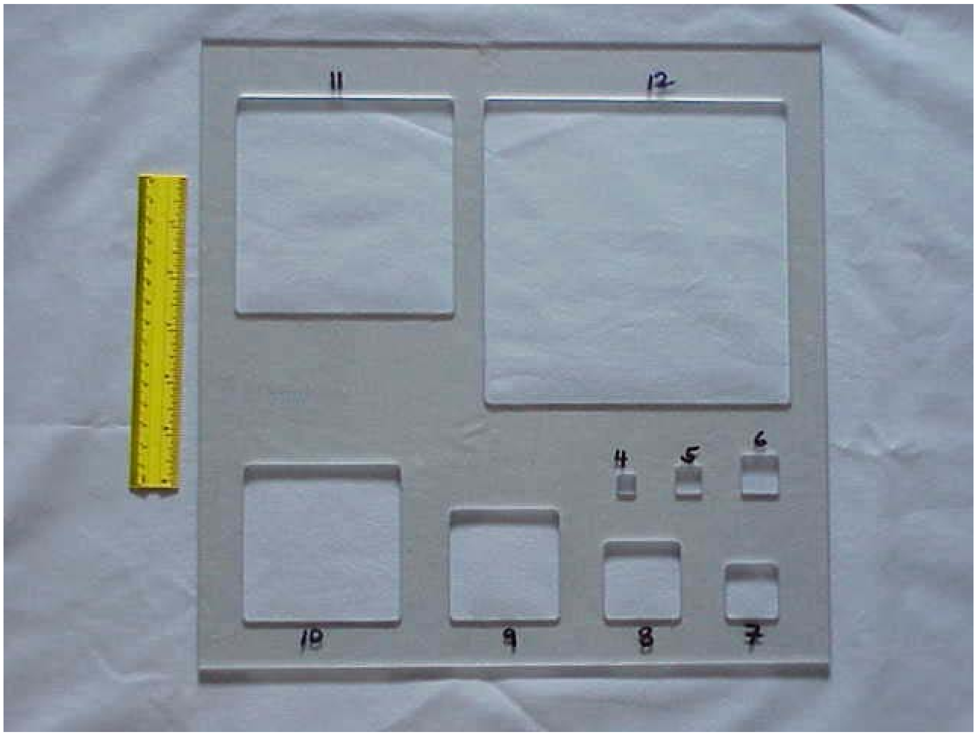


Figure 4. Gravelometer used during hybrid grid sampling.

Generally, 10 clay adhesive subsamples were collected of both the pavement and subpavement (sequentially) at each sampling station. At two sampling sites, one subsample was compromised during collection, and thus only 9 subsamples were retained. A circular-faced plunger with a diameter of 140 mm (5.5 in) was used for sample collection. For each subsample, approximately 200 g (0.4 lb) of moist potter's clay was spread evenly onto the surface of the plunger, creating an approximately 1- to 1.5-cm (3/8- to 0.5-in) layer. The potter's clay used was manufactured by Columbus Clay and classified as #C-010-105 white clay without grog (ground-up brick). A space of about 0.5 cm (0.2 in) around the outer edge of the plunger was left without clay to avoid deformation over the plunger's edge. To ensure good adhesion, the plunger was consistently, evenly pressed onto the bed surface with a large amount of force, approximately equivalent to the sampler's body weight. The layer of particles was then lifted from the bed.

Similar to the pebble counts, site selection for adhesive subsamples was also based on a random walk within the sampling zone. If an area at a distance of 5 paces did not exclusively contain particles less than 40 mm (1.6 in) in diameter, a sample was not taken and the operator paced the next distance. At four sites, T60, LCS5B, T28, and T20 (not included in Figure 2), no adhesive samples were collected because although some smaller particles were present, the operator could not find areas with all particles finer than approximately 40 mm. Thus, information at these sites consisted only of grid sampling data.

Adhesive subsamples were collected from both wet and dry bed surfaces, depending on the conditions at each site. Wet versus dry portions of the bed varied from site to site with wet areas ranging from as low as 15% to approximately 30% of the cross-section width. The depth of water ranged from approximately 2.5 to 15 cm (1 to 6 in) at all but two sites where portions of the cross-sections were under approximately 0.5 m (1.6 ft) of water. For dry bed samples, a thin film layer of silt and clay sized particles was often observed on the underside of larger sample particles, the effect being more pronounced for subpavement samples. At very heavily silted sites, this clumping may have resulted in the addition of a layer of silt and clay sized particles approaching 10 mm (0.4 in) at points. Wet bed samples generally did not exhibit any significant degree of clumping or film build-up, except for station LCS6 where sticking was observed for both silt and sand materials collected from the fully wet cross-section.

Particle Size Analysis

Particle size distributions for each grid sample were obtained through a frequency by number analysis of the gravelometer and caliper data. For caliper measurements, an equivalent sieve diameter for each particle size was determined with the following equation (Church *et al,* 1987):

$$\frac{D}{b} = \frac{1}{\sqrt{2}} * \sqrt{1 + \left(\frac{c}{b}\right)^2} \tag{3}$$

where D is the sieve diameter and c and b are field-measurements of the shortest and intermediate particle axes, respectively.

Adhesive samples were analyzed by performing a series of wet and dry sieve tests (Figure 5). Laboratory analysis for each air-dried sample began by soaking the material in distilled water for several days to loosen the dried, cemented fines. The wetted sample was then manually agitated until most of the clay was in suspension. In accordance with sections 6.1.2-6.1.4 of ASTM D 2217-85, *Standard Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants*, the sample was split at a particle size of 2 mm (0.08 in) by passing it through a standard No. 10 sieve. The portion of section 6.1.3 of the ASTM procedure calling for the coarse fraction to be dry sieved on a No. 10 sieve and the material passing to be added to the fine fraction was omitted due to the potential of significant breakage of soft shale, sandstone, and siltstone particles during sieving.

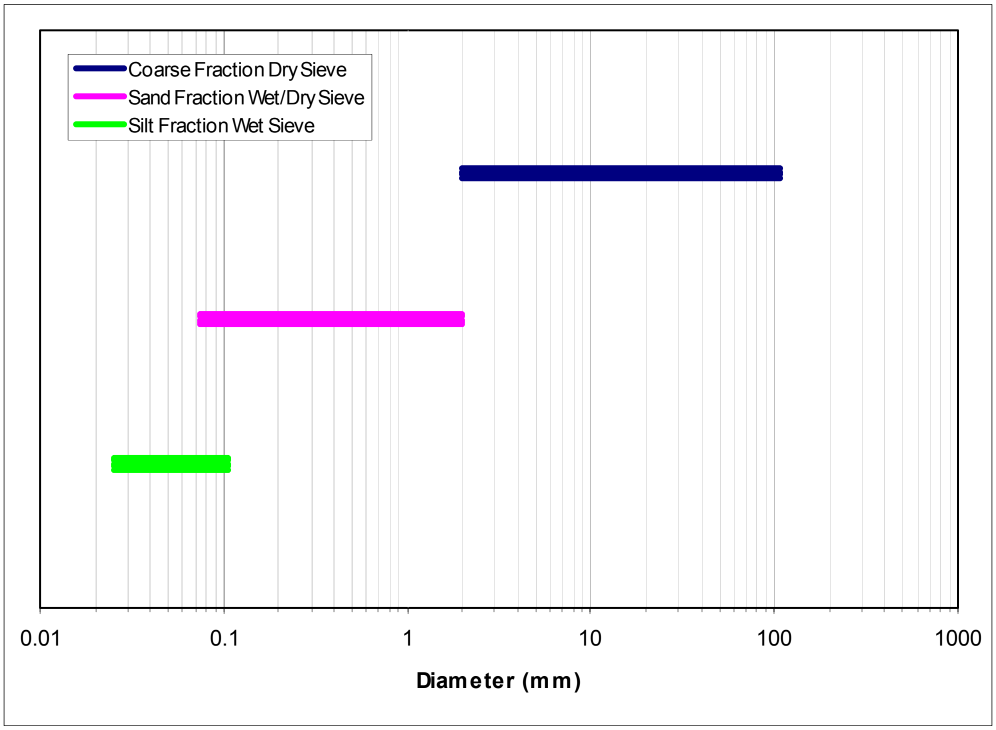


Figure 5. Method of analysis for each particle size range.

Dry sieve analysis was performed on the coarse fraction of each sample according to section 6 of ASTM method D 422-63, *Standard Test Method for Particle-Size Analysis of Soils*. A Ro-Tap Testing Sieve Shaker, Model B made by W.S. Tyler, Inc. was used for all dry sieving tests. All retained weights were determined with a balance sensitive to 0.01 g (3.5 oz).

The fine fraction of each sample was subsampled using the method of quartering described in ASTM C 702-93, *Standard Practice for Reducing Samples of Aggregate to Testing Size*. Subsamples consisted of two ~100-g (0.2 lb) samples used to characterize silt content, one ~25-g (0.06 lb) sample for hygroscopic moisture analysis, performed in accordance with section 8 of ASTM test method D 422-63, and one ~200-g (0.4 lb) archive sample. The fine material remaining after subsampling (approximately 2000 g or

4 lb of natural sediments and adhesive clay), the two ~100-g samples, and the hygroscopic test sample were dried to constant mass at 110 ± 5°C.

The two dry ~100-g samples were weighed and then soaked for at least 8 h in 125 mL of 40 g/L sodium hexametaphosphate solution (a dispersing agent). The samples were each subsequently passed through a series of sieves using a modified version of the wet procedure described in section 7.3 of ASTM method D 1140-97, *Standard Test Method for Amount of Material in Soils Finer Than the No. 200 (75-μm) Sieve*. Standard sieve sizes No. 140 (0.106 mm=4.18 x 10^{-3} in), No. 200 (0.075 mm=2.96 x 10^{-3} in) and No. 500 (0.025 mm=9.85 x 10^{-4} in) were used for this portion of the procedure rather than a single No. 200 sieve. The mass of material retained on each sieve was determined in accordance with sections 7.4 and 7.4.1 of ASTM D 1140-97.

The ~2000-g fine fraction sample was analyzed to characterize the adhesive sample particle size distribution between 0.075 mm and 2 mm (0.08 in). It was first soaked for at least 8 h in a 40 g/L (0.25 lb/ft^3) hexametaphosphate solution. After soaking, the wetted sample was further dispersed with a paint stirring paddle attached to an electric drill. The suspension was poured and washed through a standard No. 100 (0.150 mm=5.91 x 10^{-3} in) sieve resting on a separate container so that the washings could be collected. The material retained on the No. 100 sieve was transferred to an oven-safe container. The washings were wet sieved through a No. 200 sieve using the method described in section 7.3 of ASTM D 1140-97. Wet sieving had to be performed in several increments to prevent clogging of the sieve. The material retained on the sieve for each increment was transferred to an oven-safe collection container before the next increment was poured into the sieve. The material retained on each sieve was dried in its respective container to a constant mass at 110 ± 5°C. The dry material was then combined, weighed, and dry sieved according to section 6 of ASTM D 422-63 using a series of sieves with mesh sizes between 0.075 mm and 2 mm. Figure 6 summarizes the separation and analysis process used for adhesive samples.

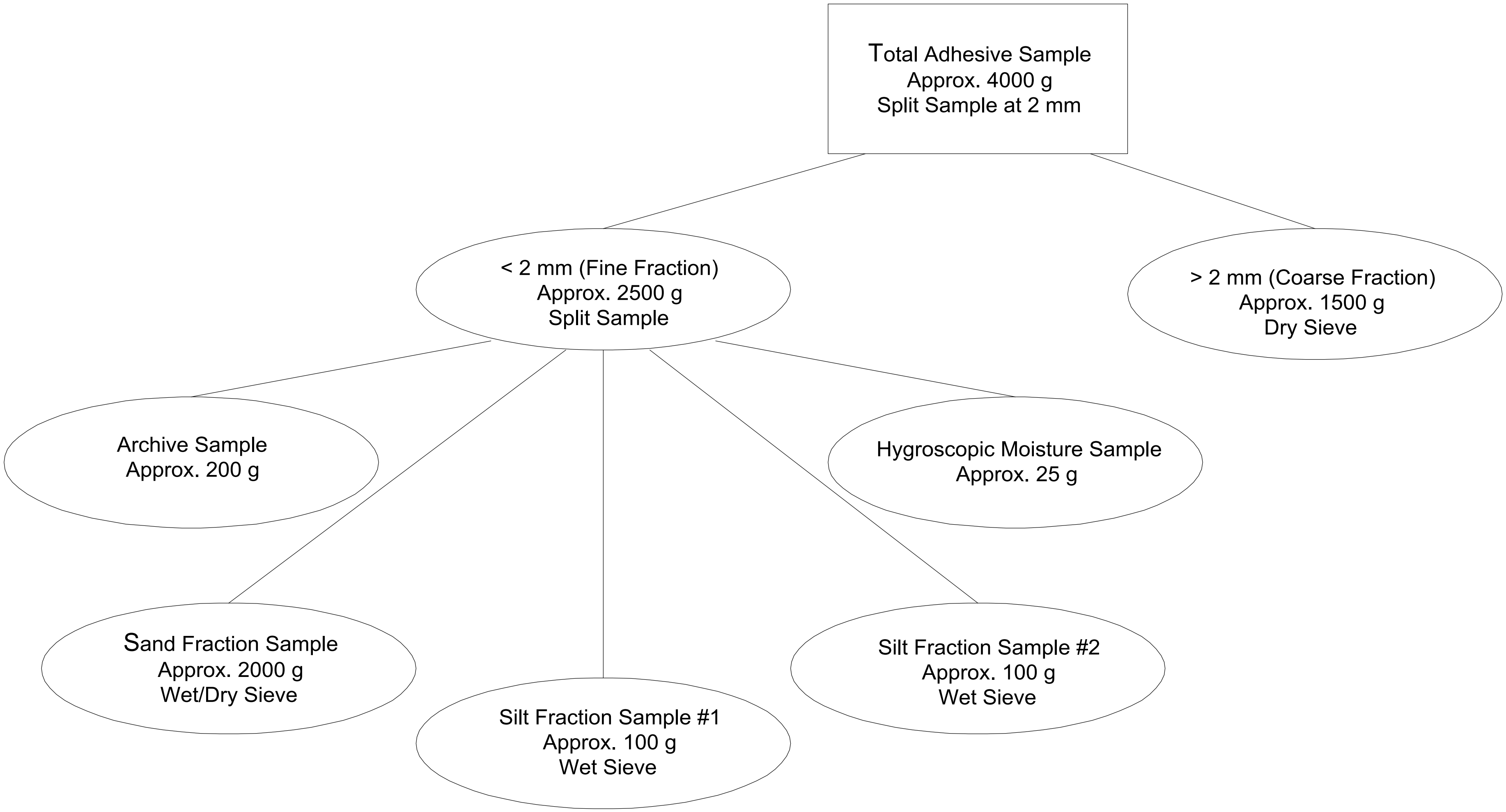


Figure 6. Adhesive Sample Analysis Procedure

Calculation of Hybrid Particle Size Distributions

All areal sample distributions were converted to equivalent volumetric distributions using Equation (1). A two-exponent approach was used, -1 for size fractions above a geometric mean diameter of 1.4 mm (5.5 x 10^{-2} in) and 0 for all fractions below 1.4 mm. The following modified conversion equations were applied:

$$p(V-W)_i = C_1 p(A-W)_i D_i^{x1} \tag{4}$$

$$p(V-W)_j = C_2 p(A-W)_j D_j^{x2} \tag{5}$$

With the first equation correcting the distribution at each size fraction, *i*, above 1.4 mm with an exponent, x_1, of –1 and the second equation applying a correction exponent, x_2, of 0 to each size fraction, *j*, below 1.4 mm.

At the 1.4 mm diameter, the two conversion methods are equivalent, yielding the following expression:

$$C_1 p(A-W)_{1.4} 1.4^{x1} = C_2 p(A-W)_{1.4} 1.4^{x2} \tag{6}$$

which simplifies to:

$$C_1 1.4^{x1} = C_2 1.4^{x2} \tag{7}$$

Equation 7 was used with the following modified proportionality expression to solve for the constants, C_1 and C_2:

$$\sum C_1 p(A-W)_i D_i^{x1} + \sum C_2 p(A-W)_j D_j^{x2} = 1 \tag{8}$$

Volumetric conversion of grid sample distributions was not needed due to the inherent equivalence between the two methods.

The overall bed material distributions for pavement sites were obtained by combining the corrected areal and grid distributions according to the method described in Fripp and Diplas (1993). A uniform geometric mean diameter of 15.55 mm (0.613 in) was used as the match point for all samples.

RESULTS

Assessment of the Hybrid Method

Sample Truncation

The grid, areal, and resulting hybrid distributions (Table A1 in Appendix) were plotted and assessed for each sample. A typical pavement sample, T25PAV, is provided as Figure 7. For this particular sample, it can be seen that grid sampling was effective for particles in the range of approximately 6 to 200 mm (0.2 to 8 in) and provided a median particle diameter of 24.9 mm (0.98 in), while areal sampling removed particles in the range of approximately 0.01 to 10 mm (3.9 x 10-4 to 0.39 in) and resulted in a median particle diameter of 4.24 mm (0.17 in). The hybrid distribution includes the ranges of both the grid and areal samples and results in a mean diameter of 6.69 mm (0.26 in). The difference in mean diameter obtained from the three distributions demonstrates the effect of sample truncation on the accuracy of extracted metrics and the ability of the hybrid method to increase accuracy by reducing this truncation.

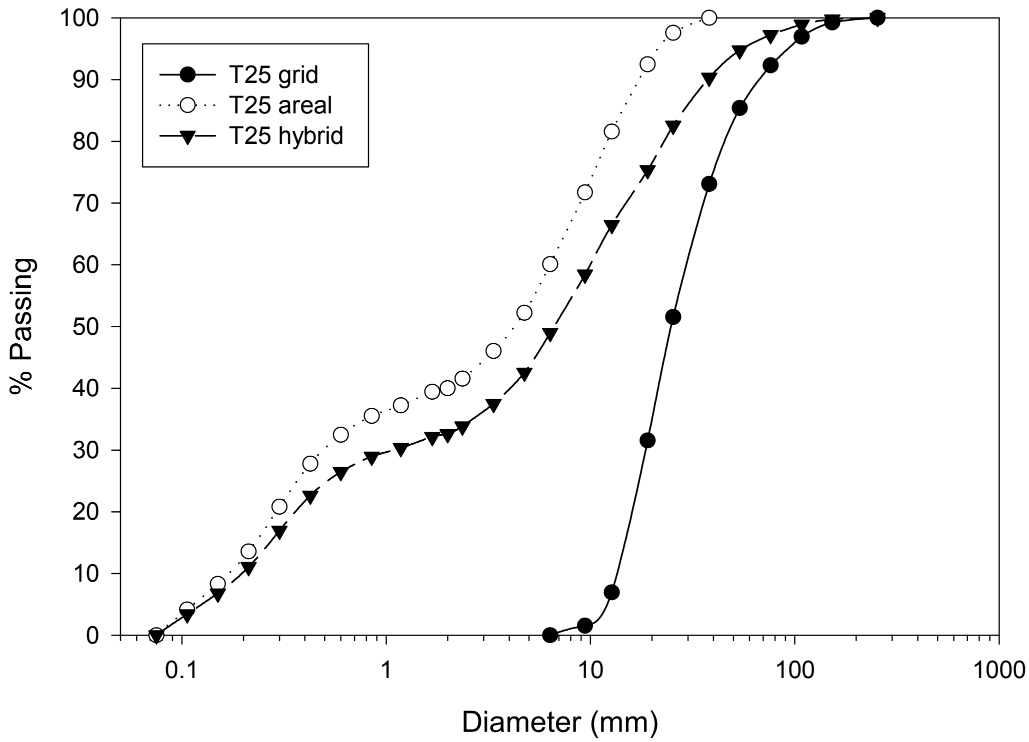


Figure 7. Grid, areal, and hybrid particle size distributions for typical pavement sample, T25PAV.

Accounting for Adhesive Contribution

The finest available bulk potter's clay was used as the adhesive in areal sample collection. Because the clay was anticipated to be made up of only particles in the fine silt and clay size range (less than approximately 62 μm or 2.4 x 10^{-3} in), below the target size fractions to be included in the bed material size distribution analysis, the mass of clay used to collect each areal subsample was not recorded prior to sampling. Several wet sieve tests performed prior to sample analysis revealed that approximately 22% of the clay material was between 0.025 and 0.075 mm (9.9 x 10^{-4} and 3.0 x 10^{-3} in) in diameter. This silt and sand content resulted in an overlap between the natural sediment distribution and the distribution of the clay used to collect the sample. As a result, further particle size analysis was performed in order to more accurately characterize the adhesive distribution. Four representative samples of the pure adhesive were wet sieved through standard sieve sizes No. 100, No. 140, No. 200, and No. 500. The graph of replicate and average distributions for the adhesive can be found as Figure A1 in the Appendix. The analysis showed that 99.97% of the adhesive material was finer than 0.150 mm, 99.75% was finer than 0.106 mm, 98.18% was finer than 0.075 mm, and 75.86% was finer than 0.025 mm. Using the clay distribution and an estimate of the mass of clay added to each sample, an attempt was made to subtract the clay from the natural sediment distributions. However, data for size fractions finer than 0.075 mm were found to consistently overwhelmed by the pure adhesive content. More intensive error analysis also showed some interference in fractions larger than 0.075 mm for samples containing a smaller than average percentage of natural sediment finer than 2 mm (approximately less than 4% by weight).

Because of the errors seen in extracting fine sediment data when clay is used as the adhesive, it is recommended that for future applications of the hybrid method, an alternate adhesive such as wax or tape be used when fine sediment analysis is desired.

Volumetric Conversion

Because of the bias inherent in areal sampling, it was necessary to convert all areal distributions to equivalent volumetric distributions. Initially, an exponent of –1 was chosen based on the experimental findings of Diplas and Fripp (1992), whose analysis of samples collected using a clay adhesive was limited to fractions larger than 0.125 mm (4.93×10^{-3} in). However, for this study an exponent of –1 was found to grossly overcorrect the percentage of fine material, resulting in distributions that appeared distorted. This effect was also noted by Proffitt (1980), who stated that “the conversion technique is very sensitive to sampling errors in the finer sizes as a result of the negative exponent." Proffitt addressed the deficiency by ignoring the finest 1% of the areal distribution, but because one of the primary goals of this research was to examine the presence and impact of silt- and fine sand-sized particles in the streambed, this approach was not taken. In addition, the degree of overcorrection observed in this study's distributions has likely not previously been encountered or anticipated since most studies truncate distributions above the 1 mm size fraction. Other exponents, such as Proffitt's experimentally determined value of –0.47 for wax sampling, were tested with similar resulting distortions.

In order to be able to apply a correction to the larger size fractions without grossly distorting the lower portion of the distribution, it was decided to use a correction exponent of –1 above a geometric mean diameter of 1.4 mm and an exponent of 0 for all smaller diameters. This correction was also used by Diplas and Fripp (1992) for wax areal sample conversion of framework-supported gravel samples, as it was concluded that wax can sample clumps of fine particles volumetrically. Due to the heavily silted conditions at many of the sites, as well as the presence of clumping on many of the dry-bed samples, the use of a two-exponent technique for this study was deemed reasonable. Further investigation into the appropriate volumetric conversion method for distributions containing very fine fractions is warranted.

Figure 8 demonstrates the effect of varying the correction exponent on the areal distribution for the pavement sample taken at LCS1. Likewise, the change in D_{50} values associated with these different correction techniques is illustrated in Figure 9.

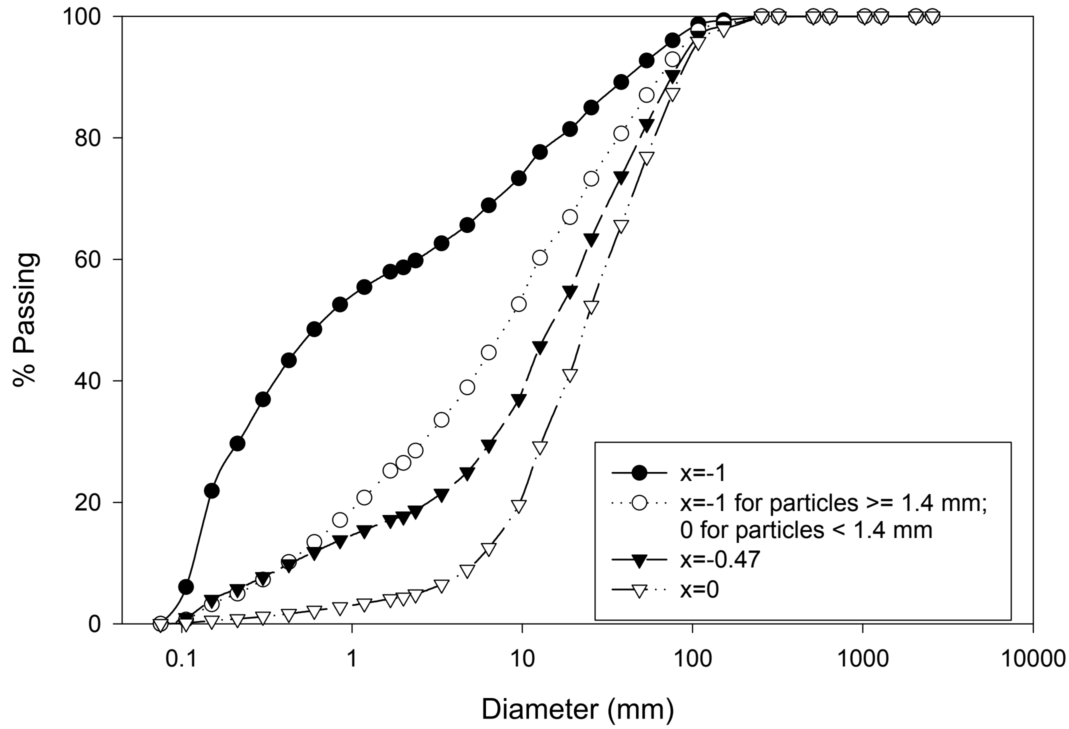


Figure 8. Effect of varying correction exponent on areal distributions for pavement sample LCS1.

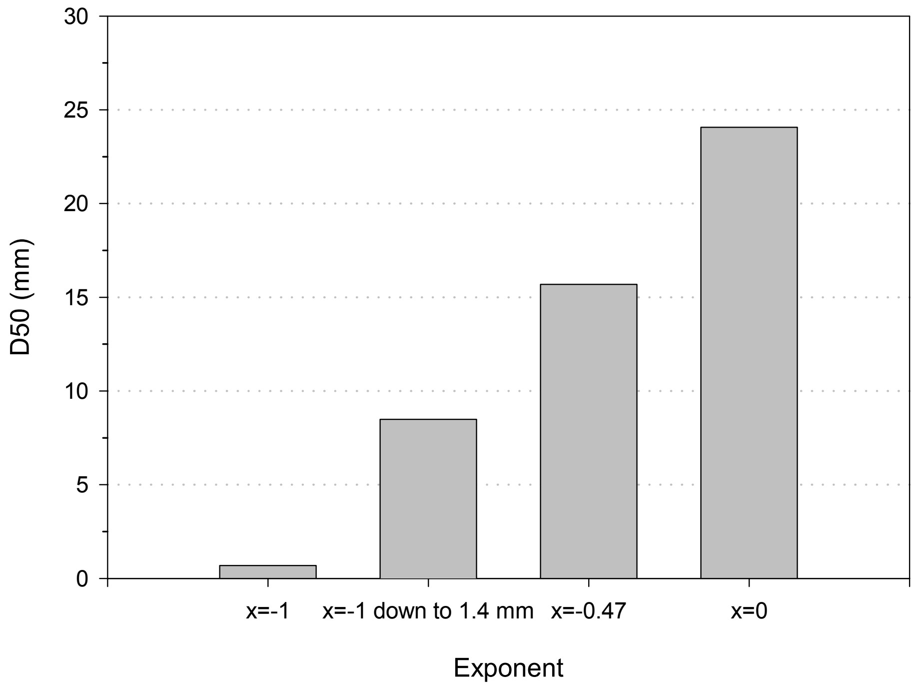


Figure 9. Effect of varying correction exponent on D_{50} values for pavement sample LCS1.

Combining Grid and Areal Samples

Because of the overlap of several sampled particle sizes between grid and areal samples, a common particle diameter had to be chosen and consistently applied as the match point for all pavement samples. This diameter was chosen by first preparing a box plot of the ratios of the percentage value of the areal distribution over the percentage value of the grid distribution (termed the match point ratio) at common geometric mean diameters 45.27 mm (1.784 in), 31.11 mm (1.226 in), 22.00 mm (0.8668 in), 15.55 mm (0.6127 in), 11.00 mm (0.4344 in), and 7.78 mm (0.3065 in) for each sample (Figure 10). Based on the plot, the diameter of 15.55 mm was chosen as the most appropriate match point, as the value of its ratio was closest to 1.0. As expected, the average match point ratio for the 45.27 mm diameter size fraction is approximately zero because adhesive sampling could not consistently retain this large. Likewise, match point ratios for the 7.78 mm size fraction show a large degree of variability due to the lack of consistency with which these particles could be sampled by a human operator during grid sampling. The match point ratios for pavement samples are provided in Table A2 in the Appendix.

The significance of using a different match point or selecting the most appropriate match point for each hybrid pavement sample rather than for the entire set of samples is unknown. Further investigation and possible standardization of the process is likely necessary.

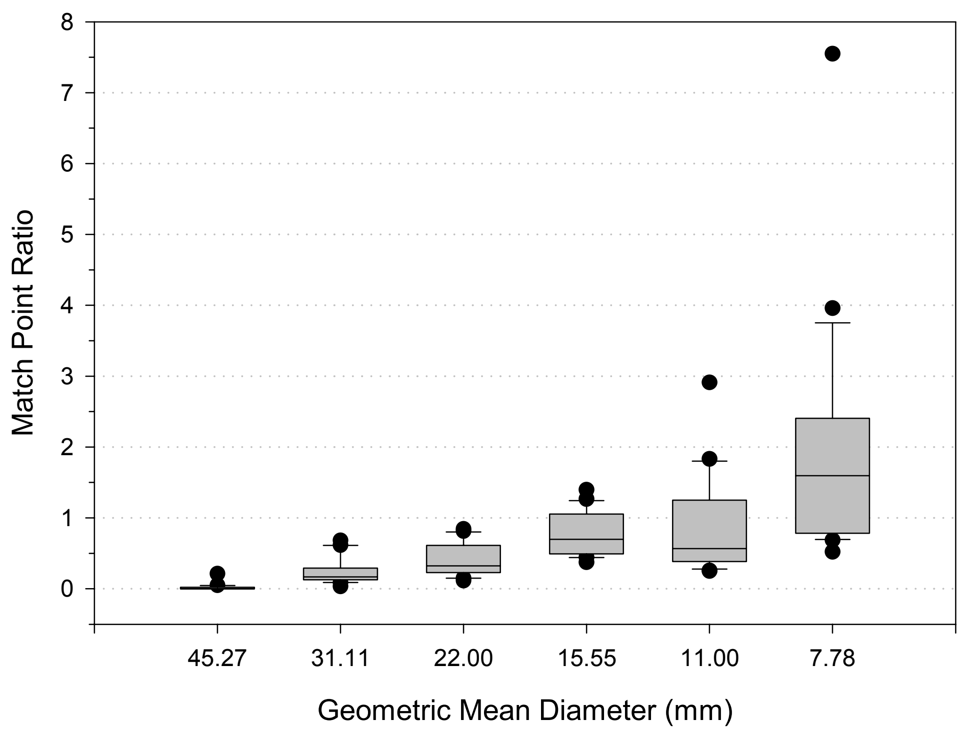


Figure 10. Match point ratios for diameters common to areal and grid samples.

Leading Creek Hybrid Sample Analysis

From each complete pavement and subpavement distribution, values for D_{10}, D_{15}, D_{35}, D_{50}, D_{65}, D_{85}, and D_{90} were determined (see Table A3 in Appendix). Other particle size statistics including the percent of material coarser than 10 mm (0.4 in), finer than 1 mm (0.04 in), finer than 2 mm (0.8 in), and finer than 0.125 mm (4.93 x 10^{-3} in) were also calculated for each sample. As expected, hybrid pavement sample distributions were found to be significantly coarser than their associated subpavement distributions for every sampling site. This is demonstrated in Figure 11, which compares pavement and subpavement distributions for three Leading Creek sampling sites. In addition, pavement samples were found to be significantly more variable, as shown by box plots of D_{10} and D_{50} values (Figure 12). For example, the ratio of the average D_{50} values for pavement and subpavement samples is approximately 6.5, with standard deviations for the pavement and subpavement D_{50} statistics being 6.7 mm (0.26 in) and 0.83 mm (0.033 in), respectively. Similar expected results were obtained when comparing the percentages of material coarser than 10 mm and finer than 2 mm calculated for pavement and subpavement samples (See Figures A7 and A8 in Appendix). A box plot of the percentage of material finer than 0.125 mm for pavement and subpavement samples (See Figure A9 in Appendix) showed a deviation from this trend, although most likely because of the error in estimating the amount of material finer than 0.075 mm caused by adhesive contributions.

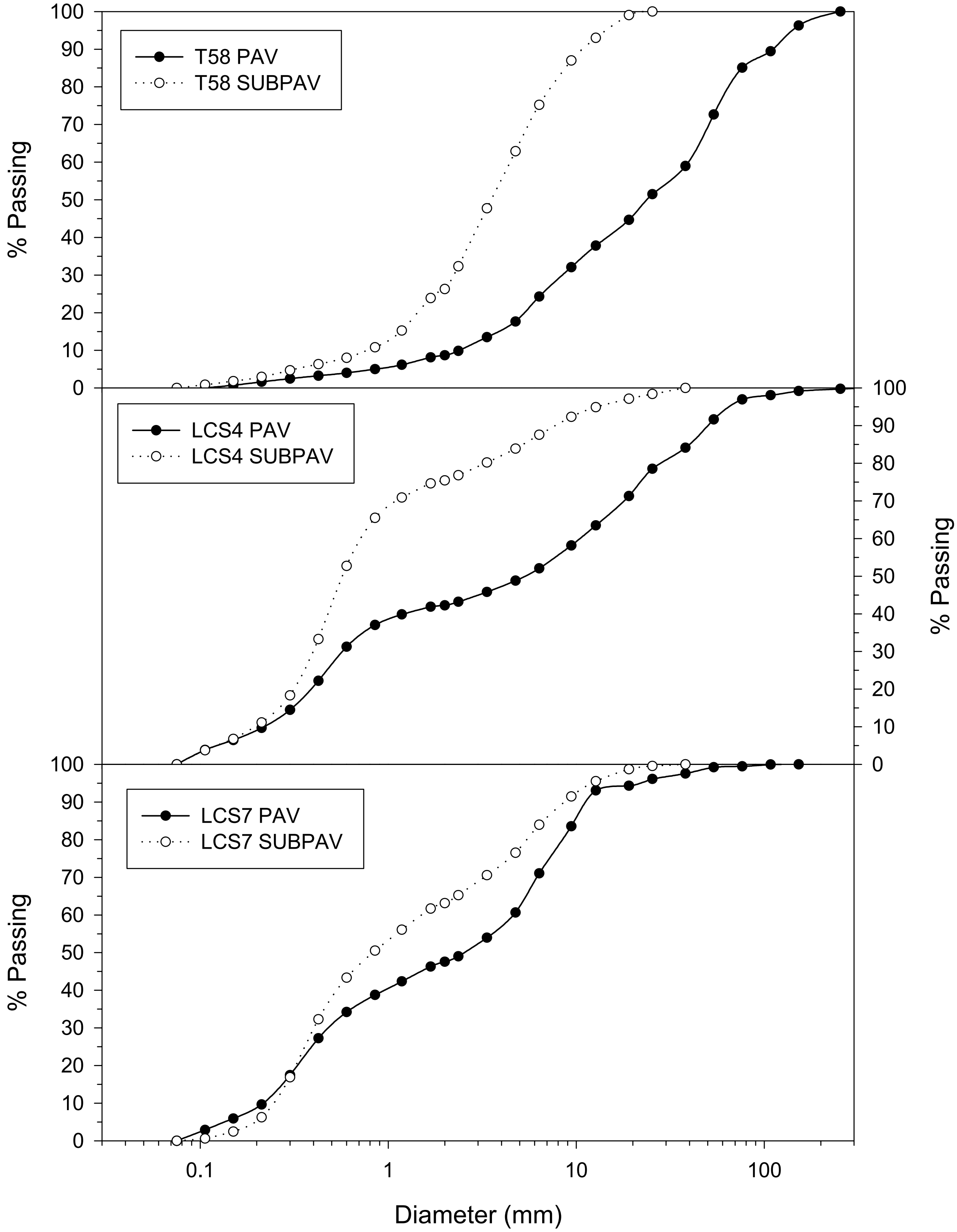


Figure 11. Pavement and subpavement distributions for sampling sites T58, LCS4 and LCS7 (51.1 km, 36.2 km, and 17.3 km from confluence with Ohio River, respectively).

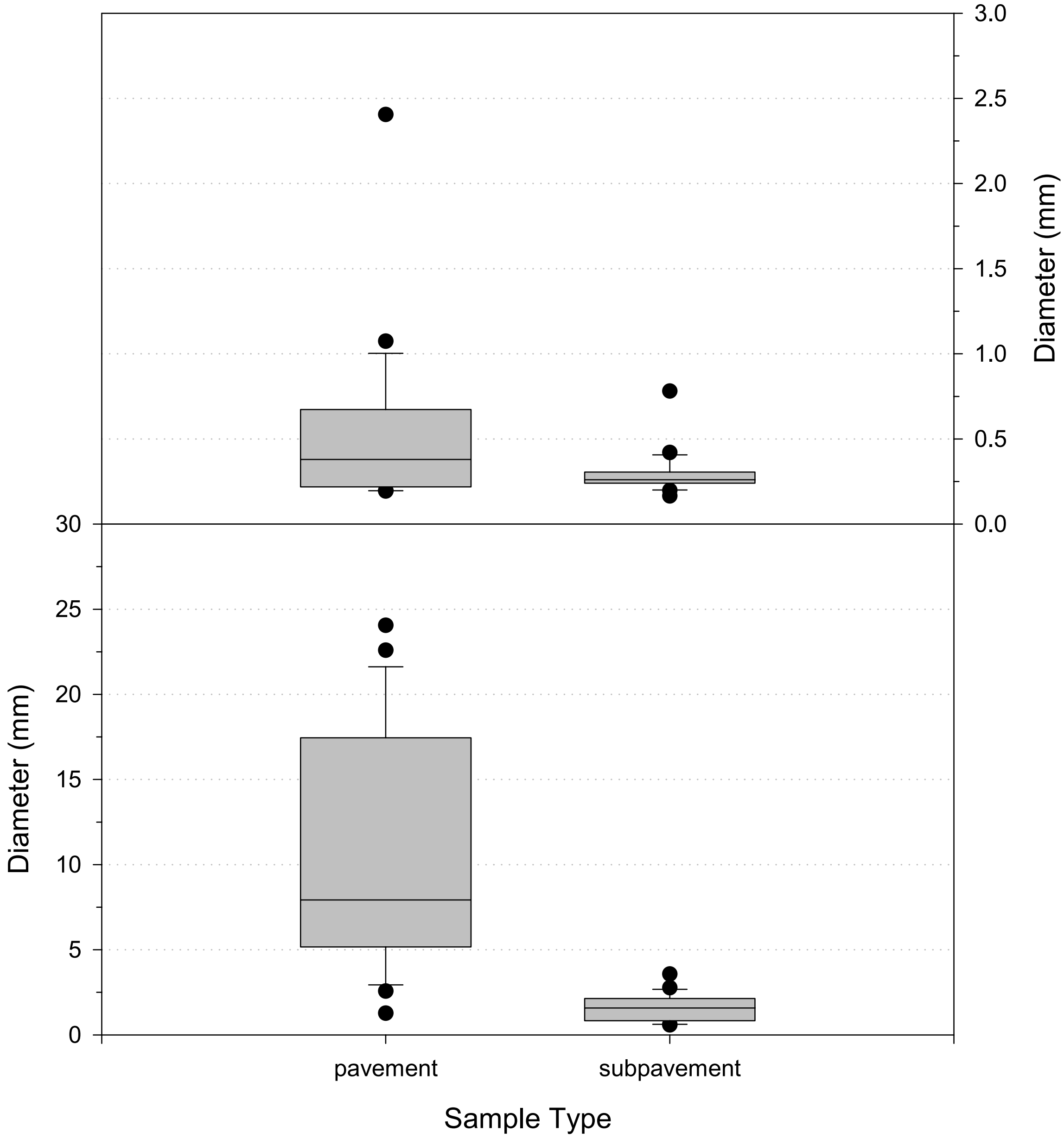


Figure 12. Comparison of pavement and subpavement D_{10} and D_{50} values (n=17).

Figure 11 also demonstrates a change in the relationship between pavement and subpavement layers as one moves downstream. A shift in the percentages of sampled size fractions can be seen, as LCS4 and LCS7 samples are shown to have a much higher sand content, or are more bimodal, than the uppermost sampling site, T58. Examination of a plot of the slope-energy profile along the creek as compared to the change in mean particle diameter for subpavement samples (Figure 13) shows a likely relationship between the sudden change in the bed slope profile and a slight coarsening of the streambed, possibly due to an increased deposition of sand. This point of bed slope change is shown to occur at approximately 40 km (25 mi) from the Ohio River, which appears to correspond with the pronounced bimodal distributions obtained for site T44 (located 40.4 km from the Ohio River), as well as for downstream sites LCS4, LCS6, T25, and LCS7. Also thought to contribute to the bimodal trend is the influence of abandoned and reclaimed mine lands, which are concentrated in the lower portion of the watershed. These areas have been observed to be covered in thick beds of unconsolidated sand and rock, with little vegetation to prevent erosion (Figure 14). Thus, the entrance of these larger particles into Leading Creek appears to be reflected in the distorted bed material distributions for sites downstream of LCS4.

The effect of signature mine land cover seems to extend as well to a deviation in the trend of downstream fining that is typically seen in gravel-bed streams. This is demonstrated by Figure 12, which shows no distinct fining of the texture of pavement and subpavment distributions corresponding to the six LCS sampling sites, or those sites not immediately downstream of a tributary confluence. The same is true of pavement and subpavement distributions for samples collected at sites just downstream of a tributary confluence (Figures A10 and A11 in Appendix).

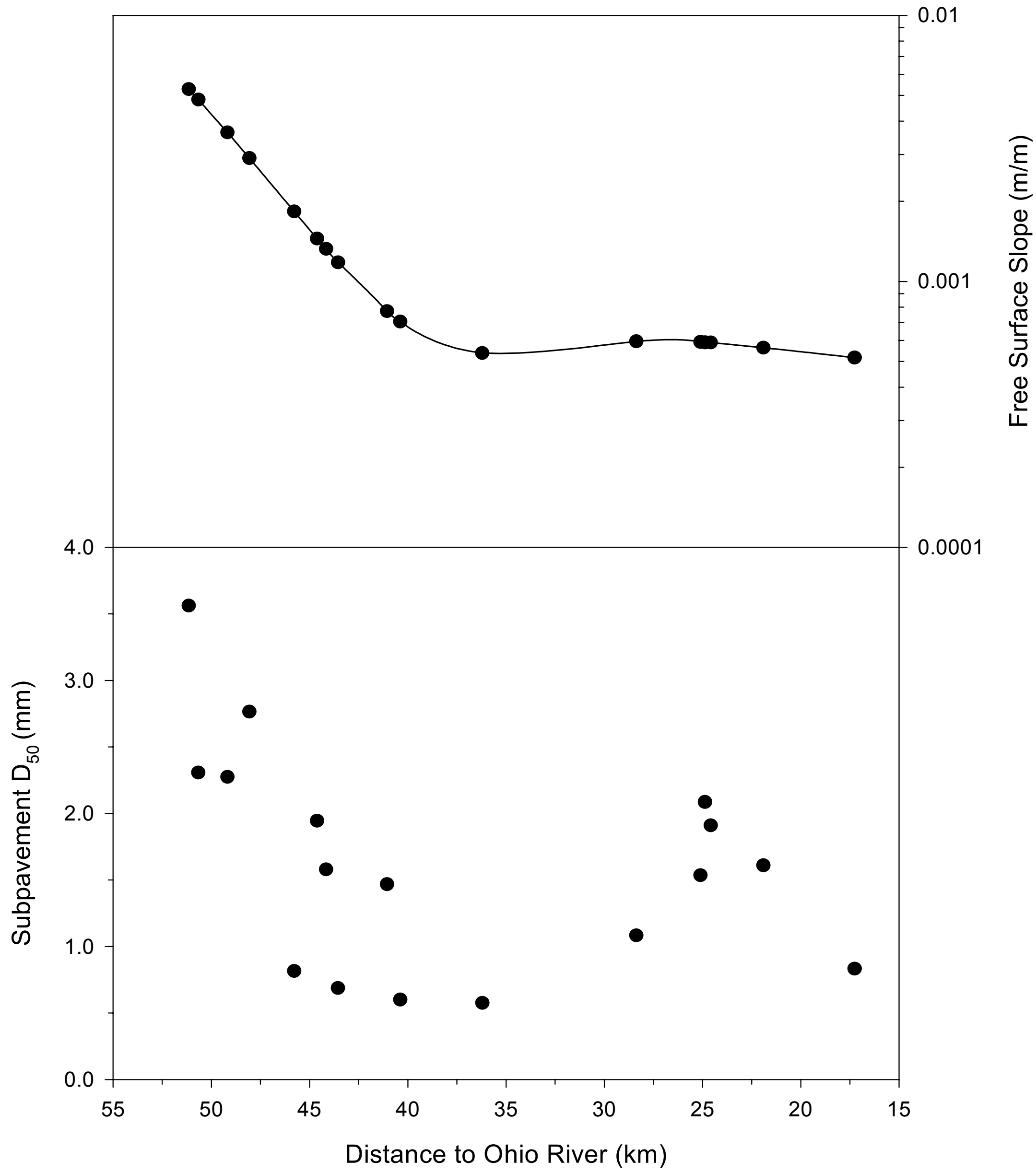


Figure 13. Comparison of Leading Creek bed slope profile and change in subpavement D50 values.

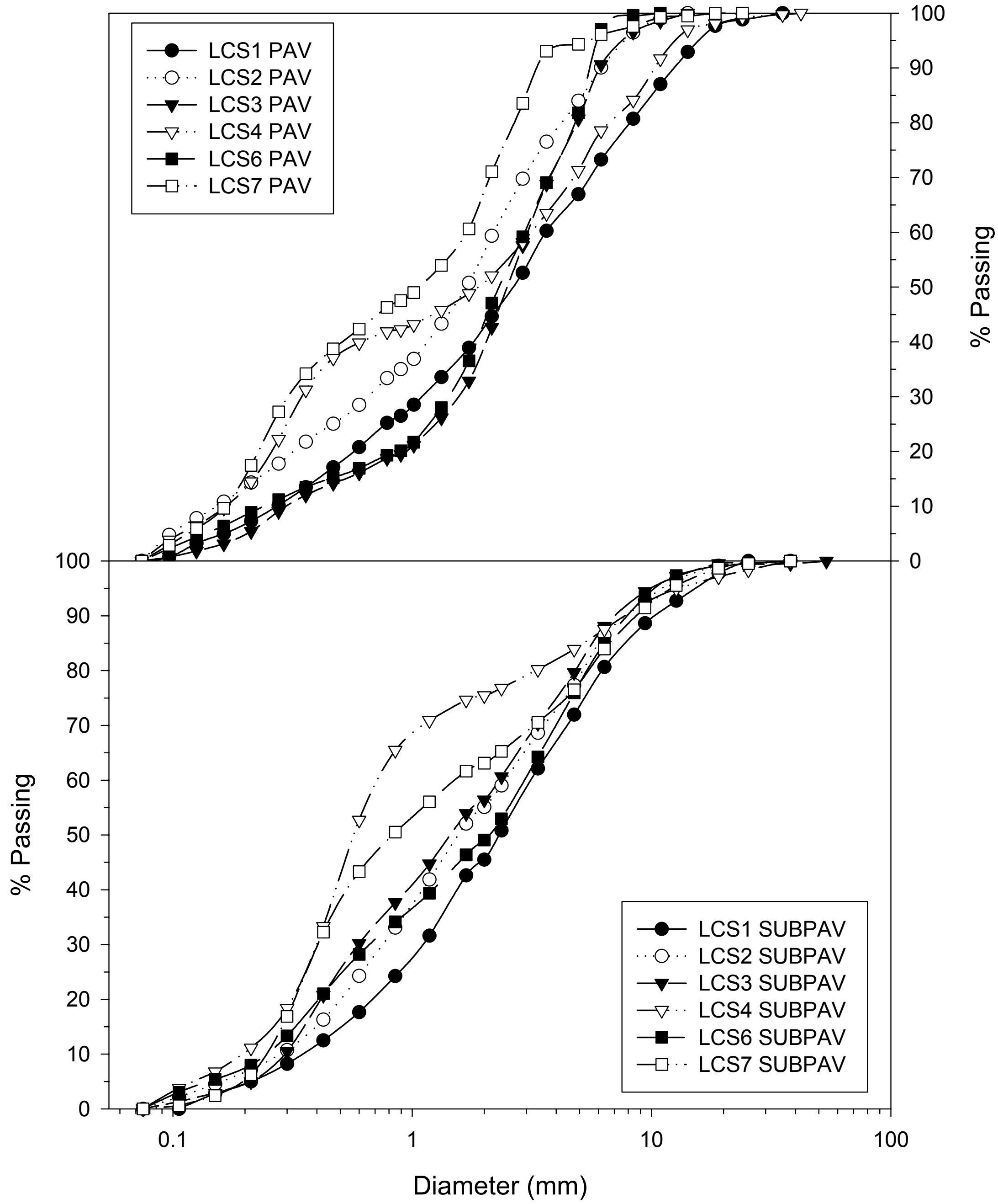


Figure 14. Pavement and subpavement distributions for sites not associated with a tributary confluence.

Analysis of Sediment Texture and Ecological and Land-Use Parameters

An analysis of possible relationships between streambed texture and both ecological quality and land-use along Leading Creek was performed. A Pearson correlation analysis was run with pavement and subpavement particle size statistics, sampling site slope and location data, and ecological and land-use data collected during the Leading Creek watershed study. The ecological data incorporated in this analysis were taxon richness and abundance measurements for both total species and Ephemeroptera-Plecoptera-Trichoptera (EPT; aquatic insect species that are the main food source for fish) only, USEPA's Rapid Bioassessment Protocols (RBP) (USEPA, 1989) embeddedness and substrate quality scores, and Ohio EPA's Qualitative Habitat Evaluation Index (QHEI) (Rankin, 1989) substrate and riffle scores. These data, provided in Table 1, were limited to the six LCS-sites and T30, for which LCS5A data used because of the close proximity of the sites to each other. Land-use data included percent bare soil, percent abandoned strip mine land (ASML), percent abandoned underground mine land (AUML), and percent urban land upstream of the sampling station (Table 2).

Station ID	Total Abundance	Total Taxa	EPT Abundance	EPT Taxa	RPB Substrate/Cover Score	RBP Embeddedness Score	QHEI Substrate Score
LCS1	133	25.7	82.0	10.0	6	14	12
LCS2	139	26.7	76.5	12.0	16	8	13
LCS3	76.7	23.7	15.0	6.5	0	0	8
LCS4	124	25.3	61.5	8.5	8	4	11
LCS5A	131	32.0	54.5	9.5			
LCS6	84.7	21.1	27.0	4.5	15	12	12
LCS7	267	35.6	52.8	6.8	16	7	14

Note: LCSA used with T39 date because stations in close proximity to each other.

Table 1. Leading Creek ecological data (Cherry *et al*, 1999).

Sample ID	% Bare Soil	% ASML	% AUML	% Urban
T58	8.9	0	0	5.5
LCS1	8.3	0	0	4.9
T55	6.5	0	0	3.3
T54	6	0	0	3
T51	5.1	0	0	2.4
T50	5.4	0	0	2.4
LCS2	4.4	0	0	1.2
T48	4.7	0	0	1
LCS3	4.4	0	0	0.9
T44	4.1	0	0	0.7
LCS4	4.6	0	0	0.5
T30	3	0.98	0.62	0.3
T26	2.8	0.91	0.6	0.2
LCS6	2.8	0.9	0.6	0.2
T25	2.6	0.85	0.56	0.2
T22	2.6	0.96	0.67	0.2
LCS7	2.5	1.11	0.82	0.2

Table 2. Leading Creek land-use data (Cherry *et al*, 1999).

R-values obtained from the correlation analysis are summarized in Table 3. A general positive relationship between streambed particle size statistics and slope was found. This is an expected conclusion since a steeper slope will tend to cause smaller particles to be washed downstream. In addition, subpavement statistics yielded higher R-values for slope correlation than did pavement statistics (a range of 0.56 to 0.83 compared to a range of 0.43 to 0.67 for the latter), which was likely due to the general higher variability of pavement distributions. Interestingly, the smaller particle size statistics (i.e. D_{10}, D_{15}, D_{35}, and D_{50}) for both pavement and subpavement samples were generally better correlated with slope than the larger particle size statistics. The same was found to be true for particle size correlations with ecological quality data.

The correlation results also provided evidence of a relationship between biodiversity measurements and pavement texture, as total abundance and total taxon richness data were found to be negatively correlated with pavement particle size statistics. R-values with magnitudes between 0.71 and 0.81 were calculated for total abundance and pavement D_{15}, D_{35}, D_{50}, percent less than 2 mm, and percent less than 1 mm, and a value of –0.89 was obtained for pavement percent greater than 10 mm. R-values of 0.71 and -0.85 were obtained for total taxon correlation with D_{50} and percent greater than 10 mm, respectively. Subpavement correlations with total biodiversity measurements, as well as EPT abundance and taxon correlations with both pavement and subpavement data were not significant. In his research, Babendreier (2000) found TSS concentrations in Leading Creek at high flows to be correlated with land-use data (% bare soil in particular). The Pearson correlation analysis, however, did not reveal a significant relationship between pavement and subpavement texture and % bare soil data.

	Slope	% Bare soil	% ASML	% AUML	% Urban	EPT Abundance	EPT Taxa	Total Abundance	Total Taxa	RBP Embeddedness	RBP Substrate	QHEI Substrate	QHEI Riffle
D10_PAV	0.67	0.62	-0.21	-0.21	0.67	-0.47	-0.30	-0.58	-0.38	-0.01	-0.74	-0.70	-0.60
D15_PAV	0.58	0.53	-0.18	-0.18	0.60	-0.64	-0.46	-0.71	-0.60	-0.03	-0.62	-0.72	-0.73
D35_PAV	0.44	0.41	-0.17	-0.18	0.47	-0.53	-0.30	-0.73	-0.56	0.09	-0.50	-0.69	-0.63
D50_PAV	0.50	0.47	-0.19	-0.20	0.52	-0.22	-0.11	-0.81	-0.71	0.18	-0.69	-0.66	-0.41
D65_PAV	0.53	0.52	-0.21	-0.22	0.56	0.18	0.07	-0.58	-0.63	0.27	-0.63	-0.44	-0.04
D85_PAV	0.56	0.58	-0.27	-0.28	0.60	0.46	0.29	-0.34	-0.46	0.30	-0.50	-0.22	0.27
D90_PAV	0.64	0.65	-0.30	-0.30	0.68	0.52	0.35	-0.28	-0.40	0.32	-0.47	-0.17	0.34
%<1mm _PAV	-0.38	-0.30	0.02	0.04	-0.34	0.42	0.16	0.76	0.57	-0.17	0.40	0.54	0.52
%<2mm_PAV	-0.35	-0.28	0.01	0.03	-0.32	0.48	0.25	0.81	0.63	-0.12	0.47	0.61	0.60
%>10mm_PAV	0.44	0.44	-0.28	-0.29	0.47	-0.15	-0.06	-0.89	-0.85	0.03	-0.66	-0.69	-0.39
D10_SUB	0.74	0.67	-0.23	-0.23	0.71	0.25	0.38	-0.20	-0.07	0.42	-0.36	-0.12	0.18
D15_SUB	0.78	0.71	-0.27	-0.27	0.75	0.43	0.47	-0.25	-0.26	0.54	-0.26	-0.03	0.33
D35_SUB	0.83	0.74	-0.28	-0.28	0.80	0.30	0.25	-0.36	-0.47	0.67	-0.16	0.00	0.23
D50_SUB	0.73	0.60	-0.14	-0.15	0.70	0.03	-0.02	-0.44	-0.56	0.67	-0.07	-0.04	0.00
D65_SUB	0.63	0.46	-0.04	-0.05	0.61	-0.02	-0.05	-0.19	-0.31	0.61	0.05	0.09	0.03
D85_SUB	0.59	0.51	-0.17	-0.16	0.63	0.36	0.03	0.28	-0.03	0.76	0.07	0.41	0.49
D90_SUB	0.56	0.52	-0.21	-0.19	0.62	0.50	0.10	0.30	-0.08	0.78	0.09	0.49	0.68
%<1mm _SUB	-0.73	-0.57	0.11	0.12	-0.69	-0.06	-0.12	0.30	0.34	-0.56	0.05	0.00	-0.06
%<2mm_SUB	-0.72	-0.56	0.10	0.10	-0.69	0.01	0.05	0.27	0.39	-0.63	0.00	-0.04	-0.02
%>10mm_SUB	0.56	0.55	-0.26	-0.24	0.63	0.65	0.26	0.36	0.05	0.63	0.00	0.47	0.74

Table 3. R-values from Pearson correlation analysis

One factor thought to contribute to the lack of strong trends in the particle size data is the uncommonly wide range of armor ratios (ratio of pavement to subpavement statistics) that were seen throughout the stream. Parker (1980) found median armor ratios in the range of 1.5 to 3.0, while Figure 15 demonstrates that Leading Creek D_{50} armor ratios ranged between approximately 1.5 and 15. Such a variation could indicate that the settling behavior of fines fluctuates greatly throughout the stream; however, it is possible that the higher values seen for Leading Creek sites can be attributed the wider range of particles sizes that were able to be sampled using the hybrid method.

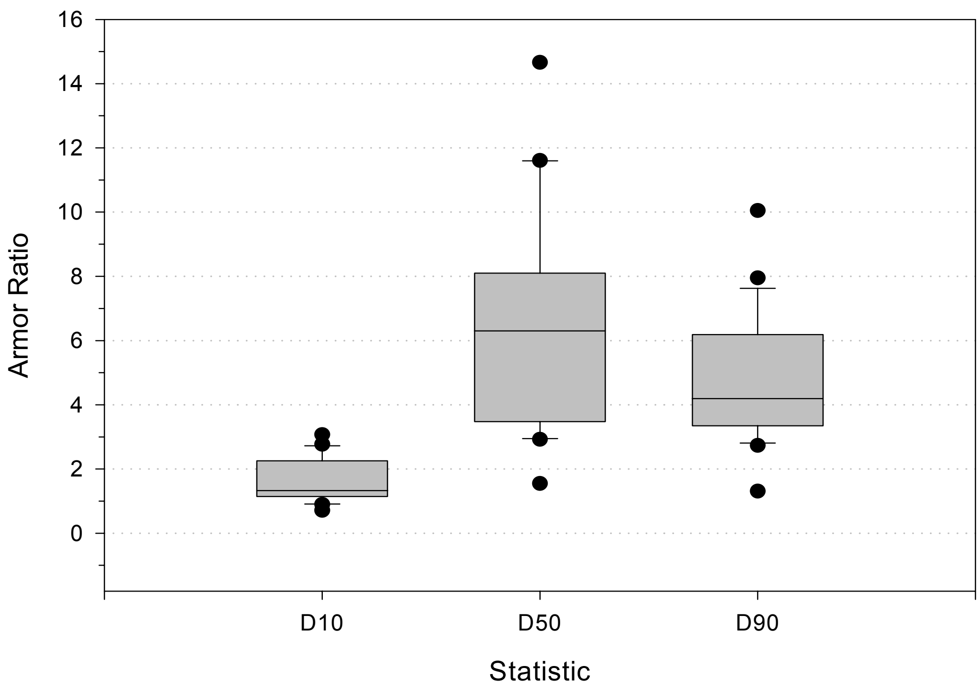


Figure 15. Armor ratios for D_{10}, D_{50}, and D_{90} statistics (n=17).

DISCUSSION

Because hybrid sampling in Leading Creek was the first watershed-scale application of the technique, it has provided valuable data for an extensive evaluation of the technique itself. As previously discussed, one obstacle to extracting the most accurate distributions possible was the addition of an unknown amount of clay adhesive during sample collection. Because the clay used contained a significant amount of silt and fine sand, it was difficult to confidently describe the true content of those fractions in the Leading Creek samples. Consequently, it is recommended that an alternate adhesive, one that does not have the potential to add mass to the collected samples, be used when quantification of silt and sand is desired. Furthermore, the clumping observed on samples collected from exposed areas of the streambed suggests that the technique is best suited for submerged conditions.

Limitations to existing areal to volumetric conversion techniques have also been revealed. Past uses of the Modified Cube Model (Diplas and Sutherland, 1988) have been limited to material greater than 0.2 mm (7.9×10^{-3} in) in diameter. Because the conversion model obtains volume-by-weight estimates by dividing the area-by-weight percentage for each size fraction by its associated diameter, the resulting percentages for very fine fractions are likely to be much greater than their actual abundance in the streambed. This is supported by Leading Creek data, as for one sample the D_{50} calculated using a correction exponent of –1 was found to be nearly 35 times greater than that calculated with an exponent of 0. The sensitivity of fine fractions to traditional conversion models has been noted by other researchers, such as Proffit (1980), and warrants further examination.

The hybrid technique was shown to allow a wide range of particle sizes to be consistently sampled. Areal sampling was found to retain particles from 0.025 mm (9.9 x 10^{-4} in) to upwards of 50 mm (2.0 in), while grid sampling measured particles between 9.4 mm (0.37 in) and 694 mm (27.3 in) (in-place boulders). This lack of truncation is only currently achievable through the use of the hybrid sampling technique, making it a promising tool in streambed analysis for both watershed monitoring and regulatory applications. Particularly, if the technique can be refined to consistently and accurately measure the amount of fines in a streambed, it could potentially be incorporated into regulatory programs aimed at controlling sources of excess sediment.

The pavement layer of Leading Creek was consistently found to be coarser than the subpavement, with the median ratio of pavement to subpavement D_{50}'s being 6.3. This is higher than literature values of between 1.5 and 3.0 (Parker, 1980), but may be attributed to the silted conditions of many sites in conjunction with the presence of boulders as large as 256 mm in diameter at others. Consequently, the increased sampling range of the hybrid technique may have allowed the calculation more accurate armor ratios than previously possible.

Although research in stream biology has uncovered a strong correlation between siltation and degraded ecological health (Diplas and Parker, 1992; Waters, 1995), the ecology data collected at Leading Creek was not sufficient to fully evaluate this relationship. The fact that some evidence of a negative correlation between sediment size and ecological health may be attributed in part to the overriding influence of surrounding landscape conditions on stream ecology. For example, although site LCS7 had one of the finest particle size distributions, its lack of direct urban, agricultural, and mining impact most likely controlled its high biodiversity measurements. Similarly, severe fluctuations in water quality (particularly pH) along the watershed due to AMD influences certainly has a greater effect on ecological health than does sediment texture. Correlations between ecology/land-use and particle size data, as well as typical watershed-scale trends such as downstream fining, were also likely absent because of the influence of abandoned and reclaimed mine land, which contributes large, unconsolidated material to the lower portion of the watershed. One interesting observation, however, is that unlike total species data, EPT abundance and taxon richness generally decreased along with pavement particle size statistics. Although the R-values for these positive correlations were not high enough to draw firm conclusions, the data suggest, as would be expected, that benthic invertebrates are more impacted by sediment characteristics than are other organisms.

CONCLUSIONS

1. When used during a study of Leading Creek Watershed in Ohio, the hybrid sampling method was shown to effectively isolate pavement and subpavement layers and reduce truncation. The technique was able to measure streambed particles in the range of silt (0.062 mm or 2.44 x 10^{-3} in) to boulders (>256 mm or 10 in).

2. The choice of adhesive used for areal sampling was found to be an important consideration, as clay adhesive has the potential to interfere with the analysis of material finer than 0.125 mm (4.93 x 10^{-3} in) in the streambed. It is suggested that for future use of the method, other adhesives such as wax or tape be used if fine sand and silt are to be analyzed.

3. The traditional exponent of –1 for volumetric conversion of areal samples collected with clay appeared to overcorrect the amount of fine material present when applied to distributions containing material finer than 0.2 mm (7.9 x 10^{-3} in) in diameter. Investigation into an appropriate conversion exponent or combination of exponents for the conversion of distributions containing very fine particles is needed.

4. Questions remain whether clay adhesive sampling is appropriate in some dry bed conditions, as clumping of fine material was observed on such samples. In addition, a consistent method for selecting a match point for combining grid and areal sample distributions would be helpful in advancing the hybrid technique toward full field use.

5. Because the sediment loading in Leading Creek differs from a traditional watershed due to the influence of AML, trends such as downstream fining were obscured.

Ecological and land-use trends also appeared to be more influenced by landscape and water quality than by sediment texture.

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APPENDIX

	T58 PAV			T58 SUBPAV	LCS1 PAV			LCS1 SUBPAV	T55 PAV			T55 SUBPAV	T54 PAV			T54 SUBPAV	T51 PAV			T51 SUBPAV
Diameter (mm)	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive
320.0																				
254.0		100.0	100.0			100.0	100.0													
152.4		94.4	95.0			97.5	97.9			100.0	100.0									
108.0		84.3	85.9		100.0	94.9	95.8			98.2	98.3			100.0	100.0			100.0	100.0	
76.2		77.8	80.1		100.0	84.7	87.4			95.5	95.8			98.4	98.5			98.4	98.6	
53.8	100.0	59.3	63.6	100.0	99.1	72.0	76.9			88.4	89.1		100.0	94.4	94.6			94.4	95.3	
38.1	100.0	38.9	45.4	100.0	99.1	58.5	65.7		100.0	75.9	77.4		99.4	81.5	82.3	100.0	100.0	81.5	84.4	
25.4	92.4	27.8	35.4	100.0	89.4	42.4	52.3	100.0	95.5	49.1	52.2	100.0	95.7	54.8	57.0	98.4	92.3	54.8	62.0	100.0
19.1	84.1	17.6	26.3	99.0	81.4	28.8	41.1	97.8	81.9	29.5	33.8	98.4	84.3	32.3	35.5	97.4	87.1	32.3	43.0	98.9
12.7	71.2	7.4	17.2	93.0	73.2	14.4	29.2	92.7	64.3	12.5	17.9	94.7	64.8	14.5	18.6	92.7	80.5	14.5	28.1	96.0
9.4	60.4	3.7	11.9	87.0	64.0	5.9	19.6	88.6	54.4	4.5	11.6	90.1	53.1	5.6	11.4	88.3	78.2	5.6	24.5	93.6
6.4	45.8	0.0	6.7	75.2	54.3	0.0	12.5	80.6	44.2	0.0	7.0	80.0	41.4	0.0	6.3	79.3	74.3	0.0	20.1	87.1
4.8	33.3		3.6	62.9	47.3		8.9	71.9	35.9		4.3	70.4	33.4		3.8	69.0	70.2		16.8	79.6
3.4	25.4		2.2	47.7	40.8		6.5	62.1	29.9		2.9	61.0	28.1		2.7	57.2	66.2		14.5	72.2
2.4	18.5		1.3	32.3	34.6		4.8	50.8	25.1		2.1	51.0	23.5		1.9	45.0	62.5		13.0	65.1
2.0	16.3		1.1	26.3	32.2		4.3	45.5	23.5		1.9	46.6	21.8		1.7	40.1	60.9		12.5	62.4
1.7	15.3		1.0	23.9	30.6		4.1	42.6	22.4		1.8	44.2	20.7		1.6	37.1	59.8		12.2	61.3
1.2	11.5		0.7	15.2	25.2		3.3	31.6	21.2		1.7	35.6	16.9		1.3	27.5	55.4		11.3	56.1
0.9	9.4		0.6	10.8	20.8		2.8	24.2	17.6		1.4	28.5	13.8		1.1	20.5	50.7		10.4	51.0
0.6	7.5		0.5	8.0	16.3		2.2	17.6	14.0		1.1	21.3	10.9		0.9	14.5	43.8		8.9	44.0
0.4	6.1		0.4	6.3	12.4		1.6	12.5	10.5		0.9	14.4	8.5		0.7	10.1	33.5		6.8	34.1
0.3	4.6		0.3	4.7	8.8		1.2	8.2	7.4		0.6	8.6	6.2		0.5	6.8	21.8		4.4	23.2
0.2	3.0		0.2	2.9	6.0		0.8	5.0	4.9		0.4	5.1	4.1		0.3	4.6	12.9		2.6	14.5
0.2	1.4		0.1	1.8	3.9		0.5	2.8	2.9		0.2	3.0	2.4		0.2	3.2	7.2		1.5	8.6
0.1	0.0		0.0	0.8	0.8		0.1	0.0	0.9		0.1	0.3	1.0		0.1	1.4	3.2		0.7	4.1
0.1	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0

Table A1. Adhesive, grid, and hybrid distributions for Leading Creek sampling stations.

	T50 PAV			T50 SUBPAV	LCS2 PAV			LCS2 SUBPAV	T48 PAV			T48 SUBPAV	LCS3 PAV			LCS3 SUBPAV	T44 PAV			T44 SUBPAV
Diameter (mm)	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive
320.0																				
254.0		100.0	100.0																	
152.4		99.2	99.1																	
108.0		97.5	97.4							100.0	100.0									
76.2		86.7	86.3			100.0	100.0			99.3	99.3			100.0	100.0					
53.8	100.0	70.8	70.0			97.6	97.5			95.8	96.0			97.6	97.3	100.0	100.0	100.0	100.0	
38.1	99.3	56.7	55.4	100.0	100.0	91.9	91.7	100.0	100.0	90.2	90.8		100.0	94.3	93.7	99.5	98.9	94.6	94.3	
25.4	90.6	42.5	40.8	97.9	98.7	77.4	76.8	99.5	97.7	72.7	74.3	100.0	98.1	84.6	82.8	99.5	96.3	78.4	77.2	100.0
19.1	77.9	27.5	25.4	94.1	95.6	63.7	62.8	99.1	92.0	56.6	59.1	99.7	93.4	68.3	64.7	99.5	90.1	53.2	50.6	98.8
12.7	61.6	15.8	13.4	90.8	87.1	46.8	45.4	96.6	82.2	35.7	39.3	98.1	79.7	48.8	42.9	97.1	74.6	32.4	28.7	95.8
9.4	52.7	5.8	8.8	84.2	79.4	16.1	34.3	92.8	75.3	16.8	29.5	96.0	66.6	22.0	28.4	94.4	64.6	6.3	18.7	92.0
6.4	43.2	0.0	5.3	77.3	67.6	0.0	22.2	86.4	66.5	0.0	20.7	91.8	49.4	0.0	14.8	88.1	54.5	0.0	11.6	85.4
4.8	36.0		3.4	69.0	57.8		15.2	77.3	58.1		14.7	86.5	38.0		8.5	79.7	47.3		8.0	79.2
3.4	30.8		2.4	61.3	49.3		10.8	68.6	49.9		10.5	80.3	30.2		5.3	70.4	41.4		5.9	72.8
2.4	26.6		1.8	53.6	42.0		8.1	59.0	43.7		8.2	73.1	24.4		3.7	60.6	37.3		4.9	66.4
2.0	24.9		1.7	50.3	39.9		7.5	55.1	41.4		7.6	70.0	22.5		3.3	56.4	36.4		4.7	64.3
1.7	24.4		1.6	48.6	38.0		7.0	52.1	40.7		7.4	68.6	21.7		3.1	53.9	35.6		4.5	63.1
1.2	21.6		1.4	42.1	32.4		6.0	41.8	36.9		6.7	62.4	18.6		2.7	44.7	33.7		4.3	59.4
0.9	19.4		1.3	36.7	28.5		5.3	33.1	33.3		6.1	56.6	16.4		2.3	37.7	32.2		4.1	56.5
0.6	16.5		1.1	29.5	24.8		4.6	24.3	28.0		5.1	46.5	13.9		2.0	30.2	28.8		3.7	50.0
0.4	12.9		0.9	21.4	20.2		3.7	16.3	20.2		3.7	30.5	10.5		1.5	20.7	21.1		2.7	33.9
0.3	8.2		0.5	12.7	16.3		3.0	10.7	12.8		2.3	16.3	6.3		0.9	10.5	11.7		1.5	13.9
0.2	4.2		0.3	6.8	12.3		2.3	7.2	7.7		1.4	8.6	3.6		0.5	5.0	7.0		0.9	5.5
0.2	2.0		0.1	3.7	8.9		1.6	4.5	4.1		0.7	4.1	2.1		0.3	2.8	4.7		0.6	2.8
0.1	0.0		0.0	1.2	5.4		1.0	2.2	1.6		0.3	1.2	0.8		0.1	1.3	3.2		0.4	1.4
0.1	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0

Table A1 cont.

	LCS4 PAV			LCS4 SUBPAV	T30 PAV			T30 SUBPAV	T26 PAV			T26 SUBPAV	LCS6 PAV			LCS6 SUBPAV	T25 PAV			T25 SUBPAV
Diameter (mm)	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive
320.0		100.0	100.0																	
254.0		99.4	99.4							100.0	100.0							100.0	100.0	
152.4		98.1	98.3							97.4	97.4							99.2	99.5	
108.0		95.5	96.1							94.1	94.1							96.9	97.8	
76.2	100.0	92.9	93.8			100.0	100.0			89.5	89.4							92.3	94.6	
53.8	99.7	80.8	83.2			99.3	99.4		100.0	74.3	74.3			100.0	100.0			85.4	89.7	
38.1	99.4	63.5	68.0	100.0	100.0	94.6	95.3	100.0	99.4	55.9	55.8	100.0	100.0	99.3	99.2	100.0	100.0	73.1	81.1	
25.4	96.3	50.6	56.8	98.4	99.8	87.8	89.5	99.7	95.4	42.8	42.6	99.1	99.4	94.9	94.4	99.5	97.6	51.5	66.0	100.0
19.1	90.9	34.0	42.2	97.1	97.6	73.5	77.2	99.1	86.0	30.3	30.1	98.2	95.0	68.6	65.7	99.2	92.5	31.5	51.9	99.7
12.7	81.0	16.0	26.5	94.9	85.0	44.9	52.7	97.3	73.1	19.1	18.9	95.4	80.3	46.7	41.8	97.3	81.6	6.9	34.6	96.2
9.4	74.2	5.8	18.9	92.3	72.0	11.6	35.0	95.1	64.9	4.6	13.9	91.5	68.7	18.2	28.6	93.5	71.7	1.5	23.5	91.2
6.4	66.4	0.0	12.8	87.5	56.2	0.0	19.6	90.1	52.2	0.0	8.4	84.2	54.7	0.0	17.2	85.0	60.1	0.0	14.3	80.7
4.8	62.2		10.5	83.9	44.5		11.6	84.0	40.8		4.9	75.7	42.5		10.2	75.9	52.2		9.9	71.7
3.4	58.4		8.9	80.2	36.9		7.8	76.5	32.8		3.1	65.9	32.5		6.0	64.2	46.0		7.4	62.2
2.4	55.1		8.0	76.8	30.7		5.7	67.8	27.1		2.2	57.2	25.2		3.9	52.9	41.5		6.1	53.5
2.0	53.9		7.7	75.4	28.5		5.1	63.8	25.3		2.0	53.4	23.3		3.5	49.1	40.0		5.8	50.4
1.7	53.4		7.6	74.6	27.5		4.8	61.3	24.5		1.9	51.9	22.4		3.3	46.3	39.4		5.7	49.1
1.2	50.8		7.3	70.9	23.7		4.2	52.3	22.0		1.7	45.2	19.6		2.9	39.3	37.2		5.3	44.3
0.9	47.2		6.7	65.4	20.7		3.6	44.5	19.7		1.5	39.6	17.7		2.6	34.1	35.5		5.1	40.3
0.6	39.8		5.7	52.7	17.0		3.0	34.4	16.6		1.3	31.5	15.6		2.3	28.2	32.5		4.7	34.8
0.4	28.3		4.0	33.3	12.4		2.2	22.5	13.2		1.0	21.7	13.0		1.9	21.0	27.8		4.0	27.7
0.3	18.4		2.6	18.3	8.5		1.5	11.1	10.0		0.8	12.7	10.3		1.5	13.3	20.8		3.0	18.0
0.2	12.3		1.8	11.1	5.3		0.9	4.4	7.1		0.6	7.0	7.4		1.1	8.0	13.5		1.9	10.1
0.2	8.2		1.2	6.7	3.6		0.6	1.8	4.8		0.4	4.0	5.0		0.7	5.4	8.3		1.2	5.6
0.1	4.9		0.7	3.7	1.9		0.3	0.5	2.5		0.2	1.9	2.6		0.4	3.0	4.2		0.6	2.3
0.1	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0

Table A1 cont.

	T22 PAV			T22 SUBPAV	LCS7 PAV			LCS7 SUBPAV
Diameter (mm)	Adhesive	Grid	Hybrid	Adhesive	Adhesive	Grid	Hybrid	Adhesive
320.0								
254.0		100.0	100.0					
152.4		99.3	99.4			100.0	100.0	
108.0		97.2	97.7			99.3	99.4	
76.2		94.4	95.4			94.7	94.8	
53.8		89.6	91.4			92.1	92.2	
38.1	100.0	70.1	75.3	100.0	100.0	75.7	76.0	100.0
25.4	95.5	52.1	60.4	98.7	98.6	61.2	61.7	99.5
19.1	89.5	34.7	46.0	97.6	96.6	43.4	44.1	98.7
12.7	73.5	13.2	28.2	95.3	87.8	30.9	31.8	95.5
9.4	59.5	4.9	17.2	91.4	78.8	13.2	22.8	91.4
6.4	45.2	0.0	9.3	84.5	67.1	0.0	14.4	83.9
4.8	35.4		5.4	75.1	57.2		9.5	76.5
3.4	29.0		3.6	66.0	50.9		7.2	70.5
2.4	23.8		2.5	57.0	46.3		6.1	65.2
2.0	21.9		2.2	53.3	44.9		5.8	63.1
1.7	21.1		2.1	51.2	43.7		5.6	61.7
1.2	18.2		1.8	43.0	40.0		5.1	56.0
0.9	16.0		1.6	36.3	36.6		4.7	50.5
0.6	13.1		1.3	26.7	32.3		4.1	43.3
0.4	10.0		1.0	17.1	25.7		3.3	32.2
0.3	7.1		0.7	10.1	16.5		2.1	16.9
0.2	4.4		0.4	5.8	9.1		1.2	6.2
0.2	2.6		0.3	3.5	5.6		0.7	2.4
0.1	0.3		0.0	0.7	2.7		0.3	0.6
0.1	0.0		0.0	0.0	0.0		0.0	0.0

Table A1 cont.

Sample ID	Diameter					
	45.27	31.11	22.00	15.55	11.00	7.78
LCS 1 PAV	0.00	0.60	0.59	0.56	1.10	1.63
LCS 2 PAV	0.00	0.09	0.23	0.50	0.25	0.74
LCS 3 PAV	0.00	0.19	0.29	0.71	0.49	0.79
LCS 4 PAV	0.02	0.24	0.33	0.56	0.66	1.34
LCS 6 PAV	0.00	0.14	0.17	0.67	0.40	0.77
LCS 7 PAV	0.00	0.09	0.12	0.70	0.51	0.90
T 22 PAV	0.00	0.25	0.35	0.74	1.68	2.93
T 25 PAV	0.00	0.11	0.26	0.44	1.83	7.55
T 26 PAV	0.03	0.30	0.75	1.16	0.57	2.76
T 30 PAV	0.00	0.03	0.15	0.44	0.39	1.37
T 44 PAV	0.21	0.16	0.24	0.75	0.38	1.60
T 48 PAV	0.00	0.13	0.35	0.47	0.37	0.52
T 50 PAV	0.05	0.62	0.84	1.40	0.89	1.63
T 51 PAV	0.00	0.29	0.23	0.37	0.26	0.69
T 54 PAV	0.04	0.14	0.50	1.10	1.32	2.06
T 55 PAV	0.00	0.17	0.69	1.04	1.23	2.29
T 58 PAV	0.00	0.68	0.81	1.27	2.91	3.96

Table A2. Match point ratios for hybrid pavement samples.

Sample ID	D_{10} (mm)	D_{15} (mm)	D_{35} (mm)	D_{50} (mm)	D_{65} (mm)	D_{85} (mm)	D_{90} (mm)
T 58 PAV	2.40	3.86	11.10	24.05	45.06	76.08	111.76
T 58 SUBPAV	0.78	1.16	2.53	3.56	5.03	9.00	11.13
LCS 1 PAV	0.42	0.71	3.73	8.49	17.22	48.79	65.15
LCS 1 SUBPAV	0.35	0.51	1.33	2.31	3.76	8.09	10.59
T 55 PAV	0.71	1.94	9.39	17.52	24.96	40.26	49.63
T 55 SUBPAV	0.33	0.44	1.15	2.28	3.94	7.93	9.50
T 54 PAV	1.07	2.42	10.09	17.43	23.87	36.60	43.08
T 54 SUBPAV	0.42	0.62	1.57	2.77	4.28	8.37	10.77
T 51 PAV	0.19	0.25	0.52	1.26	5.86	25.39	32.58
T 51 SUBPAV	0.16	0.22	0.44	0.82	2.35	5.90	7.77
T 50 PAV	0.72	2.42	13.12	22.58	36.69	67.84	77.68
T 50 SUBPAV	0.26	0.33	0.79	1.95	4.02	9.92	12.31
LCS 2 PAV	0.20	0.33	2.00	4.61	8.08	20.12	25.37
LCS 2 SUBPAV	0.28	0.40	0.92	1.58	2.98	6.10	8.14
T 48 PAV	0.27	0.37	1.50	4.43	8.62	21.99	27.83
T 48 SUBPAV	0.23	0.29	0.47	0.69	1.39	4.42	5.81
LCS 3 PAV	0.48	1.00	5.10	7.92	11.63	21.82	25.03
LCS 3 SUBPAV	0.29	0.36	0.76	1.47	2.80	5.77	7.31
T 44 PAV	0.31	0.39	3.93	8.81	15.48	24.53	29.25
T 44 SUBPAV	0.26	0.31	0.44	0.60	2.12	6.24	8.57
LCS 4 PAV	0.22	0.31	0.76	5.35	13.96	39.98	50.40
LCS 4 SUBPAV	0.20	0.26	0.44	0.58	0.84	5.24	8.00
T 30 PAV	0.38	0.58	3.60	6.15	9.22	16.72	19.87
T 30 SUBPAV	0.29	0.34	0.61	1.08	2.11	5.02	6.33
T 26 PAV	0.61	1.88	7.84	17.75	31.98	59.79	70.46
T 26 SUBPAV	0.26	0.33	0.71	1.54	3.25	6.70	8.86
LCS 6 PAV	0.36	0.82	4.50	7.12	11.39	20.39	22.47
LCS 6 SUBPAV	0.25	0.33	0.91	2.09	3.44	6.36	8.22
T 25 PAV	0.20	0.27	2.68	6.69	12.11	29.44	37.62
T 25 SUBPAV	0.21	0.27	0.61	1.91	3.76	7.65	9.15
T 22 PAV	0.66	1.61	7.00	11.63	19.14	39.71	47.21
T 22 SUBPAV	0.30	0.39	0.82	1.61	3.24	6.59	8.89
LCS 7 PAV	0.22	0.27	0.64	2.56	5.42	10.02	11.68
LCS 7 SUBPAV	0.24	0.28	0.47	0.83	2.32	6.80	8.91

Table A3. Summary of particle size statistics for Leading Creek hybrid samples.

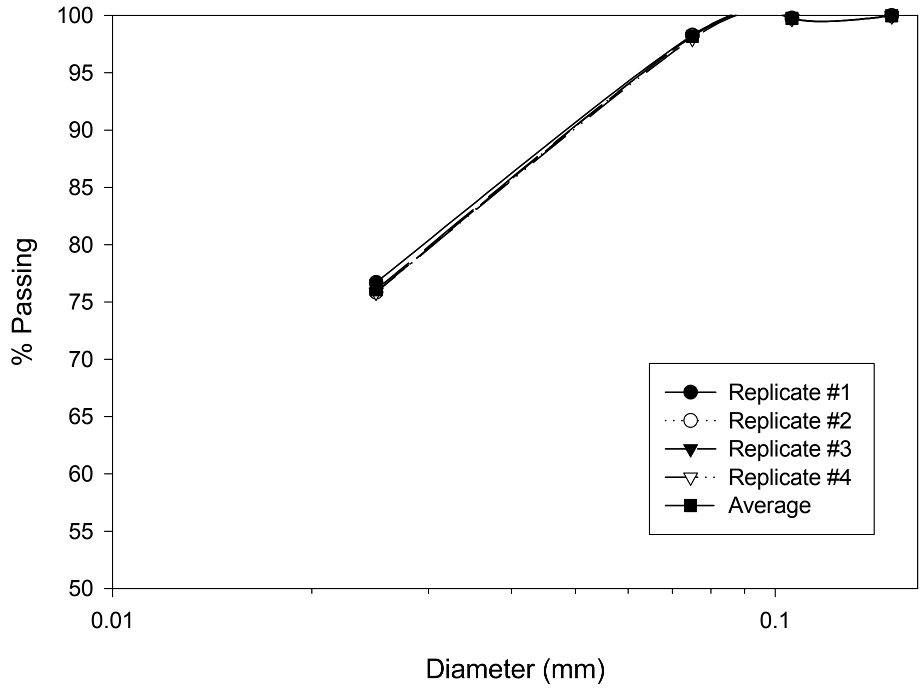

Figure A1. Pure adhesive distributions obtained from wet sieve tests.

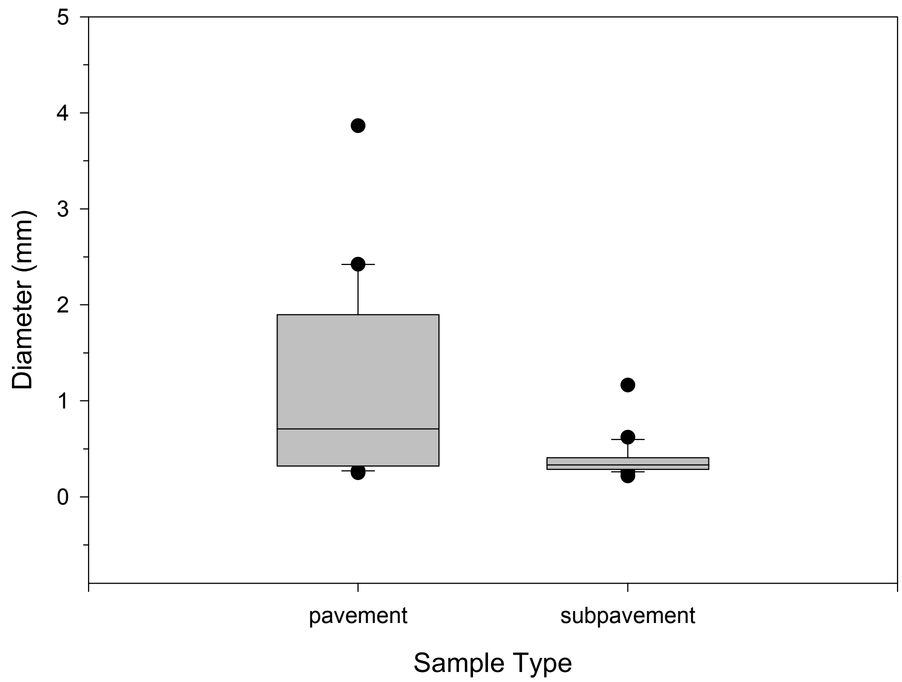

Figure A2. Comparison of pavement and subpavement D_{15} values (n=17).

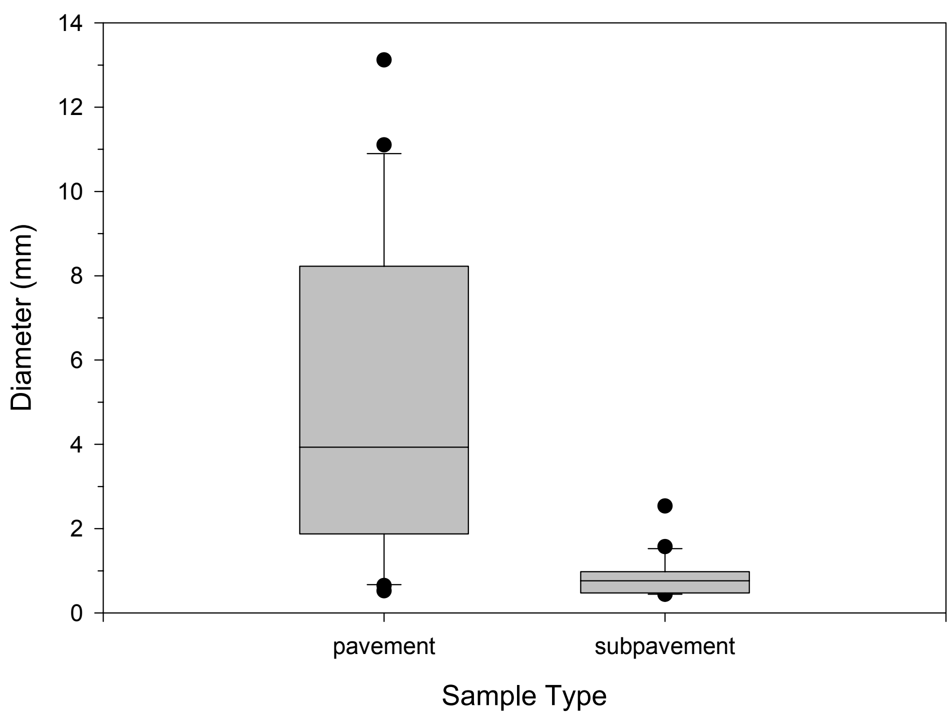

Figure A3. Comparison of pavement and subpavement D_{35} values (n=17).

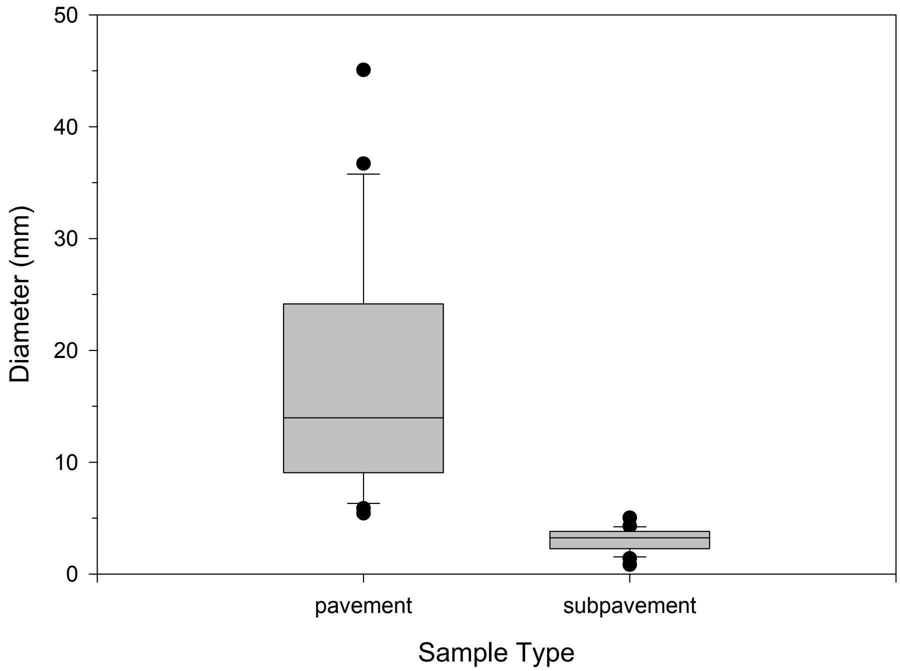

Figure A4. Comparison of pavement and subpavement D_{65} values (n=17).

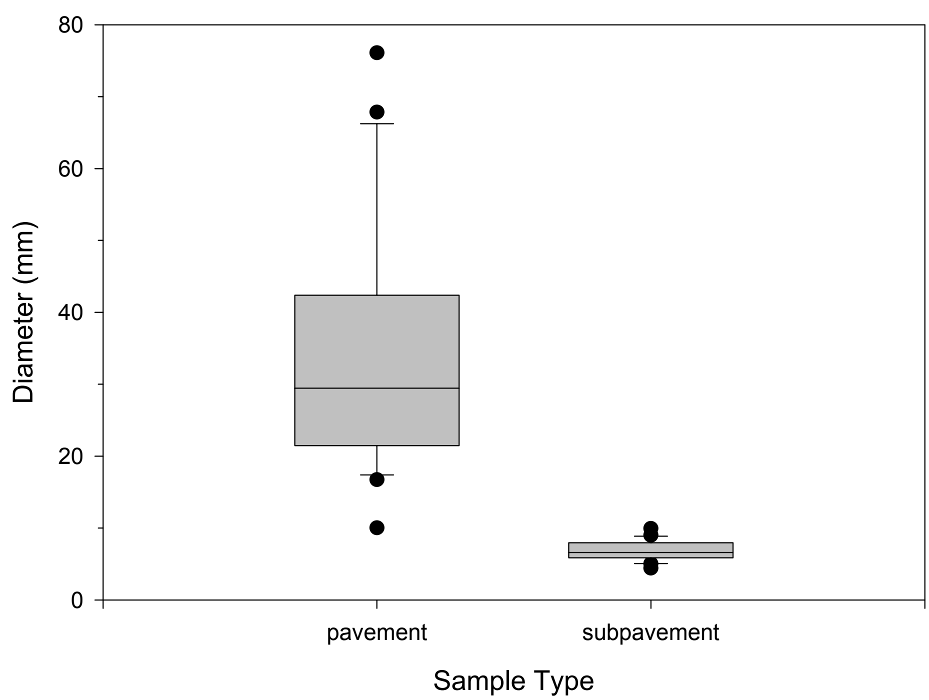

Figure A5. Comparison of pavement and subpavement D_{85} values (n=17).

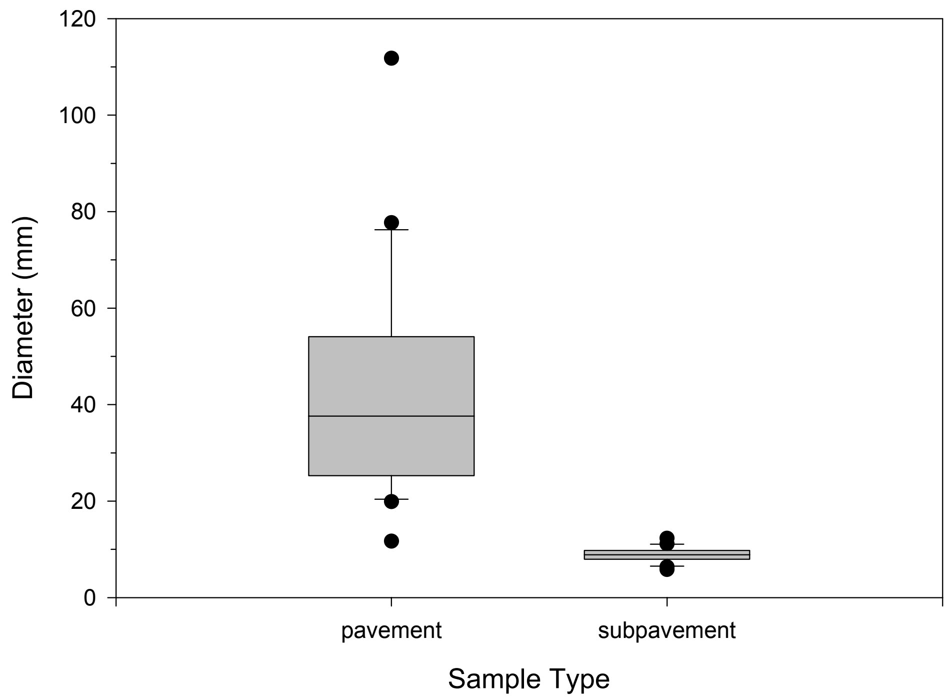

Figure A6. Comparison of pavement and subpavement D_{90} values (n=17).

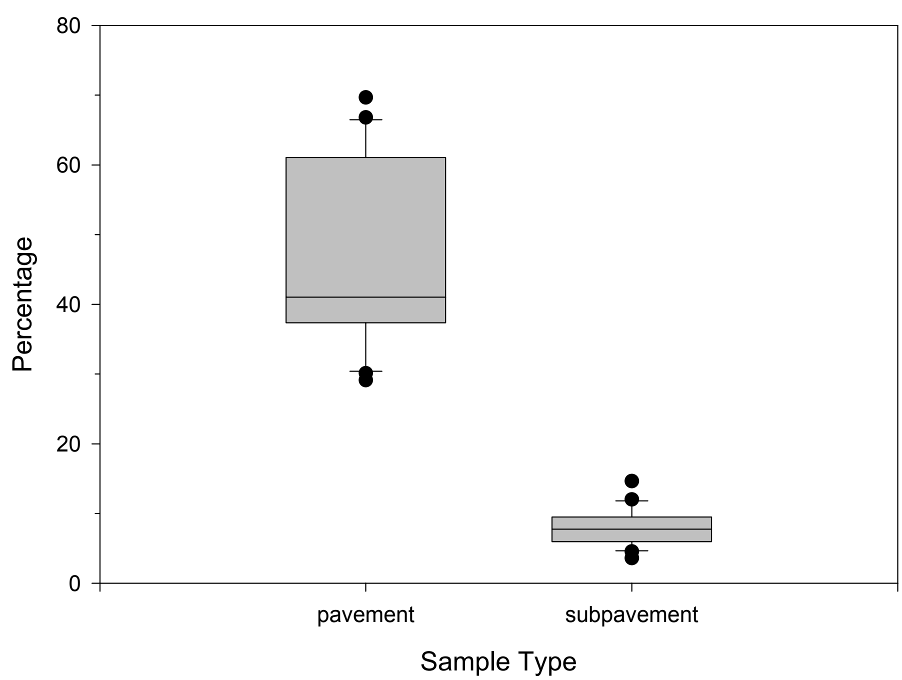

Figure A7. Comparison of percentage of material coarser than 10 mm for pavement and subpavement samples (n=17).

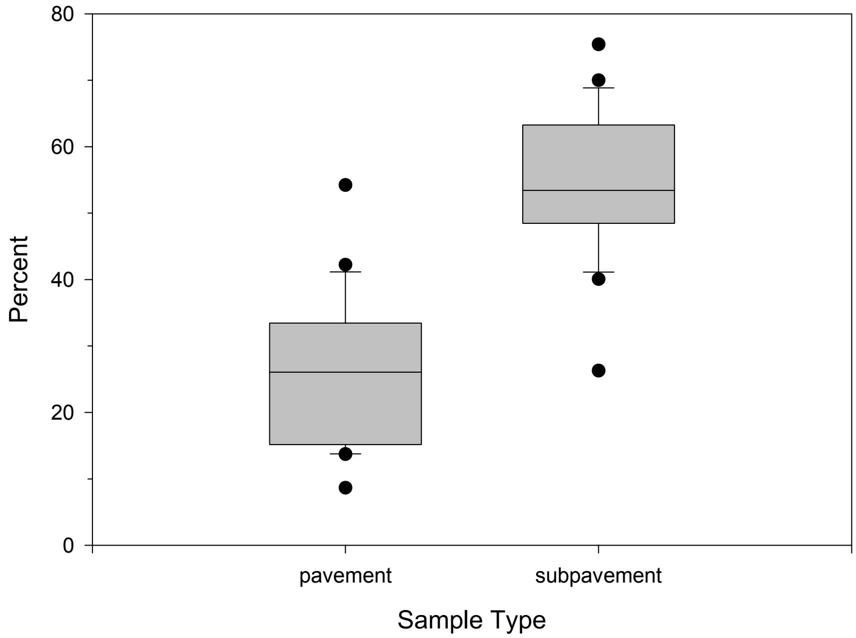

Figure A8. Comparison of percentage of material finer than 2 mm for pavement and subpavement samples (n=17).

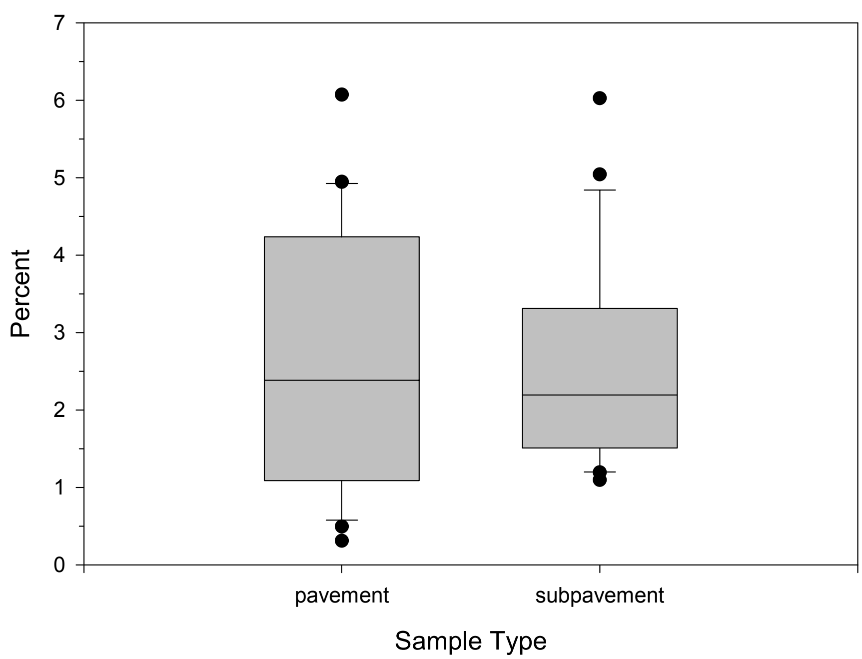

Figure A9. Comparison of percentage of material finer than 0.125 mm for pavement and subpavement samples (n=17).

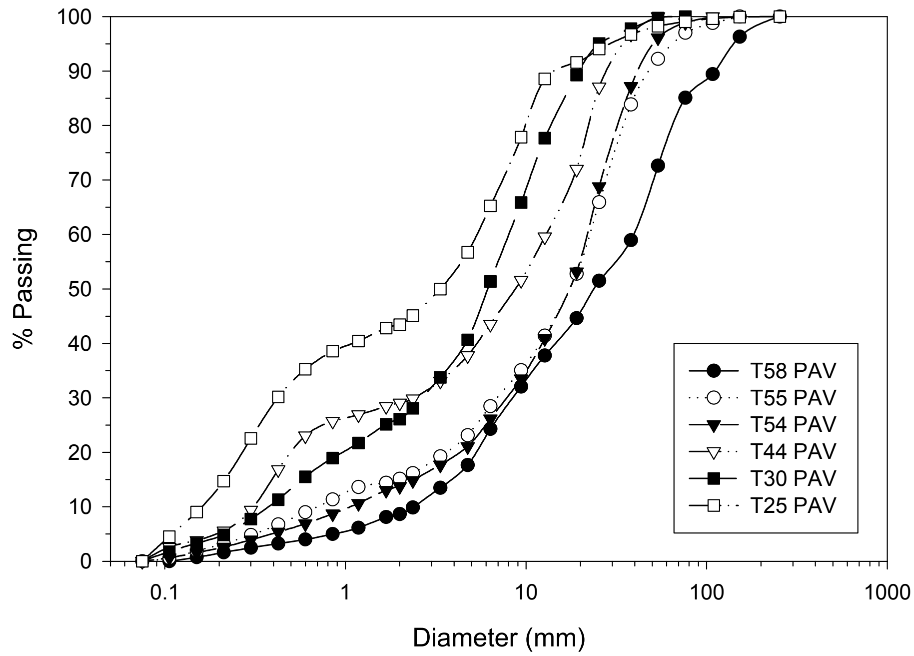

Figure A10. Pavement distributions for six Leading Creek tributary sites.

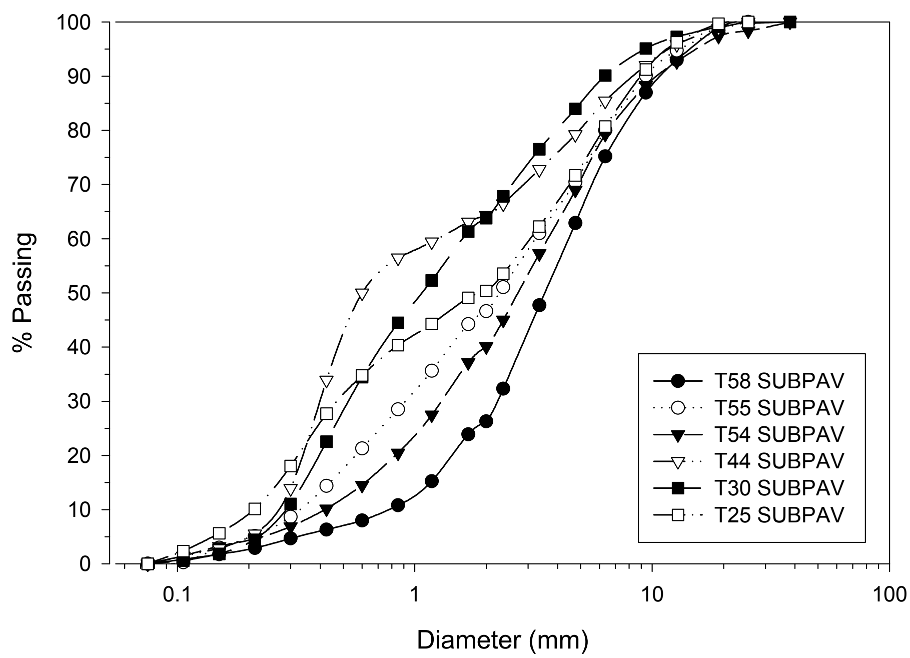

Figure A11. Subpavement distributions for six Leading Creek tributary sites.

VITA

Amanda Lee Dalecky was born on April 18, 1977 on an Air Force Base in Bitburg, Germany. She graduated from Virginia Polytechnic Institute and State University (Virginia Tech) in Blacksburg, VA in 1998 with a BS Degree in Environmental Engineering. In January of 1999, she entered the Master of Science program in Environmental Engineering at Virginia Tech. Upon finishing coursework for her MS Degree, she gained employment with Olver Incorporated in Blacksburg Virginia as a Project Engineer in the Water and Wastewater Division.