AN ABSTRACT OF THE THESIS OF

Beth C. Lambert for the degree of Master of Science in Geography presented on June 17, 1997.

Title: The Effects of Hillslope and Fluvial Processes on Particle Size of the Stream Bed at the Watershed, Reach, and Within-Reach Scales in a Fifth-Order Mountain Stream

Abstract approved:___________________________

(Julia Allen Jones)

This study addressed the effects of hillslope and fluvial processes on spatial patterns of stream bed particle size at the watershed, reach and within-reach scales. The study was conducted in Lookout Creek watershed, a fifth-order, 64 km² basin in the Western Cascades mountains of Oregon. Stream bed particle size was measured at 25 sites on first- through fifth-order streams. Boulder density was measured from the headwaters of the mainstem of Lookout Creek to its mouth, approximately 16 kilometers of stream length. In Lookout Creek watershed, spatial patterns of particle size result from a hierarchy of hydraulic and hillslope controls. At the watershed scale, hydraulic controls explain around 50% of the variation in d50 and d84. Particle size is related to watershed-scale trends in stream power and stream competence. At the reach scale, debris flows and landslides leave a patchy signature on stream bed particle size. Patches of both high and low boulder density are associated with landslides. A peak in density is associated with a February 1996 debris flow. Hydraulic controls are less evident at this scale, although the degree of reach constraint may affect particle size in fourth- and fifth-order Lookout Creek. At the within-reach scale, hydraulic controls are responsible for around 20% of the observed particle size variation. The effects of the largest flood on record at Lookout Creek were documented at 7 sites.
that had been sampled before the flood. At the watershed scale, a fining in particle size was observed; this is consistent with the hypothesis that Lookout Creek has an armor layer which the flood disturbed. At the within-reach scale, changes in particle size appeared stochastic, and provided little information about the role of hydraulic controls at that scale.
The Effects of Hillslope and Fluvial Processes on Particle Size of the Stream Bed at the Watershed, Reach and Within-Reach Scales in a Fifth-Order Mountain Stream

by:

Beth C. Lambert

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APPROVED:

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Major Professor, representing Geography

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Chair of Department of Geosciences

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University Libraries. My signature below authorizes release of my thesis to any reader upon request.

______________________________
Beth C. Lambert, Author
Acknowledgment

This research would not have been possible without the help and support of many people. First, my advisors Julia Jones and Gordon Grant gave me guidance and advice throughout the entire thesis process. They created an intellectually challenging and stimulating research atmosphere. My project also benefited from in-the-field discussions with Fred Swanson. Field assistance was provided by Cyndy Hines, Kristin Vanderbilt, Heidi Fassnacht, and (most importantly) by Allison Thomson. Second, I appreciated having access to computer facilities and the staff at the Forest Science Lab (FSL) of the Department of Forest Science at Oregon State University. I used the FSL computers to access Geographic Information System (GIS) data layers and to run spatial analysis programs written by Barbara Marks. I used GIS data layers, particle size data, and stream cross-section data from the Forest Science Database (FSDB). The Quantitative Sciences Group provided assistance with the statistical analysis. Finally, I would like to thank my friends and family for their love and moral support over the past three years. This research was funded under USDA Forest Service agreement PNW 92-0273.
# Table of Contents

1. **INTRODUCTION** .................................................................................................................. 1

2. **METHODS** ........................................................................................................................ 3
   2.1 STUDY AREA .................................................................................................................... 3
   2.2 CONCEPTUAL APPROACH ............................................................................................... 4
   2.3 FIELD METHODS ............................................................................................................. 9
   2.4 DATA ANALYSIS ............................................................................................................. 19

3. **RESULTS** .......................................................................................................................... 29
   3.1 SPATIAL PATTERNS IN PARTICLE SIZE VARIATION .................................................... 29
   3.2 RESULTS OF HYPOTHESIS TESTS ................................................................................ 33

4. **DISCUSSION** ..................................................................................................................... 50
   4.1 WATERSHED-SCALE HYDRAULIC CONTROLS ............................................................. 50
   4.2 REACH-SCALE HILLSLOPE AND HYDRAULIC CONTROLS ......................................... 54
   4.3 WITHIN-REACH HYDRAULIC CONTROLS .................................................................... 58
   4.4 THE EFFECTS OF A LARGE FLOOD ON PARTICLE SIZE ................................................ 60

5. **CONCLUSIONS** .................................................................................................................. 63

REFERENCES ............................................................................................................................ 65
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Conceptual diagram of the watershed, reach and within-reach scales</td>
<td>5</td>
</tr>
<tr>
<td>2. Relationship between stream order and stream power in Lookout Creek</td>
<td>7</td>
</tr>
<tr>
<td>3. Map of sampling reaches</td>
<td>11</td>
</tr>
<tr>
<td>4. Grid design a) for large streams and b) for small streams</td>
<td>15</td>
</tr>
<tr>
<td>5. Boulder density sampling design</td>
<td>18</td>
</tr>
<tr>
<td>6. Particle at incipient motion with increasing stage</td>
<td>24</td>
</tr>
<tr>
<td>7. Particle size with distance from headwaters</td>
<td>30</td>
</tr>
<tr>
<td>8. Relationship between d50 and d84</td>
<td>31</td>
</tr>
<tr>
<td>9. Boulder density and d84 with distance from headwaters</td>
<td>32</td>
</tr>
<tr>
<td>10. Relationship between stream order and stream power</td>
<td>35</td>
</tr>
<tr>
<td>11. Particle size and recurrence intervals of mobilization</td>
<td>36</td>
</tr>
<tr>
<td>12. Moran's I and lag distance</td>
<td>41</td>
</tr>
<tr>
<td>13. Boulder density pattern interpreted using Moran's I</td>
<td>42</td>
</tr>
<tr>
<td>14. Relationship between gradient and particle size</td>
<td>43</td>
</tr>
<tr>
<td>15. Particle size, pre- and post-flood</td>
<td>47</td>
</tr>
<tr>
<td>16. Pre- and post-flood particle size at the Mack Creek cross-sections</td>
<td>48</td>
</tr>
<tr>
<td>17. Pre- and post-flood particle size</td>
<td>49</td>
</tr>
</tbody>
</table>
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Particle size sampling sites</td>
<td>13</td>
</tr>
<tr>
<td>2. The return intervals at which (d_{16}, d_{50} \text{ and } d_{84}) are mobilized</td>
<td>37</td>
</tr>
<tr>
<td>3. The relationship between gradient and particle size</td>
<td>45</td>
</tr>
</tbody>
</table>
The Effects of Hillslope and Fluvial Processes on Particle Size of the Stream Bed at the Watershed, Reach and Within-Reach Scales in a Fifth-Order Mountain Stream

1. INTRODUCTION

The hillslope and fluvial processes that interact in mountain streams operate over a wide range of spatial and temporal scales. At the particle scale, a single boulder deposited by a debris flow can create local turbulence in the streamflow, protecting smaller particles from being moved by the stream. At a more intermediate scale, slow-moving earthflows encroach on the stream channel over thousands of years, pushing it against the opposite valley wall. At the watershed scale, geologic history and climate shape the drainage basin over millions of years. The physical structure of the stream at any one point is a product of the influence of these controls and others, each with its own spatial and temporal extent of influence. How these controls interact to produce the physical structure of mountain streams, however, is not well understood.

The particle size distribution of the stream bed is expected to be sensitive to both hillslope and fluvial controls, and thus can serve as a medium through which to study the relative importance of each type of contribution to the stream. This study examines spatial patterns of stream-bed particle size in relation to hillslope and fluvial processes in a single, 64 km² watershed in the western Cascades Mountains of Oregon.

Most previous studies of particle size patterns have focused on longitudinal variation in particle size. These studies have attempted to link longitudinal gradients in sediment transport with observed downstream fining trends in particle size (e.g. McPhereson, 1971; Knighton, 1982). Downstream fining trends are generally believed to be a product of the fluvial processes of selective transport, selective deposition, and abrasion (Pizzuto, 1995).

In mountain streams, a hierarchical approach to understanding particle size patterns is expected to be more appropriate than a strict longitudinal approach. Particle size patterns in a watershed are likely to result from competitions among broad, watershed scale hydraulic trends, the mass-wasting regime, and complex interactions between
hydraulics, large woody debris, and boulders. The purpose of this investigation is to use a hierarchical approach to spatial patterns of particle size by examining the effects of hillslope and fluvial controls on particle size at three spatial scales. This investigation addresses size patterns at the watershed scale (across the entire channel network), at the reach scale (stream lengths on the order of hundreds of meters) and at the within-reach scale (stream lengths on the order of tens of meters).
2. METHODS

2.1 STUDY AREA

Lookout Creek watershed is a forested 64 km$^2$ watershed in the western Cascade Mountains of Oregon. Elevation in the basin ranges from 412 to 1630 meters. Precipitation averages around 2500 millimeters, and falls during the fall, winter, and early spring. Winter precipitation falls as rain in the lower portions of the watershed and as snow in the upper portions; seasonal snowpacks develop at elevations over 1000 meters (Harr, 1981). Streamflow patterns reflect the precipitation patterns with highest streamflows in the winter. Rain-on-snow events are responsible for the largest peak flows (Harr, 1981).

The basin has a complex geomorphic and geologic history, and has been shaped by volcanism, glaciation, stream erosion, and mass-wasting. The Lookout Creek drainage development began around 4 million years ago, when late Pliocene volcanic eruptions filled a pre-existing drainage with basaltic and andesitic lavas (Swanson and James, 1975a). The late Pliocene volcanics flowed across volcanic bedrock that had been highly weathered and hydrothermally altered (Swanson and James, 1975b). The watershed was glaciated at least twice, once at lower elevations, and once at the upper elevations; glaciation occurred most recently during the late-Wisconsin, approximately 10,000 to 35,000 years before present (Gottesfeld and Swanson, 1981). Glaciers left behind till and outwash deposits in the higher-elevation valleys. After the latest glaciation, Lookout Creek aggraded. The river has since incised into this deposit, which is now 5 to 8 meters above the present channel. The terrace was abandoned at least 7000 years ago, and debris flows and fluvial processes in tributaries have constructed alluvial fans on the terrace (Swanson and James, 1975b). The basin continues to be shaped by mass-wasting processes in the present time, as the combination of stable basalts and andesites overlying highly weathered volcanic rocks creates unstable slopes. Large slow-moving earthflows, debris flows, and landslides are all persistent forms of mass-wasting in the watershed.
2.2 CONCEPTUAL APPROACH

In Lookout Creek watershed, both hillslope and fluvial processes interact with the stream network. Debris flows, landslides, and bank erosion deliver sediment to the stream, while large floods mobilize and sort sediment. As a result, at any particular point Lookout Creek owes much of its sediment to hillslope processes along the length of the channel as well as to fluvial processes delivering sediment from upstream. This project tests the hypotheses that watershed-scale hydraulic trends control the spatial patterns of stream-bed particle size at a range of spatial scales, while the residual variation can be explained by hillslope processes.

This study has three parts: 1) describing the spatial pattern of particle sizes; 2) testing for degree to which observed patterns can be explained with respect to spatially varying stream competence; and 3) explaining the residual variation in size by looking for patchiness in size that would indicate the influence of hillslope controls. For the purpose of this study, "watershed" refers to the Lookout Creek watershed, "reach" refers to a length of stream hundreds of meters in length, and "site" or "within-reach" refers to a length of stream tens of meters in length (Figure 1). "Patch" is used to describe a location at which the particle size is homogenous and different from the surrounding area.

2.2.1. Hydraulic, In-Channel Controls

This study tests the hypotheses that shear stress and stream power affect the particle size distribution at the watershed, reach and within-reach scales. Stream power and shear stress serve as quantitative measures of hydraulic controls on sediment transport.

Stream power is the rate at which the stream does work, and is frequently used by geomorphologists as a rough index for the ability of the stream to mobilize material.

Stream power is defined as

\[ \Omega = \text{power} = \rho g Q S \]
Figure 1: Conceptual diagram of the watershed, reach, and site scales.
where \( \rho \) is the density of water, \( g \) is gravity, \( Q \) is discharge, and \( S \) is the energy gradient, or water surface slope. In practice, when the discharge of the stream is not known, drainage area is used as a surrogate for discharge. Stream power is a useful variable for watershed-scale questions because it can be estimated using the slope and drainage area measured from a topographic map. It is sensitive to changes in drainage area and slope, and thus is a product of the inherent basin shape. In Lookout Creek, stream power is lowest in first-order streams, and then increases linearly with increasing stream order (Figure 2). In this study, I use stream order as a proxy for general, watershed-scale trends in stream power.

Shear stress is the force per unit area that moving water exerts on the stream bed. The ability of the stream to mobilize a particle of a given size depends on this force. Average boundary shear stress is defined as

\[
\text{shear stress} = \gamma RS
\]

where \( \gamma \) is the specific weight of water, \( R \) is the hydraulic radius of the channel cross-section, and \( S \) is the energy gradient or water surface slope. In wide channels \( R \) approaches the depth of the channel, so depth is frequently substituted for \( R \) (Leopold et al., 1964). The process of sediment transport occurs when the average boundary shear stress equals or exceeds the force necessary to mobilize a particle of a given size.

It follows from the above equation that shear stress may operate in a hierarchical manner on the stream bed. At the watershed scale, I expect that shear stress is influenced by the channel slope and water depth, or discharge. At the reach scale, where I expect the stream gradient to be comparatively constant, degrees of channel constraint affect shear stress, with higher shear stresses expected in constrained, hence deeper, than unconstrained, hence shallower, reaches (Wohl, 1992; Grant and Swanson, 1995). Within a reach, local variations in gradient and the cross-section shape of the channel would cause shear stresses to differ. At the channel unit scale, shear stresses vary as the flow interacts with large woody debris, boulders and bedforms (Furbish, 1993; Lisle, 1987). Finally,
Figure 2: Relationship between stream order and stream power in Lookout Creek. The error bars represent the standard errors of the calculated stream power values from each of the sampling reaches.
shear stresses differ from particle to particle, as turbulence affects the flow and large particles hide small particles (Komar, 1989).

This study looks for the effects of watershed, reach, and within-reach differences in shear stress on the particle size distribution. Stream order, degree of channel constraint, and the water surface gradient are substituted for hydraulic controls at the watershed, reach and within-reach scales respectively. If hydraulic controls dominate at any particular scale, then I would expect to see close correlation between stream power, shear stress, and particle size.

2.2.2 Hillslope, Extra-Channel Controls

This study tests the hypothesis that debris flows and stream-side slides leave a patchy, reach-scale signature on patterns of stream bed particle size. Bedrock lithology, slow-moving earthflows, debris flows, streamside slides and bank erosion are extra-channel controls that operate at the watershed, reach, and within-reach scales to potentially control the spatial pattern of stream bed particle size.

In Lookout Creek watershed, the spatial pattern of mass-wasting events is controlled by bedrock lithology. Cohesive basalts and andesites overlie highly weathered volcaniclastic rocks. Because of differing weathering properties, the zone of contact between the two tends to be an area of unstable slopes from which both catastrophic (landslides, debris flows) and chronic (slow-moving earthflows) mass-wasting events originate (Swanson and James, 1975a). As a result, mass-wasting events tend to be concentrated below elevations of 800 meters (Swanson and James, 1975b). The pattern of bedrock lithologies underlying the watershed results in a watershed-scale pattern of slow-moving earthflows, debris flows and landslides.

Slow-moving earthflows, debris flows, landslides and bank erosion interact with the stream in two ways: by moving material from the valley floor to the channel edge and by physically delivering material to the channel from either the valley floor or the channel edge. Slow-moving earthflows are large (hectares in area) shallow slides that creep downslope at rates of millimeters to meters per year (Swanson and James, 1975a). Earthflows transport material from the valley floor to the edge of the stream; rotational
slumps and slides then move sediment into the channel. Debris flows are rapid (>10 meters per second) movements of sediment, water and organic debris that are initiated in first-order streams.

These mass-wasting events are expected to affect the size of the sediment of the stream bed by depositing large amounts of fine or coarse material in the stream, creating patchy size variation. Debris flows, for example, leave patches of boulders at the junction of the tributary channel with the larger stream. Debris flows can also construct boulder terraces and levees hundreds of meters long in third-order streams (Benda 1990). Landslides are defined as both rotational stream-bank slumps and shallow mass movements. Both types of landslides deposit sediment sizes ranging from silt to boulders in the stream. If these events control the particle size of the stream bed, then I would expect to see patches of fine sediment or coarse sediment associated with landslides and debris flows.

2.3 FIELD METHODS

Two kinds of particle size data were collected: information about the full particle size distribution and information about boulder density variation. Particle size distribution data were collected at point locations around the watershed, while boulder density data were collected along the entire length of the mainstem of Lookout Creek. Both types of data were used to document the spatial variation of particle size and to test the effects of fluvial and hillslope processes at the watershed, reach, and within-reach scales.

2.3.1 The Particle Size Distribution Sampling Design

Particle size distribution data were collected during the summers of 1995 and 1996 to describe watershed-scale patterns of particle size. Sampling was designed in a nested, hierarchical fashion. A total of 21 reaches were selected for sampling. Within each reach, particle size measurements were conducted at 1 to 6 sites. The data collected were used to characterize the size distributions of each individual site. The data from the sites at a
reach were averaged to combine the size distribution of the reach. The sampling design thus provided a data set that could be used for hypotheses tests at the watershed, reach, and within-reach scales.

2.3.1.1 Reach selection

During the summer of 1995, particle size data were collected at sites at seven reaches in the Lookout Creek watershed. These reaches were chosen to document the size distributions in streams of different sizes and to describe longitudinal size patterns in the mainstem of Lookout Creek. The data from these reaches were used to develop initial hypotheses and to construct the sampling design for 1996.

During the summer of 1996, particle size data were collected at 21 reaches in the Lookout Creek watershed, including those reaches sampled during 1995 (Figure 3). The reaches were chosen to document the spatial pattern of particle sizes at the watershed scale and to test the effects of bedrock lithology and stream order on particle size. These reaches were stratified by bedrock lithology, stream order, and location within the stream network. Three classes of bedrock lithology were used: the Oligocene to Miocene Little Butte Formation (highly hydrothermally-altered breccias and ashflows); the Middle- to late-Miocene Sardine Formation (less-altered breccias and ashflows); and the upper unit of the Sardine Formation (basalt and andesitic flows). The bedrock lithology of a particular site was determined from a GIS layer of the geology of the H.J. Andrews Experimental Forest; the original source of the coverage is in Swanson and James (1975a). Stream order was determined from a GIS coverage of the perennial stream network. Of the 21 reaches, 8 were given additional stratification criteria; these were selected at tributary junctions to test the effects of tributaries of a range of stream orders on the particle size in a larger streams. Thus, these reaches were stratified by the order of the tributary and the order of the larger stream. The reaches from 1995 were revisited to document the effects of a large flood that occurred during February of 1996. The length of each reach was determined by the number of sites at each reach and the length of each site. Reaches ranged from 10 to 120 meters in length.
Figure 3: Map of sampling reaches.
Particle size data were collected by other workers at four additional reaches at long-term cross-section sites on second- through fifth-order streams. These data are part of an on-going channel monitoring project conducted by the H.J. Andrews Long Term Ecological Research program; the data, stored in the Forest Science Data Bank (FSDB) at OSU, were accessed and included in tests at the reach and watershed scales.

2.3.1.2 Within-reach site selection

Within each reach, 1 to 6 sites were selected for sampling (Table 1). Sites were chosen to test the effects of stream gradient on particle size, and thus were stratified by gradient. At reaches without tributary junctions, 2 to 6 sites were chosen for particle size measurements. At reaches with tributary junctions, 3 sites were chosen immediately upstream of the tributary entrance and 3 sites were chosen immediately downstream of the tributary entrance. At all stream reaches, sites were no more than 20 meters apart from each other.

Initially, sites were chosen at adjacent channel units in order to test differences in particle size in different channel units. In lower order streams, however, the morphology of the stream was such that the stream could not be classified easily into units. The stream bed material did not appear to be organized into clearly defined units. In addition, different people classify channel units differently. Because of these problems, stratifying sites by channel unit would be difficult and might result in confusion among different workers. Water surface slope, on the other hand, is a reproducible measurement and is believed to be associated with channel unit type (Grant et al., 1990). Thus, water surface slope was used to stratify sites instead of channel unit type.

2.3.1.4 The Wolman method

Wolman's method (Wolman, 1954) was chosen for sampling the particle size distribution because it allows the user to estimate all percentiles of the cumulative size distribution. It has been widely used by researchers because it is relatively fast and uses
Table 1: Particle size sampling sites. Bedrock lithology classes are (1) the upper unit of the Sardine Formation (basalt and andesitic flows); (2) the Middle- to late-Miocene Sardine Formation (less-altered breccias and ashflows); and (3) the Oligocene to Miocene Little Butte Formation (highly hydrothermally-altered breccias and ashflows).

<table>
<thead>
<tr>
<th>reach</th>
<th>subbasin</th>
<th># of sites / location upstream or downstream of tributary</th>
<th>bedrock type</th>
<th>stream order</th>
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<td>Lookout</td>
<td>3 / u.s.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1b</td>
<td>Lookout</td>
<td>3 / d.s.</td>
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<td>3</td>
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<tr>
<td>2</td>
<td>McCrae</td>
<td>6 / 3 u.s., 3 d.s.</td>
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<td>4</td>
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<td>3</td>
<td>5</td>
</tr>
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<td>3</td>
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<td>2</td>
<td>4</td>
</tr>
<tr>
<td>6c</td>
<td>Mack</td>
<td>2 / at mouth</td>
<td>2</td>
<td>3</td>
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little equipment. The Wolman method uses a regular sampling grid to determine the relative area of the stream bed covered by particles of a particular size. The grid cell size is chosen so that the grid covers the area of interest and so that the grid cells are larger than the largest particle at the site. Traditionally, the intermediate or “b” axis of each particle is measured. The resulting measurements are used to generate a cumulative frequency distribution of particle sizes for the area covered by the grid.

2.3.1.5. Grid design

During both 1995 and 1996, rectangular grid plots were used, with two sides of the rectangle spanning the active channel from bank to bank. In small streams, the sampling design was modified from a grid to parallel longitudinal transects (Figure 4). This design produces results equivalent to those from a grid-based design (Bevenger and King, 1995).

2.3.1.6. Sample size

Sources differ on the number of particle measurements needed to generate a cumulative frequency distribution that accurately estimates the population being sampled. Wolman (1954) recommends measuring 100 particles to estimate the median particle size at a site. Other workers recommend samples ranging from 60 (Brush, 1961) to 100 (Hey and Thorne, 1983) to estimate the mean and 200 to 400 (Fripp and Diplas, 1993) to estimate percentiles other than the median. Rice and Church recommend measuring 400 particles to accurately estimate the 84th and 16th percentiles and bootstrapping to estimate the errors from smaller samples (Rice and Church, in press). During the summer of 1995 300 particles were measured at a site. During the summer of 1996, 300 particles were measured at the original 7 sites and 100 particles were measured at each new site.

2.3.1.7 Additional site measurements

At each site, the dimensions of the grid and the width of the summer low-flow channel were measured. A clinometer was used to measure the water-surface slope. Each site was photographed.
Figure 4: Grid design a) for large streams and b) for small streams.
2.3.1.8 Sources of error

The Wolman method had several sources of error. The first was the degree of precision and accuracy to which a particle could be measured. Most particles were too heavy to lift and were under water. Reading the ruler through the water was sometimes difficult. In addition, many particles were partly buried in the stream bed or trapped by other particles, so the true intermediate axis could not always be determined. Second, error resulted from different users. Different users are likely to select and measure the same particles differently (Marcus et al., 1995). Because the particle measurements at each cross-section reach were measured by different groups of people, error was probably introduced into the data. In addition, different groups of people sampled the cross-section sites between 1995 and 1996. Third, Wolman’s method results in bias towards larger stones because large stones have a greater chance of lying beneath a grid node (Dunkerley, 1996).

To minimize error, particles were measured to the nearest five millimeters, which was judged to be the limits of the precision and accuracy of the measurements. Partially buried particles could not be excavated, the intermediate axis of the exposed portion was measured. No method was used to account for bias towards larger particles.

The grid design may also have resulted in some error in making between-site comparisons. Because of differences in stream width and particle size among first through fifth-order streams, grids covered different lengths of the stream. In second-order streams, for example, where the largest particles were extremely large (>1 m) relative to the width of the channel (5-10 m), the grid extended downstream 30 to 40 meters. In contrast, grids extended only 10 meters downstream in fourth and fifth-order streams. As a result, grids in low-order streams probably incorporated more local sediment sources, and thus more size variation, than grids in higher order streams.
2.3.2 Longitudinal Boulder Density Data Collection

The sampling design was constructed to document the longitudinal variation in boulder density along a single drainage line, to characterize the landforms next to each reach, and to note the locations of debris flows, landslides and bank erosion along the channel.

2.3.2.1 Boulder sampling design

The entire length of Lookout Creek was sampled from its headwaters where Forest Road 1506 crosses it to its mouth where reservoir water backs it up (Figure 3). Because the scale of the pattern was unknown, a stratified-random sampling design was used. The stratified-random design included elements of both systematic and random sampling. This design would be more likely to detect spatial patterns than a purely systematic design (Fortin et al., 1989) because it could capture variation at a range of scales. To delineate the sampling reaches, Lookout Creek was divided into reaches 100 meters in length. A point was randomly chosen within each reach, and the distances between randomly selected points became sampling reaches (Figure 5). Sampling reaches ranged from ten to 199 meters in length, with an average length of 100 meters.

2.3.2.2 Reach measurements

For each reach, the number of boulders greater than one meter in intermediate diameter was counted. The numbers of tributaries, debris slides, debris flows were also counted. For each reach, the presence or absence of bedrock walls, floodplains and side-channels were noted. These landforms were noted as present if the landform was more than one channel-width in length. The gradient of each reach was measured using a clinometer.
Figure 5: Boulder density sampling design. a) Lookout Creek was divided into reaches 100 m in length; b) a point was randomly chosen within each reach; c) distances between the random points became the sampling reaches.
2.4 DATA ANALYSIS

2.4.1 Preliminary Data Treatment

Particle size distribution data were summarized using standard techniques (Church et al., 1987). The measurements from each site were converted into cumulative size distributions and the d16, d50, and d84 (16th, 50th and 84th size percentile) values were calculated for each site. At sites with 100 size measurements, the percentiles were determined from the 100 measurements. At sites with 300 measurements, the percentiles were determined using all 300 measurements. These site values were used to test hypotheses at the within-reach scale.

Analyses of the particle size data were conducted to test hypotheses at the within-reach and watershed scales, and the data were treated differently for the two spatial scales. To test hypotheses at the within-reach scale, d16, d50 and d84 values were calculated for each site as described above. These site values were used in analyses. For analyses to test hypotheses at the watershed scale, however, where comparisons were being made across reaches, it was necessary to combine the site values into reach values. This was necessary because the site values within a reach were autocorrelated with each other. Data must be independent for parametric statistics to be used. Reach d16, d50 and d84 values were calculated by averaging the values from the sites within the reach. The mean gradient was also calculated for each reach by averaging the gradients measured at each site within the reach. Each reach was assigned an indicator variable according to the underlying bedrock lithology: (3) for streams draining the Oligocene to Miocene Little Butte Formation (highly hydrothermally-altered breccias and ashflows); (2) for the Middle- to late-Miocene Sardine Formation (less-altered breccias and ashflows); and (1) the upper unit of the Sardine Formation (basalt and andesitic flows). Each reach was also assigned a stream order. Reaches that spanned a change in stream-order were treated as two separate reaches with different stream order values, gradients, and percentile values.

During data pretreatment, it was assumed that the size percentiles of each reach were accurately estimated by taking the mean of the site values within the reach. Similarly, it was assumed that taking the average of the gradient measurements accurately
estimated the gradient of the reach. These assumptions may not be correct because not all of the sites were immediately adjacent to each other. Thus, averaging the site values from a reach may not have accurately reflected the size distribution of the reach, because parts of the reach were not sampled. Likewise, sites within a reach were of slightly different lengths. Taking the average of the gradients without accounting for the distance over which each gradient was measured may also introduce some inaccuracy.

Prior to regressions, the particle size percentile data were tested for normality and equality of variances. Because d50 and d84 values showed increasing variance with increasing explanatory values, d50 and d84 values were log10-transformed. A squared stream order term was added to the statistical models for d50 and d84 to account for a change in the rate of increase in d50 and d84 with respect to increasing stream order.

Paced reach distances along the longitudinal boulder transects were converted to true distances using landmarks that had been referenced to UTM coordinates, including tributaries, roads, trails, and edges of clearcuts. The number of boulders per stream reach was then converted to a density by dividing the number of boulders in the reach by the reach length.

Prior to analysis of variance (ANOVA), boulder density data were tested for autocorrelation (lack of spatial independence) using Moran's I, a spatial autocorrelation coefficient. Positive autocorrelation indicates that data within a particular distance are similar to each other. This information is useful because it might indicate the spatial extent of geomorphic processes. However, autocorrelation distorts the results of parametric statistical tests such as regression and analysis of variance by returning falsely significant results, and thus must be identified and removed before parametric statistics can be used (Legendre and Fortin, 1989). Moran's I was calculated for the boulder density data to determine statistically significant boulder density patch lengths and inter-patch distances. Moran's I values were calculated for the boulder density data using a computer program written in C by Barbara Marks of the Forest Science Lab at Oregon State University in Corvallis, Oregon.

Significant autocorrelation was found in the boulder density data up to lag distances of around 300 to 400 meters. The effect of autocorrelation was removed by
combining reach data into larger reaches around 300 meters in length; recalculation of Moran’s I confirmed that spatial autocorrelation had been removed.

Stream order and distance from headwaters values were all calculated from geographic information system (GIS) Arc/Info coverages of the H.J. Andrews Experimental Forest. Distance from headwaters was measured from a stream network coverage called GeoHydro. Stream order was calculated from the same stream coverage using Strahler’s (1957) ordering system. The ordering system includes perennial streams. Bedrock geology was determined from a geologic map coverage which was derived from Swanson and James (1975a). Drainage area was calculated from the digital elevation model and a flow routing algorithm developed for ARC/INFO (see Wemple, 1994). The coverages were accessed using computer facilities at the Forest Science Lab, in Oregon State University’s department of Forest Science.

2.4.2 Hypotheses

2.4.2.1 Watershed-scale effects of hydraulic controls on particle size

Hydraulic controls on particle size were tested at the watershed scale by using stream order as the independent variable in 3 multiple linear regressions to predict (1) d16, (2) d50, and (3) d84 values. Each regression used the reach mean percentiles from all the sampled reaches in the watershed (n = 29). Particle size was expected to be positively related to stream order, the substitute for stream power.

2.4.2.2 Watershed-scale trends in stream power

Watershed-scale stream power trends were calculated by multiplying the drainage area of each particle size sampling reach by its average gradient. It was expected that stream power would increase with distance from headwaters, following theoretical relationships between drainage area and gradient outlined by Lawler (1995).
2.4.2.3 Stream Competence at the watershed scale

The portion of the particle size distribution controlled by fluvial processes was determined by calculating the recurrence interval in which the stream bed is mobilized among second through fifth-order streams. Several workers have described first and second-order streams as having low stream power (e.g. Benda 1990); competence was expected to increase with increasing stream order.

To explore differences in competence among streams of different orders, the frequencies with which the stream mobilizes d16, d50, and d84 were calculated for four sites representative of second through fifth-order streams: second-order Cold Creek, third-order Mack Creek, fourth-order Middle Lookout Creek, and fifth-order Lower Lookout Creek (Figure 3). The frequencies were calculated using surveyed cross-sections, a cross-section analysis program called WINXSPRO, and the long-term stream flow record.

Model Selection

WINXSPRO and an incipient motion equation developed from the Meyer-Peter and Müller bedload transport equation (see Yang, 1996) were used to calculate the flows necessary to mobilize d16, d50 and d84 at the cross-section sites. WINXSPRO is a cross-section analysis program designed by the United States Forest Service specifically for steep mountain streams. WINXSPRO uses cross-section survey data and water surface slope data chosen by the user to calculate discharge, Manning’s n, flow velocity, and shear stresses for a range of stage heights. The appropriate hydraulic variables were then used in the Meyer-Peter and Müller incipient motion equation

\[ d = \frac{SD}{K_1(n/d_{90}^{1/6})^{3/2}} \]

where d is surface sediment size (in millimeters), S is slope, D is mean flow depth in meters, \( K_1 \) is a constant (0.058 when D is in meters), n is the Manning’s roughness coefficient, and \( d_{90} \) is from the surface sediment size distribution. The Meyer-Peter and
Müller incipient motion equation was not designed for steep mountain streams or for a grain size distribution with a wide range, and thus is used in this project as an exploratory exercise.

Choosing an appropriate method to calculate the particle at incipient motion is important, because different methods produce different size estimates. For example, using Lower Lookout Creek cross-section 2 and the 1996 flood stage, the Meyer-Peter and Müller and Shields equations both estimate that the particle at incipient motion during the flood was around 475 millimeters, while the Komar method estimates a size of 1.3 meters (Figure 6). More research is needed to determine an incipient motion equation appropriate for Lookout Creek.

Hydraulic Analysis

Cross-section data were taken from a database of long-term stream channel cross-sections maintained by the H.J. Andrews Long Term Ecological Research site personnel and stored in the FSDB at Oregon State University. Three cross-sections each were selected from sites at Cold Creek, Mack Creek, Middle Lookout Creek, and Lower Lookout Creek. The sites are considered to be representative of second- through fifth-order streams. WINXSPRO assumes uniform flow, so cross-sections were chosen that were part of straight reaches and had no large woody debris. Survey data collected during the summer of 1996 were used for all sites.

WINXSPRO requires the user to enter low- and high-flow water-surface slopes. At Cold and Mack Creeks, water-surface slopes were measured perpendicular to each of the cross-sections along the length of the channel during summer low flows. The mean of the measured slopes was used to represent the slope of the reach. This average was used for the high-flow water-surface slope also. At Middle and Lower Lookout Creek, the locations and elevations of high-water marks from a February 1996 flood were surveyed. The slopes calculated from these data were used as both the low-flow and high-flow water-surface slopes.

WINXSPRO requires the user to choose a resistance equation which is then used by the program to calculate flow velocity and thus discharge. For all four sites, the
Figure 6: Particle at incipient motion with increasing stage for Lower Lookout Creek cross-section 2. Three different calculation methods were used.
Thorne and Zevenbergen method of calculating resistance was used, which is recommended for cobble and boulder bedded mountain streams with gradients above 0.02. Further details on these methods can be found in the WINXSPRO User’s Manual (1996) and Thorne and Zevenbergen (1985). WINXSPRO was used to calculate discharge, Manning’s $n$, flow velocity, and shear stresses at each cross-section for stage heights ranging from summer low flows to winter flood flows.

The average size of the particle at incipient motion at each stage was calculated using the hydraulic radius, cross-sectional area and Manning’s $n$ from the WINXSPRO output and the Meyer-Peter and Müller equation. Because the hydraulic parameters were averaged across the cross-section by WINXSPRO, the size of the particle at incipient motion was calculated for the average depth of the cross section, rather than for the deepest point. Thus, for any given flow, both smaller and larger particles would be mobilized by the stream. The stages and the associated discharges at which $d_{16}$, $d_{50}$ and $d_{84}$ would be at incipient motion were identified. The recurrence intervals of these discharges were then found. The discharge estimates converted to unit-area discharges. The unit-area discharges were compared with unit-area discharges from the H.J. Andrews long-term flow record, which is maintained in the FSDB. Discharges from the Lower and Middle Lookout Creek and Mack Creek sites were compared to flow records from the gage at Lower Lookout Creek. Although Mack Creek has a gage, the stage-to-discharge rating curve had not been tested at the time of this project, so the Lower Lookout Creek gage was used instead. Cold Creek does not have a gage, so unit-area discharges from Cold Creek were compared with Watershed 8, a watershed of a similar size and elevation.

2.4.2.4 Bedrock lithology controls on particle size at the watershed scale

The presence of bedrock controls on particle size at the watershed scale was tested by using bedrock lithology as an independent indicator variable in 3 multiple linear regressions to predict (1) $d_{16}$, (2) $d_{50}$, and (3) $d_{84}$ values. Each regression used the reach mean percentiles from all the sampled reaches in the watershed ($n = 29$). Particle size in streams draining heavily weathered volcanic bedrock was expected to be finer than particle size in streams draining the harder basalt and andesite bedrock.
2.4.2.5 Reach-scale effects of hydraulic controls on boulder density

The presence of hydraulic controls on boulder density at the reach scale was determined by comparing the number of boulders in constrained reaches to those in unconstrained reaches using ANOVA. Constrained reaches were expected to have higher densities of boulders than unconstrained reaches.

Each reach was rated according to four degrees of channel constraint. In the field, each sampling reach had been rated according to the presence or absence of floodplains, side-channels, and bedrock walls. For this analysis, these ratings were treated as degrees of constraint. Reaches with bedrock walls were considered the most constrained, while reaches with floodplains and/or side channels were considered the least constrained. Each reach was given an indicator variable for 1) the presence of bedrock walls; 2) the presence of floodplains/side-channels; 3) the presence of both floodplains/side-channels and bedrock walls; and 4) miscellaneous.

Initially, the statistical analysis used multiple linear regression to test the effects of reach type after accounting for gradient. Gradient proved to have no significant effect, so analysis of variance was used instead. Analyses were conducted on both the autocorrelated data and the data with autocorrelation removed.

2.4.2.6 Reach-scale effects of landslides and debris flows on boulder density

Moran's I correlograms were interpreted following suggestions in Fortin et al. (1989) to detect patches of high and low boulder density associated with sediment inputs from landslides and debris flows. Patches of both high and low boulder density might be expected to be associated with landslides, since landslides deposit both fine sediment and boulders in the stream. Initially, the fine sediment buries the boulders, producing patches of low boulder density. Over time the fine material is winnowed away, leaving behind larger boulders; hence older slides would be associated with patches of high boulder density. Debris flows would produce patches of high boulder density downstream of
tributary junctions. These high density patches would be tens to hundreds of meters in length. Debris flows affect particle size by depositing clumps of boulders at the mouths of tributaries and by building boulder terraces next to the stream for hundreds of meters (Benda 1990).

2.4.2.7 Within-reach effects of hydraulic controls on particle size

Hydraulic controls on particle size at the within-reach (site) scale were tested by using gradient as the independent variable in 3 linear regressions to predict (1) d16, (2) d50, and (3) d84 values. Each regression used the site percentile values from all sites without tributaries (n = 31). Particle size was expected to be positively related to gradient, the proxy for shear stress.

Hydraulic controls on particle size at 9 reaches that spanned tributary junctions were tested by using gradient as the independent variable in 3 linear regressions to predict (1) d16, (2) d50, and (3) d84 site values for each tributary junction, a total of 27 regressions. There were too few data points at each tributary junction (n = 6) to test for the statistical significance of the relationship, so r² values were used as an estimate of the strength of the relationship between gradient and particle size. Particle size values from upstream sites were visually compared with the particle size values from downstream sites. Sediment inputs from tributaries were expected to overwhelm the ability of the stream to transport and sort the material. It was expected that there would be no relationship between gradient and particle size in the reach. Instead, particle size was expected to be coarser or finer downstream of the tributary, reflecting the nature of the input.

2.4.2.8 The effects of a large flood on particle size

During February of 1996, the largest flood on record at the lower Lookout Creek gage occurred, with the highest recorded unit area discharge of 4.93 m³/s/km². The flood provided the opportunity to test the effects of a large flow on particle size distributions. Although much research has been done on spatial variation of particle size distributions,
very little information has been published on how the particle size distribution at a site might vary over time (Church et al., 1987) or of the effects of particular flow events on the particle size distribution at a site.

The effects of the February 1996 flood on particle size were tested at seven sites that were sampled the previous summer. Particle size data were collected at the seven sites during the summer after the flood. Other workers measured particle size at the four long-term cross-section sites. Particle size percentiles from before the flood were compared with those from the same sites after the flood.
3. RESULTS

3.1 SPATIAL PATTERNS IN PARTICLE SIZE VARIATION

3.1.1 Spatial Patterns of the Particle Size Distribution

Mack, McCrae and Lookout Creeks show similar spatial patterns of particle size variation, and for all streams, d84 shows the most variation in size (Figure 7). None of the streams show any pattern in d16 values with distance from the headwaters. D50 is lowest at the site closest to the headwaters for all three streams and then increases with distance from the headwaters. All three streams show similar means and standard errors in d84 for the first 4000 meters from the headwaters; Lookout and McCrae Creeks are similar up to 8000 meters from the headwaters. In all three streams, d84 is smallest closest to the headwaters, and then increases with distance. In Mack Creek and McCrae Creeks, d84 reaches one maximum size, while in Lookout Creek d84 reaches two maxima. Of the three percentiles, d84 shows the most variation with distance from headwaters. In general, d50 and d84 follow the same trends, but the relationship between the two is poorly defined for d50 values greater than 70 millimeters (Figure 8).

3.1.2. Spatial Patterns of Boulder Density

Boulder density values and d84 values seem to follow the same general spatial pattern. The boulder density data, however, show more spatial variability than is shown in the particle size data (Figure 9a).

Three scales of spatial patterns of boulder density are present along the approximately 16 kilometer length of the mainstem of Lookout Creek. First, densities vary from sampling point to sampling point (Figure 9a). Second, densities seem to occur in patches of around 400 meters in length. These patches are apparent to the eye when the data were smoothed using a 300 meter running average (Figure 9b). Examples of density patches are the series of high density points between 5000 and 6000 meters and
Figure 7: Particle size with distance from headwaters for a) Mack Creek, b) McCrae Creek and c) Lookout Creek. Error bars show the standard error of the mean value at each site.
Figure 8: Relationship between d50 and d84 for all sampling reaches.
Figure 9: a) Boulder density and d84 with distance from headwaters; b) Boulder density smoothed using a 300 meter moving average.
the low densities around 15,500 meters. Third, a broader scale of variation is present. Boulder densities are low at the headwaters of Lookout Creek, higher from 2000 to 9000 meters, low from about 9000 m to 12000 meters, and then higher from 12,000 to the mouth.

3.2 RESULTS OF HYPOTHESES TESTS

3.2.1 Watershed-Scale Effects of Hydraulic Controls on Particle Size

The effects of theoretically based stream power differences on particle size were tested by using stream order in a regression on the mean d16, d50 and d84 values from each reach. The results show that d50 increases, but at a decreasing rate, over the range of stream orders in the watershed (2-sided p values < 0.0001 and < 0.0005 for stream order and stream order^2). These results suggest that stream order controls 45% of the variation in d50 at the watershed scale. The model for the relationship between d50 and stream order is as follows:

\[
\log(d_{50}) = 2.9 + 0.8(\text{stream order}) - 0.1(\text{stream order})^2 (r^2 = 0.45)
\]

The results also showed that d84 increases, but at a decreasing rate, with increasing stream order over the range of orders in the watershed (two-sided p values < 0.0001 for both stream order and stream order^2). The results indicate that stream power controls 59% of the variation in d84 at the watershed scale. The model is as follows:

\[
\log(d_{84}) = 3.3 + 1.6(\text{stream order}) - 0.2(\text{stream order})^2 (r^2=0.59)
\]

In both of the above models, the squared stream order term shows that the rate of increase in the dependent variable decreases, so that the relationship between the independent and dependent variable is non-linear.
3.2.2 Watershed-Scale Trends in Stream Power Compared to Particle Size Trends

Stream power increases, but at a decreasing rate, with increasing stream order. This watershed-scale trend is similar in shape to the relationship between stream order and particle size (Figure 10).

3.2.3 Stream Competence Controls on Particle Size at the Watershed Scale

The recurrence intervals in which the bed is mobilized were calculated at three cross-sections each from second-order Cold Creek, third-order Mack Creek, fourth-order Lookout Creek, and fifth-order Lookout Creek. The results show that particles larger than 95 mm are rarely mobilized in second-order Cold Creek. The largest particles (200-300 mm) are transported the most frequently at third-order Mack Creek, and are transported slightly less frequently at fourth-order Middle Lookout Creek and fifth-order Lower Lookout Creek (Figure 11).

Fluvial processes are able to transport d16 at least once a year in the stream reaches sampled (Table 2). Calculations for Cold Creek, Mack Creek, Middle Lookout Creek and Lower Lookout Creek cross-sections show that d16 is transported at each cross-section at least once a year. The sizes of d16 are relatively similar between sites, ranging from 2 to 36 millimeters. The ability to transport d50 appears to be similar among the third through fifth order reaches, but different for second order Cold Creek. Calculations show that d50, which is similar for all four sites, is moved by annual to two-year flows in Middle Lookout Creek, Lower Lookout Creek, and Mack Creek. D50 is moved around every 48 years at Cold Creek. D50 ranges from 81 to 125 millimeters. The ability of the stream to transport d84 differed among second through fifth order stream reaches. Calculations suggest that d84 (250-460 millimeters) was not mobilized at the Cold Creek cross-sections during the 48 year period of record. At third order Mack Creek, d84 (262-520 millimeters) is mobilized around every 2 years. At fourth order Lookout Creek, d84 (165-308 millimeters) is mobilized every 12 years. At fifth order Lookout Creek, the stream mobilized d84 (242-310 millimeters) once in the 48 year history.
Figure 10: a) Relationship between stream order and stream power. Drainage area was substituted for discharge in this calculation. b) Relationship between stream order and particle size for all sample reaches.
Figure 11: Particle size and recurrence intervals of mobilization at second- through fifth-order stream reaches.
Table 2: The return intervals at which d16, d50 and d84 are mobilized for the second- through fifth-order cross-section sites.

<table>
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<th>Site</th>
<th>Order</th>
<th>d16 (mm)</th>
<th>Qincip (cms)</th>
<th>RI (yrs)</th>
<th>d50 (mm)</th>
<th>Qincip (cms)</th>
<th>RI (yrs)</th>
<th>d84 (mm)</th>
<th>Qincip (cms)</th>
<th>RI (yrs)</th>
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</tbody>
</table>
There are many sources of error associated with these calculations. First, errors of precision and accuracy are associated with field-data collection. Second, the cross-sections do not adequately represent the hydraulic conditions during high flow events. For example, cross-sections at Middle Lookout Creek do not extend across the floodplain or side channels. The discharge at a cross-section, therefore, may depend more on the longitudinal morphology of the reach than on the shape of the channel cross-section. As a result, discharge estimates calculated by the model for the main channel may not adequately represent the volume of water moving through the site. Next, the cross-sections do not meet the assumptions for hydraulic calculations. Hydraulic calculations assume uniform flow. This means that no channel constrictions or bends should be present upstream, downstream, or in a cross-section. If bedforms and large roughness objects such as logs and boulders are near a cross-section, these may also violate the assumptions by causing local changes in the direction and velocity of the stream flow (Furbish, 1993). Both the Lower and Middle Lookout Creek cross-section reaches contain bends, bedforms, and large woody debris. Although cross-sections from straight sections were used, it is possible that bends upstream and downstream of the cross-sections affect the flow of water in a way that is not reflected by the analysis process. Mack and Cold Creeks also contain large woody debris. In addition, the accuracy of the equations used in WINXSPRO has not been tested. For example, three cross-sections from Lower Lookout Creek were used to calculate the discharge of the February 1996 flood. High water marks from the flood were surveyed onto the cross-sections, so the stage of the event was known. For the flood stage from each of the three cross-sections, WINXSPRO calculated three different discharges, ranging from 325 to 425 cubic meters per second (cms). Other workers in the area estimated discharges of 175 to 275 cms for the same event, while the US Geological Survey estimated a discharge of around 150 cms (G.Grant, 1997, personal communication). The uncertainties in the discharge estimates from WINXSPRO lead to errors in finding the return interval at which those discharges occur, and thus errors in the frequency with which particles are mobilized. Finally, many different methods exist to calculate the size of the particle expected to move during a given flow. Different methods yield different estimates of the size of the particle expected
to move for the same discharge. More work is needed to calibrate the discharge estimates from WINXSPRO and to determine an appropriate equation for the shear stress needed to mobilize particles of a given size. Nonetheless, the results do suggest that third-order streams have the highest competence.

3.2.4 Bedrock Lithology Controls on Particle Size at the Watershed Scale

Bedrock controls on particle size at the watershed scale were tested by using bedrock lithology as an indicator explanatory variable in a multiple linear regression predicting d16, d50 and d84 after accounting for the effects of stream order. The results showed no relationship between bedrock lithology and particle size (p > 0.1).

3.2.5 Reach-Scale Effects of Hydraulic Controls on Boulder Density

The distribution of boulders by reach type was tested using ANOVA. Each reach was classified according to its channel environment: the presence of bedrock, the presence of floodplain or side channels, the presence of both bedrock and floodplains or side channels, and miscellaneous. Using the original boulder density data, ANOVA shows a weak difference between the density of boulders in bedrock-lined reaches and the density in reaches bordered by floodplains/side channels (p = 0.04) but no significant differences among the other categories (p > 0.05). The average boulder density of reaches bordered by bedrock is 0.15 boulders/meter; for reaches bordered by floodplains/side channels it is 0.09 boulders/meter. Using the boulder density data with the autocorrelation removed, the differences are not significant, although the average boulder density in bedrock-bordered reaches is still higher than boulder density in floodplain/side-channel bordered reaches.

3.2.6 Reach-Scale Effects of Landslides and Debris Flows on Boulder Density

Moran’s I correlograms were interpreted for the longitudinal boulder density data to identify spatial autocorrelation in the data and to detect patches of high and low boulder density associated with landslides and debris flows. Positive values of Moran’s I indicate lag distances at which boulder densities are similar, while negative values indicate lag
distances at which density values are different. The plot of Moran's I versus lag distance for the boulder density data with 95% confidence intervals shows two scales of pattern in boulder densities (Figure 12). The plot shows significant positive autocorrelation in boulder densities to a lag distance of around 400 meters. This means that boulder densities tend to occur in patches up to 400 meters in length. The Moran's I plot also shows significant positive correlations at lag distances of 1200 and 4800 meters. These results show a periodicity with wavelengths of 1200 to 4800 meters in the boulder density data. Negative correlations at 3000 meters show the lag distance at which boulder densities differ; this is a peak-to-trough distance.

Some peaks and troughs in boulder density seem to correspond to debris flows, landslides, and reaches bordered by floodplains (Figure 13). A significant boulder density peak is seen at the entrance of a February 1996 debris flow. Both peaks and troughs also seem to correspond to landslides. Troughs in boulder density are associated with floodplain-bordered reaches, but only in the lower half of Lookout Creek.

3.2.7 Within-Reach Effects of Hydraulic Controls on Particle Size

Hydraulic controls on particle size at the within-reach (site) scale were tested by using gradient as the independent variable in 3 linear regressions to predict (1) d16, (2) d50, and (3) d84 values for sites from all reaches without tributary entrances (n=31). The results show that gradient is positively related to d16, d50, and d84 for all sites from reaches without tributary entrances (Figure 14). The models are as follows:

\[
\begin{align*}
\text{d16} &= 11.5 + 1.5\text{(gradient)} \\
\text{d50} &= 57.8 + 5.6\text{(gradient)} \\
\text{d84} &= 232.8 + 20.1\text{(gradient)}
\end{align*}
\]

\(r^2 = 0.23\) 
\(r^2 = 0.21\) 
\(r^2 = 0.26\)
Figure 12: Moran’s I and lag distance. Moran’s I indicates significant autocorrelation and periodicity in the boulder density pattern.
Figure 13: Boulder density pattern interpreted using Moran's I. Patches associated with landslides are marked "L", patches associated with floodplain areas are marked "F".
Figure 14: Relationship between gradient and particle size for all sites from reaches without tributary entrances.
Hydraulic controls on particle size at 8 reaches that spanned tributary junctions were tested by using gradient as the independent variable in 3 linear regressions to predict (1) d16, (2) d50, and (3) d84 site values for each tributary junction, a total of 24 regressions. The $r^2$ value of each regression was used as an estimate of the strength of the relationship between gradient and particle size at each reach, with higher $r^2$ values indicating a stronger relationship. The results show that hydraulic controls on within-reach particle size are strongest at same-order tributary junctions, where the drainage area (and thus discharge and stream power) would be expected to double (Table 3). The $r^2$ values for d50 and d84 were highest at the junctions of same-order tributaries. An exception is the reach spanning the entrance of a February 1996 debris flow from a second-order tributary into fifth-order Lookout Creek; both d16 and d50 showed the highest $r^2$ (0.51 and 0.98) in this reach. In general there was no relationship between gradient and d16 in the reaches with tributary junctions.

Tributaries appear to have a negligible effect on particle size at the reaches that were sampled. Two reaches showed particle size changes downstream of the tributary entrance. Particle size was finer downstream of a third-order tributary junction with McCrae Creek, and coarser downstream of the February 1996 debris flow into fifth-order Lookout Creek. These results were consistent with field observations; the tributary at McCrae Creek appeared to be building a small delta of fine material that extended into McCrae Creek, and the debris flow deposited large numbers of boulders in Lookout Creek.

3.2.8 The Effects of a Large Flood on Particle Size

During February of 1996, the largest flood on record for Lookout Creek occurred with the highest recorded unit discharge, 4.93 m$^3$/s/km$^2$. The effects of the flood on particle size distributions were tested by sampling again the seven sites that had been sampled during the summer of 1995. Particle size data at the cross-section sites were also sampled again by other workers; these data, maintained in the FSDB, were accessed and used in the analysis.
Table 3: The relationship between gradient and particle size at tributary junctions.

<table>
<thead>
<tr>
<th>site</th>
<th>n</th>
<th>tributary order</th>
<th>mainstem order</th>
<th>d16 downstream</th>
<th>r2</th>
<th>d50 downstream</th>
<th>r2</th>
<th>d84 downstream</th>
<th>r2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>6</td>
<td>1*</td>
<td>4</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>no diff.</td>
<td>0.04</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>0.04</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>0.43</td>
<td>no diff.</td>
<td>0.58</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>2*</td>
<td>5</td>
<td>no diff.</td>
<td>0.51</td>
<td>no diff.</td>
<td>0.98</td>
<td>coarser</td>
<td>&lt;0</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>finer</td>
<td>0.31</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>finer</td>
<td>&lt;0</td>
<td>finer</td>
<td>&lt;0</td>
<td>finer</td>
<td>&lt;0</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>finer</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>&lt;0</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>no diff.</td>
<td>&lt;0</td>
<td>no diff.</td>
<td>0.71</td>
<td>no diff.</td>
<td>0.21</td>
</tr>
</tbody>
</table>

*debris flow entrance site
3.2.8.1 Watershed-scale effects of the flood

The results show considerable fining in the post-flood particle measurements (Figure 15). The results show that post-flood particle sizes are finer at sites from around 4000 meters from the headwaters to 14000 meters from the headwaters. Where post-flood fining occurs, it occurs in all three percentiles (d16, d50 and d84).

3.2.8.2 Reach-scale effects of the flood

The results show that the effects of the flood on particle size differed by sample reach. At third-order Mack Creek, very few changes were observed (Figure 16). Some local fining and coarsening occurred; cross-section 1 was finer after the flood, for example, while cross-section 10 coarsened. No clear pattern of size changes was evident, however. At fourth-order Middle Lookout Creek, in contrast, most cross-sections showed finer particle size measurements after the flood in d16, d50, and d84 (Figure 17). At Lower Lookout Creek, most cross-sections showed finer d16 measurements. However, there was no consistency among changes among d50 and d84 measurements. Some cross-sections such as 9 were finer after the flood, while 11 was coarser. Cross-sections 2 through 5 did not change (Figure 17).
Figure 15: Particle size, pre- and post-flood, with distance from headwaters.
Figure 16: Pre- and post-flood particle size at the Mack Creek cross-sections.
Figure 17: Pre- and post flood particle size at a) the Middle Lookout Creek cross-sections and b) the Lower Lookout Creek cross-sections.
4. DISCUSSION

In Lookout Creek, the impact of hydraulic controls decreases as the scale shifts from the watershed to the reach to the within-reach scale. The results show strong evidence for hydraulic controls on particle size at the watershed scale. Hydraulic controls at this scale explain half the observed size variation. There is strong evidence that much of the additional variation can be explained by the impacts of hillslope processes observed at the reach scale and by stochastic within-reach hydraulic controls. Comparing pre- and post-flood particle size patterns at the watershed scale suggests that Lookout Creek, like other gravel-bedded streams, has an armor layer; this armor layer was disturbed by the flood. More information is needed to interpret particle size changes at the reach scale.

4.1 WATERSHED-SCALE HYDRAULIC CONTROLS

The results show strong evidence that stream power plays a significant role in controlling particle size at the watershed scale, although it may explain only part of the observed size variation.

The effects of hydraulic controls on particle size at the watershed scale were examined by 1) comparing the watershed-scale particle size pattern with watershed-scale trends in stream power (Figure 10); 2) calculating the return interval in which the stream mobilizes its bed in second-, third-, and fourth- order streams; and 3) testing the effects of stream order (a substitute for stream power) on particle size using multiple linear regression. Stream power increases, but at a decreasing rate, with increasing stream order. Return interval calculations confirm this trend by suggesting that the stream bed is mobilized more frequently in third through fifth order streams than in second order streams. Similarities between the stream power trends and the particle size pattern suggest particle size is closely associated with stream power. This is further supported by the significance of stream order (a substitute for stream power) as an explanatory variable in multiple linear regression models predicting \(d_{50}\) and \(d_{84}\). The \(r^2\) values of 0.45 for the
model predicting d50 and 0.59 for the model predicting d84 show that stream order controls around half the size variation of both percentiles.

The watershed-scale stream power trend reflects the relative importance of drainage area and stream gradient in different parts of the stream network. Stream power is lowest in first-order streams in Lookout Creek and highest in fifth order Lookout Creek, where it also shows the greatest variance. Stream power is low in first order streams because although the gradient is high in these streams (20-50% in the reaches sampled), the drainage area is small. Stream power increases with increasing order as drainage area increases and the gradient remains relatively steep (4 to 15% in second- and third- order sampling reaches). Average stream power remains relatively constant in fourth- and fifth-order Lookout Creek because although the drainage area is doubled for fourth-order streams and doubled again for fifth-order streams, the gradient is much gentler. Stream power varies the most in fourth- and fifth-order Lookout Creek, however. This is because when drainage area is relatively constant, stream power is sensitive to small changes in gradient. In sampling reaches from fifth-order Lookout Creek, for example, gradient measurements range from 0 to 4%, and stream power varies accordingly.

The watershed-scale trend in stream power can be used to interpret the watershed-scale pattern of particle sizes. Particle size is small in first-order streams because, in the absence of stream power, it reflects the texture of the colluvium deposited by landslides and soil creep. First-order streams are by definition streams without tributaries (Strahler, 1957). This means that there is no upstream source of sediment. As a result, the sediment present in the stream bed is a function of hillslope delivery mechanisms. Because stream power is low, the stream is unable to mobilize much of the sediment deposited by hillslope processes. The stream bed material resembles material on the surrounding hillslopes, and thus is relatively small.

This hypothesis is supported by field observations made at the headwaters of Lookout Creek during the summer of 1996 and by the work of other researchers. Field observations showed that stream bed material in first-order streams resembled the mixture of cobbles, gravel, soil, and organic material that mantled the hillslopes. Very few large
particles were seen on the adjacent hillslopes, and very few large particles were seen in the stream bed. Pieces of large woody debris lay in the stream with conifer saplings growing from the tops, suggesting that the wood had not been recently mobilized by the stream. Other researchers support the hypothesis that the particle size of first order streams is controlled by hillslope rather than fluvial processes. Studies in the Coast Range of Oregon have concluded that first order streams act mainly as reservoirs for material deposited there by landslides, tree throw, and creep (Deitrich and Dunne, 1978; Benda, 1990). The stream lacks the power to sort or transport these sediments except during extreme debris flow events (Benda, 1990).

The increase in particle size from first- to third-order streams probably reflects an increase in the size of particles delivered to the stream by hillslope processes and increased competence. Field observations show that the hillslopes were providing larger particles to second- and third-order streams than to first-order streams. At the headwaters of Lookout Creek, the colluvium mantling the hillslope was primarily composed of soil, gravel, pebbles and cobbles. In second-order Lookout Creek, however, material of a much broader range of sizes was exposed in the stream bank. The exposed particles ranged in size from silt or clay to large boulders (>2 meters in diameter). The number of small stream-side slides appeared to increase between first- and second-order Lookout Creek. The stream banks in second- and third-order Lookout Creek frequently had a scalloped appearance, suggesting that they had been excavated by small slides or rotational slumps. The increase in stream power from first- to third-order streams implies similar increases in channel competence. The recurrence interval calculations confirm the implied competence increase; calculations show that third order streams are capable of moving larger particles more frequently than second-order streams (Table 3.1). It is likely that hillslope processes deposit a wide range of particle sizes in the stream, and the stream removes much of the smaller material. Thus, particle size increases with increasing stream order.

The decline in particle size between third- and fifth-order Lookout Creek suggests that a transition from a hillslope controlled system to a fluvially controlled system occurs in Lookout Creek. Downstream fining trends are considered to be an indicator of fluvial
sediment transport processes. These trends are present in rivers around the world, from Scotland (Furguson and Ashworth, 1991) to Pennsylvania (Pizzuto, 1995) and have been reproduced in experimental flumes (Paola et al., 1992). How fluvial sediment transport processes produce downstream fining trends is not well understood by researchers, but the trends are generally believed to be produced by selective transport (Knighton, 1982; Dawson, 1987; Hoey and Ferguson, 1994), selective deposition of particular fractions of the particle size distribution (Paola and Seal, 1995), and longitudinal changes in gradient (Furguson and Ashworth, 1991).

Selective deposition is probably the mechanism that causes downstream fining in Lookout Creek. Although stream power increases with increasing stream order, the variation in stream power increases also. In Lookout Creek, the transition from third to fourth and fifth-order streams coincides with an increase in the range of depositional environments, as suggested by the relatively large standard error bars on the calculated stream power value for fifth-order Lookout Creek (Figure 3.4). This results in more places where smaller particles can be deposited, and thus an overall decrease in average particle size. Because stream power fluctuates with changes in gradient and cross-section shape, unit stream power might be a more appropriate measure of the ability of the stream to transport sediment. Calculating unit stream power for the sampling sites might better show whether particle size declines due to selective deposition.

The effects of bedrock lithology on particle size after accounting for the effects of stream order were tested by adding bedrock as an indicator explanatory variable to the regression models predicting d16, d50 and d84. There was no evidence that bedrock lithology has any effect on particle size in the stream reaches I sampled. It is possible that bedrock lithology may affect particle size in first order streams, where the physical weathering of bedrock is an important source of sediment (Lawler, 1995). It is also possible that using stream order as an explanatory variable in the analysis eliminated the statistical effects of bedrock lithology. In Lookout Creek, many first-order streams tend to be in the parts of the watershed underlain by basalt and andesite, while fourth- and fifth-order streams flow through parts of the watershed underlain by the weathered volcanics.
Thus the stream order variable may already incorporate the effects of bedrock on particle size. More work is needed to investigate these potential relationships.

Other sources of particle size variation may be found in the watershed-scale pattern of glacial deposits, Pleistocene river terraces, and mass-wasting events. Much of upper Lookout Creek Watershed was glaciated during the latest Wisconsin, at least 10,000 years before the present (Swanson and James, 1975a). Particles of a range of sizes were moved from ridgetops and deposited in the broad cirque valleys that form upper Lookout and McCrae Creek. Glacial outwash deposits have been noted along the length of Lookout Creek from its headwaters to its confluence with Mack Creek (Swanson and James, 1975a). Next, much of lower Lookout Creek is bordered by river terraces that were abandoned around 7000 years before the present (Swanson and James, 1975b). These terraces contain particles ranging from gravel to boulders. Bank erosion and landslides deposit these particles in the stream. Finally, the lower part of the watershed is underlain by highly weathered volcanic rocks. These unstable rocks create a zone of debris flows and slow-moving earthflows in the lower part of the watershed. Slow-moving earthflows move glacial and other eroded sediments from the valley floor to the edge of the stream, where landslides then deposit them in the stream. More research is needed to compare this watershed-scale pattern of sediment sources with the longitudinal boulder density pattern.

4.2. REACH-SCALE HILLSLOPE AND HYDRAULIC CONTROLS

The results show strong evidence for the presence of reach-scale hillslope controls on particle size and provide only mixed evidence of hydraulic controls. The effects of hillslope controls on particle size were examined by testing for patches of high and low boulder density associated with landslides and debris flows. Boulder density in constrained reaches was compared with boulder density in unconstrained reaches; constrained reaches were expected to have higher boulder densities in agreement with hypothesized higher shear stresses during floods (Wohl, 1990; Florsheim and Keller, 1987). The results show patches of both high and low boulder density associated with
landsides and patches of high boulder density associated with debris flows. Constrained and unconstrained reaches tend to be next to one another, and thus are spatially autocorrelated. When autocorrelated data are used, the results show weak differences in boulder density between constrained and unconstrained reaches, with constrained reaches having higher densities. When the autocorrelation is removed by grouping the sampling reaches into “bins” approximately 300 meters in length, these differences are no longer statistically significant.

4.2.1 Reach-Scale Hillslope Controls

Stream-side slides and debris flows were expected to leave patchy boulder density signatures at the reach scale, and the statistical analysis provides strong evidence for patches of both high and low boulder density associated with landslides and debris flows. Calculations of Moran’s I, a spatial autocorrelation coefficient, identify statistically significant boulder density patch sizes of around 300 to 400 meters (Figure 12). Several of these peaks and troughs appear to be associated with specific debris flows or landslides (Figure 13). The density value, length, and spacing of patches would be expected to depend on the spatial and temporal frequency of hillslope events and the competence of the channel; although these hypotheses can be supported through field observations and the literature, more work is needed to understand the relationship between hillslope processes and boulder density patterns.

The boulder density of a reach probably depends on the timing of hillslope events and the location of the event relative to other events, and the competence of the stream channel. Field observations showed, for example, that recent landslides left patches of fine material in the stream, resulting in low boulder densities. Over time it is likely that the fine material would be winnowed away, leaving a patch of boulders behind. Thus, old slides would show high boulder densities in the stream. Individual landslides that are in a particularly landslide-prone area would not be expected to leave a density patch distinguishable from other events. Landslides both upstream and downstream would contribute a large number of boulders to the stream, and thus the individual event would not leave a signature that distinguished it from events around it.
The stream length of a high density patch may depend whether the hillslope event contributing the boulders is a debris flow or landslide and on the competence of the stream channel. Debris flows, which usually occur during times of high stream discharge, may flow from the first order stream down a second or third order stream (Benda 1990); it is likely that these events would create long boulder patches in the second or third order stream. A landslide that took place in a highly competent area would create a boulder density trail downstream as boulders were gradually transported downstream from the source. A landslide in an area of low competence would leave a relatively short patch close to the source.

The Moran's I test for spatial autocorrelation suggests that there is a periodicity to the pattern of boulder density peaks and boulder density troughs. The periodicity probably represents either the spatial frequency of mass-wasting events, the temporal frequency of events, or both. The lag distance between peaks, for example, may represent the distance between tributaries that periodically have debris flows. The spacing between peaks and troughs could also indicate the temporal frequency of events. Debris flows episodically deliver large boulders from tributaries to the larger stream (Benda and Dunne, 1987). It is possible that these clumps of boulders form a boulder “pulse” that then slowly moves downstream over time. Eventually, another debris flow occurs, contributing a new “pulse” of sediment that moves slowly downstream. To further test this hypothesis, it would be necessary to have more information about the timing of hillslope events, the competence of the stream, or a larger sample area.

4.2.2 Reach-Scale Hydraulic Controls

The results provide mixed information about the extent to which variations in shear stress control particle size at this scale. This may be for computational or for geomorphic reasons. The statistical analysis may not have tested for the effects of shear stress in an appropriate manner. On the other hand, there is significant evidence for the impact of hillslope events at the reach scale which could over-ride hydraulic controls.

The statistical analysis of the effects of reach-scale shear stress differences on boulder density yielded mixed results. The results showed that boulder densities were
higher in constrained reaches than in unconstrained reaches. These results are consistent with the hypothesis that constrained reaches have higher shear stresses than unconstrained reaches during high flow events. During high flow events, sediment is scoured from the bed in constrained reaches, leaving behind only the large boulders. Sediment is deposited in unconstrained reaches, where shear stresses are lower (Grant and Swanson, 1995). The differences in boulder density in constrained and unconstrained reaches are weakly significant when the autocorrelated data are used. When the autocorrelation is removed, the relationship is not statistically significant. Thus, there is conflicting evidence for the effects of reach scale shear stress differences on boulder density.

Problems with reach-designation and with the statistical analysis may have contributed to the lack of evidence for reach-scale hydraulic controls. The method of testing the effects of channel constraint (shear stress) on boulder density was problematic. Because there was no independent measure of channel constraint, landforms were substituted. Bedrock reaches were expected to be the most constrained and floodplain reaches were expected to be the least constrained. This substitution may not be appropriate. Many reaches in small order streams, for example, are bordered by floodplains but are still relatively constrained by close proximity of steep valley walls. Also, many reaches in the lower portion of Lookout Creek are constrained by landforms other than bedrock such as alluvial fans. These fans may provide sediment to the stream, including large boulders. Reaches which are closer to the hillslopes (more constrained), are more likely to be affected by hillslope processes than reaches that are bordered by floodplains. Any given reach, therefore, is responding to both boulder delivery potential and the effects of the constraint. Rating each reach on its boulder delivery potential as well as its degree of constraint might help to untangle the effects of the two influences.

Second, the reaches were categorized imprecisely. Reaches were categorized based on the presence or absence of bedrock or floodplain/side-channel landforms, and not by the percent of the reach bordered by them. Thus a reach with a small exposure of bedrock received the same rating as one which was entirely bordered by bedrock. This imprecision was probably increased when the reaches were combined into reaches around 300 meters in length to remove the autocorrelation. Next, the statistical analysis was not spatially
explicit. The analysis tested the effects of reach type along the entire length of Lookout Creek and did not test how the strength of the reach-type controls varied spatially. Finally, the reach-type designation may incorporate hillslope delivery variations as well as the competence of the reach.

4.2.3 A Transition From Hillslope to Hydraulic Controls

A transition from hillslope controlled particle size to a more fluvially influenced system may occur between third and fourth order Lookout Creek. This is suggested by visually examining the boulder density pattern and the spatial distribution of mass-wasting events and reach types (Figure 13). In first- through third-order Lookout Creek, boulder density peaks and troughs appear to be associated with mass-wasting events, but not with floodplain or bedrock reaches. In fourth- and fifth-order Lookout Creek, however, the situation is different: most troughs are associated with floodplains, supporting the hypothesis of Grant and Swanson (1995). A more spatially explicit statistical analysis could better test the association between hillslope processes, channel constraint, and boulder density at the reach scale.

4.2.4 Other Possible Sources of Variation at the Reach Scale

Large wood jams may also contribute to particle size variation at the reach scale by forcing local changes in gradient and creating reservoirs of fine sediment. Wood jams in second and third order streams frequently span the entire channel, forming a dam. Sediment collects behind the dam, eventually changing the local gradient (Swanson and Nakamura, 1992). Fine sediment is deposited behind the jam, burying larger particles. Deposition of fine material can extend for tens of meters upstream of the wood jam (Rice and Church, 1996).

4.3 WITHIN-REACH HYDRAULIC CONTROLS

The analysis of the relationship between gradient and particle size at the within-reach scale suggests that local shear stress variations exert only a weak control on within-
reach particle size variation. Tributaries that contribute extremely fine or extremely coarse material may contribute to the unexplained variation. Most tributaries, however, do not have a distinguishable effect either on the relationship between particle size and gradient or on downstream particle size.

At the within-reach scale, local variations in shear stress control a small portion of the observed variation. The results of regressions predicting d16, d50 and d84 shows that gradient, a substitute for shear stress, has a positive relationship with d50 and d84 for all 2-5 order stream sites. However, the low r^2 of .20 shows that gradient controls very little of the observed variation. Most of the variation in particle size is explained by factors other than local shear stress.

Sediment inputs from tributaries may contribute to some of the variation that is not explained by local shear stress changes. Tributaries that contribute sediment that is finer or coarser than that of the larger stream may have an effect on downstream particle size. Of the 8 tributary junctions that were examined, one showed finer particle size downstream of the tributary entrance. One of these tributaries had built a small delta of fine material that was encroaching into the larger stream. One site showed distinct coarsening downstream of the tributary entrance. This was the site of a February 1996 debris flow; field observations showed that the debris flow had deposited many large boulders into Lookout Creek. Most sites showed a weak relationship between gradient and particle size, suggesting that tributary inputs did not disrupt the hydraulic control of particle size. In general, most tributaries do not leave a consistent signature downstream of the junction.

Tributaries may lack a distinguishable imprint for several reasons. First, stream power in the larger stream may be strong enough to incorporate the sediment inputs from tributaries without leaving a signature. This is supported by the relationship between stream order and stream power. Since stream power increases with stream order, the stream power in the larger stream will always be higher than that in the tributary. Thus, tributary inputs may not have an effect. Second, there is so much variability already present at the within-reach scale that it may be impossible to distinguish tributary inputs from other sources of variability. Finally, the size distribution of bedload material
transported by most tributaries may not be distinguishable from the particle size distribution in the larger stream. Although particle size was measured upstream and downstream of tributary entrances, particle size was not measured in the tributaries. The range of particle sizes transported by each tributary is not known. In order to understand the impact of tributary sediment inputs on particle size, it would be necessary to understand the process of sediment transport in the tributary stream.

Many additional sources of particle size variation exist at this scale, including spatial variations in shear stress; the hydraulic effects of large wood, boulders and bedrock outcrops; and sediment inputs from the erosion of terraces, alluvial fans, and glacial deposits. Shear stress is likely to vary at the site scale in response to both cross-section and gradient changes. In this study, gradient was used as a substitute for shear stress, but it is likely that cross-section shape contributes to shear stress changes equally. It is also possible that particle size may affect local gradients as well as vice versa. Boulders deposited by debris flows, for example, may cause local steepening of the gradient. Large woody debris, boulders and bedrock outcrops affect hydraulics and thus erosion and deposition by affecting resistance and directing the force of the flow.

4.4 THE EFFECTS OF A LARGE FLOOD ON PARTICLE SIZE DISTRIBUTIONS

A large flood in Lookout Creek during February of 1996 presented a unique opportunity to document the effects of the flood on particle size at the watershed, reach, and within-reach scales. This flood was the largest flood on record, with a unit discharge of 4.93 m³/s/km². A rigorous examination of the sediment transport regime of extreme floods in Lookout Creek is beyond the scope of this project. However, particle size changes can be used to develop hypotheses about the relative importance of hillslope and fluvial controls on particle size during large events. The results indicate that hydraulic controls play a large role in determining particle size at the watershed scale but may have an unpredictable impact at the within-reach scale.

The results of comparisons between watershed-scale particle size data from before and after the flood show that most sites exhibited finer particle sizes after the flood. These
results suggest that large floods destroy the coarse stream-bed armor layer, releasing and transporting finer sediments through out the watershed. Workers have suggested that, like lowland gravel-bedded streams, the beds of mountain streams are armored (Whittaker and Jaeggi, 1982). An armored stream bed is one in which a layer of coarse particles on the stream bed surface covers subsurface material of a finer size distribution. These smaller particles sift between the cracks of the larger particles into the subsurface or are winnowed away by small flow events. The armor layer covers the finer subsurface layer, protecting it from being mobilized by the stream. As a result, the finer subsurface particles are only transported during events that disturb the armor layer (Gomez, 1995).

The post-flood fining trend is consistent with the hypothesis that the flood disturbed the coarse armor layer and mobilized and transported the finer subsurface material. As the flood waters receded, the stream dropped the coarser particles first. These were then covered by a layer of finer material that had previously formed the subsurface. This hypothesis can easily be tested by measuring particle size distributions at the same sites in successive years. If the flood disturbed an armor layer, then over time the armor layer will develop again. Some fine material will be winnowed away, while other fine particles will sift between the large particles, forming the subsurface. Measuring particle size at the same sites in the future should show progressive coarsening over time.

At the reach scale, pre- and post- flood changes in particle size are difficult to interpret, and may not necessarily show 1) whether sediment was transported at a site; 2) the size of the sediment transported; or 3) whether significant morphologic change occurred in the reach. First, the lack of change in the particle size distribution is difficult to interpret. Many of the cross-sections did not show changes in the post-flood particle size distribution. The lack of change could indicate two equally possible but conflicting situations: either the flood transported sediment at the site, but the size distribution remained the same, or no sediment was mobilized. At Mack Creek, for example, very little change occurred in cross sections 6 and 7 (Figure 16), suggesting that the bed was not mobilized at these sites. On the other hand, changes did occur at cross-sections 1 and 9, which suggests that sediment was mobilized by the flood in this reach. Second, changes in particle size do not represent the size of the material transported by the flood. Cross-
sections 1 and 9 at Mack Creek showed significant coarsening. Again, this could be because of two conflicting situations. Coarsening could have occurred because large particles were mobilized by the flood and deposited at that site. On the other hand, coarsening could occur if fine materials were scoured from the site, excavating large boulders. Third, changes in the particle size distribution do not necessarily indicate the presence or absence of morphologic changes. For example, both Middle Lookout Creek and Lower Lookout Creek experienced significant morphological changes as a result of the flood. A large wood jam was built at Middle Lookout Creek, contributing to the development of extensive channel-side cobble and boulder bars and directing the force of the flow against the opposite bank, causing scouring and bank excavation. This site shows extensive fining in the particle size distribution. Lower Lookout Creek also experienced significant morphologic change as a result of the flood. Yet, post-flood particle measurements show only slight fining in post-flood d16 values, and very little change in particle size.

Examining the cross-sections themselves and channel morphology changes could provide insight into pre- and post-flood particle size comparisons. Comparing the shapes of pre- and post-flood cross-sections at Mack Creek could show evidence for sediment transport that is not indicated by the particle counts. Looking at the cross-sections would also show whether coarsening occurred because of the deposition of large particles or because fine material was scoured from the bed. Without this information, particle size changes at the reach scale are difficult to interpret.
5. CONCLUSIONS

The results of this study show that 1) particle size patterns can be used to test for both hillslope and fluvial controls on the stream bed; and 2) a hierarchical approach is useful in understanding the effects of hillslope and fluvial processes.

This study shows that spatial patterns of stream bed particle size can be used to better understand the ways in which hillslope and fluvial processes interact to create the physical structure of the stream. In low-land streams, downstream fining trends have been used as indicators of fluvial processes; this study shows that particle size patterns can be used to identify hillslope processes as well.

The processes which control particle size patterns in lowland streams are different from the controlling processes in mountain streams. In lowland streams, stream power decreases with distance from the headwaters. As stream power decreases, the ability of the stream to transport large particles decreases. At the same time, the only source of sediment is from upstream. These fluvially transported sediments are continually reworked by the stream. As the sediments are reworked, the particles are abraded and sorted. As stream power decreases and abrasion and sorting increase, particle size decreases. Thus, in lowland streams, the decrease in stream power and increased reworking lead to downstream fining trends.

In Lookout Creek, in contrast, the particle size pattern is a result of a hierarchy of both fluvial and hillslope controls. Both kinds of controls are important, but at different spatial scales. Watershed-scale hydraulic trends are overprinted by hillslope processes at the reach and within-reach scale. The watershed-scale hydraulic trends are controlled by the shape of the watershed, which is a product of its geologic and climatic history. These hydraulic trends control the general shape of particle size patterns, which can be most clearly seen in the relationship between particle size, stream power, and stream order. As the scale increases from the watershed to the reach and within reach scales, the relative importance of hillslope processes increases. Debris flows and landslides are the main sources of size variation at the reach scale, although some variation in Lower Lookout Creek may be attributed to fluvial processes. At the within-reach scale, fluvial processes
control only a small portion of the particle size distribution. The rest of the variation is attributable to stochastic interactions between hydraulics and large woody debris, boulders, bedforms, and the shape of the channel.
REFERENCES


