AN ABSTRACT OF THE THESIS OF

Karl T. Hopkins for the degree of Master of Science in Rangeland Resources


Title: The Thermal Characteristics of Hydrologically Intact Type C and E Streams in Eastern Oregon

Abstract approved:

Tony J. Švejčar

Many streams in eastern Oregon are listed as water quality impaired on the basis of water temperature. However, it is often difficult to predict water temperature for these streams even if there are no anthropogenic impacts. We measured air and water temperature and stream characteristics on three Type C and E channel streams to determine if stream type can help predict stream thermal characteristics. All six streams were hydrologically intact, assessed as Proper Functioning Condition (PFC), and were located in eastern and south central Oregon.

Water and air temperatures and stream geomorphic data were taken during the summer months of 1998 and 1999. Average daily maximum and minimum water temperature and average daily maximum and minimum rates of change in water temperature following normalization of data with estimated water residence time were analyzed. There was more variation within stream type than across groups, which precluded separation of stream types based on thermal characteristics. Most streams regardless of type and year exhibited similar daily
mean nighttime recoveries of approximately 0.53°C/hour cooling in the downstream direction following normalization by water residence time. All of the streams heated at least 1.0°C/hour during the day with some streams gaining 2.25°C/hour in the downstream direction following normalization by water residence time. Thermal variation among the streams was likely a result of the daily initial water temperature, the gradient between stream and thermal environment, and the varied physical character of each stream within type. Atmospheric temperature is probably the single most critical factor for characterizing stream temperature behavior during the periods of heating and cooling.
The Thermal Characteristics of Hydrologically Intact Type C and E Streams in Eastern Oregon

by
Karl T. Hopkins

A THESIS submitted to Oregon State University in partial fulfillment of the requirements for the degree of Master of Science

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Karl Thomas Hopkins, Author
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I would like to thank the Oregon State University Agricultural Experiment Station for the generous funding of this project. I would also like to thank my committee, Dr. Tony J. Svejcar (USDA Agricultural Research Service Eastern Oregon Agricultural Research Center), Dr. David R. Thomas (professor emeritus Statistics Oregon State University), and Dr. Douglas E. Johnson (Rangeland Resources Oregon State University) for their guidance and advice on the successful completion (and sane survival) of graduate school. Dr. Tamzen K. Stringham (Rangeland Resources Oregon State University) was a large contributor to this project and I thank her for her hard work and familiarity with riparian issues. This project succeeded through the support of many hard working individuals. Some of these people are:

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CONTRIBUTION OF AUTHORS

Dr. Tony J. Svejcar guided the writing and direction of this thesis. Dr. David R. Thomas was involved in the data preparation and analysis. Dr. Thomas wrote the SAS programs for data importation, formatting, statistical analysis, and the final outputs and summary tables. Dr. Tamzen Stringham was involved with the project design and early development of the thesis.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER ONE</th>
<th>INTRODUCTION</th>
<th>PROJECT JUSTIFICATION</th>
<th>BACKGROUND</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER TWO</th>
<th>LITERATURE REVIEW</th>
<th>INTRODUCTION</th>
<th>GEOMORPHIC ATTRIBUTES</th>
<th>PHYSICS OF WATER HEATING AND COOLING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

**LITERATURE CITED** ........................................................................................................... 31

<table>
<thead>
<tr>
<th>CHAPTER THREE</th>
<th>THE THERMAL CHARACTERISTICS OF HYDROLOGICALLY INTACT TYPE C AND E STREAMS IN EASTERN OREGON</th>
<th>ABSTRACT</th>
<th>INTRODUCTION</th>
<th>MATERIALS AND METHODS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>38</td>
<td>39</td>
<td>41</td>
</tr>
</tbody>
</table>

**RESULTS** .................................................................................................................. 48

**DISCUSSION** ................................................................................................................. 57

**CONCLUSION** ................................................................................................................ 61

**LITERATURE CITED** ...................................................................................................... 62
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a. Type C maximum changes in water temperature from cross-section one to three normalized by residence time during 1998...51</td>
<td></td>
</tr>
<tr>
<td>1b. Type E maximum changes in water temperature from cross-section one to three normalized by residence time during 1998...51</td>
<td></td>
</tr>
<tr>
<td>2a. Type C maximum changes in water temperature from cross-section one to three normalized by residence time during 1999...52</td>
<td></td>
</tr>
<tr>
<td>2b. Type E maximum changes in water temperature from cross-section one to three normalized by residence time during 1999...52</td>
<td></td>
</tr>
<tr>
<td>3. Type C and E maximum changes in water temperature from cross-section one to three normalized by residence time during 1998...53</td>
<td></td>
</tr>
<tr>
<td>4. Type C and E maximum changes in water temperature from cross-section one to three normalized by residence time during 1999...53</td>
<td></td>
</tr>
<tr>
<td>5a. Relationship between maximum daily air temperature and maximum water temperature at cross-section three measured on 39 days in July, August, and September 1998 for three Type C study reaches...54</td>
<td></td>
</tr>
<tr>
<td>5b. Relationship between maximum daily air temperature and maximum water temperature at cross-section three measured on 39 days in July, August, and September 1998 for three Type E study reaches...55</td>
<td></td>
</tr>
<tr>
<td>6a. Relationship between maximum daily air temperature and maximum water temperature at cross-section three measured on 22 days in July and August 1999 for three Type C study reaches...55</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6b.</td>
<td>Relationship between maximum daily air temperature and maximum water temperature at cross-section three measured on 22 days in July and August 1999 for three Type E study reaches.</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rosgen stream type for each stream used in study</td>
<td>43</td>
</tr>
<tr>
<td>2. Complete temperature days in 1998 and 1999</td>
<td>49</td>
</tr>
<tr>
<td>3a. Estimate residence times during 1998 by stream</td>
<td>49</td>
</tr>
<tr>
<td>3b. Estimated residence times during 1999 by stream</td>
<td>50</td>
</tr>
<tr>
<td>4. Average daily maximum and minimum water temperature at</td>
<td>50</td>
</tr>
<tr>
<td>cross-section three, change in water temperature normalized by</td>
<td></td>
</tr>
<tr>
<td>residence time, and air temperature for 1998</td>
<td></td>
</tr>
<tr>
<td>5a. Regression data of daily maximum water temperature at</td>
<td>56</td>
</tr>
<tr>
<td>cross-section three (dependent) and daily maximum air temperature</td>
<td></td>
</tr>
<tr>
<td>for study reach (independent) for all streams by type for 1998</td>
<td></td>
</tr>
<tr>
<td>5b. Regression data of daily maximum water temperature at</td>
<td>56</td>
</tr>
<tr>
<td>cross-section three (dependent) and daily maximum air temperature</td>
<td></td>
</tr>
<tr>
<td>for study reach (independent) for all streams by type for 1999</td>
<td></td>
</tr>
</tbody>
</table>
## LIST OF APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: ANOVA Tables</td>
<td>72</td>
</tr>
<tr>
<td>2: Methods for Stream Classification</td>
<td>77</td>
</tr>
<tr>
<td>3: Vegetation Functional Groups</td>
<td>80</td>
</tr>
<tr>
<td>4: Riparian Complexes</td>
<td>98</td>
</tr>
<tr>
<td>5: Stability Classes and Successional</td>
<td>101</td>
</tr>
<tr>
<td>6: Stream Sinuosity and Cross-Section Profiles</td>
<td>103</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1: Greenline Stream C1 Cross-Section 1 Left Side</td>
<td>80</td>
</tr>
<tr>
<td>2: Greenline Stream C1 Cross-Section 1 Right Side</td>
<td>80</td>
</tr>
<tr>
<td>3: Greenline Stream C1 Cross-Section 3 Left Side</td>
<td>81</td>
</tr>
<tr>
<td>4: Greenline Stream C1 Cross-Section 3 Right Side</td>
<td>81</td>
</tr>
<tr>
<td>5: Cross-Section Composition Stream C1 Cross-Section One</td>
<td>82</td>
</tr>
<tr>
<td>6: Cross-Section Composition Stream C1 Cross-Section Three</td>
<td>82</td>
</tr>
<tr>
<td>7: Greenline Stream C2 Cross-Section 1 Left Side</td>
<td>83</td>
</tr>
<tr>
<td>8: Greenline Stream C2 Cross-Section 1 Right Side</td>
<td>83</td>
</tr>
<tr>
<td>9: Greenline Stream C2 Cross-Section 3 Left Side</td>
<td>84</td>
</tr>
<tr>
<td>10: Greenline Stream C2 Cross-Section 3 Right Side</td>
<td>84</td>
</tr>
<tr>
<td>11: Cross-Section Composition Stream C2 Cross-Section One</td>
<td>85</td>
</tr>
<tr>
<td>12: Cross-Section Composition Stream C2 Cross-Section Three</td>
<td>85</td>
</tr>
<tr>
<td>13: Greenline Stream C3 Cross-Section 1 Left Side</td>
<td>86</td>
</tr>
<tr>
<td>14: Greenline Stream C3 Cross-Section 1 Right Side</td>
<td>86</td>
</tr>
<tr>
<td>15: Greenline Stream C3 Cross-Section 3 Left Side</td>
<td>87</td>
</tr>
<tr>
<td>16: Greenline Stream C3 Cross-Section 3 Right Side</td>
<td>87</td>
</tr>
<tr>
<td>17: Cross-Section Composition Stream C3 Cross-Section One</td>
<td>88</td>
</tr>
<tr>
<td>18: Cross-Section Composition Stream C3 Cross-Section Three</td>
<td>88</td>
</tr>
<tr>
<td>19: Greenline Stream E1 Cross-Section 1 Left Side</td>
<td>89</td>
</tr>
<tr>
<td>20: Greenline Stream E1 Cross-Section 1 Right Side</td>
<td>89</td>
</tr>
<tr>
<td>21: Greenline Stream E1 Cross-Section 3 Left Side</td>
<td>90</td>
</tr>
<tr>
<td>22: Greenline Stream E1 Cross-Section 3 Right Side</td>
<td>90</td>
</tr>
<tr>
<td>23: Cross-Section Composition Stream E1 Cross-Section One</td>
<td>91</td>
</tr>
<tr>
<td>24: Cross-Section Composition Stream E1 Cross-Section Three</td>
<td>91</td>
</tr>
<tr>
<td>25: Greenline Stream E2 Cross-Section 1 Left Side</td>
<td>92</td>
</tr>
<tr>
<td>26: Greenline Stream E2 Cross-Section 1 Right Side</td>
<td>92</td>
</tr>
<tr>
<td>27: Greenline Stream E2 Cross-Section 3 Left Side</td>
<td>93</td>
</tr>
</tbody>
</table>
## LIST OF APPENDIX FIGURES (CONTINUED)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>28:</td>
<td>Greenline Stream E2 Cross-Section 3 Right Side</td>
<td>93</td>
</tr>
<tr>
<td>29:</td>
<td>Cross-Section Composition Stream E2 Cross-Section One</td>
<td>94</td>
</tr>
<tr>
<td>30:</td>
<td>Cross-Section Composition Stream E2 Cross-Section Three</td>
<td>94</td>
</tr>
<tr>
<td>31:</td>
<td>Greenline Stream E3 Cross-Section 1 Left Side</td>
<td>95</td>
</tr>
<tr>
<td>32:</td>
<td>Greenline Stream E3 Cross-Section 1 Right Side</td>
<td>95</td>
</tr>
<tr>
<td>33:</td>
<td>Greenline Stream E3 Cross-Section 3 Left Side</td>
<td>96</td>
</tr>
<tr>
<td>34:</td>
<td>Greenline Stream E3 Cross-Section 3 Right Side</td>
<td>96</td>
</tr>
<tr>
<td>35:</td>
<td>Cross-Section Composition Stream E3 Cross-Section One</td>
<td>97</td>
</tr>
<tr>
<td>36:</td>
<td>Cross-Section Composition Stream E3 Cross-Section Three</td>
<td>97</td>
</tr>
<tr>
<td>37:</td>
<td>Stream C1 Sinuosity</td>
<td>103</td>
</tr>
<tr>
<td>38:</td>
<td>Stream C1 Cross-Section One Profile (1998)</td>
<td>104</td>
</tr>
<tr>
<td>39:</td>
<td>Stream C1 Cross-Section Two Profile (1998)</td>
<td>104</td>
</tr>
<tr>
<td>40:</td>
<td>Stream C1 Cross-Section Three Profile (1998)</td>
<td>105</td>
</tr>
<tr>
<td>41:</td>
<td>Stream C1 Cross-Section One Profile (1999)</td>
<td>105</td>
</tr>
<tr>
<td>42:</td>
<td>Stream C1 Cross-Section Two Profile (1999)</td>
<td>106</td>
</tr>
<tr>
<td>43:</td>
<td>Stream C1 Cross-Section Three Profile (1999)</td>
<td>106</td>
</tr>
<tr>
<td>44:</td>
<td>Stream C2 Sinuosity</td>
<td>107</td>
</tr>
<tr>
<td>45:</td>
<td>Stream C2 Cross-Section One Profile (1998)</td>
<td>108</td>
</tr>
<tr>
<td>48:</td>
<td>Stream C2 Cross-Section One Profile (1999)</td>
<td>109</td>
</tr>
<tr>
<td>49:</td>
<td>Stream C2 Cross-Section Two Profile (1999)</td>
<td>110</td>
</tr>
<tr>
<td>50:</td>
<td>Stream C2 Cross-Section Three Profile (1999)</td>
<td>110</td>
</tr>
<tr>
<td>51:</td>
<td>Stream C3 Sinuosity</td>
<td>111</td>
</tr>
<tr>
<td>52:</td>
<td>Stream C3 Cross-Section One Profile (1998)</td>
<td>112</td>
</tr>
<tr>
<td>53:</td>
<td>Stream C3 Cross-Section Two Profile (1998)</td>
<td>112</td>
</tr>
<tr>
<td>54:</td>
<td>Stream C3 Cross-Section Three Profile (1998)</td>
<td>113</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>55:</td>
<td>Stream C3 Cross-Section One Profile (1999)</td>
<td>113</td>
</tr>
<tr>
<td>56:</td>
<td>Stream C3 Cross-Section Two Profile (1999)</td>
<td>114</td>
</tr>
<tr>
<td>57:</td>
<td>Stream C3 Cross-Section Three Profile (1999)</td>
<td>114</td>
</tr>
<tr>
<td>58:</td>
<td>Stream E1 Sinuosity</td>
<td>115</td>
</tr>
<tr>
<td>59:</td>
<td>Stream E1 Cross-Section One Profile (1998)</td>
<td>116</td>
</tr>
<tr>
<td>60:</td>
<td>Stream E1 Cross-Section Two Profile (1998)</td>
<td>116</td>
</tr>
<tr>
<td>61:</td>
<td>Stream E1 Cross-Section Three Profile (1998)</td>
<td>117</td>
</tr>
<tr>
<td>62:</td>
<td>Stream E1 Cross-Section One Profile (1999)</td>
<td>117</td>
</tr>
<tr>
<td>63:</td>
<td>Stream E1 Cross-Section Two Profile (1999)</td>
<td>118</td>
</tr>
<tr>
<td>64:</td>
<td>Stream E1 Cross-Section Three Profile (1999)</td>
<td>118</td>
</tr>
<tr>
<td>65:</td>
<td>Stream E2 Sinuosity</td>
<td>119</td>
</tr>
<tr>
<td>66:</td>
<td>Stream E2 Cross-Section One Profile (1998)</td>
<td>120</td>
</tr>
<tr>
<td>67:</td>
<td>Stream E2 Cross-Section Two Profile (1998)</td>
<td>120</td>
</tr>
<tr>
<td>68:</td>
<td>Stream E2 Cross-Section Three Profile (1998)</td>
<td>121</td>
</tr>
<tr>
<td>69:</td>
<td>Stream E2 Cross-Section One Profile (1999)</td>
<td>121</td>
</tr>
<tr>
<td>70:</td>
<td>Stream E2 Cross-Section Two Profile (1999)</td>
<td>122</td>
</tr>
<tr>
<td>71:</td>
<td>Stream E2 Cross-Section Three Profile (1999)</td>
<td>122</td>
</tr>
<tr>
<td>72:</td>
<td>Stream E3 Sinuosity</td>
<td>123</td>
</tr>
<tr>
<td>73:</td>
<td>Stream E3 Cross-Section One Profile (1998)</td>
<td>124</td>
</tr>
<tr>
<td>74:</td>
<td>Stream E3 Cross-Section Two Profile (1998)</td>
<td>124</td>
</tr>
<tr>
<td>75:</td>
<td>Stream E3 Cross-Section Three Profile (1998)</td>
<td>125</td>
</tr>
<tr>
<td>76:</td>
<td>Stream E3 Cross-Section One Profile (1999)</td>
<td>125</td>
</tr>
<tr>
<td>77:</td>
<td>Stream E3 Cross-Section Two Profile (1999)</td>
<td>126</td>
</tr>
<tr>
<td>78:</td>
<td>Stream E3 Cross-Section Three Profile (1999)</td>
<td>126</td>
</tr>
</tbody>
</table>
LIST OF APPENDIX TABLES

Table                                                                 Page

1. Analysis of Variance for the daily maximum change from
cross-section one to three normalized by
daily water residence time.................................................74

2. Analysis of Variance for the daily maximum water temperature
at cross-section three............................................................75

3. Analysis of Variance for the daily maximum air temperature
for the study reach..............................................................76
DEDICATION

I dedicate this work to Dawn, the woman in my life that embodies all that I hold sacred in a marriage. I am also indebted to all of my parents, brothers, and sisters who provided the love and support to continue and complete this Master of Science.
The Thermal Characteristics of Hydrologically Intact Type C and E Streams in Eastern Oregon

CHAPTER ONE

INTRODUCTION

PROJECT JUSTIFICATION

Throughout the state of Oregon, water quality is a topic of great discussion among landowners, politicians, and ecologists. Although legislation has established water quality guidelines, all streams in Oregon are subject to the same regulations regardless of landscape setting. The landscape settings in Oregon are highly varied with marked differences between the moist areas west of the Cascades compared to the high desert regions east of the Cascades. Most of the research conducted on water quality, specifically water temperature, has been based on streams located in the region west of the Cascades. The natural thermal patterns of eastern Oregon streams in balance with their landscape settings have not yet been determined. The basic goal of this project was to examine the geomorphic and thermal characteristics of specific stream types common in arid landscapes of Oregon specifically to compare stream temperature daily maxima and/or daily minima and daily rates of change within C, E, and between C and E channels assessed as proper functioning condition (PFC), filling a recognizable gap in the literature. Understanding basic thermodynamics is essential for the assessment of stream type effects on water temperature.
BACKGROUND

Ecological sites in the state of Oregon have been described by soil, climate, topography, and vegetation (Anderson et al. 1998). Broad geological features separate the land into 15 general ecological provinces. The geological features that make an ecological province unique are examined through geomorphology, which is the description and interpretation of the earth’s relief features (Thornbury 1966). Watersheds within an ecological province have similar biological compositions and water movements as a result of similar geological materials and climate (Anderson et al. 1998). Decreasing the scale of perspective from regional to the smaller landscape scale allows for the isolation of riparian areas within a catchment.

The geomorphic components of the stream channel within the riparian area include channel sinuosity, bed material, bankfull width and depth, and channel slope all of which are influenced by valley topography and valley gradient (Rosgen 1996). These components reflect current climate and stream discharge characteristics. Periods of high stream discharge modify the characteristics of the geomorphic components through alterations in transportation and deposition of materials within and out of the channel. The movement of channel materials may change the shape and hydrologic features of the stream channel. In addition, climate changes may also modify the geomorphic components by impacting riparian vegetation and by influencing stream discharge. The biological entities potentially impacted by temperature shifts include stream micro invertebrates, vertebrates, and vegetation. The geomorphic component of stream width, for channels found within flat alluvial valleys, is strongly controlled by riparian vegetation. Riparian vegetation is impacted by alterations in climate and anthropogenic influences. Modifications of stream width may impact the thermal characteristics of the column of moving water by altering the dimensions of the air to water interface. Generally, streams that have widened experience increased fluctuations in temperature (Horne et al. 1994). The water column may experience
greater maximum temperatures due to more radiant energy contacting the surface of the water and colder minimum temperatures due to increased evaporative cooling (Ward 1985). The flora of low gradient riparian systems is crucial for bank stability during high flow events (Rosgen 1996) and for providing habitat for the fauna (Horne et al. 1994).

Geomorphology and its potential influence on the thermal characteristic of a hydrologically intact stream during low flow was the focus of this project. A thermal characteristic is the maximum and minimum water temperatures and the rates of change in water temperature that occur within a stream in space and time. Hydrologically intact is defined as a state of equilibrium between a stream's channel structure and composition with the available discharge and the quantity and character of the sediment and other water-transported materials supplied to the channel by the surrounding landscape (Leopold et al. 1992). Equilibrium is only achieved if the channel is capable of dissipating the erosional forces created by the discharge and transported material. The kinetic energy of the erosional force is dissipated through the transformation of the kinetic energy into frictional heat energy. The state of equilibrium encompasses many different factors and is defined by “the shape of the cross section of a river at any location, [which] is a function of the flow, the quantity and character of the sediment in movement through the section, and the character or composition of the materials making up the beds and banks of the channel. In nature, the last will usually include vegetation” (Leopold et al. 1992 pg 198).

Bankfull width and depth, water velocity, stream discharge, channel slope, sediment size and load, and hydraulic roughness are the primary determinants of the pattern and profile of the channel. Equilibrium is maintained through the adjustment of any combination of all or some of the characteristics through time such that excessive erosional forces are dissipated, and the channel structure remains essentially constant.
The temperature response of a specified stream reach to its thermal environment is modified by two factors: water volume and residence time (Zwieniecki and Newton 1999 and Poole and Berman 2001). A thermal environment consists of the stream channel bed and banks and the air masses surrounding it. During low flow conditions, the decreased volume of water increases stream susceptibility to increased fluctuations of temperature (Brown and Krygier 1967, Ward 1985, and Zwieniecki and Newton 1999). Increased water volume buffers streams against sudden temperature changes as energy is absorbed and released from the stream. Low flow usually coincides with decreased water velocity lengthening the residence time for a particle of water within the reach and stream volume. Increased residence time increases the time of exposure to incoming solar radiation and the associated thermal environment for that particle of water.

Temperature is an important influence upon both flora and fauna. Temperature mediates metabolism, activities, and life cycles of individuals of a zoological or botanical group (Krebs 1972). Temperature may also help determine the distribution and abundance of zoological or botanical species in space and time (Platts et al. 1983). The dissolved oxygen concentration of water has also been directly linked to the temperature of the body of water where increasing water temperature leads to decreased dissolved oxygen concentration within the water (Gordon et al. 1992). Deviations from past stream thermal characteristics have potential to alter the flora and fauna of a riparian system because biological entities have adapted to narrow temperature ranges (Horne 1994). Departures from historical stream thermal characteristics may cause shifts in the biological composition of the riparian area. Shifts in thermal characteristics can alter organisms' physiology and habitat. Increasing temperatures may produce shifts in in-stream vegetative composition that result in habitat losses (Smith 1980).
Several species of anadromous fish in the Pacific Northwest of the United States are particularly sensitive to increasing water temperatures. These species have been declining for several decades (National Research Council [U.S.] Committee on Protection and Management of Pacific Northwest Anadromous Salmonids, 1996). The common life stages that occur in Oregon streams during the summer months (mainly July and August) for these sensitive cold-water fish species are juvenile rearing, adult holding, and adult migration. Stream temperature is a key determinant of the survival of a given fish population in a stream (Brown et al. 1971). Trout production is higher at cooler water temperatures than at warmer water temperatures (Reeves 1984). The optimum aquatic life performance is species dependent and occurs within a specific temperature range (Reeves 1984). High summertime water temperatures may impact populations of cold-water fish through:

- General increased stress and metabolism (Beschta 1997).

- Susceptibility to disease and pathogens (Brown et al. 1971) especially the lethal bacterium *Chondrococcus columnaris* whose virulence increases with warmer water temperatures (Tichenor 1966).

- Reduced levels of dissolved oxygen in the stream (Brown et al. 1971). Tichenor (1966) found that at 20°C there was 9.17 mg/l of dissolved oxygen in a water sample while at 30°C that same sample had 7.63 mg/l of dissolved oxygen. High water temperatures require high dissolved oxygen concentrations for cold-water fish to adapt to the heightened metabolic rate (Tichenor 1966). Increased metabolic rates and decreased dissolved oxygen concentrations in warm waters may act synergistically in reducing cold water fish populations (Tichenor 1966).
Potential inability to compete with warm water aquatic fish populations often resulting in redistribution of native cold-water fish populations to other parts of the stream or to different streams in the watershed (Brown et al. 1971). Reeves (1984) found that in higher water temperatures, redside shiners out-competed steelhead trout and resulted in modification of the fish community in both space and time. Steelhead trout migration to cooler water was the most common response to warmer water temperatures (Reeves 1984).

The current water temperature standard for all streams in the State of Oregon is 17.77°C (64°F) for a seven day moving maximum average and is designed to protect sensitive cold-water fish populations (Boyd and Sturdevant 1997). Streams that have temperatures exceeding the Oregon Department of Environmental Quality (DEQ) requirements are placed on the list of water temperature impaired bodies (303d list). Once a stream has been placed on the 303d list for thermal pollution, a management plan must be designed to protect the most sensitive beneficial uses (cold-water fish populations). The management plan must also establish a Total Maximum Daily Load (TMDL) of stream temperature that meets the requirements of the Federal Clean Water Act (Boyd and Sturdevant 1997). A second management plan known as a Temperature Management Plan (TMP) must be constructed which will concentrate on minimizing the impacts of human activity on the stream temperature (Boyd and Sturdevant 1997).

The water temperature requirements of sensitive cold-water fish populations were mainly determined from physiological studies. The natural thermal characteristics of streams in arid systems are not well understood. This study was implemented to determine if consistent thermal patterns could be determined as a function of stream type. The hydrologic condition of the streams was determined by the geomorphic and biological components. The geomorphic components of stream width, stream depth, glide and riffle surface area and volume, pool surface
area and volume, channel gradient, stream discharge, channel sinuosity, and channel substrate were quantified. The biological components that were studied consisted of the near stream vegetative communities that were chiefly responsible for stream shade and stream bank stability. Suitable type C and E streams were selected based on hydrological fitness. A type C stream is characterized as a low gradient, meandering channel with riffles and pools and well-defined point bars (Rosgen 1996). A type E stream according to Rosgen's (1996) classification system is described as a low gradient, meandering, riffle/pool stream with a low width to depth ratio and little deposition. The differences between Type C and E streams in Rosgen's (1996) classification is that Type C streams have channel sinuosity greater than 1.2 while the Type E streams are greater than 1.5 and Type C streams have moderate to high bankfull width to depth ratios exceeding 12 while Type E streams are less than 12. The geomorphic components of these two different stream types were isolated so that their influence on stream thermal characteristics could be studied. The ability to isolate specific geomorphic stream attributes will enable managers to identify the relative roles of the physical and biological attributes that are influencing the streams.
CHAPTER TWO

LITERATURE REVIEW

INTRODUCTION

There is limited information available on the thermal properties of streams in the Great Basin and the interior United States. Most of the information on streams in arid settings like those in eastern Oregon consists of discharge and temperature data collected during monitoring by federal and state agencies. Those streams in eastern Oregon that experience the most agricultural use are mainly type C and E streams (Rosgen 1996). The relative importance of the geomorphic attributes in determining the thermal pattern of the studied streams was the focus of this project. Different thermal patterns between the two stream types may offer insight into the heating and cooling of streams as each stream type exhibits defined geomorphic traits that may be associated with unique stream heating and cooling trends. Thermal differences between the two stream types may also encourage riparian management schemes that consider the potential thermal patterns of those streams currently under management.

The thermal characteristics of eastern Oregon streams are a result of a complex interaction between many dynamic physical components (Gebhardt et al. 1989, Winward and Padgett 1987, and Poole and Berman 2001). The physical components of a stream are the water, channel bed and bank material, channel gradient, and the air surrounding the system. The heating of a column of water is governed chiefly by radiant energy from the sun (Johnson and Jones 2000) and by the ambient radiation emitted by the atmosphere and earth (Brown and Krygier 1967 and Larson and Larson 1996). Ward (1985) described the thermal character
of a stream as the response of the water to the hydrology of the watershed, the radiant energy inputs to the water as modified by channel morphology and shade, and the climate. The source of the stream water, the characteristics of the tributaries, the occurrence of groundwater, and the discharge of the main stream are the most important constituents of hydrology to be examined when studying stream temperature (Ward 1985). Stream temperature is generally cumulative from the headwaters to increasing stream order (Reeves 1984 and Zwieniecki and Newton 1999). The water temperature of the largest stream in a watershed is partly determined by the water temperatures of its smaller tributary streams.

Insolation is the unimpeded impact of solar radiation on the earth’s surface and is the primary source of energy for stream heating (Younus et al. 2000, Johnson and Jones 2000, and Zwieniecki and Newton 1999). The impacts of insolation on streams is modified by the channel form and by the amount of shade provided to the stream by riparian vegetation and/or topographic features (Ward 1985 and Johnson and Jones 2000). Climate is modified by continental position, latitude, elevation, cloud cover, wind speed, vapor pressure, and precipitation at the local level (Ward 1985). Climate is very important in order to understand stream temperature because climate modifies the atmosphere and its temperature. The atmosphere is one of the largest bodies in the thermal environment of a stream that is readily associated with energy transfers between the stream and itself.

The daily temperature pattern of water in a stream is influenced by its initial temperature at sunrise, the volume of water, thermal loading, surface area, and discharge (Larson and Larson 1997). Decreasing elevation often results in increasing water, air, and soil temperatures through adiabatic lifting of air (Boyd and Sturdevant 1997, Larson and Larson 1997, and Isaak and Hubert 2001). The occurrence and pattern of specific stream units (glides, riffles, and pools) offer different physical environments that may impact the thermal characteristics of a parcel of water (Mosley 1983 and Fukushima 2000). Different discharge rates,
water volumes, and surface areas characterize the stream units. Riparian vegetation changes in composition and structure along a stream’s greenline result in different levels of shade and bank stability. By the time the parcel of water has left the stream reach into a tributary it has experienced many different thermal environments.

GEOMORPHIC ATTRIBUTES

Rosgen (1996) developed a stream classification system based upon the following objectives:

1. Predict a river’s behavior as related to its appearance.

2. Develop specific hydraulic and sediment relationships for a given stream type and state.

3. Provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics.

4. Provide a consistent frame of reference for communicating stream morphology and condition among a variety of disciplines and interested parties.

This classification scheme consists of four levels that are used to describe a stream as one of 94 different types. Level one examines the basin relief, landform, valley morphology, channel pattern, and channel gradient. In level one classification, stream types are determined on the basis of valley landforms and those channel dimensions that are observable on aerial photographs. The basic eight stream types, A, G, F, B, E, C, D, and Da, are based only on level one classification. Level two is concerned with bankfull channel width to depth ratios,
channel entrenchment ratios, channel sinuosity, and channel and bed substrate. In level two classification, stream types are determined with field measurements from specific channel reaches and fluvial features with in the stream’s valley. The level three classifications require more specific field measurements that allow for the 94 stream types to be determined. Level one refers to the general stream type and is denoted by capital letters. While the level two classification fine tunes the general stream type with substrate and is denoted by numbers. Level two classification also provides better insight on the potential stream response to disturbance, and level three determines stream state or condition. Level four is the validation of stream traits, which is quantifying specific stream features. All quantifiable stream traits are described in a continuum of possible values so that some degree of variation can exist between streams of the same type.

Following determination of stream type, stream equilibrium or balance with the landscape can be assessed with the USDI Bureau of Land Management (BLM) technique of proper functioning condition (PFC) (Prichard et al. 1993). Proper functioning condition is a qualitative method of assessing stream hydrological fitness by examining specific hydrologic, vegetative, and lithologic features. Riparian area function is determined by the interaction among geology, soil, water, and vegetation (Prichard et al. 1993). Several questions on the PFC standard checklist address the topic of hydrology; with hydrology being the most relevant to this particular project.

Field application of stream hydrology as outlined by Rosgen (1996) is beneficial for exploring the PFC standard checklist. Rosgen’s method of describing streams is the most current and is partly based on the well-accepted principles of stream hydrology originally developed by scientists like Leopold and Wolman. Rosgen described inclusively stream geomorphic characteristics and developed the hierarchy for stream differentiation. Rosgen (1996) describes the synthesis and importance of floodplains in dissipating stream energy during periods
of seasonal high flow. Stream sinuosity, bankfull width to depth ratio, and stream gradient are also well described by Rosgen (1996) as essential characteristics of any stream in balance with its landscape setting.

The PFC standard checklist also addresses geomorphic stream attributes. Two of the hydrology questions asked in the PFC standard checklist are directly concerned with stream floodplain, sinuosity, bankfull width to depth ratio, and gradient. These two questions are also the most important of the hydrology section as they both address a stream's ability to dissipate high-energy runoff without experiencing damage to its channel and larger riparian area. Lack of balance between a stream and its upland area (landscape setting) will commonly be exhibited as a flaw in any one or all of its geomorphic attributes of floodplain, sinuosity, bankfull width to depth ratio, and gradient. Poor balance between the stream and upland area would indicate that there is a problem in the uplands that is forcing the stream to negotiate higher than historic rates of overland flow and perhaps displaced soil. Streams that are assessed as proper functioning condition are believed to have all of the necessary features that a healthy stream would posses. A PFC stream should withstand a moderate flow event that may occur every one-half to two years and would also have desirable water quality.

PHYSICS OF WATER HEATING AND COOLING

Temperature is the measure of the average speed of the atoms and molecules of a given substance where higher temperatures correspond to faster atomic and or molecular speeds (Ahrens 1993). Heat is the transfer of energy from one body to another. Energy cannot be destroyed; it is only transferred from one body with greater energy content to a body with lesser energy content (Fuchs 1996). The Zeroth Law of Thermodynamics states that energy moves from one body to another until an energy equilibrium is reached where there is no net flow of energy between the two different systems (Cutnell 1995 and Fuchs 1996). The
First Law of Thermodynamics states that energy cannot be created, only transferred from one system to another (Cutnell 1995). The Second Law of Thermodynamics states that energy movement occurs from areas of high-energy concentration to areas of low energy concentration and is non-reversible (Cutnell 1995). Heat energy will move from hot bodies to cold bodies by interactions through either direct (conduction) or indirect (convection) means. The physical composition of the body determines its thermal behavior in the system. Bodies that consist of different substances are expected to absorb, store, and emit energy differently than other bodies. For a substance like water, phase of matter (solid, liquid, and gas) will also modify a body’s energy absorbing, storing, and emitting characteristics.

Boyd and Sturdevant (1997) and McRae and Edwards (1994) both reported that the high specific heat capacity of water is the main reason for water’s ability to retain energy for long periods of time. The long retention of energy simply means that water changes temperature very slowly when compared to other liquids. Changes in stream temperature are in response to energy movements between the stream and the thermal environment as the system seeks equilibrium (Boyd 1996).

The thermal environment, which causes changes in stream temperature, consists of the atmosphere, stream, and terrestrial environment. The air and soil serve as thermal reservoirs that can influence stream temperature (Larson and Larson 1997). Thermal equilibrium within a stream is reached when the energy additions and energy subtractions between the stream and its environment are reached (Boyd and Sturdevant 1997). Once a stream has reached equilibrium with its environment, the stream’s daily mean temperature is always very near the daily mean air temperature (Adams and Sullivan 1989). Streams will not cool to a temperature that is less than the temperature of the thermal environment (Larson and Larson 1996). The thermal character of a stream results from 1) the stream expressing equilibrium with the air temperature, 2) the quantity and quality of solar radiation available to the stream as modified by shade effects, and 3) the quantity
and temperature of groundwater inputs into the stream (McRae and Edwards 1994). Any fluctuations in the daily mean stream temperature are commonly attributed to changes in insolation and/or diurnal fluctuations in air temperature (Adams and Sullivan 1989). Stream temperature is indicative of the thermal environment through which it flows (Boyd 1996 and Larson and Larson 1997).

Stream heating is often examined at two different scales. The first scale is seasonal and is concerned with the energy dynamics within a riparian area that occur on a monthly basis (Boyd 1996). The maximum amount of energy that is available to heat a Pacific Northwest stream generally occurs during the months of July and August and the minimum amount of energy for this same stream will occur during the months of December and January. The second scale focuses on the energy dynamics in a riparian area on a daily basis. Streams experience the greatest amount of energy when the sun is at its zenith and the lowest amount of energy at night. The initial period of stream heating or cooling during the day moves the stream’s temperature to that which is nearly in balance with the thermal environment (Adams and Sullivan 1989). The diurnal pattern of stream heating is mainly due to the temporal variation in solar inputs and air temperature (Adams and Sullivan 1989).

Four primary processes (convection, evaporation, advection, and conduction) must be considered in understanding the energy budget for a stream and that energy (heat) can move either into or away from the stream depending on the relationship of these forces. Once heat energy has entered the column of water, the heat energy moves within the column and out of the column by four forces.

Convection and Evaporation

Convection is a process where energy is carried from place to place by the bulk movement of fluid (Cutnell 1995). Convection is one of the most efficient processes for the transfer of energy because the bodies involved are readily mixed
together. The bulk transfer of fluid occurs through the differential heating of the bodies involved. Energy movement by convection occurs from bodies of high-energy concentration to bodies of low energy concentration (Boyd and Sturdevant 1997). Warm fluids (gases or liquids) expand and become less dense resulting in a fluid that is lighter than the ambient fluid. The warm fluid rises and the cooler more dense ambient fluid moves in to fill the void left by the rising warm fluid (Cutnell 1995). For watersheds, the system consists of the landmasses around the riparian area, the atmosphere surrounding the watershed, and the stream itself. The fluids that are commonly involved in convection within a watershed are water vapor from the stream and the air from the atmosphere. Convective flux occurs at the water and air interface as heat energy moves between the air and the column of water (Leblanc et al. 1997). Microclimate modifications that reduce the air velocity within the riparian area modify the convection between the stream and its thermal environment (Mosley 1983).

Evaporation is a phase change from liquid to vapor, and in the case of water, results in significant cooling of the evaporative surface. Evaporation is the most important process in the dissipation of energy from a stream (Adams and Sullivan 1989 and Boyd 1996). Cooling of the stream by the process of evaporation is possible because evaporation utilizes the energy stored in the stream to initiate the transformation of water from its aqueous state to its gaseous state. The energy is carried away from the stream within each individual water molecule that escapes as a gas (Ahrens 1993). The stream experiences a decrease in temperature through the evaporative process by the following mechanism. Molecules that are in closest proximity to an air mass are generally at an increased kinetic state. The higher kinetic state increases the probability of water molecules to break the surface tension of the water and exit the stream. As these water molecules exit the stream, a net decrease in water molecules results. The temperature of the stream is decreased because the average kinetic speed of the
stream is lowered with every loss of a highly energetic water molecule to the air mass (Ahrens 1993).

Evaporation can be augmented through the forces of the wind by preventing air mass saturation with water molecules (Ahrens 1993). Wind combined with high vapor pressure gradient between the stream and the air mass often leads to very high rates of evaporation from the stream (Boyd 1996). If the air mass were to become saturated with water molecules, evaporation and condensation would occur at an equal rate preventing energy removal from the stream. Tichenor (1966) modeled the effect of evaporation on stream temperature and the physical components of surface water configuration that impact evaporation rates. Evaporation depends on the characteristics of the water surface and on the turbulent region immediately above the water surface (Tichenor 1966). The surface waves that modify the water surface are caused by hydraulic factors (channel gradient, channel roughness, and quantity of flowing water) and to some extent the wind (Tichenor 1966).

Transpirational losses from streams may lead to stream cooling. Stream cooling may occur during the warmest time of the day as evapotranspirational losses from phreatophyte vegetation increases (Zwieniecki and Newton 1999). Streams cool through this process as warmer water is removed by photosynthetic active vegetation adjacent to the stream.

Advection

Advective flux is the exchange of heat energy between two bodies when they are mixed together (Leblanc et al. 1997). The release of cool reservoir water at a high discharge has a significant cooling affect on streams at low flow during the summer (Hansen and Crumrine 1991). McRae and Edwards (1994) conducted a study in Wisconsin that explored the impacts of air temperature and especially beaver ponds on stream temperature. They found that large beaver ponds increased
the water temperature downstream from the pond due to increased residence time at the pond. The magnitude of stream warming was moderated by groundwater inputs and stream shading by riparian vegetation and topography (McRae and Edwards 1994). Hansen and Crumrine (1991) also found that large bodies of water store energy for long periods of time. Reservoirs that experience fall releases to ensure sufficient storage capacity for spring run off often result in stream warming. The stream warming was attributed to the large amount of energy that was stored in the reservoir during the summer (Hansen and Crumrine 1991).

Another facet of advection is precipitation that may enter the stream’s environment. Cloud cover and especially precipitation that directly strikes the stream seriously alters the energy relationship between the stream and its environment (Boyd 1996). McSwain (1987) also found that cloud cover and precipitation that fell directly into the stream resulted in lowered maximum stream temperatures during summer low flow.

Adective forces become more important at the channel substrate and water interface where the groundwater and stream water mix (Leblanc et al. 1997, Ward 1985, Younus et al. 2000, Johnson and Jones 2000, and Poole and Berman 2001). Under special hydrological conditions, groundwater with a temperature similar to the soil readily enters the column of water from the alluvial aquifer through phreatic flow (Poole and Berman 2001). The quantity of ground water that enters a stream depends on the time of year, geological character of the valley setting, and the area of the watershed (Adams and Sullivan 1989). The actual impact of the groundwater on stream temperature depends on both stream and groundwater discharge and the valley gradient (Adams and Sullivan 1989). Brown et al. (1971) reported that it takes very little groundwater, an amount that is not detectable with normal current meters, to cool a small stream (less than 0.1 cfs) since the temperature gradient between the two water bodies is so great. However, Holaday (1992) found that the high mainstream volume negates the cooling influence of groundwater inputs. Adams and Sullivan (1989) and Bohle (1994) both recognized
that ground water influx is an important thermal modifier in many streams. Groundwater inputs may attenuate increased stream temperature during summer low flow (Ward 1985). Caldwell et al. (1991) noted that some smaller type 4 streams in western Washington were very responsive to groundwater input; the water temperature of the stream was controlled by the groundwater temperature and discharge. Stringham et al. (1998) found that groundwater return flow in an irrigated hay meadow cooled the source stream from 1 to 3°C lower than the non-irrigated upstream portion of the same stream. Stringham et al. (1998) concluded that groundwater is an important factor in moderating stream temperature during high summer air temperature and low flow conditions. Meisner (1990) found that groundwater is influenced by air temperature and that the rate of groundwater discharge into a stream is the most critical process to lowering stream temperature.

In addition to groundwater inputs, advective cooling can occur under conditions that promote hyporheic flow. Hyporheic flow is the action of stream water entering and remaining in the alluvial aquifer and later re-entering the stream channel some distance downstream at a cooler temperature. Hyporheic flow will also maintain a similar diurnal temperature pattern as the stream water (Poole and Berman 2001). Constantz et al. (1994) discovered that increased water temperature in a stream increased the hydraulic conductivity of water into the streambed and alluvial aquifer. The increased hydraulic conductivity was mainly due to decreased viscosity of the warmer water. In a related study, Constantz and Murphy (1991) found that infiltration into two different stream substrates during ponded conditions was strongly dependent upon water temperature.

Streams that exhibit high frequency of pools and riffles, high channel sinuosity, and a cobble substrate are most likely to experience the cooling benefit of hyporheic flow (Fukushima 2000 and Poole and Berman 2001). McSwain (1987) found that those tributaries that had very low maximum water temperatures generally flowed subsurface as a result of channel aggregation. The amount of
water leaving the channel into the alluvial aquifer was greater than the amount of water leaving the channel through evaporation-transpiration.

Ebersole (1994) found 88 cold-water areas (refugia), locations where groundwater or hyporheic flow is entering the channel, in the Joseph Creek Basin of the Blue Mountains in northeast Oregon. The author’s definition of cold-water refugia was a small area of the stream that contains water that is 3°C cooler than the ambient water of the stream (Ebersole 1994). The temperature range for these cold pools was from 13.7 to 15.9°C while the ambient stream water had a temperature range from 17.0 to 24.5°C. Ebersole (1994) found that there were specific types of seeps associated with specific valley geomorphic features. For example, floodplain seeps were common in leveed outwash valleys that had steep gradients, abundant abandoned stream channels, and a substrate dominated by coarse materials. The main finding of Ebersole’s (1994) study is that cold pool formation and spatial distribution within the stream is influenced both by valley geomorphology as well as by local riparian vegetation and the stream channel expression within the valley setting. Patterns of valley fill and ground water discharge determine the capacity for cold pool development in streams.

Bilby (1984) found a total of 39 cold-water areas in a 3.5 km study reach of Thrash Creek in Washington. The author identified four types of cold-water areas—lateral seeps, pool bottom seeps, cold-water tributary mouths, and flow-through-the-bed of the stream channel—with the lateral seeps being the most common type. The most interesting conclusion of Bilby’s (1984) study are that flow-through-the-bed seeps had similar diurnal fluctuations as the rest of the stream and the pool bottom seeps did not have the same diurnal patterns as the ambient stream.

The impact of tributary water temperature on mainstream water temperature is a function of tributary discharge and the temperature gradient between the two streams (Brown et al. 1971). For small tributaries to have a temperature impact on a larger stream, the temperature gradient between the two streams must be large. Tributaries higher up in the watershed have greater impacts on the main stream...
temperature compared to tributaries that are closer to the mouth due to downstream volume increases (Brown et al. 1971).

Conduction

Conduction is the process where energy is transferred from one body to another directly through a separating material with no bulk movement of matter (Cutnell 1995). Conduction occurs between bodies that are in direct contact with each other or indirectly through another material. For watersheds, conduction is more common through direct contact of those bodies that comprise the thermal environment.

Air and soil temperature are the main components that influence the general temperature of a stream by the actions of conduction. Air temperature is mainly determined by the climate and reflects the average amount of kinetic energy contained in the atmosphere. Air temperature increases with decreasing elevation (Larson and Larson 1997 and Isaak and Hubert 2001). Adams and Sullivan (1989) and McRae and Edwards (1994) consider air temperature to be the single most important parameter influencing average daily mean stream temperature when equilibrium between the stream and the environment has been achieved. Bartholow (1989) found that water temperature and air temperature exhibit similar trends during periods of low stream flow. Air temperature not only exerts a thermal force on the column of water but also on soil temperature, which in turn impacts groundwater temperature (Ward 1985). In addition to insolation, water exposed to air warmer than itself resulted in stream warming for streams in western Oregon (Zwieniecki and Newton 1999).

In a study conducted in England on eight different streams Crisp and Howson (1982) found that standard air temperature could be used in conjunction with calculated regressions to predict weekly mean stream water temperatures even when the air temperature was recorded up to 54 km away from the stream. Larsson
and Larson (1997) also found that stream temperature mimicked air temperature; a
definite lag period was apparent with stream temperature following air temperature.
Large bodies of water (high volume) are less responsive to air temperature than
smaller volumes of water (Ward 1985). Shallow rivers (less than 0.61 m deep) had
a 4-hour lag time while deep rivers (4.57 m deep) lagged 7 days behind air
temperature. Applying lag time to stream temperature greatly improved stream
temperature estimates (Stefan and Preud’homme 1993). For a stream in Wisconsin,
air temperature was found to account for an average of 63 percent of the variability
in lagged stream temperature (McRae and Edwards 1994). Stefan and
Preud’homme (1993) examined the accuracy of stream temperature estimates from
simple linear regression with air temperature and found that water temperature
mimics air temperature in a linear manner with a definite lag time.

McRae and Edwards (1994) found that the temperature of a Wisconsin
stream closely followed air temperature even in areas of active groundwater influx.
Holaday (1992) found a strong correlation between air temperature and water
temperature in streams of the Umpqua Watershed in Oregon. Meays (2000) found
a strong association between stream temperature and atmospheric conditions.
When studying stream temperature, it is important to measure the temperature
gradient between the air and stream (Larson and Larson 1997). By the Laws of
Thermodynamics, a stream will attempt to equilibrate itself with the adjacent air
and the other constituents of the thermal environment.

Conductive flux also occurs between the stream and the earth as heat energy
is transferred between the channel bottom and sides and the column of water
(Brown 1969 and Leblanc et al. 1997). Johnson and Jones (2000) found that in
some streams in Western Oregon, conduction between the water and channel
substrate was a very important factor in stream heating. McRae and Edwards
(1994) recognized the importance of measuring soil temperature when examining
stream temperature. Soil temperature is a result of a complex interaction with air
temperature and radiant energy from the sun, atmosphere, and geologic structures.
The heat energy of the soil is transported to other objects by conduction or to the atmosphere by convection. Conduction is the most common energy modifying force that channel bed material and a column of water will experience during the heating and cooling of the two bodies. Boyd and Sturdevant (1997) reported that the rate of energy transfer through conduction between a water body and an air mass is very slow. Boyd (1996) found that conductive heat from the streambed generally increases the diurnal stream temperature range. The conversion of a stream channel bed from gravel to bare bedrock resulted in a modification of the water temperature (Brown et al. 1971). In an earlier study by Brown (1969) bare bedrock channel bottoms were considered significant factors in determining the energy balance of small western Oregon streams. The bare rock acted as energy sinks during the midday hours and as an energy source later in the day.

Thermal Stratification

Ebersole (1994) found that there was some thermal stratification occurring in the larger pools that had weak inflow. These stratified pools were 0.5 m deeper than the other pools of the stream. Thermally stratified pools were most common in low gradient channels of alluvial valleys. Thermal stratification of pools may occur in other streams as summer low flow discourages pool mixing (Ebersole 1994). Pools with greater inflows were found to be well mixed with little to no thermal stratification occurring. Bilby (1984) found no thermal stratification in the pools of his study reach unless there was a large pool bottom seep adding enough cool groundwater to cause stratification. There was no thermal or dissolved oxygen stratification detected in the pools of some southwestern Oregon steams (McSwain 1987). Thermal stratification of pools is most pronounced in the middle of the afternoon (Ward 1985).

Soil temperature is also stratified by depth with cooler temperatures occurring at 100 cm compared to 10 cm from the soil surface (Johnson and Jones
The temperatures occurring deeper in the soil profile had reduced diurnal fluctuations and were temporarily lagged as maximum temperatures at 100 cm occurred in early September while those at 10 cm occurred in mid August. The stratification of air temperature by elevation is well documented. Thermal stratification of air in riparian areas has not been well researched.

Radiant Energy and Shade:

Only 19 percent of the solar radiation striking the Earth’s atmosphere actually reaches the Earth’s lithosphere (Larson and Larson 1996). Once the solar radiation has reached a stream, the visible spectrum of light will penetrate very deep into a clear stream (Larson and Larson 1996). Larson and Larson (1996) reported that almost 100 percent of the near infrared portion of the solar radiation that reaches a stream would be absorbed in the top 10.16 cm of the water. Stream absorptivity and emissivity of long wave radiation is high (Adams and Sullivan 1989). Streams emit and absorb roughly equal amounts of long wave radiation throughout a 24-hour day (Beschta 1997). The equal movement of long wave radiation between the stream and atmosphere makes the visible portion of the solar radiation (short wave) an important factor in stream heating (Beschta 1997).

Insolation is the unimpeded impact of radiant energy upon the earth and its terrestrial features. Ward (1985) reported that direct solar radiation warms streams faster than air temperature alone. The principle source of energy leading to stream heating is direct insolation of the water (Boyd and Sturdevant 1997, Zwieniecki and Newton 1999, Younus et al. 2000, Johnson and Jones 2000, Poole and Berman 2001, and Isaak and Hubert 2001). Brazier and Brown (1973) found that removal of the forest canopy during clearcut logging was associated with large increases in stream temperature. Prevention of excessive stream heating can be achieved by properly designed buffer strips along the streams that also allow commercial harvesting of timber in the surrounding area. McSwain (1987) felt that the large
diurnal fluctuation in stream temperature at her study sites was mainly due to insolation. In the southwestern Oregon coastal area, McSwain (1987) reported that the highest stream temperatures were recorded in July when the sun is at its greatest solar angle for the Northern Hemisphere, which supports the hypothesis, that insolation greatly contributes to stream temperature fluctuations. Larson and Larson (1996) found that the greatest solar angle in the Pacific Northwest is at 12:00 am on June 21. Johnson and Jones (2000) discovered that the timing of maximum stream heating occurred earlier in the summer following removal of riparian vegetation. The stream’s geographic location, cloud cover, topographic features, and riparian vegetation modify the amount of insolation reaching the stream.

Topographic shading is as important as vegetative shading when protecting a stream from insolation (McSwain 1987). In a study by Johnson and Jones (2000), stream maximum and minimum water temperature range increased following removal of riparian vegetation. Any benefits of groundwater inputs into a stream may be quickly negated in small volume streams if there is no shade available downstream from the input (McRae and Edwards 1994). Shade provides the most protection from short wave radiation, but shade-producing objects will intercept and store long wave radiation, which can be released into the air and may eventually warm the stream. Riparian vegetation is a source of long wave radiant energy (Leblanc et al. 1997). Release of the stored long wave radiation will occur when thermal gradients shift to favor the emission of the energy into the cooler atmosphere though long wave radiation is continuously being radiated by riparian bodies throughout a 24-hour day (Boyd and Sturdevant 1997). The combination of groundwater inputs and riparian cover reduces the rate of water warming in streams during the summer and may also warm streams in the winter due to the release of stored long wave radiation by the riparian cover (Ward 1985). Riparian vegetation has a greater impact on direct solar radiant energy than the air movements that will modify rates of evaporation.
Vegetation greatly contributes to stream shading in some riparian areas and is well researched. Most of the research has been conducted in forested systems of western Oregon and little attention has been given to the arid systems of the interior northwestern United States. Riparian vegetation intercepts radiant sun energy causing a reduction in the amount of radiant sun energy that can strike the column of water (Beschta 1997). Shade does not cool a stream; shade only prevents further heating of the stream by insolation (Boyd and Sturdevant 1997, Larson and Larson 1996, and Ward 1985). McRae and Edwards (1994) found that air temperature in shaded areas was 2°C cooler than the ambient temperature. Boyd and Sturdevant (1997) state that when analyzing the impact of riparian shade on stream temperature that both shade duration and shade density should be examined. Brazier and Brown (1973) found that for a western Oregon stream, angular canopy density along the path of incoming solar radiation best predicts the ability of the buffer strip to control stream temperature. The effectiveness of shade decreases with increasing stream width. In addition, east and west flowing streams experience greater insolation than north and south flowing streams with equal amounts of shade.

Following a fire in southern Oregon, loss of riparian cover resulted in an increase in maximum stream temperatures (Amaranthus et al. 1989). Amaranthus et al. (1989) found that the variation in maximum stream temperature was strongly correlated with summer stream discharge and percent shade. The greatest stream temperatures were recorded on those streams that had the lowest summer stream discharge and percent shade (Amaranthus et al. 1989). In the Sprague River system of south-central Oregon, Friedrichsen (1996) found that the highest water temperatures were recorded in open non-shaded portions of the streams. Stream cover was significantly related to seven-day average maximum stream temperatures and diurnal fluctuations in stream temperature (Friedrichsen 1996). Logging activity, tree harvesting and road building have also been attributed to 2°C and 6°C degree increases in stream temperature due to losses of shade (Beschta and Taylor...
July had the highest average maximum stream temperature and December and January had the lowest average stream temperature for an area in the Salmon Creek Watershed of Western Oregon (Beschta and Taylor 1988). Beschta and Taylor (1988) found no correlation between the average daily maximum air and water temperatures in this watershed. Maloney et al. (1999) found that streams with at least 75 percent shade measured with a Solar Pathfinder maintained acceptable stream temperature levels.

In an artificial shade study conducted in central Oregon, Peterson (1999) found that shade provides thermal protection that minimizes the water heating caused by solar energy inputs. The greatest thermal protection from artificial shade occurred at 100 and 80 percent shade. Substantial protection from insolation was provided at 60 percent shade, and moderate to minimal protection was provided at 20 percent (Peterson 1999). A high level of overhead shade (100 to 80 percent) may be common in forested systems, but streams on rangeland rarely experience such high amounts of thermal protection, making shade less important to the thermal environment of streams located in the interior northwestern United States.

Re-growth of riparian vegetation following disturbance resulted in a decrease of water temperature in a western Oregon stream of the Umpqua Watershed (Holaday 1992). Holaday (1992) found that re-growth of riparian vegetation provided shade over small streams, which resulted in a decrease of the energy inputs from solar radiation. The most interesting aspect of the Holaday (1992) study is that some streams did not respond to the increased shade. Holaday (1992) attributed this lack of a response to the stream's having a historically high stream temperature.

Geomorphology

Stream depth, discharge, and width are the primary physical characteristics of a stream that modify its response to the energy transfer processes occurring
within and between the stream and its thermal environment (Adams and Sullivan 1989). Discharge and volume are two physical characteristics of a stream that influence the thermal characteristics of a stream in both space and time. Stream volume and water temperature are greatly interconnected to a degree that Poole and Berman (2001) argue stream temperature should be described by simply dividing heat energy flux by the volume of water involved. Discharge characteristics of a stream are modified by the shape of the channel, channel bed material, wetted perimeter, and valley gradient (Bauer and Burton 1993). Discharge impacts the thermal qualities of a column of water by controlling the exposure time that a parcel of water has to a certain thermal environment (Larson and Larson 1997). Stream flow may modify stream temperature to a greater degree than does riparian vegetation, thus it may be more important in management schemes that are implemented to ameliorate higher than normal stream temperatures (Poole and Berman 2001). Spring run off increases stream volume and flow, and at this time streams are generally not at risk for increasing water temperature since the column of water has a small residence time within the channel as well as enhanced thermal buffering. During the early spring, streams at high flow experience a milder thermal environment compared to the summer months. Boyd (1996) found that water acts as a heat sink and will absorb and store large amounts of energy. The short residence time, large water temperature buffering capacity of the increased water volume, and cold environment all provide an opportunity for reduced rate of stream warming. In the summer months, when solar radiation peaks, air temperature is higher, and flow is decreased, the potential for higher water temperatures increases (Leblanc et al. 1997). Decreased discharge is the main factor in increased water residence time within the channel making the column of water more available to the thermal environment of the channel (Brown and Krygier 1967, and Mosley 1983). Decreased discharge is usually combined with less water volume making the column of water more susceptible to increased temperature (Boyd and Sturdevant 1997, Brown and Krygier 1967, Mosley 1983,
and Zwieniecki and Newton 1999). In summary, as volume decreases, a body has less ability to buffer heat energy.

Ward (1985) compared smaller streams with reduced water volume to streams with greater water volume and found that the smaller streams were very responsive to ambient conditions, experienced greater maximum summer temperatures, lower minimum winter temperatures, and greater diel fluctuations in water temperature. Constantz et al. (1994) found that stream discharge exhibits a diurnal character that is roughly half a day out of phase with diurnal stream temperature. This means that the lowest stream temperature occurred in the morning hours and the lowest stream discharge occurred in the evening. Stefan and Preud’homme (1993) experienced their best modeling results on shallow streams because the low volume streams were more responsive to air temperature (the main model variable) and had a smaller thermal inertia than the larger volume streams.

Another aspect of stream geomorphology that modifies the thermal character of flowing water is channel width and surface area. Loss of riparian vegetation will generally result in poor channel bank stability. Riparian vegetation increases bank stability through root masses resulting in decreased potential for bank degradation during high flow events (Beschta 1997). A loss of vegetation may result in degradation of the channel banks leading to an increase in stream width and a decrease in stream depth. Degradation of stream banks generally causes channel widening making the surface area of the water greater (Leblanc et al. 1997). Greater fluctuations in water temperature would be expected for those streams that have experienced an increase in surface area with no change in volume (Ward 1985).

For streams draining a western Oregon watershed, channel width was found to be a greater modifier of stream temperature than riparian cover (Beschta and Taylor 1988). Amaranthus et al. (1989) found that stream temperature was modified by both groundwater inputs and stream channel width to depth ratios.
Tributaries in a southwestern Oregon coastal watershed with width to depth ratios that exceeded 14 generally had large diurnal fluctuations in stream temperature (McSwain 1987). In a large study of several western Washington streams, Caldwell et al. (1991) found that smaller type 4 streams are influenced by several geomorphological characteristics. Type 4 streams exhibited a maximum thermal equilibrium where a stream would not heat further even if the air temperature increased. The maximum thermal equilibrium was determined mainly by elevation and shade. Isaak and Hubert (2001) also discovered the importance of elevation in that elevation allowed for the prediction of air temperature, which would influence stream temperature.

Maloney et al. (1999) studied many different geomorphological characteristics influencing stream temperature in 12 different forested sites in the John Day, Oregon area. Maloney et al. (1999) found that the average maximum stream temperatures were between 12.5 and 27.8°C with four of the streams exceeding the predicted lethal maximum stream temperature (24°C) for cold-water fish. The minimum stream temperatures were similar in all sites and generally fell in the 3.5 to 5.0°C range (Maloney et al. 1999). Maloney et al. (1999) discovered that those streams that had the coolest temperatures experienced the highest average shade, highest 7-day discharge during the summer, highest elevation, and shortest residence time. The streams in the meadows were very sensitive to shade because of the very long residence time (Maloney et al. 1999). Boyd and Sturdevant (1997) reported that stream temperature is very sensitive to stream width to depth ratios and to stream discharge.

Stream geomorphology is a key component in beginning to recognize the physical features of a riparian area that are responsible for modifying the energy movements and transformations within and around a constantly changing column of water. Most of the variation in stream temperature maxima is a function of the surrounding landscape and general geomorphic characteristics found within the
watershed (Isaak and Hubert 2001). Understanding how the physical components of a riparian area modify the energy movements and transformations within the stream is a daunting task that requires reduction. Many factors influence stream temperature with stream geomorphology being a key factor, but from an experimental standpoint, it is difficult to isolate geomorphology from all the interacting variables. There have been limited attempts to determine if stream geomorphology can be used to help predict stream temperature profiles in semiarid landscapes. Stream width, depth, and discharge are three components of geomorphology that receive the most attention when discussing stream temperature. Stream geomorphology plays a role in shaping a stream’s thermal character as it receives energy from the sun and from the environment surrounding the stream. Streamside vegetation and other objects along the stream bank will block some of the direct solar radiation and act as secondary emitters of long wave radiation. Streamside vegetation can be actively managed for increased stream shading, enhanced bank protection, and to reduce stream width where appropriate. Energy that reaches the stream will be transferred through the processes of conduction, advection, convection, and evaporation. These processes occur as the stream attempts to thermally equilibrate itself with its environment. The thermal character of a stream is important for biologists to understand, as cold-water fish populations are sensitive to greater water temperature ranges, which are detrimental to population abundance, distribution, and general health.
LITERATURE CITED


CHAPTER THREE

THE THERMAL CHARACTERISTICS OF HYDROLOGICALLY INTACT TYPE C AND E STREAMS IN EASTERN OREGON

Karl T. Hopkins, Tony J. Svejcar, and David R. Thomas
ABSTRACT

Many streams in eastern Oregon are listed as water quality impaired on the basis of water temperature. However, it is often difficult to predict water temperature for these streams even if there are no anthropogenic impacts. We measured air and water temperature and stream characteristics on three Type C and E channel streams to determine if stream type can help predict stream thermal characteristics. All six streams were hydrologically intact, assessed as Proper Functioning Condition (PFC), and were located in eastern and south central Oregon. Water and air temperatures and stream geomorphic data were taken during the summer months of 1998 and 1999. Average daily maximum and minimum water temperature and average daily maximum and minimum rates of change (°C/ Hour) in water temperature following normalization with estimated daily water residence time were analyzed. There was more variation within stream type than across types, which precluded separation of stream types based on thermal characteristics. Most streams regardless of type and year exhibited similar daily mean nighttime recoveries of approximately 0.53°C/hour cooling in the downstream direction following normalization by water residence time. All of the streams heated at least 1.0°C/hour during the day with some streams gaining 2.25°C/hour in the downstream direction following normalization by water residence time. Thermal variation among the streams was likely attributed to the daily initial water temperature, gradient of heating between stream and thermal environment, and the varied physical character of each stream within type. Atmospheric temperature is probably the single most critical factor for characterizing stream temperature behavior during the periods of heating and cooling.
INTRODUCTION

The geomorphic components of the stream channel within the riparian area include channel sinuosity, bed material, bankfull width and depth, and channel slope all of which are influenced by valley topography and valley gradient (Rosgen 1996). These components reflect current climate and stream discharge characteristics. Periods of high stream discharge modify the characteristics of the geomorphic components through alterations in transportation and deposition of materials into, within, and out of the channel. The movement of channel materials may change the shape and hydrologic features of the stream channel. In addition, climate changes may also modify the geomorphic components by impacting riparian vegetation and by influencing stream discharge. The geomorphic component of stream width, for channels found within flat alluvial valleys, is strongly controlled by riparian vegetation.

Hydrologically intact is defined as a state of equilibrium between a stream’s channel structure and composition with the available discharge and the quantity and character of the sediment and other water-transported materials supplied to the channel by the surrounding landscape (Leopold et al. 1992). Bankfull width and depth, water velocity, stream discharge, channel slope, sediment size and load, and hydraulic roughness are the primary determinants of the pattern and profile of the channel. Equilibrium is maintained through the adjustment of any combination of all or some of the characteristics through time such that excessive erosional forces are dissipated, and the channel structure remains essentially constant.

Water volume and residence time (Zwieniecki and Newton 1999 and Poole and Berman 2001) influence the temperature response of a specified stream reach to its thermal environment. The thermal environment consists of the stream channel bed and banks and the air masses surrounding it. Low flow usually is expressed by decreased water velocity and stream volume. Decreased water velocity lengthens the residence time for a particle of water within the reach and
stream volume, which increases the time of exposure to incoming solar radiation and the associated thermal environment for that particle of water.

Stream temperature influences both riparian flora and fauna. Temperature may also help determine the distribution and abundance of zoological or botanical species in space and time (Platts et al. 1983). The dissolved oxygen concentration of water has also been directly linked to the temperature of the body of water where increasing water temperature leads to decreased dissolved oxygen concentration within the water (Gordon et al. 1992). Deviations from past stream thermal characteristics have potential to alter the flora and fauna of a riparian system because biological entities have adapted to narrow temperature ranges (Horne 1994). Departures from historical stream thermal characteristics may cause shifts in the biological composition of the riparian area. Shifts in thermal characteristics can alter organisms' physiology and habitat. Increasing temperatures may shift in-stream vegetative composition that result in habitat losses (Smith 1980).

The water temperature requirements of sensitive cold-water fish populations were mainly determined from physiological studies. The natural thermal characteristics of streams in arid systems are not well understood. This study was implemented to determine if consistent thermal patterns could be determined as a function of stream type. The geomorphic components of stream width, stream depth, glide and riffle surface area and volume, pool surface area and volume, channel gradient, stream discharge, channel sinuosity, and channel substrate were quantified. The biological components that were studied consisted of the near stream vegetative communities that were chiefly responsible for stream shade and stream bank stability. Suitable type C and E streams were selected based on hydrological fitness. The geomorphic components of these two different stream types were isolated so that their influence on stream thermal characteristics could be studied. The ability to isolate specific geomorphic stream attributes will enable managers to identify the relative roles of the physical and biological attributes that
are influencing the streams. Geomorphology and its potential influence on the thermal characteristic of a hydrologically intact stream during low flow was the focus of this project. Thermal characteristics include the maximum and minimum water temperatures and the rates of change in water temperature that occur within a stream in space and time. The primary objectives of this study are to compare stream temperature average daily maxima, minima, and rates of change within C, E, and between C and E channels assessed as hydrologically intact.

MATERIALS AND METHODS

Study Sites

This study included three Type C and three Type E streams. The study area extended as far north as North Powder City, Ore. and as far south as the Steens Mountains and west to Silver Lake, Ore. The elevation range for the sites was from 915 m (3,001 ft) to 1,829 m (6,001 ft). The study area is located between 42 degrees 10 minutes latitude and 45 degrees zero minutes latitude. The project required consistent stream type selection (Rosgen 1996) and demonstration of stream hydrological balance with the landscape (Prichard et al. 1993). A type C stream is characterized as a low gradient, meandering channel with riffles and pools and well-defined point bars. The floodplain for a type C stream is primarily composed of alluvial soils and is broad and well defined with some terraces (Harrelson et al. 1994). A type E stream according to Rosgen's (1996) classification system is described as a low gradient, meandering, riffle/pool stream with a low width to depth ratio and little deposition. These streams are very efficient dissipaters of high flow energy and tend to be stable. Stability is usually a result of high sinuosity and adequate vegetative cover (Harrelson et al. 1994). Type E streams are typically located in broad valleys with alluvial soils. The differences between Type C and E streams in Rosgen's (1996) classification is that Type C streams have channel sinuosity greater than 1.2 while the Type E streams are
greater than 1.5 and Type C streams have moderate to high bankfull width to depth ratios exceeding 12 while Type E streams are very low less than 12. Six properly functioning streams (Prichard et al. 1993), three type E and three type C, were selected using Rosgen's (1996) level two classification (Table 1).

Following determination of stream type, stream equilibrium or balance with the landscape was assessed with the USDI Bureau of Land Management (BLM) technique of proper functioning condition (PFC) (Prichard et al. 1993). Proper functioning condition is a qualitative method of assessing stream potential by examining specific hydrologic, vegetative, and lithologic features. Riparian area function is determined by the interaction among geology, soil, water, and vegetation (Prichard et al. 1993). An interdisciplinary team consisting of specialists in vegetation soils, hydrology, and fisheries/wildlife performs the assessment (Prichard et al. 1993). Streams that are assessed as proper functioning condition are believed to have all of the necessary features that a healthy stream should have to withstand a moderate flow event that may occur every one-half to two years and also have desirable water quality. All of the streams selected for this project were in proper functioning condition.

The approximate stream locations according to Ecological Province (Anderson et al. 1998) are one type C stream in the John Day Ecological Province, a type C stream in the Mazama Ecological Province, a type C stream in the Snake Ecological Province, two type E streams in the High Desert Ecological Province, and a type E stream in the Mazama Ecological Province.
Table 1. Rosgen stream type for each stream used in study\textsuperscript{1}.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Cl</th>
<th>C2</th>
<th>C3</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>width (m)</td>
<td>8.35</td>
<td>9.38</td>
<td>12.42</td>
<td>2.19</td>
<td>3.14</td>
<td>1.30</td>
</tr>
<tr>
<td>Mean depth (m)</td>
<td>0.28</td>
<td>0.75</td>
<td>0.81</td>
<td>0.37</td>
<td>0.48</td>
<td>0.38</td>
</tr>
<tr>
<td>Bankfull X-section area (m\textsuperscript{2})</td>
<td>2.34</td>
<td>7.04</td>
<td>10.07</td>
<td>0.81</td>
<td>1.51</td>
<td>0.50</td>
</tr>
<tr>
<td>W/D ratio</td>
<td>29.8</td>
<td>12.51</td>
<td>15.5</td>
<td>5.9</td>
<td>6.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Max depth (m)</td>
<td>0.44</td>
<td>0.86</td>
<td>1.21</td>
<td>0.46</td>
<td>0.55</td>
<td>0.71</td>
</tr>
<tr>
<td>Width of flood prone area (m)</td>
<td>55.0</td>
<td>141.1</td>
<td>547.0</td>
<td>30.5</td>
<td>35.6</td>
<td>34.2</td>
</tr>
<tr>
<td>Entrenchment ratio</td>
<td>6.6</td>
<td>15.0</td>
<td>44.0</td>
<td>13.9</td>
<td>11.3</td>
<td>26.3</td>
</tr>
<tr>
<td>Water surface slope (m/m)</td>
<td>0.0035</td>
<td>0.0087</td>
<td>0.0014</td>
<td>0.0065</td>
<td>0.0051</td>
<td>0.0051</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>2.3</td>
<td>2.3</td>
<td>1.78</td>
<td>1.9</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Rosgen Stream Type</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
</tbody>
</table>

\textsuperscript{1} All measurements taken at bankfull following procedures listed in Rosgen (1996).

Study Design

The thermal traits of three Type C and three Type E (Table 1) streams were examined to determine the average thermal characteristic of Type C and E streams. The streams were not selected at random and the sample population reflects privately owned eastern Oregon streams. All of the streams were located in semi-wet meadows that were generally lacking in woody vegetation and other sources of overhead stream shading. The streams selected are found in five different ecological provinces. Streams within each stream type and across types were compared to each other to find a type C and E specific thermal characteristic.

Study Reach Selection

Study reaches were selected to characterize the entire portion of the stream that had been assessed as being in PFC and of the proper stream type. Study reaches maintained a consistent stream type, were hydrologically balanced with the
landscape, and were long enough to approximate a one-hour residence time for a hypothetical parcel of water during low flow. Residence time was calculated using flow rate.

Cross-sections were installed to monitor water movement through the study reach. The reach was split into two halves of approximately equal length. Three permanent cross-sections were placed in the study reach with one marking the beginning of the first section, one in the middle marking the bottom of the first section and beginning of the second section, and one marking the bottom of the second section. The first-cross section location was randomly selected from ten possible sites within a 15.24 m (50 feet) length of channel. The possible sites were portions of the stream channel where the channel bottom was fairly constant. Cross-sections were not placed on curves or meanders and were constructed perpendicular to flow.

Study reach length was measured by pacing the length of the stream channel. The locations of all head stakes were triangulated with unique and unmovable objects in the immediate area. Once the cross-section had been installed, bankfull width, wetted width, and water depth were measured. Stream discharge was calculated using USGS protocol (United States Department of the Interior 1982).

Sampling Procedures

Stowaway® XTIs with an accuracy +/- 0.2 °C encased in the factory provided plastic watertight capsules were used for recording air and water temperature. The thermocouple style thermistors were lab tested before and after field data collection to ensure accuracy of data. Lab testing was done following the protocol described by the Oregon Plan for Salmon and Watersheds except that the factory provided plastic capsules were used for each thermistor instead of plastic bags (Oregon Plan for Salmon and Watersheds 1999). Temperature data were
collected from the middle of July 1998 to the end of September 1998. Data were collected during the next season from the middle of June 1999 to the end of September 1999 (Table 2). There were 39 days used in 1998 and 22 days in 1999.

The logging interval of the thermistors for 1998 remained constant throughout the season for each cross-section. The logging interval for each cross-section was calculated from the water velocity during July 1998 and the stream reach length. Most cross-sections had different thermistor logging intervals. Thermistors were programmed to measure and record the temperature at a time interval that was flow dependent for 1999. The time interval was chosen to correspond to approximately the time that it would take for a hypothetical parcel of water to flow between the cross-sections. Average water velocity for each cross-section was divided by study reach section length to find time in seconds for a hypothetical parcel of water to move from the present cross-section to the next one down stream. Section one length was used for first and second cross-sections and section two length was used for cross-section three. Logging intervals were increased to compensate for a decrease in water velocity.

Thermistors were placed at well-mixed sites in the channel 1 m down stream from the cross-sections and anchored to the channel bottom with rebar, wire, and weights. Two thermistors were used at each cross-section with both thermistors being placed at the same level on the rebar.

In 1998, ambient air temperature was measured using Stowaway® XTI thermistors encased in the provided plastic capsules. The encapsulated thermistors were wrapped with dark shade cloth and suspended in full shade at an approximate height of 107 cm and on the north side of the shade-casting object. Air temperature was taken within 10 m of the cross-section. In 1999, in addition to the standard encapsulated thermistors, ambient air temperature was also measured using Stowaway® XTI thermistors protected by mini radiation shields. The air temperature-logging interval was set to match the water temperature-logging interval at the adjacent cross-section.
Stream flow was measured using United States Geological Survey protocol for wadable streams (USDI Geological Survey 1982). Measurements were taken with a 1.83 m (6 ft) top setting wading rod, a Price AA 1:1 magnetic head flow meter for flow greater than 0.20 cms, a Pygmy whisker wire flow meter for flows less than 0.20 cms, and an Aquacalc® computer (JBS Instruments 1993). Water depth was measured at 30 cm intervals in the active flow areas for the width of the cross-section. The 30 cm intervals began in those active flow areas immediately after and before the wetted edges of the channel. Water velocity was measured at a depth of 0.4 from the channel bottom. From the velocity measurements and calculated cross sectional area, flow was calculated. Water velocity and stream flow was measured every two or three weeks on each stream.

Data used for statistical analyses

Three type C (C1, C2, and C3) and three type E (E1, E2, and E3) streams provided the data for analysis. Table 2 displays the days used in analysis. These days were complete in that the water and air thermistors recorded for the entire 24-hour period for all six streams.

The stream water temperature measurements were reduced to daily maximum and minimum temperatures at cross-section one and maximum and minimum differences from cross-section one to three. The maximum and minimum changes in water temperature from cross-sections one to three were examined as the regular change in temperature and also following normalization by daily stream residence time. Normalization permitted description of maximum and minimum changes in water temperature as a rate (°C/ Hour). Normalization also allowed for better comparison of all streams as streams varied by physical character.

Residence times were estimated using flow data collected periodically during the months of temperature data collection. Tables 3a and 3b contain the
dates when flow was taken for each stream, average daily residence times, and the constant lengths of the study reaches. Flow varied by date and by stream and was used to estimate the total residence time \( \text{RT}_{13} \) in hours) of water in each stream reach for those days on which flow measurements were made. This estimate was obtained as the sum of the estimated residence times in the two sections bounded by cross-sections 1 and 2 and cross-sections 2 and 3, respectively

\[
\text{RT}_{13} = \{1/2(1/V_1 + 1/V_2)L_{12}\} + \{1/2(1/V_2 + 1/V_3)L_{23}\}
\]

where \( V_1, V_2, \) and \( V_3 \) denotes the velocities (meters per hour) at the three cross-sections and \( L_{12} \) and \( L_{23} \) the lengths (meters) of the two sections of a reach. Linear interpolation/extrapolation of these residence times were used to further estimate residence times on days when temperature data were measured but flow was not measured. Estimates of residence time \( \text{RT}_{13} \) then permitted estimation for the change in water temperature as it flowed down a reach of length \( L_{13} = L_{12} + L_{23} \).

For any time \( t_1 \) that a water temperature \( W_i \) is recorded at cross-section one, the approximate water temperature \( W_3 \) at cross-section three arriving at time \( t_3 = t_1 + \text{RT}_{13} \) is found through linear interpolation of the two water temperatures measured at cross-section 3 just before and just after the estimated arrival \( t_3 \). The estimated change in water temperature is then calculated as the difference

\[
\Delta W_{13} = W_3 - W_i.
\]

Because the flow rates varied among and within streams and the lengths varied among streams the water temperature changes were normalized by dividing by the residence time, \( \Delta W_{13} / \text{RT}_{13} \), to give a rate of change \( \text{C}^\circ/\text{hour} \).

Air temperature was collected at cross-sections one and three. Cross-sections one and three were averaged to produce daily mean, minimum, and maximum values. For example, daily maximum air temperature was found for cross-sections one and three. These two values were averaged together to provide daily maximum air temperature for the entire reach a similar method was applied to
the daily minimum and average air temperatures. Air temperature was used to partly explain water temperature characteristics found in the study reaches.

Analysis began with 3 runs corresponding to 3 response variables (minimum and maximum water temperature at cross-section three, difference in water temperature from cross-section one to three, difference in water temperature from cross-section one to three normalized by residence time). Each run was similar with a 2-way ANOVA with days as blocking factors and stream as the treatment with comparison of the stream means (Appendix 1). Autocorrelated day effects were explored using mixed models based on the assumption of independent day contributions. Non-independent day contributions were considered with little difference from the independent day analysis. The relationship between air temperature and water temperature was explored using general linear regression models in SAS.

RESULTS

Parameters were averaged over 39 days for 1998 and 22 days for 1999 (Table 2). Variation between streams within each stream type prevented the determination of an overall thermal characteristic of stream temperature average daily maximum, minimum, and rates of change for each stream type. Most of the model error was accounted for by stream within type rather than type. Most p-values were very small (<0.0001) suggesting that there were statistical differences between the thermal characteristics of the streams (Appendix 1). The individual character of the streams within each type produced a lot of variation in daily maximum change in water temperatures from cross-section one to three normalized by residence time (rate of heating, °C/Hour) during 1998 as seen in Figs. 1a and 1b. The 1998 daily maximum air temperatures for the type C and E streams are also illustrated in Figs. 1a and 1b. Similar results for 1999 are given as Figs. 2a and 2b. Rates of heating for all six streams during 1998 and 1999 are plotted in Figs. 3 and
4. Averaged daily maximum and minimum water temperature at cross-section three and averaged daily maximum and minimum air temperature for the streams over the entire summer months (July, August, and September for 1998 and July and August for 1999) of data collection are given in Table 4. Table 4 also contains average minimum and maximum change in water temperature from cross-section one to three normalized by residence time.

Figs. 5a, 5b, 6a, and 6b illustrate the regression of daily maximum water temperature at cross-section three with daily maximum air temperature. Tables 5a and 5b provide additional regression data. From Table 5a, daily maximum water temperature at cross-section three increased by 0.262, 0.272, and 0.238°C for every 1°C increase in daily maximum air temperature during 1998 for streams C1, C2, and C3. During the same period, daily maximum water temperature at cross-section three increased by 0.356, 0.319, and 0.439°C for every 1°C increase in daily maximum air temperature for streams E1, E2, and E3.

### Table 2. Complete temperature days in 1998 and 1999.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>24, 25, 26, 27, 28, 29, 30, 31</td>
<td>01, 02, 03, 04, 05, 06, 09, 10, 12, 13, 14, 15, 16, 17, 18, 19, 21, 23, 27, 28, 29, 30, 31</td>
<td>01, 02, 03, 04, 05, 06, 07, 09</td>
</tr>
<tr>
<td>1999</td>
<td>22, 23, 24, 25, 26, 27</td>
<td>04, 05, 06, 08, 15, 16, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3a. Estimated residence times during 1998 by stream. Length of reach (L) varied with stream.

<table>
<thead>
<tr>
<th>C1 L = 1155 m</th>
<th>C2 L = 1382 m</th>
<th>C3 L = 2724 m</th>
<th>E1 L = 1036 m</th>
<th>E2 L = 1284 m</th>
<th>E3 L = 805 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>R 3</td>
<td>Date</td>
<td>R 3</td>
<td>Date</td>
<td>R 3</td>
</tr>
<tr>
<td>7-13</td>
<td>1.101</td>
<td>7-23</td>
<td>0.913</td>
<td>7-16</td>
<td>1.139</td>
</tr>
<tr>
<td>8-11</td>
<td>2.063</td>
<td>7-30</td>
<td>0.984</td>
<td>8-08</td>
<td>1.489</td>
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<tr>
<td>8-26</td>
<td>2.376</td>
<td>8-20</td>
<td>1.107</td>
<td>8-25</td>
<td>2.575</td>
</tr>
<tr>
<td>9-16</td>
<td>2.358</td>
<td>9-08</td>
<td>1.147</td>
<td>9-15</td>
<td>1.467</td>
</tr>
</tbody>
</table>

1 R 3 denotes the residence time in hours from cross-section one to three.
### Table 3b. Estimated residence times during 1999 by stream. Length of reach (L) varied with stream.

<table>
<thead>
<tr>
<th></th>
<th>C1 L = 1155 m</th>
<th>C2 L = 1382 m</th>
<th>C3 L = 2724 m</th>
<th>E1 L = 1036 m</th>
<th>E2 L = 1284 m</th>
<th>E3 L = 805 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>R 3(^1)</td>
<td>Date</td>
<td>R 3</td>
<td>Date</td>
<td>R 3</td>
<td>Date</td>
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<tr>
<td>6-18</td>
<td>0.400</td>
<td>6-16 0.858</td>
<td>6-21 0.591</td>
<td>6-15 1.206</td>
<td></td>
<td></td>
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<tr>
<td>7-06</td>
<td>1.129</td>
<td>7-08 1.401</td>
<td>7-17 0.996</td>
<td>7-03 1.303</td>
<td></td>
<td></td>
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<tr>
<td>8-14</td>
<td>2.158</td>
<td>8-07 0.877</td>
<td>8-03 1.522</td>
<td>8-07 1.150</td>
<td>8-01 1.486</td>
<td>8-29 1.280</td>
</tr>
</tbody>
</table>

\(^1\) R 3 denotes the residence time in hours from cross-section one to three.

### Table 4. Average daily maximum and minimum water temperature at cross-section three, change in water temperature normalized by residence time, and air temperature for 39 days in 1998 (July, August, and September) and 22 days in 1999 (July and August).

<table>
<thead>
<tr>
<th>Year</th>
<th>Stream</th>
<th>Water T (°C)(^1)</th>
<th>Water T-Residence (°C/Hour)(^2)</th>
<th>Air Temp (°C)(^3)</th>
<th>Water T (°C)(^1)</th>
<th>Water T-Residence (°C/Hour)(^2)</th>
<th>Air Temp (°C)(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>C1</td>
<td>13.94</td>
<td>-0.82</td>
<td>04.00</td>
<td>22.25</td>
<td>1.39</td>
<td>33.70</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>10.88</td>
<td>-0.44</td>
<td>04.51</td>
<td>18.01</td>
<td>2.26</td>
<td>30.66</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>18.39</td>
<td>-0.49</td>
<td>07.01</td>
<td>24.58</td>
<td>1.22</td>
<td>34.40</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>14.45</td>
<td>-0.37</td>
<td>10.90</td>
<td>21.22</td>
<td>1.14</td>
<td>33.18</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>10.99</td>
<td>-0.51</td>
<td>04.42</td>
<td>18.26</td>
<td>2.10</td>
<td>30.06</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>08.82</td>
<td>-0.59</td>
<td>06.93</td>
<td>20.54</td>
<td>2.13</td>
<td>32.37</td>
</tr>
<tr>
<td>1999</td>
<td>C1</td>
<td>13.20</td>
<td>-0.54</td>
<td>02.31</td>
<td>21.57</td>
<td>1.67</td>
<td>32.26</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>10.00</td>
<td>-0.46</td>
<td>03.47</td>
<td>16.83</td>
<td>2.17</td>
<td>30.90</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>17.57</td>
<td>-0.55</td>
<td>06.99</td>
<td>24.24</td>
<td>1.12</td>
<td>30.02</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>13.23</td>
<td>-0.46</td>
<td>08.84</td>
<td>19.87</td>
<td>1.28</td>
<td>32.92</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>10.25</td>
<td>-0.49</td>
<td>03.52</td>
<td>17.60</td>
<td>2.35</td>
<td>29.21</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>07.71</td>
<td>-0.61</td>
<td>05.36</td>
<td>19.98</td>
<td>2.49</td>
<td>29.34</td>
</tr>
</tbody>
</table>

\(^1\) The average maximum and minimum water temperature at cross-section three

\(^2\) The average change in water temperature form cross-section one to three normalized by residence time (°C/Hour).

\(^3\) Average study reach air temperature.
Fig. 1a. Type C maximum changes in water temperature from cross-section one to three normalized by residence time during 1998.

Fig. 1b. Type E maximum changes in water temperature from cross-section one to three normalized by residence time during 1998.
Fig. 2a. Type C maximum changes in water temperature from cross-section one to three normalized by residence time during 1999.

Fig. 2b. Type E maximum changes in water temperature from cross-section one to three normalized by residence time during 1999.
Fig. 3. Type C and E maximum changes in water temperature from cross-section one to three normalized by residence time during 1998.

Fig. 4. Type C and E maximum changes in water temperature from cross-section one to three normalized by residence time during 1999.

Figs. 1a, 1b, 2a, and 2b illustrate the daily maximum air temperatures for the streams used in this study. Table 4 contains the average minimum and
maximum air temperatures for the streams in 1998 and 1999. Scatterplots of daily
maximum air and daily maximum water temperature at cross-section three are
given in Figs. 5a and 5b for 1998 and 6a and 6b for 1999 data. Tables 5a and 5b
contains the regression information for the 1998 and 1999 data.

Fig. 5a. Relationship between maximum daily air temperature and maximum
water temperature at cross-section three measured on 39 days in July,
August, and September 1998 for three Type C study reaches.
Fig. 6a. Relationship between maximum daily air temperature and maximum water temperature at cross-section three measured on 22 days in July and August 1999 for three Type C study reaches.

Fig. 5b. Relationship between maximum daily air temperature and maximum water temperature at cross-section three measured on 39 days in July, August, and September 1998 for three Type E study reaches.
Fig. 6b. Relationship between maximum daily air temperature and maximum water temperature at cross-section three measured on 22 days in July and August 1999 for three Type E study reaches.

Table 5a. Regression data of daily maximum water temperature at cross-section three (dependent) and daily maximum air temperature for study reach (independent) for all streams by type for 1998.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Equation</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$y = 0.278x + 12.586$</td>
<td>0.660</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>C2</td>
<td>$y = 0.352x + 5.942$</td>
<td>0.868</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>C3</td>
<td>$y = 0.339x + 14.083$</td>
<td>0.477</td>
<td>0.0002</td>
</tr>
<tr>
<td>E1</td>
<td>$y = 0.322x + 9.266$</td>
<td>0.579</td>
<td>0.0001</td>
</tr>
<tr>
<td>E2</td>
<td>$y = 0.389x + 6.254$</td>
<td>0.711</td>
<td>0.0005</td>
</tr>
<tr>
<td>E3</td>
<td>$y = 0.383x + 8.738$</td>
<td>0.560</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Table 5b. Regression data of daily maximum water temperature at cross-section three (dependent) and daily maximum air temperature for study reach (independent) for all streams by type for 1999.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Equation</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$y = 0.262x + 13.425$</td>
<td>0.566</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>C2</td>
<td>$y = 0.272x + 9.668$</td>
<td>0.494</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>C3</td>
<td>$y = 0.238x + 16.374$</td>
<td>0.421</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>E1</td>
<td>$y = 0.356x + 9.414$</td>
<td>0.656</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>E2</td>
<td>$y = 0.319x + 8.659$</td>
<td>0.599</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>E3</td>
<td>$y = 0.439x + 6.317$</td>
<td>0.642</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
DISCUSSION

Stream thermal characteristics appear to respond more to the ambient air temperature than any other variable we measured. It also appears that stream response to air temperature depends more on individual stream characteristics than on stream channel classification (Types C and E). Streams cooled 0.37 to 0.82°C/hour during 1998 and 0.46 to 0.61°C/hour during 1999 (Table 4).

Through maintenance of equilibrium between a stream and its thermal environment, heat energy is released into the surrounding environment from the stream once the main source of heat energy is removed from the system. The main source of heat energy is the sun, which can heat a stream through both direct radiation and indirectly through the heating of the air mass above the stream. Streams will balance themselves with their thermal environments regardless of the time of day. The removal of the sun from the thermal equation for understanding nighttime recovery greatly simplifies the search for a possible answer to similar nighttime recoveries for all streams. Even though the maximum air temperatures among streams are more similar than the minimum air temperatures, rates of stream cooling at night were much more consistent than rates of stream heating during the day (Table 4). Stream orientation, stream morphology, and the vegetation of the thermal environment modify the influence of radiant energy from the sun upon the stream. Channel orientation, stream morphology, and the vegetation are different for each stream and it is very possible that the quality and quantity of the radiant energy striking the stream is also different for each stream. This feature accounts for the differing thermal characters of each stream during the day even though the air temperature is similar. Radiative and evaporative cooling may also be different among streams partially influencing rates of heating. During the night, the driving force in the determination of the thermal character of the stream must be the air mass and the streambed. These are the two largest thermal masses in the thermal environment once the sun has been removed from the equation.
When the sun’s radiant energy begins warming the air masses, the terrestrial environment around the stream, and the steam itself, the streams used in this study expressed different rates of warming (Figs 3, 4 and Table 4). The streams within type did not exhibit a consistent rate of warming. Differences in rates of warming are probably due to dissimilar thermal gradients between the water temperature and ambient air temperature for each stream. It is very important to know the initial water temperature before daily heating begins. For example C2 started off very cold but heated at a much greater rate compared to C3 (Figs 1a, 2a, 3, 4 and Table 4). Stream C3 heated at a reduced rate compared to C2 because C3 has a larger volume (Table 1) and a smaller temperature gradient between the stream and the thermal environment. Even though C3 and C2 heated at very different rates (Figs 3, 4 and Table 4), air temperature regression slopes were very similar between the two (Tables 5a and 5b). Stream C2 had a much cooler initial water temperature and similar air regression to C3 and therefore exhibited a cooler daytime temperature despite increased rate of heating. Streams had similar regression slopes of daily maximum water on air (Figs 5a, 5b, 6a, and 6b) and similar rates of cooling from cross-section one to three (Table 4) because all streams shared the same regional air mass.

The initial water temperature of a stream is an important determinate of rate of heating. The greater the gradient between the stream’s initial water temperature and the atmosphere, the greater the potential for warming. Different physical characteristics of streams such as geomorphology and any groundwater interactions should also be considered when examining rates of stream heating. The individuality of each stream cannot be stressed enough as each stream did exhibit a host of features that made it unique even within its type. For example streams C3 and E1 are heavily influenced by agricultural activity and typically experience sudden changes in residence time (Tables 3a and 3b) that are attributed to irrigation diversion. Those streams used in this study exhibited good hydrological fitness and
had physical traits that were similar enough to be considered members of their respective type.

Similar temperature trends can be seen in both the water and air temperature plots (Figs 1a, 1b, 2a, and 2b) suggesting correlation between air and water temperature. These findings are similar to other studies conducted in riparian areas of North America (Adams and Sullivan 1989, McRae and Edwards 1994, and Stefan and Preud’homme 1993). The air temperatures for all streams were similar in both seasonal trend and absolute value. Positive associations between daily maximum air and daily maximum water temperature are evident for all streams during both years (Figs 5a, 5b, 6a, and 6b). When daily air and water temperatures were compared, the Type C and E streams were not significantly different. However, the smaller volume Type E streams appear more responsive to air temperature than the well-buffered Type C streams. The Type C streams had lower slopes in 1998 but not in 1999 (Tables 5a and 5b). Of the Type C streams, C3 was consistently the warmest and C2 the coolest (Figs 5a and 5b). These streams travel through different thermal environments and reach different average daily maximum water temperatures (Table 4). These two streams also heat at different rates (Figs. 1a and 2a). The relationship C3 and C2 have with air temperature (Figs. 5a and 6a) is remarkably similar despite the other differences these streams exhibit when heating and cooling. The close association between water and air temperature is likely due to the large thermal mass that the atmosphere represents in the stream’s thermal environment. As discussed earlier, water temperature should mimic air temperature as the stream seeks thermal equilibrium with its environment. At the sun’s zenith, radiant energy heats both the atmosphere and the un-shaded stream directly as solar radiation impacts the exposed column of water. Direct insolation of the stream may greatly increase stream heating as the stream continues to equilibrate with the warming atmosphere.
Overhead riparian cover may reduce direct insolation of the stream. The effect of shade produced by overhead cover on streams has been an emphasis for many studies conducted in Oregon (Beschta 1997, Boyd and Sturdevant 1997, and Brown 1969). These studies have expressed the importance of stream shading in riparian systems of western Oregon where potential for continuous overhead cover is great. The riparian areas studied in this project do not have the natural capacity to achieve the levels of stream shading described by scientists in western Oregon.

In spite of the fact that the C and E channel types have different bankfull width/depth ratios (Table 1), we could not separate the two channel types based on rate of heating (Figs 3 and 4). The narrower Type E streams did have lower rates of heating than the Type C streams. A similar rate of heating trend for all streams studied is readily evident in Fig. 4. The effect of air mass on regional stream rates of heating is remarkable considering the varied physical character of the streams studied and their locations in eastern Oregon. The largest of the streams was C3 (Table 1) and this stream was more buffered from the early August drop in regional stream temperatures measured in 1999. However, the data clearly demonstrates that air mass changes can impact stream temperatures across large geographic regions.

Groundwater input into each stream was not quantified but must be considered when discussing thermal properties of streams. Groundwater inputs into both C2 and E2 were possible given the proximity of the streams to each other and the cobble composition of the channel substrate that may encourage water movement between the streams and ground water. The impact of groundwater on the thermal character of the stream is dependent on the flow of both the stream and the groundwater and the temperature gradient between the entering groundwater and the water contained in the stream. Groundwater generally suppresses stream heating and cooling (Stringham 1998). Stream C2 did have reduced stream cooling in 1998 and 1999 compared to the other Type C streams (Table 4). The potential of groundwater influence on stream C2 is difficult to determine because the stream starts each day with cooler water temperature and heats more than the other
streams. If groundwater is impacting this stream, the effects are evident during the nighttime recovery as stream cooling is reduced.

CONCLUSION

The effects of air temperature and the other components of the thermal environment that determine the thermal properties of water moving in a stream channel may be modified by stream geomorphology. Stream geomorphology, or the physical traits of a stream, may be a key element in understanding the thermal characteristics of streams. Stream depth, width, width to depth ratio, discharge, volume, and surface area are some of the main morphological components that may alter the thermal properties of a stream in space and in time. These morphological components differ between individual streams and may account for the variations among streams in thermal characteristics.

The thermal characteristics of the stream channels contained within this study were independent of stream type. All streams, regardless of type and year exhibited similar nighttime recoveries of approximately 0.53°C/hour cooling from cross-section one to three. All of the streams heated at least 1.0°C/hour during the day with some streams gaining 2.25°C/hour from cross-section one to three. The rate of heating varied between streams and was largely determined by initial stream temperature and the thermal gradient between the stream and its environment.

Atmospheric temperature provides an index of the stream thermal environment as water temperature mimics air temperature trends. Plots of average daily air temperature reveal similar seasonal patterns among all streams suggesting a regional air mass. The actual average daily air temperature is different among the streams but the trends are similar. The differences between average daily air temperature between the streams is likely due to variations in instrument location, quality of shade that the instruments were mounted under, topography, and local wind patterns. Air temperature may be important data to know when exploring
nighttime recovery of streams since the atmosphere and the terrestrial features are the only active components of the thermal environment once the sun sets. During the day, water temperature is positively associated with air temperature. Streams exhibited a similar response to air temperature as the regional air mass received radiant energy.

LITERATURE CITED


BIBLIOGRAPHY


# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: ANOVA Tables</td>
<td>72</td>
</tr>
<tr>
<td>2: Methods for Stream Classification</td>
<td>77</td>
</tr>
<tr>
<td>3: Vegetation Functional Groups</td>
<td>80</td>
</tr>
<tr>
<td>4: Riparian Complexes</td>
<td>98</td>
</tr>
<tr>
<td>5: Stability Classes and Successional</td>
<td>101</td>
</tr>
<tr>
<td>6: Stream Sinuosity and Cross-Section Profiles</td>
<td>103</td>
</tr>
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</table>
APPENDICES

APPENDIX 1: ANOVA TABLES

Tables 1-3 give ANOVA tables for the daily maximum change in water temperature from cross-section one to three, the daily maximum water temperature at cross-section three, and the daily maximum air temperature for the study reach. Parts A and B of each table contain analyses of data within each year (1998 and 1999) and Part C analyses of data for both years. The general linear model procedure (proc glm) in SAS was used to obtain the ANOVA tables.

For analyzing the data in both years (Parts C) there are two temporal factors: Year and Day and two spatial factors Type and Stream. Year, Type, and Stream are considered fixed factors and Day a random factor. The days are nested within years, denoted as Day(Year), and streams are nested within types, Stream(Type). In an ANOVA for both years there are eight sources of variation corresponding to main effects for the temporal factors: Year and Day(Year), main effects for spatial factors Type and Stream(Type), and the four interactions comprised of the interaction effects of each temporal factor with each spatial factor: Type*Year, Type*Day(Year), Year*Stream(Type), and Stream(Type)*Day(Year). For the F-tests for fixed effects, Day(Year) is the error for Year, Type*Day(Year) is the error for Type and Type*Year, and Stream(Type)*Day(Year) is the error for Stream(Type) and Year*Stream(Type). Type III sums of squares were used. The Type III sums of squares differ from Type I sums of squares only for the two sources that involve averages over years: Type and Stream(Type). This is because the design is unbalanced only with respect to years. All six streams were observed on each day but unequal numbers of days (39 and 22) were observed in 1998 and 1999. Note that the Year*Stream(Type) interactions are all highly significant which motivates separate analyses of Streams(Type) for each year.

For an ANOVA within year (Parts A and B) there are five sources of variation: Day, Type, Stream(Type), Day*Type, and Stream(Type)*Day(Year).
For the F-tests for fixed effects, Day*Type is the error for Type, and Stream(Type)*Day is the error for Stream(Type). Since the within year design is balanced the Type I and Type III sums of squares are identical. The means of streams within both stream types were found to be not all equal in all cases (P<0.0001 for Stream(Type)). These ANOVA tables are for maximum temperatures and rates of change (°C/Hour). Minimum temperatures and rates of change would be similar.
Table 1. Analysis of Variance for the daily maximum change from cross-section one to three normalized by daily water residence time.

A. 1998 (n = 39)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>38</td>
<td>10.284</td>
<td>0.2706</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>1</td>
<td>1.622</td>
<td>1.6218</td>
<td>34.01</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Day*Type</td>
<td>38</td>
<td>1.812</td>
<td>0.0477</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stream(Type)</td>
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<td>48.911</td>
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B. 1999 (n = 22)

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C. Both years (n=61)

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Table 2. Analysis of Variance for the daily maximum water temperature at cross-section three.

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C. Both years \((n=61)\)

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Table 3. Analysis of Variance for the daily maximum air temperature for the study reach.

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B. 1999 (n = 22)

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C. Both years (n=61)

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APPENDIX 2: METHODS FOR STREAM CLASSIFICATION

**Substrate-**

The channel material composition was determined using a modified Wolman pebble count (Burton et al. 1992 and Harrelson et al. 1994). Modification was necessary because of time constraints and the realization that the data would mainly be used to confirm stream type. The modified Wolman Pebble count was characterized by disproportional sampling of stream units. Pools were not measured because of excessive depth. The final substrate data produced in this study are too coarse for all streams. Substrate data were collected 2 m down stream from each cross section. This procedure was also done at the midpoints of each section for a total of five data collections per study reach.

**Vegetation-**

For the vegetation data, plant community types were identified by a dominant and subdominant plant species. Estimating percent cover determined dominance and sub-dominance. Back in the office, each community type was given a functional group label that was determined by soil moisture requirements of the plant species. Soil moisture requirements for each plant species is given in a nationally recognized data base (USDA, NRCS 1999). Once the functional groups of each plant community had been determined, the dominant plant functional group was noted. The functional groups used for this study are defined (Crowe and Clausnitzer 1997):

- OBL (Obligate Wetland) refers to species that almost always occur (99% probability) under natural conditions in wetlands.
- FACW (Facultative Wetland) refers to species that usually occur (67-99% probability) in wetlands but are occasionally found in non-wetlands.
- FAC (Facultative) refers to plants that are equally likely to occur (34-66% probability) in wetlands or non-wetlands.
• FACU (Facultative Upland) refers to plants usually occurring (67-99% probability) in non-wetlands but occasionally (1-33% probability) found in wetlands.

• UPL (Upland Obligate) refers to species that occur (99% probability) almost always under natural conditions in non-wetlands.

• In addition, + (positive) and – (negative) signs are occasionally used with FACW, FAC, and FACU categories. The positive sign indicates a frequency towards the higher end of the category (i.e. more frequently found in wetlands) and the negative sign indicates a frequency towards the lower end of the category (less frequently found in wetlands).

For both the greenline and cross section vegetation data, the transects were described in terms of functional group composition and by dominant plant community.

**Greenline:**

The greenline is “the first perennial vegetation from the water’s edge, Riparian areas that are in high seral status with stable stream banks will exhibit a continuous line of vegetation at the bankfull discharge level. Rocky stream types may have a significant amount of rock causing breaks in the vegetation. This rock is considered part of the greenline. Other breaks may occur in the first perennial band of vegetation (water courses or bare ground). The amounts of these (perennial vegetation, rock, and bare ground) should be recorded.” (Burton et al. 1992). The greenline is important since it contains the majority of the vegetation that buffers the stream banks from the abrasive forces of high flow. Greenline was quantified by grouping plants into communities along a 110.64-m (363-ft) upstream and downstream transect (Cagney 1993). The amount of transect that a riparian community occupies was recorded in feet. The collection of different communities and their widths on the transect was converted to a percentage that reflected the composition of the greenline. Greenline was measured for both sides of the stream at the first and last cross sections. At the first cross section, greenline was measured
travelling downstream. At the last cross section, the greenline was measured travelling upstream. For type C streams (Rosgen 1996) that naturally cut on one side of the meander, the greenline was that portion of the vegetation and/or other buffering agent(s) that formed a continuous band immediately adjacent to the flowing water.

**Cross Section Community Typing:**

Riparian vegetation complexes were also identified and quantified using valley cross sectional transects that grouped vegetation into community types, identified stream type, determined soil characteristics, and described valley form (Winward 2000). Two transects for each study reach were placed 2 m downstream from the first and last permanent stream cross sections. The starting point of each transect began outside of the riparian area. The transect included the stream width. The community composition of the transect was determined by the width of the community divided by the length of the transect (Winward 1984, Burton et al. 1992, and Hudak et al. 1991). Communities were recognized as those plant species that could be aggregated into groups of similar floristic and structural components in both the overstory and undergrowth layers based on estimated percent cover (Burton et al. 1992). Formulas were used to approximate the ecological condition and successional status of the riparian area (Burton et al. 1992).

**Woody plants:**

Woody plants were inventoried by species and placed into size and age classes (Cagney 1993). The same transects used for the greenline surveys were used for the woody plant surveys. The width of the woody plant surveys was 1.83 m (6 ft).
APPENDIX 3: VEGETATION FUNCTIONAL GROUPS

Figure 1: Greenline Stream C1 Cross-Section 1 Left Side

Figure 2: Greenline Stream C1 Cross-Section 1 Right Side
Figure 3: Greenline Stream C1 Cross-Section 3 Left Side

Figure 4: Greenline Stream C1 Cross-Section 3 Right Side
Figure 5: Cross-Section Composition Stream C1 Cross-Section One

Figure 6: Cross-Section Composition Stream C1 Cross-Section Three
Figure 7: Greenline Stream C2 Cross-Section 1 Left Side

Figure 8: Greenline Stream C2 Cross-Section 1 Right Side
Figure 9: Greenline Stream C2 Cross-Section 3 Left Side

Figure 10: Greenline Stream C2 Cross-Section 3 Right Side
Figure 11: Cross-Section Composition Stream C2 Cross-Section One

Figure 12: Cross-Section Composition Stream C2 Cross-Section Three
Figure 13: Greenline Stream C3 Cross-Section 1 Left Side

Figure 14: Greenline Stream C3 Cross-Section 1 Right Side
Figure 15: Greenline Stream C3 Cross-Section 3 Left Side

Figure 16: Greenline Stream C3 Cross-Section 3 Right Side
Figure 17: Cross-Section Composition Stream C3 Cross-Section One

Figure 18: Cross-Section Composition Stream C3 Cross-Section Three
Figure 19: Greenline Stream E1 Cross-Section 1 Left Side

![Bar chart showing percent cover of plant functional groups OBL, FACW+, FAC+, FACW.]

Figure 20: Greenline Stream E1 Cross-Section 1 Right Side

![Bar chart showing percent cover of plant functional groups OBL, FACW+, FACU, FACW.]

Figure 21: Greenline Stream E1 Cross-Section 3 Left Side

![Graph showing plant functional groups and their percent cover.]

Plant Functional Groups

Figure 22: Greenline Stream E1 Cross-Section 3 Right Side

![Graph showing plant functional groups and their percent cover.]

Plant Functional Groups
Figure 23: Cross-Section Composition Stream E1 Cross-Section One

![Chart showing percent cover for different plant functional groups]

Figure 24: Cross-Section Composition Stream E1 Cross-Section Three

![Chart showing percent cover for different plant functional groups]
Figure 25: Greenline Stream E2 Cross-Section 1 Left Side

Figure 26: Greenline Stream E2 Cross-Section 1 Right Side
Figure 27: Greenline Stream E2 Cross-Section 3 Left Side

Figure 28: Greenline Stream E2 Cross-Section 3 Right Side
Figure 29: Cross-Section Composition Stream E2 Cross-Section One

Figure 30: Cross-Section Composition Stream E2 Cross-Section Three
Figure 31: Greenline Stream E3 Cross-Section 1 Left Side

![Graph showing percent cover of different plant functional groups on the left side of the stream cross-section.]

- OBL
- FACW+
- FAC
- FACW

Figure 32: Greenline Stream E3 Cross-Section 1 Right Side

![Graph showing percent cover of different plant functional groups on the right side of the stream cross-section.]

- OBL
- FACW+
- FAC
- FACW
- Bare Bank
Figure 33: Greenline Stream E3 Cross-Section 3 Left Side

Figure 34: Greenline Stream E3 Cross-Section 3 Right Side
Figure 35: Cross-Section Composition Stream E3 Cross-Section One

Figure 36: Cross-Section Composition Stream E3 Cross-Section Three
APPENDIX 4: RIPARIAN COMPLEXES

Riparian complex classifications for each stream were useful in describing stream settings in terms of vegetative community type, Rosgen level-2 stream classification, dominant soil description, and landscape setting.

Type C Streams

Stream C1 cross section 1:

Stream C1 cross section 3:
Willow/ Mesic graminoid community type (Manning and Padgett 1995) and Willow/ Kentucky bluegrass community type (Crowe and Clausnitzer 1997)--- C4 (Rosgen 1996)--- Fine-silty, mixed, Cumulic Cryaquolls (Stringham 1996)--- Broad moderate elevation valley (USDA Forest Service 1979) Riparian Complex.

Stream C2 cross section 1:
Lodgepole pine/ Aquatic sedge association (Kovalchik 1997) and Lodgepole pine/ Kentucky bluegrass community type (Kovalchik 1997)--- C4 (Rosgen 1996)--- Ashy over loamy, glassy over mixed, super active, frigid, Aquandic Endoquolls (Keller 2000)--- Broad moderate elevation valley (USDA Forest Service 1979) Riparian Complex.

Stream C2 cross section 3:
Willow/ Aquatic sedge association (Kovalchik 1997) and Willow/ Wooly sedge association (Kovalchik 1997)--- C4 (Rosgen 1996)--- Ashy over loamy, glassy over mixed, super active, frigid, Aquandic Endoquolls (Keller 2000)--- Broad moderate elevation valley (USDA Forest Service 1979) Riparian Complex.
Stream C3 cross section 1:

*Elymus spp./ Poa pratensis* community type (not described) and *Elymus glaucus/Cirsium arvense* community type (not described) --- C4 (Rosgen 1996) --- Fine-loamy, mixed (calcareous), mesic, Typic Haplaquepts (USDA/Natural Resources Conservation Service 1997) --- Broad moderate elevation valley (USDA Forest Service 1979) Riparian Complex.

Stream C3 cross section 3:

*Elymus spp./ Poa pratensis* community type (not described) and *Elymus glaucus/Carex lanuginosa* community type (not described) --- C4 (Rosgen 1996) --- Fine-loamy, mixed (calcareous), mesic, Typic Haplaquepts (USDA/Natural Resources Conservation Service 1997) --- Broad moderate elevation valley (USDA Forest Service 1979) Riparian Complex.

Type E Streams

Stream E1 cross section 1:


Stream E1 cross section 3:

Stream E2 cross section 1:
Lodgepole pine/ Aquatic sedge association (Kovalchik 1997)--- E4 (Rosgen 1996)--- Ashy over loamy, glassy over mixed, super active, frigid, Aquandic Endoquolls (Keller 2000)--- Broad moderate elevation valley (USDA Forest Service 1979) Riparian Complex.

Stream E2 cross section 3:
Aquatic sedge association (Kovalchik 1997)--- E4 (Rosgen 1996)--- Ashy over loamy, glassy over mixed, super active, frigid, Aquandic Endoquolls (Keller 2000)--- Broad moderate elevation valley (USDA Forest Service 1979) Riparian Complex.

Stream E3 cross section 1:

Stream E3 cross section 3:
APPENDIX 5: STABILITY CLASSES AND SUCCESSIONAL STATUS

The following bank stability classes and greenline vegetation successional status ratings were obtained from Winward (2000).

**Type C Streams**

**Stream C1 cross section 1:**
Stability class = Moderate
Successional status = Early

**Stream C1 cross section 3:**
Stability class = Good to Excellent
Successional status = Early

**Stream C2 cross section 1:**
Stability class = Good
Successional status = Late

**Stream C2 cross section 3:**
Stability class = Good
Successional status = Late

**Stream C3 cross section 1:**
Stability class = Moderate
Successional status = Early
Stream C3 cross section 3:
Stability class = Moderate
Successional status = Early

Type E Streams
Stream E1 cross section 1:
Stability class = Excellent
Successional status = Late

Stream E1 cross section 3:
Stability class = Moderate to Excellent
Successional status = Late

Stream E2 cross section 1:
Stability class = Good
Successional status = Late

Stream E2 cross section 3:
Stability class = Excellent
Successional status = Late

Stream E3 cross section 1:
Stability class = Moderate to Excellent
Successional status = Late

Stream E3 cross section 3:
Stability class = Good to Excellent
Successional status = Late
APPENDIX 6: STREAM SINUOSITY AND CROSS-SECTION PROFILES

The following channel cross-section profiles illustrate water depth for the given dates on which stream discharge was measured. Along the depth(m) axis, 0.00 represents the water's edge. Along the same axis, 0.05 is that portion of the channel from the water's edge to the approximated bankfull for both sides of the channel. Approximate bankfull location is given as 0.10m. From these cross-section figures, monthly changes in water depth, approximation of channel volume and surface area, and changes in channel substrate between years can be appreciated. Sinuosity figures illustrate study reach sinuosity, location of cross-sections, reduced overhead shade, and general study reach setting.

Figure 37: Stream C1 Sinuosity
Figure 38: Stream C1 Cross-Section One Profile (1998)

Figure 39: Stream C1 Cross-Section Two Profile (1998)
Figure 40: Stream C1 Cross-Section Three Profile (1998)

Figure 41: Stream C1 Cross-Section One Profile (1999)
Figure 42: Stream C1 Cross-Section Two Profile (1999)

Figure 43: Stream C1 Cross-Section Three Profile (1999)
Figure 44: Stream C2 Sinuosity
Figure 45: Stream C2 Cross-Section One Profile (1998)

Figure 46: Stream C2 Cross-Section Two Profile (1998)
Figure 47: Stream C2 Cross-Section Three Profile (1998)

Figure 48: Stream C2 Cross-Section One Profile (1999)
Figure 49: Stream C2 Cross-Section Two Profile (1999)

Figure 50: Stream C2 Cross-Section Three Profile (1999)
Figure 5.1: Stream C3 Sinuosity
Figure 52: Stream C3 Cross-Section One Profile (1998)

Figure 53: Stream C3 Cross-Section Two Profile (1998)
Figure 54: Stream C3 Cross-Section Three Profile (1998)

Figure 55: Stream C3 Cross-Section One Profile (1999)
Figure 56: Stream C3 Cross-Section Two Profile (1999)

Figure 57: Stream C3 Cross-Section Three Profile (1999)
Figure 58: Stream E1 Sinuosity
Figure 59: Stream E1 Cross-Section One Profile (1998)

Figure 60: Stream E1 Cross-Section Two Profile (1998)
Figure 61: Stream E1 Cross-Section Three Profile (1998)

Figure 62: Stream E1 Cross-Section One Profile (1999)
Figure 63: Stream E1 Cross-Section Two Profile (1999)

Figure 64: Stream E1 Cross-Section Three Profile (1999)
Figure 65: Stream E2 Sinuosity
Figure 66: Stream E2 Cross-Section One Profile (1998)

Figure 67: Stream E2 Cross-Section Two Profile (1998)
Figure 68: Stream E2 Cross-Section Three Profile (1998)

Figure 69: Stream E2 Cross-Section One Profile (1999)
Figure 70: Stream E2 Cross-Section Two Profile (1999)

![Figure 70: Stream E2 Cross-Section Two Profile (1999)](image)

Figure 71: Stream E2 Cross-Section Three Profile (1999)

![Figure 71: Stream E2 Cross-Section Three Profile (1999)](image)
Figure 72: Stream E3 Sinuosity
Figure 73: Stream E3 Cross-Section One Profile (1998)

Figure 74: Stream E3 Cross-Section Two Profile (1998)
Figure 75: Stream E3 Cross-Section Three Profile (1998)

Figure 76: Stream E3 Cross-Section One Profile (1999)
Figure 77: Stream E3 Cross-Section Two Profile (1999)

Figure 78: Stream E3 Cross-Section Three Profile (1999)