In presenting this thesis in partial fulfillment of the requirements for a master’s degree at Western Washington University, I agree that the Library shall make its copies freely available for inspection. I further agree that copying of this thesis in whole or in part is allowable only for scholarly purposes. It is understood however, that any copying or publication of this thesis for commercial purposes, or financial gain, shall not be allowed without my written permission.

Signature ________________________________

Date ________________________________
STREAMFLOW CALIBRATION OF TWO SUB-BASINS IN THE LAKE WHATCOM WATERSHED, WASHINGTON USING A DISTRIBUTED HYDROLOGY MODEL

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Katherine D. Kelleher
March 2006
ABSTRACT
Lake Whatcom provides drinking water to the City of Bellingham and portions of Whatcom County. Therefore, quantifying streamflow into the lake is important to establish the contribution of ground water and surface water runoff in the Lake Whatcom water budget. Runoff is nearly 74% of the total inputs to the lake, thus the runoff provides the most water and nutrients to the lake. The primary goal of this study was to determine the ability of the Distributed Hydrology-Soils-Vegetation Model (DHSVM) to simulate the hydrologic processes in two sub-basins of the Lake Whatcom watershed.

DHSVM is a physically based model that simulates a water and energy balance at the scale of a digital elevation model (DEM). GIS maps of topography (DEM), the watershed boundary, soil texture, soil thickness, vegetation, and a flow network define the characteristics of a watershed. The input meteorological requirements for DHSVM include time-series data representing air temperature, humidity, wind speed, incoming shortwave radiation, incoming longwave radiation and precipitation. Meteorologic data were compiled from recent records of a local weather station, except for longwave radiation, which was estimated. I calibrated and validated DHSVM for water years 2002 – 2003, using streamflow records from Austin and Smith Creeks within the Lake Whatcom watershed. Simulations were performed using one-hour time steps and a 30-meter pixel size. Sensitivity analyses were performed with the model to determine the model’s sensitivities and ability to capture hydrologic processes within the watershed by altering soils, vegetation types, and precipitation inputs.

The calibration simulations for WY 2002 had a calibration error of 1% for Austin Creek and -3% for Smith Creek. Both simulation errors are less than the recommended maximum error of +/-5%. The validation was more problematic because of gaps within the recorded streamflow data. However, for the time frame where the simulated flow and recorded flow did overlap, the validation simulation error was -5% for Austin Creek and 3% for Smith Creek.

The sensitivity analyses provided insight into parameter influences. The soil sensitivity simulations in Smith Creek have high mass balance errors indicating that
model calculations were not performing adequately. The high mass balance error suggests that the model is over-estimating either the storage or the output.

The vegetation sensitivity simulations did not affect streamflow other than slightly increasing storm peaks. More realistic simulations that capture vegetation removal through deforestation and urbanization would require the use of a road and storm sewer networks within the model to appropriately simulate decreased infiltration and re-routing of storm water runoff.

Additional precipitation gage data added to the model, illustrated an increase in peaks in Austin Creek. Smith Creek did not have the increase in peaks, primarily due to the distance from the precipitation gage at Brannian Hatchery. The overall streamflow in Austin Creek did not increase with the addition of three precipitation gages to the input file, although the volume of storm event peaks did increase. I also simulated streamflow for Austin Creek and Smith Creek with two other interpolation methods (INVDIST and VARCRESS) using the additional precipitation gages. The INVDIST interpolation method provided the greatest increase in both Austin Creek and Smith Creek, again primarily increasing peak volumes with little change in base flow.

Future efforts should focus on modeling the individual subbasins, rather than attempting to model the entire Lake Whatcom watershed. The heterogeneities between the individual sub-basins are captured by DHSVM which increase the difficulty in modeling the entire watershed.
ACKNOWLEDGEMENTS

I would like to acknowledge my advisor, Dr. Robert Mitchell for his constant support and enthusiasm for my project from beginning to the end; as well my thesis committee: Dr. Douglas Clark, and Dr. Scott Babcock. I must also acknowledge all those who helped me with various and seemingly never-ending computer questions: Jay Chennault, Mike Hilles, Matt Paskus, Steve Walker, and Ed Maurer. Both Vicki Critchlow and Chris Sutton in the Geology Department provided valuable assistance for all things academic.

I give particular acknowledgement to Dr. Pascal Storck. Without his help, none of this could have been possible. I am very grateful for his patience and assistance over the years by telephone, email, and in person. I acknowledge Joanne Greenberg and Karen Welch for endless encouragement and assistance with many hydrology and modeling questions. Finally, I acknowledge the much needed support and encouragement from Dianne Meyer, Conor Callaghan, and Kirk Heim, through all the good days and most particularly the bad days.

Strength is not the ability to lift heavy objects; strength is the will to endure.
B. Choudry
# TABLE OF CONTENTS

ABSTRACT

ACKNOWLEDGEMENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

2.0 BACKGROUND

2.1 Lake Whatcom Watershed and Austin and Smith Creek Sub-basins

2.1.1 Topography

2.1.2 Geology

2.1.3 Soils

2.1.4 Vegetation

2.1.5 Hydrology

2.1.6 Climate

2.1.7 DHSVM

2.2 Previous Work

2.2.1 Lake Whatcom Watershed and Smith and Austin Sub-basins

2.2.3 DHSVM Studies

3.0 RESEARCH OBJECTIVES

4.0 METHODOLOGY

4.1 Basin Setup

4.1.1 Digital Elevation Model (DEM)

4.1.2 Sub-basin Masks and Analysis Domain

4.1.3 Soil Textures

4.1.4 Soil Thickness

4.1.5 Vegetation Data

4.1.6 Flow Network

4.1.7 Constant Basin Parameters

4.2 Meteorological Data

4.3 Streamflow Gages in Lake Whatcom Watershed

4.4 Initial Calibration and Validation

4.4.1 Initial Calibration

4.4.2 Validation

4.5 Model Sensitivity Analyses

4.6 Modeling Assumptions

5.0 RESULTS & DISCUSSION

5.1 Basin Setup

5.2 Meteorological Data

5.3 Calibration

5.3.1 Annual Calibration

5.3.2 Monthly Calibration Results and Streamflow

5.3.3 Descriptive Statistical Comparison of Calibration Simulations and Recorded Flow

vii
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4 Validation of Model to Austin Creek and Smith Creek Sub-basins</td>
<td>37</td>
</tr>
<tr>
<td>5.5 Sensitivity Analyses for Austin Creek and Smith Creek</td>
<td>38</td>
</tr>
<tr>
<td>5.3.2 Soil Sensitivity Analyses</td>
<td>38</td>
</tr>
<tr>
<td>5.3.2 Vegetation Sensitivity Analyses</td>
<td>42</td>
</tr>
<tr>
<td>5.3.2 Precipitation Sensitivity Analyses</td>
<td>44</td>
</tr>
<tr>
<td>6.0 CONCLUSIONS</td>
<td>52</td>
</tr>
<tr>
<td>7.0 FUTURE WORK</td>
<td>55</td>
</tr>
<tr>
<td>8.0 REFERENCES</td>
<td>56</td>
</tr>
<tr>
<td>Appendix A: GIS Basin Set-up Procedures and Input Data CD</td>
<td>98</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1. Hydrologic Constant Parameters for Lake Whatcom simulations .................. 60
Table 2. Austin Creek hydrologic simulations performed using DHSVM .................... 61
Table 3. Smith Creek hydrologic simulations using DHSVM ................................. 62
Table 4. Calibration parameters for Austin Creek and Smith Creek ....................... 63
Table 5. Descriptive statistics for Austin Creek and Smith Creek recorded and simulated flows for WY2002. ................................................................. 63
Table 6. Descriptive statistics for Austin Creek residuals for best-match calibrated flows for WY2002. ................................................................. 64
Table 7. Descriptive statistics for Smith Creek residuals for best-match calibrated flows for WY2002. ................................................................. 64
Table 8. Input values for soil texture simulations (soil sensitivity selections highlighted in grey) ......................................................................................... 65
Table 9. Soil water content for Austin Creek soil simulations for WY 2002 .............. 66
Table 10. Soil water content for Smith Creek soil simulations for WY 2002 ............ 66
Table 11. Total evapotranspiration from the calibration and vegetation sensitivity simulations for WY 2002 in Austin Creek sub-basin ........................ 66
Table 12. Total evapotranspiration from the calibration and vegetation sensitivity simulations for WY 2002 in Smith Creek sub-basin ................. 67
Table 13. Rainfall totals for various gages in Lake Whatcom Watershed during Water Year 2002 ................................................................. 67
Table 14. Direct Weighted Precipitation on Lake Whatcom in Inches (courtesy of Dr. Mitchell, 2004) ................................................................. 68
Table 15. Total Simulated Precipitation in each sub-basin for the different precipitation sensitivity simulations, WY 2002 ................................. 68
LIST OF FIGURES

Figure 1. Location of Lake Whatcom watershed, Whatcom County. .......................... 69
Figure 2. Topography and streams of Lake Whatcom Watershed from the USGS 10 meter DEMs. ................................................................. 70
Figure 3. Geologic map of Lake Whatcom Watershed ............................................. 71
Figure 4. Soil groups and infiltration rates within the Lake Whatcom Watershed from the NRCS STATSGO soils database ........................................... 72
Figure 5. Vegetation types in the Lake Whatcom Watershed reclassified from the USGS 1992 National Land Cover data set ............................................. 73
Figure 6. Hillshade representation of Lake Whatcom watershed with stream network and sub-basin masks for model analysis .................................................. 74
Figure 7. Soil textures for Lake Whatcom Watershed from CONUS database .......... 75
Figure 8: Soil depth modified from predicted soil depth generated by an AML process. 76
Figure 9: Locations of meteorologic (met) stations and precipitation gages in Lake Whatcom watershed ............................................................... 77
Figure 10: Recorded flow for Smith Creek and Austin Creek for WY2002. ............... 78
Figure 11: First simulation of Austin Creek with DHSVM default parameters for WY2002 ................................................................. 78
Figure 12: First simulation of Smith Creek with DHSVM default parameters for WY2002 ................................................................. 79
Figure 13. Austin Creek streamflow with the annual calibration simulation with a precipitation lapse rate of 0.0020m/m. ................................................. 79
Figure 14. Austin Creek summer flow with the annual calibration simulation with a precipitation lapse rate of 0.0020m/m ........................................... 80
Figure 15. Beginning of WY 2002 simulation for Austin Creek with a precipitation lapse rate of 0.0020m/m showing a decrease in lag time in ‘warming’ up the model........ 80
Figure 16. Cumulative depth plot of precipitation, streamflow and simulated streamflow in Austin Creek sub-basin for WY 2002 ........................................ 81
Figure 17. Smith Creek streamflow with the annual calibration simulations with a precipitation lapse rate of 0.0004 and 0.0005 m/m ........................................... 81
Figure 18. Smith Creek summer flow with the annual calibration simulations with a precipitation lapse rate of 0.0004 and 0.0005 m/m ........................................... 82
Figure 19. Cumulative depth plot of precipitation, recorded flow, and simulated flow over Smith Creek sub-basin, WY 2002 ................................................. 82
Figure 20. Comparison of basin averaged streamflow depths with different lateral conductivities by month for Austin Creek, WY 2002 .......................... 83
Figure 21. Final calibration simulation of Austin Creek with precipitation lapse rate of 0.0020 m/m and lateral hydraulic conductivity of 0.02 m/s for WY 2002 ............ 83
Figure 22. Final calibration simulation of Smith Creek with precipitation lapse rate of 0.0004 m/m and lateral hydraulic conductivity of 0.01 m/s for WY 2002 ............ 84
Figure 23. Slope percentage in the Lake Whatcom watershed using ArcGIS spatial analysis of the watershed DEM. .................................................. 85
Figure 24. Comparison of basin averaged streamflow depths with different lateral conductivities by month for Smith Creek, WY 2002. .......................................................... 86
Figure 25. Recorded and simulated flows with different lateral hydraulic conductivity values for Smith Creek for WY 2002. .......................................................... 86
Figure 26. Recorded and simulated flows with different lateral hydraulic conductivity values for Smith Creek for summer of 2002.......................................................... 87
Figure 27. Frequency histogram of Austin Creek’s recorded and simulated streamflow data for WY 2002 indicating the lack of normality, with an exponential decay to the right.......................................................... 88
Figure 28. Frequency histogram of Smith Creek’s recorded and simulated streamflow data for WY 2002 indicating the lack of normality, with an exponential decay to the right.......................................................... 88
Figure 29. Hourly residuals of the calibration simulation and recorded flow for Austin Creek for WY 2002.......................................................... 89
Figure 30. Hourly residuals of the calibration simulation and recorded flow for Smith Creek for WY 2002.......................................................... 89
Figure 31. Validation simulation of Austin Creek for WY 2003. ............................. 90
Figure 32. Validation simulation of Smith Creek for WY 2003............................. 90
Figure 33. Soil texture sensitivity simulations for Austin Creek sub-basin, WY 2002... 91
Figure 34. Soil texture sensitivity simulations for Smith Creek sub-basin, WY 2002... 91
Figure 35. Vegetation sensitivity simulations for Austin Creek sub-basin, WY2002.... 92
Figure 36. Vegetation sensitivity simulations for Smith Creek sub-basin, WY2002...... 92
Figure 37. Comparison of rainfall depths at Northshore Climate Station, Brannian Hatchery Climate Station, and Geneva Rain Gage in Lake Whatcom Watershed for December 2002. .......................................................... 93
Figure 38. Rainfall totals by month for WY 2002 for the Northshore climate station, Geneva rainfall gage, and the Brannian Creek Hatchery rainfall gage................. 93
Figure 39. Calibration simulation and two precipitation gages simulation for Austin Creek, WY 2002. .......................................................... 94
Figure 40. Calibration simulation, two precipitation gage simulation and recorded flow in Austin Creek for summer months of WY2002................................. 94
Figure 41. Simulations with two and three precipitation gages and the calibration simulation for Austin Creek, WY 2002.......................................................... 95
Figure 42. Comparison of Austin Creek simulated flow with two and three precipitation gages and the recorded flow for WY 2002.......................................................... 95
Figure 43. Calibration simulation and two precipitation gages simulation for Smith Creek, WY 2002. .......................................................... 96
Figure 44. Calibration simulation, two precipitation gage simulation and recorded flow in Smith Creek for summer months of WY2002................................. 96
Figure 45. Interpolation scheme simulations with calibration simulation of Austin Creek, WY2002.......................................................... 97
Figure 46. Interpolation scheme simulations with calibration simulation of Smith Creek WY2002.......................................................... 97
1.0 INTRODUCTION
Lake Whatcom provides drinking water to the City of Bellingham and portions of Whatcom County. Therefore, quantifying streamflow into the lake is important to understand in terms of water quantity and water quality.

Hydrologic studies show that stream discharge responses to climatic events are basin specific and are influenced by a number of factors including topography, soil distribution, bedrock type, and forest cover (e.g., Storck et al., 1995; Moore et al., 1991). The dynamics of the basins may also be affected by anthropogenic factors such as logging and urban development. Attempts have been made to model hydrologic mechanisms in watersheds for predictive scenarios regarding water quality, low flows, peak flows, flood intervals and erosion hazards. The results have been limited because of model limitations and lack of spatial data (e.g., Moore et al., 1991 and Walker, 1995). In the Lake Whatcom watershed, spatial data collection has increased within the last 5 years with concurrent precipitation and stream discharge data collected by the City of Bellingham. These enhanced data sets can improve the constraints on ground water and surface water inputs to the lake and provide better calibration of hydrologic models, which were lacking previously (Walker, 1995; Matthews et al., 2001). A better understanding of surface water runoff to the lake will improve the ground water estimates into the lake. These values are the primary remaining unknowns in the Lake Whatcom water balance (Matthews et al., 2001).

The primary goal of this study is to determine the ability of the Distributed Hydrology-Soils-Vegetation Model (DHSVM) to simulate the hydrologic processes in two sub-basins of the Lake Whatcom watershed. The original goal of my thesis was to quantify the surface water inputs to Lake Whatcom from all the basins. However, I was not able to calibrate the hydrologic model to the entire watershed. This thesis describes my attempt and ultimate inability to calibrate the model to the Lake Whatcom watershed, describes why the calibration did not work, discusses the successful calibration to two sub-basins of the watershed, and finally suggests how future studies might proceed with the calibration and validation of the entire watershed.
2.0 BACKGROUND

2.1 Lake Whatcom Watershed and Austin and Smith Creek Sub-basins

Lake Whatcom watershed is located in Whatcom County, with a small portion of the watershed located in Skagit County, in the northwestern section of Washington State (Figure 1). Because the original goal of this study was to calibrate the hydrologic model to the entire Lake Whatcom watershed, the topography, geology, soil textures, vegetation types, and climate of the watershed are described below, with a focus on Smith Creek and Austin Creek sub-basins.

2.1.1 Topography

The topography of the Lake Whatcom watershed is defined by topographic ridges (Squalicum, Stewart, Anderson and Lookout Mountains) that circle the lake (Figure 2). The outlet of the lake is at the northwest end of the lake. Lake level is typically at 93 m above sea level, although the level fluctuates depending on rainfall and releases from a control dam at its outlet. Relief is quite steep in some sub-basins. For example, in the Austin Creek sub-basin, the elevation gain is 780 m in 5 km horizontal distance, whereas the elevation gain is 1160 m in the Smith Creek sub-basin in 5 km (Figure 2).

Austin Creek sub-basin has a northeasterly aspect and faces Smith Creek directly across the lake. Austin Creek and Smith Creek sub-basins are the largest within Lake Whatcom watershed. Austin Creek sub-basin is 21.4 km² and Smith Creek sub-basin is 13.3 km². Total watershed area including the lake surface is 146.4 km². Lake surface alone is 21.2 km². Smith Creek and Austin Creek sub-basins, together, cover approximately 27% of the watershed’s land surface.

2.1.2 Geology

The regional geologic setting reflects tectonism related to subduction along the Cascadia subduction zone. The Puget Sound Lowlands are a basin between the Cascades and the subduction complex (Olympic Mountains; Vaccaro et al., 1998). The Lake Whatcom watershed is located in the northwest section of the Puget Sound
Lowlands, just south of the border with Canada. Significant modifications to the topography of the area occurred during repeated Pleistocene glaciations (Figure 3).

Bedrock in the Lake Whatcom watershed consists of the Chuckanut Formation, a folded and faulted sedimentary rock of Eocene age and the Darrington Phyllite, a metamorphic rock found in the lower Blue Canyon area near the south end of the lake (Weden and Associates, 1983; Easterbrook, 1973). The Darrington Phyllite is pre-Tertiary in age and is a unit of the Shuksan Metamorphic Suite. The Darrington unit is dominantly a black graphitic phyllite with quartz layers and veins (Brown, 1986). This unit contributes to sliding within the watershed because of the high angle of dip along exposed slopes and the inherent weakness in the contact between the phyllite and the Chuckanut Formation (Fox et al., 1992).

The Chuckanut Formation is an alluvial floodplain deposit that is folded into anticlines and synclines creating a porous, permeable bedrock with preferential flow paths (Easterbrook, 1973). Outcrops are susceptible to mass wasting as a result of fractures associated with these folds and faults (Easterbrook, 1973; Fox et al., 1992). The bedrock in both Austin Creek and Smith Creek sub-basins is the Bellingham Bay Member of the Chuckanut Formation (WDNR, 2003; Figure 3).

The entire watershed has been eroded and shaped by glacial advances and retreats throughout the Pleistocene, most recently during a period from ~17,000 to 12,000 years B.P., known as the Fraser Glaciation (Easterbrook, 1973). The ice was deep enough to cover the Puget Lowlands and scoured the Lake Whatcom basin to just below sea level (Behee, 2002). Vashon Stade deposits (Qgd on Figure 3) occur at the southern end of the lake near Cain and Reed Lakes and in the valleys of Brannian Creek and Anderson Creek (WDNR, 2003; Figures 2 and 3). Deposits of the Everson Glaciomarine Drift (Qgdm(e) on Figure 3) are found in the northern portion of the Carpenter Creek sub-basin (WDNR, 2003). And the most recent stade, the Sumas Stade (Qgo(s) on Figure 3), occurs in the Carpenter Creek valley (WDNR, 2003; Easterbrook, 1973; Figures 2 and 3).
A Holocene alluvial fan forms the outlet of Smith Creek. Other Holocene deposits include two large landslides. One slide is at the base of the Blue Canyon area of the southern watershed and one exists above the Olsen Creek drainage (WDNR, 2003). Other alluvial fans exist around the lake, formed by continual small slides and torrent debris flows within drainage basins, including one at the mouth of the Austin Creek (Fox, et al., 1992, and Pitz, 2005). These slides are composed of poorly sorted clays, sands, and gravels with high permeabilities (USDA, 1984).

2.1.3 Soils
Soil types and soil depth are a function of the bedrock lithology, climate, and slope of the bedrock surface (Boggs, 1995). These factors control the weathering, type of minerals that make up the soil, and the length of time that soil remains before being eroded and transported (Boggs, 1995). The Natural Resources Conservation Service (NRCS) 1992 soil survey mapped 8 different soil map units in the Lake Whatcom watershed (Figure 4). The soils units are closely related to the geology within the area. Where the soils overlay bedrock, they contain lithic fragments and high percentages of rock outcrop (NRCS, 1992). The soils overlying bedrock are not as deep as those overlying glacial deposits found in the valleys of the watershed. These soils are quite deep with moderate permeabilities in the upper horizons and lower permeability in the lower horizons due to the underlying glacial till (NRCS, 1992).

Two soil map units are mapped within the Austin Creek sub-basin by the NRCS 1992 soil survey. The Skipopa unit is poorly drained, deep silt and clayey loam soil, with slow infiltration, on slopes of 0 to 8% (NRCS, 1992). The Oakes unit is also a deep soil of gravelly and sandy loam of moderate infiltration, and typically overlies sandstone (NRCS, 1992). The Oakes unit is found on slopes that range from 5 to 80% (NRCS, 1992).

Smith Creek sub-basin is mapped with three soil units, the Skipopa, Oakes, and Rock Outcrop. The Rock Outcrop unit is dominantly sandstone with very slow infiltration rates on steep slopes of 60 to 100% (NRCS, 1992).
2.1.4 Vegetation

The vegetation of the Lake Whatcom watershed is primarily conifer and mixed conifer forests (Figure 5). Many of the forested sections are zoned for commercial logging. Small pockets of urban areas exist at the outlet of the lake that is within the Bellingham city limits. Sudden Valley in the Austin Creek sub-basin is another urban area. Residential sections are found along the south shore and portions of the north shore of the lake.

2.1.5 Hydrology

The watershed is primarily drained by 8 perennial streams: Anderson Creek, Brannian Creek, Austin/Beaver Creek, Smith Creek, Olsen Creek, Fir Creek, Wildwood Creek and Carpenter Creek (Figure 2). Walker (1995) identified a total of 36 streams within the watershed. Anderson Creek is in part, regulated by the use of a diversion dam on the Middle Fork Nooksack River. The diversion dam routes water to a pipeline that empties into Mirror Lake at the head of Anderson Creek. The diversion dam is operated by the City of Bellingham and augments the water level in Lake Whatcom for municipal use.

Two lakes exist within the watershed: Mirror Lake, at the head of Anderson Creek which is used a sediment pond for the Middle Fork diversion, and Lake Louise in Sudden Valley near the outlet of Austin Creek (Figure 2).

Ground water flow within the watershed is poorly understood. Pitz (2005) characterized the ground water flow as two systems: ground water flow into the lake through the bedrock (Chuckanut Formation and Darrington Phyllite) and ground water flow through unconsolidated valley-fill glacial deposits. The bedrock ground water flow is a function of dual-porosity processes where the primary porosity (volume of pore space within the rock) is quite low but the secondary porosity (fracture planes, joints and shear zones) can provide flow paths with greater volumes for water movement. This dual-porosity process is most likely occurring within the Smith Creek and Austin Creek sub-basins.

Pitz (2005) suggested the valley areas with glacial outwash and till provide the most ground water to Lake Whatcom. These areas have higher porosity and greater
transmissivity than the bedrock, evidenced by well log data within the watershed (Pitz, 2005). Pitz (2005) estimated that in the bedrock areas of the watershed aquifer recharge from precipitation is approximately 0.051 meters per year (2 inches per year). Vaccaro et al. (1998) provided an estimate of 0 inches per year in bedrock areas of Puget Sound regardless of the amount of precipitation. However, some ground water does exist locally in the Chuckanut Formation primarily because of secondary porosity (Cox and Kahle, 1999). On the other hand, stream valleys had higher recharge estimates that ranged from 0.43 to 1.27 meters per year (17 to 50 inches per year; Pitz, 2005). This range agrees well with the recharge estimates of the Cox and Kahle (1999) in the Sumas-Abbotsford aquifer area in northern Whatcom County. Although the outlet of the ground water is expected to end at discharge into Lake Whatcom, some volume of the flow may exit the watershed in a deep regional aquifer (Pitz, 2005). Pitz (2005) estimated the inflow of ground water to the lake during WY2003 to be between $1.23 \times 10^7$ cubic meters and $1.71 \times 10^7$ cubic meters.

2.1.6 Climate
The Puget Sound Lowland area is a mid-latitude humid marine climate with most precipitation occurring in the winter months with relatively dry summer months (Jones, 1999). This area of western Washington is affected by the winter maritime polar air mass that originates in Asia and moves across the Pacific Ocean into the Pacific Northwest (Ahrens, 1998). The Pacific Ocean increases the temperature of the air masses while increasing the levels of moisture. Once this air mass reaches Washington, the temperatures are cool and the humidity is high, leading to unstable conditions. As the air mass is pushed into the Olympic and Cascade Mountain ranges, the air rises, cools, and precipitation begins to fall. This occurrence is called the orographic effect.

The orographic effect is both regional and local, causing precipitation amounts in Western Washington to range from 76.2 centimeters (30 inches) per year in the lowlands to over 508 centimeters (200 inches) a year in the Olympic Mountains. Controls on the orographic effect are horizontal wind speed, wind
direction relative to the mountains, steepness and height of the mountains, and the temperature and humidity conditions (Dingman, 2002). This precipitation tends to fall as rain in the lowlands and along the coasts, and as winter snow in elevations above 1500 feet (Jones, 1999). Because of the moderating effect of the Pacific Ocean, western Washington does not experience daily or seasonal temperature extremes as found in eastern Washington. The mean annual temperatures typically range from 4 to 11 degrees Celsius (40 to 50 degrees Fahrenheit), with the warmest temperatures in the summer in the lowlands, and coldest temperatures found in the mountainous regions during the winter.

Gentle rain and moderate temperatures characterize Bellingham’s annual weather. Daily and seasonal fluctuations are minimal. The average high annual temperature is 14 degrees Celsius, with August as the warmest month and the average low at 6 degrees Celsius with January as the coldest month (Western Regional Climate Center, 2004). Rainfall is greatest from November to February, and July and August are the driest months. Average rainfall is 91.4 centimeters per year. Greatest evapotranspiration occurs during the summer months, and lessens during the cool, cloudy winters.

Weather patterns in the watershed are quite similar to Bellingham weather, although rainfall tends to be greater in the higher elevations due to the orographic effect (Dingman, 2002; Ahrens, 1998). This is common in Smith and Austin Creek sub-basins as rainfall amounts increase upslope. Rainfall amounts typically increase near the southern end of the lake as well as evidenced by rain gages in the watershed. Cloudiness is greater due to the mountains, forming upslope fog that is visible during rainy days throughout the year. Wind conditions can vary within the watershed from the channeling of the mountain and valleys within the watershed.

Snowfall is sporadic and infrequent as snow falls and melts several times each winter, with accumulations typically under 5 inches each event. The upper reaches of the watershed falls within the transient snow zone as defined by Berris and Harr (1987).
2.1.7 DHSVM

Distributed Hydrology-Soils-Vegetation Model (DHSVM) is a physically based distributed parameter model that provides a DEM based representation of a watershed. The spatial scale of the representation is based on the grid size of the DEM. DHSVM was originally developed by Wigmosta et al. (1994) and has evolved for use in maritime mountainous watersheds (as found in Western Washington) by Storck et al. 1995. Currently, the model consists of a two-layer canopy representation of evapotranspiration, a two layer energy balance model for ground snow pack, a multilayer unsaturated soil model, a saturated subsurface flow model, and a three dimensional overland flow representation. The DEM provides the topographic controls on the incoming short-wave radiation, precipitation, air temperature, and downslope water movement. Grid cells are assigned vegetation and soil characteristics and are hydrologically linked through surface and subsurface flow routing.

DHSVM requires meteorologic (met) inputs of air temperature, precipitation, wind, humidity, and incoming short-wave and long-wave radiation. DHSVM can distribute point measurements of meteorological data over a basin in a number of ways. Precipitation data can be distributed by a constant precipitation elevation lapse rate or by using the precipitation model PRISM developed by Daly et al. (1994). DHSVM also provides three precipitation interpolation methods for distribution of rainfall across a watershed. Temperature measurements are distributed vertically by a constant lapse rate or at a variable lapse rate that can change in time. Topographic controls on incoming solar and longwave radiation are established by a monthly series of shading maps derived from the DEM.

Unsaturated movement through multiple rooting zone soil layers is calculated using Darcy’s law. Vertical discharge from the lower rooting zone recharges the grid cell’s water table. Each grid cell exchanges water with its adjacent neighbors according to the topographic slope. Return flow and saturation overland flow are generated when the cell’s water table intersects the ground surface.
Flow in the stream channels is routed using a series of cascading linear channel reaches. Individual hydraulic parameters describe each reach. As the reach passes through grid cells, lateral inflow into the channel reach consists of both overland flow and subsurface flow. Flow is routed between channel reaches as a linear routing algorithm where each reach treated as a reservoir of constant width with outflow linearly related to storage.

Each DHSVM simulation provides three forms of output: watershed condition file, mass balance value file, and a stream discharge file. The mass balance file contains hydrologic parameter values (runoff, channel interception, sublimation, saturated subsurface flow, precipitation, evapotranspiration, soil moisture, mass balance error, etc.) for each time step. The values in the mass balance and streamflow files can be used for analysis of model function. At any time, the values in these output files can be used as the initial conditions for the next model simulation.

2.2 Previous Work

2.2.1 Lake Whatcom Watershed and Smith and Austin Sub-basins

Previous work on the watershed is limited to studies on specific topics (e.g., debris flows, urbanization, water use, and lake water quality). An example is the Syverson (1984) study on debris torrents in the Smith Creek sub-basin in which the history of debris flows and their correspondence to heavy precipitation and logging practices was detailed (i.e., logging slash left on hillsides and in stream channels). The study was in response to the debris events in 1983 that caused extensive damage to private property at the mouth of the creek.

Each year, the Institute of Watershed Studies at Western Washington University publishes the Lake Whatcom Monitoring Report, which provides a baseline water quality monitoring within the lake and selected tributaries, and a water budget for Lake Whatcom (Matthews et al., 2001). The main goal of the yearly reports is to provide long-term monitoring of Lake Whatcom’s water quality. Objectives of the studies include monitoring water quality in the lake and certain tributaries, updating of the hydrologic model, collection of water quality data from
basin 3 near Strawberry Sill, evaluations of water movement patterns in the lake and monitoring the effectiveness of Park Place and Brentwood wet ponds (Matthews et al., 2001). In the 1999/2000 report, precipitation and evaporation were first considered in the water balance equation for the lake (Matthews et al., 2001). As of the 1999/2000 report, the only unknown inputs to the lake were surface water runoff and ground water (Matthews et al., 2001).

The first hydrologic modeling within the Lake Whatcom Watershed was performed by Walker (1995). Walker used Hydrologic Simulation Program – FORTRAN (HSPF) to develop a conceptual, hydrologic response unit model in which the entire watershed and lake system was modeled from 1990 to 1994 (Walker, 1995). Walker made many assumptions on uncertainties for the simulated inputs and outputs of the watershed and the lake. Walker was unable, at the time, to calibrate the model due to the lack of concurrent streamflow and precipitation data (Walker, 1995). In contrast, my research using DHSVM uses a detailed characterization of the watershed and incorporates actual recorded precipitation and streamflow data.

2.2.3 DHSVM Studies
I used DHSVM to simulate hydrologic responses in the Smith and Austin Creeks because the model is one of the most advanced hydrologic models available and has been validated in other Cascade mountain basins. Wigmosta et al., (1994) originally developed DHSVM and verified it using the Middle Fork Flathead River in northwestern Montana. They used a 3-hour time step for a 180-meter grid. There was a 7% difference between the simulated and recorded streamflow over a four year calibration and validation period. DHSVM has since been successfully applied in some of the Pacific Northwest’s maritime and mountainous watersheds (Storck et al., 1995; 1998; Wigmosta and Perkins, 2001; and Chennault, 2004). These watersheds ranged in size from 5.2 km$^2$ to 2900 km$^2$, typically had high relief, and were dominated by spring snowmelt and rain-on-snow events.
Most studies utilizing DHSVM primarily research its effectiveness in modeling hydrologic characteristics of heavily logged watersheds (e.g., Bowling and Lettenmaier, 2001; Wigmosta and Perkins, 2001; and Storck et al., 1998). These studies examined the effects on peak stream flow from harvest practices, road building/use, and logging. Storck et al. (1998) study applied DHSVM to three different watersheds in Washington State: North Fork Snoqualmie, Hard/Ware Creeks, and the Little Naches watershed. The results suggested that the North Fork Snoqualmie catchment, which is dominated by rain-on-snow events during the winter, is sensitive to forest harvest practices at low to mid-elevations (Storck et al., 1998). In the Little Naches watershed, the spring snowmelt area at higher elevations is most sensitive to forest harvest (Storck et al., 1998). An increase in response time to storms with greater forest road networks occurred in Hard and Ware Creeks catchment (Storck et al., 1998). The calibration years for the catchments contained large floods that exceeded the 100 year flood return periods, but the study suggested that the flooding was likely due to forest harvesting practices and not solely climate variability (Storck et al., 1998).

Two studies used DHSVM to specifically model the effects of roads on watershed hydrology (Bowling and Lettenmaier, 2001; Wigmosta and Perkins, 2001). Road drainage characteristics and culvert placement determine flow path and travel time to the stream and can greatly alter the natural hydrologic processes of a stream. Bowling and Lettenmaier (2001) modeled the Hard and Ware Creeks catchment in western Washington and Wigmosta and Perkins (2001) modeled the effects of roads in the Carnation Creek watershed on the west coast of Vancouver Island, British Columbia.

Bowling and Lettenmaier (2001) determined DHSVM’s ability to evaluate the hydrological effects of forest roads on the magnitude and distribution of catchment runoff response based on a year of field investigation and 11 years of streamflow data for Hard and Ware Creek watersheds. Total simulated discharge was within 11% of the observed streamflow in Hard Creek and 1% of observed for Ware Creek (Bowling and Lettenmaier, 2001). The difference between the two catchments is likely due to
changes in precipitation amounts from microclimates within the catchments, and
differences in soil characteristics (Bowling and Lettenmaier, 2001). The study also
determined that the magnitude of response of culverts to a storm event was controlled
by subsurface flow rather than road surface runoff, particularly below harvested
slopes (Bowling and Lettenmaier, 2001).

Conclusions reached by Bowling and Lettenmaier (2001) were supported by a
Wigmosta and Perkins’ (2001) study on the Carnation Creek basin on Vancouver
Island, British Columbia. Again, DHSVM predicted greater response associated with
subsurface flow onto a road, rather than just road surface runoff. The simulated
runoff was within 2% of the recorded runoff with low flows under-simulated and
moderate flows were over-simulated (Wigmosta and Perkins, 2001).
3.0 RESEARCH OBJECTIVES
The primary objective of my research was to calibrate DHSVM to the Smith Creek and Austin Creek sub-basins of the Lake Whatcom watershed because I was unable to calibrate the model to the entire watershed. A secondary goal was to provide a basis for further hydrologic modeling studies within the watershed. To meet my objectives, I completed the following tasks: (1) established the GIS basin parameters for the Lake Whatcom Watershed, (2) created a meteorological data time series to input into the model, (3) calibrated and validated the model specifically to Austin Creek and Smith Creek sub-basins, and (4) determined sensitivity of the model of three main parameters: soil textures, vegetation types, and precipitation data.

4.0 METHODOLOGY
Methodologies used to accomplish the basin setup, meteorological data compilation, initial calibration, validation, and sensitivity analyses are described below.

4.1 Basin Setup
DHSVM requires six GIS data sets: digital elevation model (DEM), watershed boundary, soil texture, soil thickness, vegetation, and a flow network, to describe the hydrological processes of the model domain (Figures 5, 6, 7, and 8). Basin parameters in DHSVM were represented in GIS grids of approximately 162,666 individual 30-meter grid cells for the entire watershed. I performed data storage, manipulation, and display using ESRI’s ArcView 3.2, ArcGIS and ARC/INFO GIS software. These procedures are described in the ‘Basin Setup.doc’ on attached CD.

The final goal of modeling Lake Whatcom hydrology is to represent the watershed as one basin rather than separate subbasins (i.e., Smith Creek and Austin Creek subbasins). The reasons why this could not be done is discussed in the Calibration Methods section below. However, the focus of my work was to improve my understanding of DHSVM to provide recommendations for further research in building a one-basin model of Lake Whatcom watershed in DHSVM.
4.1.1 Digital Elevation Model (DEM)
The DEM is the basis for DHSVM and its distributed parameters because it provides the topographic controls required by DHSVM’s calculations (Storck et al., 1995). The DEM for Lake Whatcom Watershed was compiled from eight USGS 7.5-minute, 10-meter DEM files. I merged, filled, and aggregated the DEMs to a 30 by 30 meter grid using ARC/INFO software. The grid is a floating point raster with elevation data stored in each grid cell (Figure 2).

4.1.2 Sub-basin Masks and Analysis Domain
The sub-basin masks for Austin Creek and Smith Creek sub-basins provide the analysis domain for my DHSVM calculations (Figure 6). Since calibration was not possible on the entire watershed, sub-basin masks indicate to the model which pixels are included in the numerical simulations. The masks were created by first delineating the entire watershed boundary for Lake Whatcom Watershed using the WATERSHED command in ARC/INFO. The same command was then used to delineate Smith Creek and Austin Creek sub-basins separately. The WATERSHED command delineates all the pixels above a drainage point. Thus, the entire watershed boundary was selected based on the outlet of the lake, and each sub-basin was delineated at the outlet of each creek at the point where the creeks drain into the lake.

The entire watershed grid contained 162,666 (30m x 30m) grid cells, an area of 146.40 km\(^2\), which agrees with published values of the Lake Whatcom watershed area (e.g., Walker, 1995; Pitz, 2005). Stream gages maintained on Whatcom Creek by the USGS give a similar drainage area of 143.5 km\(^2\).

The delineated Smith Creek sub-basin mask contains 14,743 grid cells, an area of 13.27 km\(^2\), which is similar to 13.3 km\(^2\) reported by the USGS for a gage used in 1967. The delineated Austin Creek sub-basin contains 23,793 cells, an area of 21.41 km\(^2\), which agrees with the 20.02 km\(^2\) reported by the USGS for a gage also used in 1967.
DHSVM only simulates hydrologic processes on cells within the masks. If the entire watershed was simulated then the watershed boundary grid would be the basin mask. Any sub-basin within the Lake Whatcom watershed can be simulated with my basin setup, the user needs only to delineate which sub-basin is to be simulated and create a subbasin mask from the delineation.

4.1.3 Soil Textures
The soil textures grid was clipped from the CONUS soil data set and represents the dominant soil texture classes (Miller and White, 1998; Figure 7). This is a national soil grid with a resolution of 1,000 meters. DHSVM uses only the dominant soil texture of each grid cell. All grid cells with identical soil classifications are then assigned one set of soil-dependant hydraulic parameters through a lookup table contained in the input file (Storck, et al., 1995). A sample input file, “input.austin.initial1” containing the soil lookup table, is on attached CD.

4.1.4 Soil Thickness
Soil thickness data do not exist for the watershed, so a soil depth grid was generated using an Arc-Macro-Language (AML) process. The AML automates a progression of ARC/INFO commands. The soil thickness AML uses a simple regression equation that calculates deep soils depths on shallow slopes and in areas of high flow accumulation (Figure 8). Shallower soil depths are found on steeper slopes. This method provided acceptable results in comparison to soil depths published for the Lake Whatcom Watershed (USDA, 1984). The original soil depth file from the AML process ranged in depth from 1.2 meters to 2.5 meters. In order to improve my simulations and more accurately reflect soil conditions in the watershed, I decreased the soil depths using the Raster Calculator tool in ArcGIS. The new soil depth grid had a minimum soil depth of 0.8 meters and a maximum of 1.2 meters.
4.1.5 Vegetation Data

Vegetation data were compiled from the USGS National Land Cover Data set (Vogelmann et al., 2001). This data set is the result of a comprehensive inventory of the national vegetation using Landsat Thematic Mapper satellite imagery and field data collected in 1992 (Figure 5). The Washington State data were provided as a 30-meter grid, which was clipped to the watershed boundary. The vegetation classes in the data set were reclassified to the DHSVM classification scheme with the help of Dr. David Wallin (Huxley College, WWU).

DHSVM uses only the dominant vegetation type of each grid cell. All grid cells with identical vegetation classifications are then assigned one set of vegetation-dependent hydraulic parameters through a lookup table in the input file (Storck, et al., 1995). The vegetation parameters for each vegetation class are listed in the sample input file on the attached CD.

4.1.6 Flow Network

A watershed flow network was generated by running a series of AML processes that represent the flow network as a series of distinct reaches, modeled as cascading linear reservoirs (Figure 6). The network is based on the grids created from the Arc/INFO commands FLOWDIRECTION and FLOWACCUMULATION and is used to calculate the travel time to the basin outlet. Each reach is assigned attributes such as channel width, depth, maximum infiltration, and roughness. Output from the AML files includes the stream network grid for routing water, a map file that contains stream hydraulic properties for each segment, a network file that contains the routing scheme from one reach to the next, and the class file, that contains constant hydraulic parameters. This method has provided acceptable results in basins in Western Washington (Chennault, 2004).
4.1.7 Constant Basin Parameters
DHSVM contains several basin-wide constant parameters as specified in the input file (Table 1). These parameters do not change between pixels as do soil and vegetation parameters.

4.2 Meteorological Data
DHSVM requires a time-series of met data for input. The Northshore met station data from 2001 to 2004 were used for my calibration and validation of the model (Figure 9). The station data intervals varied from every fifteen minutes to hourly accumulations. The met data include precipitation, wind speed, humidity, air temperature, and incoming shortwave solar radiation. Since a one-hour time step was required for calculations, the data were reformatted to one-hour time steps and any missing data were estimated. Incoming longwave radiation data were estimated from measured values of shortwave radiation, air temperature, relative humidity, and calculated radiation at the top of the atmosphere after Dingman (2002) and Waichler and Wigmosta (2002).

In addition to the Northshore met time series, used for calibration, validation, soil sensitivity and vegetation sensitivity simulations, two additional met data files were created for use in the precipitation sensitivity simulations. One data file contained the recorded precipitation from the City of Bellingham’s Brannian Creek Hatchery met station and the other data file contained the recorded precipitation at the City’s Geneva precipitation gage (Figure 9). The remaining met parameters, for these two other data files, were taken from the Northshore time series. Partial data from Water District #10, Division 30 and the Sudden Valley rain gages were used for watershed-wide rainfall comparisons (Figure 9).

The Northshore parameters and Brannian Creek and Geneva rainfall data are on attached CD as text files: finalsc.0103, brannian.0104, and geneva.0102.
4.3 Streamflow Gages in Lake Whatcom Watershed

A consistent time series of recorded streamflow data are required to calibrate DHSVM. Smith Creek, Anderson Creek, and Austin Creek currently have the longest recorded time series of those creeks that are gaged within the Lake Whatcom watershed. Smith Creek and Austin Creek stream gage data were complied for water years (WY) 2002, and 2003 (a water year is from October 1\textsuperscript{st} through September 30\textsuperscript{th}) in an hourly format to match the DHSVM output. Both streams have SUTRON stage recorders. A rating curve determines the discharge of each creek. The rating curves are based on various flow measurements throughout the year taken at staff gage heights, and a best linear fit model is used to determine the discharge. Both Austin Creek and Smith Creek rating curves require square root transformations (Matthews et al., 2004). Additional stage measurements are needed to improve the rating curve for both creeks for high peak events. The lack of data for high peak events increases the uncertainty in both the calibration and validation of DHSVM to the Lake Whatcom sub-basins.

4.4 Initial Calibration and Validation

DHSVM is written in ANSI-C and requires a UNIX platform and at least a Pentium 200 Mhz processor with 128 MB of RAM in order to perform properly. The DHSVM code for my study was compiled on a Dell Precision (Horton) using FreeBSD (UNIX) platform in the Geology Department at WWU. The Dell has dual 3 GHz processors with 2 GB of RAM. Horton was accessed off campus via Secure ShellClient (SSH) via a modem dialup. On Horton, DHSVM required approximately twenty minutes of computing time to calculate a yearly water-mass balance on the 14,743 grid cells for the Smith Creek sub-basin and 23,793 grid cells for the Austin Creek sub-basin, using 1-hour time steps.
4.4.1 Initial Calibration

The objective of model calibration is to simulate streamflow that best matches observed streamflow. For this study, calibration involved altering some DHSVM parameters to match the recorded streamflow within Smith Creek and Austin Creek. Calibration requires a complete, high quality streamflow record. Other sub-basins within the Lake Whatcom watershed were not used for my calibration because they were either not gaged, did not have complete records at the time this research began, or had regulated flows. Smith Creek and Austin Creek have the most consistent streamflow records that also overlap the met data collected at the Northshore met station. Therefore, Smith Creek and Austin Creek streamflow records were selected for the calibration of DHSVM.

The initial goal of this study was to quantify all the surface water inputs to Lake Whatcom. Once the model was calibrated, the surface water input could be quantified and then the ground water input could be backed out using the lake’s mass balance equation. My initial attempts to calibrate the entire watershed with Smith and Austin Creek streamflow gages were unsuccessful. DHSVM is a rigorous model that captures heterogeneities between basins, which was demonstrated in the initial calibration simulations. When one parameter adjustment improved simulations for one sub-basin, the same parameter adjustment worsened the simulations for other sub-basin. Eventually, the decision was made to calibrate DHSVM to Smith Creek and Austin Creek as two separate basins. Further discussion on the differences between the sub-basins and the model’s numerical representation of the sub-basins is found in the calibration results and sensitivity sections.

Computer platforms are also a factor in model calibration. Typically, computers with higher speeds and greater memory capacity can provide better and faster model simulations. DHSVM was originally compiled on Merlin, a SUN E40 computer in the Computer Science Department. Merlin required 8 hours of computation time to simulate hourly time steps for one year for one sub-basin. Approximately 59 simulations (472 hours) were performed on Merlin and analyzed. However, a new version of DHSVM was compiled on Horton in January 2005. With
Horton, computation of one year of hourly streamflow requires 20 minutes for one basin and approximately 38 simulations were calculated on Horton fairly quickly (12.7 hours).

I began the calibration process by establishing the initial water conditions of the watershed. The first simulation (the initialization simulation) was performed with the entire meteorological dataset (January 1, 2001 to September 30, 2003). The output from this initialization simulation contained files of the initialized conditions of the watershed. The initialized conditions represent the spatial distribution of water content in the soils, vegetation and the stream channels. These initialized conditions of the watershed were used as input files for the calibration simulations because they represent more realistic initial properties of the watershed. If the model is not initialized, the calibration simulations begin with a completely dry watershed which is an unrealistic condition. All my simulations used the same initial condition file to avoid a bias in model output.

The calibration process was divided into two parts for each sub-basin: annual calibration (adjustment of the precipitation lapse rate and soil depth); and monthly calibration (adjustment of soil parameters to best capture soil water distribution throughout the year). I determined the best calibration simulation using quantitative methods (calculation of simulation error) and graphical methods (to compare peaks and base flow between the simulated flow and the recorded flow). An error analysis was performed on every simulation. The error of the simulation is the percent difference between the sum of the yearly simulation and the sum of the recorded flow for the same period. For each calibration simulation, I altered a specific parameter in a set amount in an attempt reduce the error. The closer the error is to 0%, the better the model is capturing the watershed conditions. DHSVM is expected to match recorded observations within +/- 5% (Pascal Storck, personal communication, 2004). The simulated streamflow is also plotted against the recorded flow to see how well the model output captures the timing of the peak storm events (i.e., how well the rise and fall of the hydrograph limbs match the recorded flow) and as well as the volume of the base flow throughout the year.
After the best soil depth and precipitation lapse rate values were selected during annual calibration simulations, I performed monthly calibration simulations to fine tune the selected calibration parameters. Other than the precipitation lapse rate, lateral hydraulic conductivity has the greatest affect on the streamflow (P. Storck, personal communication, 2004). Hydraulic conductivity is a soil parameter that controls the rate of water movement through the soil and is limited by the size of the soil pathways (Dingman, 2002). In DHSVM, the hydraulic conductivity of soils is separated into two components: lateral hydraulic conductivity and vertical conductivity. Lateral hydraulic conductivity is the rate of movement of water across a saturated pixel and decreases exponentially with depth (Wigmosta et al., 2002). I altered the lateral hydraulic conductivity value multiple times, until the monthly volume of simulated streamflow best matched the monthly recorded volume of streamflow. No other soil parameters, such as infiltration rate, exponential decrease, or vertical conductivity were found to affect streamflow characteristics. Although in a physical sense, altering these parameters is expected to alter streamflow characteristics, in model sense, these parameters had very little changes in flow even with order of magnitude changes in values. DHSVM does not capture all the physical conditions within a watershed, so model performance is dependent upon the forcing of certain parameters for the best calibration results.

For each monthly simulation, the error was calculated in the same manner as for the yearly calibration simulations. The simulation error during the monthly calibration process is expected to decrease over the final annual calibration parameter selection. The best parameter selection is based on a low simulation error with excellent capture of storm event timing, peaks, and base flow.

I calibrated DHSVM to Smith Creek and Austin Creek sub-basins for WY 2002. This timeframe was selected for this study because of the consistency of recorded streamflow and concurrent overlap between the meteorologic data and discharge. The calibration timeframe incorporated several large winter storm events and low summer flow. Highest recorded instantaneous peak flow for Austin Creek occurred on December 14, 2001 of 615.16 cfs (Figure 10). Smith Creek’s highest
recorded instantaneous peak flow occurred on the same day with 180.37 cfs (Figure 10). Other storm events were recorded on December 16, 2001, January 25, 2002, and February 22, 2002. Low flow for Austin Creek was recorded on September 13, 2002 of 0.04 cfs and low flow for Smith Creek occurred on September 29, 2002 of 0.18 cfs. Average recorded yearly flow is 24.24 cfs for Austin Creek and 13.72 cfs for Smith Creek.

4.4.2 Validation
The validation process is the final required step to ensure that DHSVM simulates the hydrology of Smith Creek and Austin Creek sub-basins accurately. To validate a model, the model must show that simulation output can reproduce streamflow outside of the calibration timeframe. I calibrated the model to one complete water year of data from WY 2002 and validated the model to WY 2003. The model is considered validated if the results from the validation period are similar to the calibration period.

4.5 Model Sensitivity Analyses
The purpose of model sensitivity analyses was to determine which global parameters have the greatest impact on simulation output. Since I was unable to calibrate the model to the entire watershed, the sensitivity analyses also focused on improving the parameterization of the model to the sub-basins. Some of the sensitivity analyses results, however, provided insight for further work in developing a one-model system for Lake Whatcom watershed.

The soil sensitivity simulations required the soil grids to be reclassified. Since the soils types in Lake Whatcom watershed are primarily loams (Figure 7), all the pixels within the entire watershed classified as ‘loam’ were reclassified to soil end members: ‘bedrock’ for the bedrock simulation, and ‘sand’ for the sand simulation. The Spatial Analyst function within ArcGIS was used to reclassify the soil grid to the sand grid for the sand sensitivity simulations and to the bedrock grid for the bedrock sensitivity simulation. The output from each sensitivity simulation was compared to my final calibration simulation (the one with the lowest error) in each sub-basin. In
addition to the simulated streamflow, the mass balance error value from the mass balance output file was used to determine how well the model was performing with the new soil texture grids. The mass balance error is simply the change in storage plus output (i.e., runoff, and evapotranspiration) minus the input (i.e., precipitation). Every simulation has a mass balance error for each time step. The time step mass balance error can be summed for a total simulation mass balance error. The source code for the mass balance equation is found on the attached CD in file ‘FinalMassBalance.c’. A low mass balance error indicates a higher level of model performance.

The process for creating grids for the vegetation sensitivity simulations was similar to the soil sensitivity process in which the grid classifications were modified using the Spatial Analyst function within ArcGIS. To create the separate ‘urban’ and ‘bare’ grids, all the pixels classified as ‘coastal conifer’, ‘evergreen’, ‘deciduous’, ‘mixed forest’, ‘woodland’, or ‘wooded grassland’ were reclassified to urban for the urban simulation, or to bare for the bare simulation. The differences between urban and bare classification are slight. Urban allows for a vegetation understory. Bare has neither an overstory nor an understory and is essentially a soil surface. DHSVM also accounts for impervious fraction but requires a surface routing network as found in a stormwater collection system (Lettenmaier, 2004). The impervious fraction was not used for my sensitivity simulations.

The precipitation sensitivity analyses began with the calculation of precipitation lapse rate in the Austin Creek sub-basin using two local precipitation gages: Sudden Valley airport gage and the Division 30 gage. The purpose for calculating the local precipitation lapse rate was to establish if the DHSVM lapse rate for the Austin Creek sub-basin was reasonable. The precipitation analysis also entailed adding more precipitation sites, and altering the rainfall distribution schemes across the watershed. To create another precipitation site, all the precipitation data from the met station at Brannian Hatchery were added to the met data time series from the Northshore met station, essentially creating a mock station containing the Brannian Hatchery precipitation and the remaining met parameters from the
Northshore met station. The location of the mock Brannian Hatchery met station is at the south end of the lake near the mouth of Brannian Creek (Figure 9). Meteorologic data from the actual Brannian Hatchery met station were not used since the station is in a sheltered position and may not accurately capture physical weather conditions. Another mock met station was created at the Geneva rain gage (Figure 9). The same process in creating the mock Brannian Creek met station was used in creating the mock Geneva met station. The mock Geneva met station time-series contained the rainfall recorded at the Geneva rain gage and the remaining met parameters values recorded at the Northshore met station. DHSVM allows up to three met stations for meteorologic forcing.

One simulation with two precipitation gages was performed for both Austin Creek and Smith Creek. Only the Northshore met series and the Brannian met series were used in these simulations.

In addition to allowing up to three precipitation gages, DHSVM also has three precipitation interpolation schemes: nearest neighbor (NEAREST), inverse distance (INVDIST), and variable cressman (VARCRESS). These interpolation schemes determine how the model will distribute rainfall across a basin. I used the NEAREST interpolation scheme for all my calibration and validation simulations. This interpolation simply gives the closest (nearest neighbor) met station the greatest weight in distributing rainfall. The NEAREST interpolation requires at least one met station. The other interpolation schemes require two or more met stations for their algorithms to work. The INVDIST scheme calculates weighted average values from two or more stations based on the inverse of the distance from each station. The VARCRESS scheme is similar to the INVDIST scheme although the VARCRESS uses the distance from the stations as a radius.

I examined DHSVM’s sensitivity to the interpolation schemes using multiple met time-series. One simulation was performed for Austin Creek using the Brannian met data and the Northshore met data with the INVDIST interpolation scheme. Another simulation was performed with the two met stations (Brannian and
Northshore) and the VARCRESS interpolation scheme for Austin Creek. I performed the same simulations on Smith Creek with the Northshore and Brannian met data.

The third mock met station, created with the Geneva precipitation data, was used for a precipitation interpolation sensitivity analysis on Austin Creek sub-basin only. The third precipitation gage was a control site to determine if multiple precipitation sites allowed for decreasing the Austin Creek precipitation lapse rate to match the Smith Creek precipitation lapse rate.

4.6 Modeling Assumptions
When using models to simulate physical conditions, certain assumptions are inherent in the modeling process. For this study, I am assuming that the:

- recorded streamflow data adequately capture the flow within the stream,
- recorded climate values adequately capture the climate conditions within the watershed,
- input file parameters, except for those used in calibration, provide an adequate representation of Smith Creek and Austin Creek sub-basins.
5.0 RESULTS & DISCUSSION

The results of my calibration, validation and sensitivity analyses of Austin Creek and Smith Creek sub-basins in the Lake Whatcom watershed are presented and discussed below.

5.1 Basin Setup

I produced formatted grids of the watershed elevation, two sub-basin masks, soil depths, soil textures, vegetation classification, and a stream network for routing water through channels across the watershed. Because these grids are separate and distinct input layers, each grid can be improved with updated information with the expected result of improved model output. In addition, the basin setup is complete enough to be used as a baseline for additional numerical modeling studies of the hydrology within the Lake Whatcom watershed.

5.2 Meteorological Data

I assembled a complete two and a half year meteorologic data set for DHSVM using the Northshore met station as the baseline data input. As more weather stations are installed and continue to collect data, these data sets can be used to further enhance the meteorologic data (e.g., the mock Brannian and Geneva precipitation sites). DHSVM is capable of handling multiple weather stations in its simulations and larger data sets are expected to improve the physical representation of the watershed climate.

5.3 Calibration

Consistent streamflow records of Austin Creek and Smith Creek sub-basins with overlapping meteorologic data allowed me to calibrate the model for WY 2002. Calibration involved twenty-one numerical simulations; 10 calibration simulations were performed and analyzed for Austin Creek (Table 2), and 11 simulations were
performed and analyzed for Smith Creek (Table 3). The results from the annual calibration and monthly calibration simulations are presented below.

### 5.3.1 Annual Calibration

Selection of best-fit values of DHSVM calibration parameters of modeled sub-basins (Table 4) was dependent on the values published in literature, word of mouth, and previous DHSVM modeling experience. My selection of parameters to use in calibration were based on the recommendations of Pascal Storck (personal communication, 2004), an expert with the DHSVM source code; and my review and analysis of systematic simulations. As such, the calibration procedure involved the alteration of the default values of precipitation lapse rate, soil depth, and lateral hydraulic conductivity for both sub-basins. As mentioned, the model is sensitive to precipitation lapse rate, thus original input precipitation lapse rate for the Smith Creek and Austin Creek sub-basins was set at the default value of 0.0012 m/m (P. Storck, personal communication 2004), the constant rate of increasing rainfall upslope.

The initial simulations with the default model parameters provide a baseline from which to begin parameter modification for calibration (Figures 11 and 12). The initial simulations for Austin Creek and Smith Creek immediately indicated the differences between the two sub-basins - Austin Creek streamflow is greatly under-simulated (less simulated flow than recorded flow) and Smith Creek streamflow is greatly over-simulated (greater simulated flow than recorded flow). The Austin Creek default simulation under-simulates the recorded flow by 17% (i.e., the total flow is 17% less than the recorded flow total), and the Smith Creek simulation over-simulates the recorded flow by 35% (i.e., simulated flow exceeds the recorded flow by 35%). This percent difference between the sum (or average) of recorded flow and the sum (or average) of simulated flow is also regarded as the model error.

I began the annual calibration process by altering the precipitation lapse rate parameter within the DHSVM input file. DHSVM distributes the rainfall upslope at a constant rate, using the nearest climate station as the baseline. The default precipitation lapse rate of 0.0012 m/m was used for the initialization simulation and
first calibration simulation for both the Smith Creek and Austin Creek sub-basins (Table 4). I altered the precipitation lapse rate parameter during each calibration simulation to find the closest match between the simulated and recorded annual flow both quantitatively (error analysis) and qualitatively (graphical methods).

While calibrating the model, I also examined different soil depths. The original soil depth file was created with the AML process where steeper slopes contain less soil depth (see section 4.1.4). Since a majority of the slopes in the Lake Whatcom watershed are steep (greater than 25%), not much soil is expected to develop and retain water within the watershed. Thinner soils better represent this watershed condition and provided better streamflow simulations for both sub-basins.

5.3.1.1 Austin Creek Annual Calibration Results
A precipitation lapse rate of 0.0020m/m produced the lowest error between the simulated and recorded streamflow for Austin Creek (i.e., 0.06% error). Multiple simulations were modeled to determine the best match between the recorded and simulation flow within Austin Creek. For each simulation, the lapse rate was increased from 0.0012 m/m until the simulated base flow, regression curve of the hydrographs, and the peak heights most closely match those recorded at the Austin Creek gage for WY 2002.

The next step in the calibration procedure was the alteration of soil depths to further capture the physical properties of the Lake Whatcom watershed. Due to the presence of bedrock and steep slopes within the watershed, soil depths are surmised to be fairly shallow in the hilly regions of the watershed and deeper in the valleys. The original soil depths calculated from the regression AML for the Lake Whatcom watershed ranged in depths from 1.2 meters to 2.5 meters. I created a new soil depth grid having soil depths ranging from 0.8 meters to 2.1 meters (Figure 8). This soil depth improved the simulated base flow and recession curve, especially during the summer months (Figures 13 and 14). The peak of storm events increased because the thinner soils saturated faster, allowing faster delivery of water to the stream channel. Thinner soils also produced a more rapidly decaying recession curve as soil water residence time decreased.
Another benefit of the thinner soils was improved model performance in the amount of time the model requires to achieve current soil water conditions (Figure 15). Even though DHSVM was initialized with the initialization input, the first weeks of the simulation are a warm-up period where the simulation brings the soil conditions in line with the meteorologic parameters.

A cumulative depth plot also indicates how well the model is capturing the hydrologic conditions of Austin Creek (Figure 16). I determined the flow depth displayed in Figure 16 by dividing the volume of discharge by the basin area. Streamflow should be less than precipitation to account for losses to evapotranspiration and storage. The simulated flows should mimic the recorded flow as closely as possible. The final annual calibration with the thinner soil and a lapse rate of 0.0020 m/m has a slight improvement over the deeper soils in Figure 13. My results (Figures 13 through 16) indicate that DHSVM is capturing the timing of peak events, but further calibration was required to improve the volume of peak events in Austin Creek.

5.3.1.2 Smith Creek Annual Calibration Results
The smallest error between simulated streamflow and recorded flow in Smith Creek was produced using a lapse rate of 0.0004 m/m (-3% error) and the shallower soil depth grid. The simulation with a lapse rate of 0.0005 m/m also provided an excellent prediction of Smith Creek flow with a slightly better error of 2% (Figures 17 and 18). Output from both simulations adequately capture the timing and base flow of the recorded flow in Figure 17. However, the cumulative depth plot with the simulation of 0.0004 m/m precipitation lapse rate corresponds better to the cumulative recorded flow depth in Figure 19. The simulated streamflow captures not only the timing of peak events but the volume of some events as well (e.g., December 14 and 16th, and February 21st storm events).
5.3.2 Monthly Calibration Results and Streamflow

For the monthly calibration procedure, I altered the lateral hydraulic conductivity to best capture physical hydrologic conditions within the basins, while not affecting the overall annual agreement outlined above. Lateral hydraulic conductivity controls the rate of movement of water through a pixel and is considered a primary calibration parameter in DHSVM (Storck et al., 1995 and Lettenmaier, 2004). This hydraulic conductivity of water decays exponentially with depth and is a non-linear function of the depth to the saturated zone (Lettenmaier, 2004). Therefore, soil water storage in DHSVM is highly sensitive to the lateral hydraulic conductivity value, establishing its importance in the calibration procedure (Storck, et al., 1995; Storck, et al., 1998).

The simulation output was compared to the recorded output by month to determine which values of lateral hydraulic conductivity best capture water conditions within the sub-basins during the calibration timeframe. The entire year was also plotted, and a comparison of descriptive statistics with residuals completed the analysis for each sub-basin.

5.3.2.1 Monthly Calibration Results of Austin Creek

The default value of soil lateral hydraulic conductivity is 0.01 m/s. I determined that 0.02 m/s to be the best value for lateral hydraulic conductivity for Austin Creek sub-basin with a simulation error of 1%. The streamflow was converted to depth over the watershed, again to visualize values between months (Figure 20). A higher value of lateral hydraulic conductivity decreased soil storage because water migrates through the soils at a higher rate. Thus the higher value decreased the base flow and increased the peaks of storm events.

With the determination of best match of lateral hydraulic conductivity by month, the hourly flow for the entire year was again plotted (Figure 21) for Austin Creek. October contains the highest difference between simulated and observed values. This difference is expected and is due to the initial soil water conditions of the watershed as recognized by DHSVM. Although the watershed is initialized, the model still needs to set up the water conditions based on the current meteorologic
data set. This ‘warm-up’ period is evident in other modeling studies (Chennault, 2004; Storck et al., 1998).

5.3.2.2 Monthly Calibration Results of Smith Creek

I determined that the best value for lateral hydraulic conductivity in Smith Creek was 0.01 m/s (Figure 22). Smith Creek has steeper terrain, therefore less soil depth than Austin Creek, requiring a smaller lateral hydraulic conductivity to attenuate water movement through the soil (Figure 23). Less soil required a slightly slower rate of water movement to the stream channel in order to better match the recorded flows.

Smith Creek required more analysis than Austin Creek to determine which lateral hydraulic conductivity values provided the best representation of the recorded flow. The breakdown by month of recorded and simulated depths did not provide a ‘best’ value of lateral hydraulic conductivity (Figure 24). The value of 0.03 m/s better fit the recorded flow for the months of October, December, January, February, and March (Figure 24). The value of 0.01 m/s resulted in a better fit for the remaining months of WY 2002 (Figure 24). However, when I reviewed the hydrograph plots of WY 2002 and the summer of 2002, I determined that the lateral hydraulic conductivity value of 0.01 m/s represented the recorded flow better than the value of 0.03 m/s (Figures 25 and 26). The lateral hydraulic conductivity value of 0.01 m/s captured the winter storm peaks better, as well as more of the summer base flow volumes. A higher value of lateral hydraulic conductivity is expected to increase the movement of water through soils creating higher peaks, a faster decaying recession curve, and less storage of water in the soils. However, Smith Creek simulated streamflow showed nearly the opposite effect, where the higher value of lateral hydraulic conductivity decreased storm peaks, and showed a slightly faster decay of the recession curves (Figure 25). On the other hand, the storage did not increase as shown in the summer months (Figure 26). I suspect that the soils in Smith Creek may not become saturated as often as Austin Creek’s soils due to the steep slopes and thin soils depths which can increase the speed of gravity draining of water from the soils. If the soils are unsaturated, the water movement through the soils would slow, thus decreasing the peaks and increasing the decay of the recession.
curve, as shown in Figure 25. With the lower lateral hydraulic conductivity value, the soils appear to saturate and develop better storm peaks with faster decaying recession curves while still storing enough water to mimic summer base flows (Figure 25).

As with Austin Creek simulation, October flow is under-simulated in Smith Creek (Figures 24 and 25). In both sub-basins, the model under-simulates the January 25, 2002 peak event and over-simulates the March 11 through 14 events (Figures 24 and 25). Since the model is consistent in the amount of difference between the recorded and simulated streamflow values for both sub-basins, this is likely either an artifact of the meteorologic data set, or incorrect extrapolation of recorded discharge from the rating curve developed by the Institute for Watershed Studies. The stream stage height has not been calibrated during storm events, and the linear rating curve developed by the Institute for Watershed Studies may not accurately reflect actual high flow conditions within the streams. In addition, the precipitation is highly variable throughout the watershed (as discussed in the precipitation sensitivity section). Both factors could produce error in the model simulation. Until the stage height of storm events are calibrated and more precipitation data are available, I must continue to assume that the recorded weather data and flow values that I use for this modeling study are adequate.

During the calibration process, I discovered that DHSVM cannot simulate the recorded flow of Smith Creek and Austin Creek using the same input file, because Smith Creek and Austin Creek sub-basins require different precipitation lapse rates and different lateral hydraulic conductivity values. As such, each sub-basin must be simulated with separate model input files. This reveals why earlier attempts of calibration of the entire Lake Whatcom watershed were not possible, and the focus of my study became the calibration of the two sub-basins.

5.3.3 Descriptive Statistical Comparison of Calibration Simulations and Recorded Flow

Calibration results can also be analyzed quantitatively to determine if the qualitative results are defensible. I used descriptive statistics to describe each data set while providing a method for determining the differences and similarities between the
recorded and simulated sets. The results of the descriptive statistics for the best calibration simulation and recorded flows for Smith Creek and Austin Creek sub-basins are presented in Table 5.

5.3.3.1 Descriptive Statistic of Calibration Simulations and Recorded Flow in Austin Creek

The mean, which provides an average value of the data set, is an excellent measure of comparison between recorded and simulated flow (ASCE, 1994). For Austin Creek, the mean is similar between the recorded (24.24 cfs) and simulated (24.44 cfs) streamflows. The median, the central number in a ranked series, is lower than the mean, but is similar as well. The mode is the most common value in the data sets and I suggest that the mode can be related to the base flow of the creeks. The base flow maintains creek flow between storm events and therefore should be the most commonly recorded flow value in between storm events (Dingman, 2002). The mode is under-estimated in the simulated flow for Austin Creek, indicating the model tends to under-estimate the base flow in the Austin Creek.

The standard error, standard deviation, and variance are all values that show how the discharge values deviate from the mean and the frequency of these deviations. All these values are quite similar between the recorded and simulated flows (Table 5). The sample variance for Austin Creek recorded and simulated flows is high (over 2,000 cfs), indicating a large spread of values about the mean. This is quite noticeable in the chart of hourly flow data (Figure 10). Austin Creek typically flows below 50 cfs throughout the year but has peaks over 600 cfs for large storm events, so the spread between flow values is expected to be large.

The skewness value measures a lack of symmetry in a data set relative to a normally distributed data set. A value of zero indicates that the data set is normally distributed with equal distribution on each side of the mean. Negative values indicate that the data are skewed left, and positive values denote the data are skewed right relative to a normal distribution. Austin Creek’s histogram of streamflow data has the peak to the left of the center and heavy tail to the right (Figure 27). Values are ranked from right to left, so the positive skewness values indicate a data set with more values
below mean, as shown with the low median values for Austin Creek (Figure 27). Kurtosis is the amount of peakness relative to a normal distribution. With a positive kurtosis, the values have a high peak in comparison to a negative value for kurtosis when the data set has a flat curve. Austin Creek’s recorded data have the higher value of kurtosis, although the simulated values are fairly large too (Table 5). The sum in Table 5 is the sum of the values in the data set. The sum is higher for simulated flows, as the model slightly over-estimates the flow in Austin Creek. The count is the number of data values which are equal for the recorded and simulated flows, because the number of time steps is equal for both recorded and simulated flows.

5.3.3.2 Descriptive Statistics for Calibration Simulations and Recorded Flow in Smith Creek
As in Austin Creek, the mean, the measure of the average flow, is very close in Smith Creek for the recorded flow (13.72 cfs) and the simulated flow (13.34 cfs; Table 5). The median is lower than the mean with the simulated median slightly lower than the recorded median (Table 5). The modes for recorded and simulated flow sets for Smith Creek are nearly the same, indicating that the model is adequately capturing base flow in Smith Creek. The value of sample variance is much smaller for Smith Creek than Austin Creek, highlighting the difference in flows between the two creeks (Table 5). Smith Creek recorded flows tend to be at 20 cfs or below during the year with peaks only as high as 180 cfs (Figure 10). The spread of values between the base flow and the peak flow is not as high for Smith Creek as for Austin Creek and this difference is reflected in the statistical comparison. The values for skewness and kurtosis for Smith Creek are similar to Austin Creek with the skewness to the right of the mean, and very peaked, indicating that lower flows are more common than high flows in Smith Creek, as shown in the histogram (Figure 28).

Review of the statistical values for the simulated flows in Smith Creek and Austin Creek support my calibration parameter selections. The modeled flows quantitatively represent the recorded flows in each sub-basin, particularly with the close values of mean and modes for both the recorded and simulated flows. However,
the mean provides the most accurate estimate of the model’s ability to predict discharge (ASCE, 1994). The statistics also highlight the different streamflow characteristics of each stream with the standard deviation, sample variance, skewness, and kurtosis. These values denote the difference between the volumes of flow between the two creeks, as well as the differences between the base low versus the peaks for storm events within each creek.

5.3.3.3 Descriptive Statistics for Residuals for Smith Creek and Austin Creek

Residuals are the difference between the recorded values and simulated values, and a residual analysis provides another method for determining the model performance. Residuals of hydrologic models are also referred to as an error time series (Pebesma et al., 2004). Just as I calculated the error as the difference between annual and monthly flows, the error for each time step can be evaluated as residuals. The results of the residual calculations for Austin Creek and Smith Creek are plotted in Figures 29 and 30 and the descriptive statistics are in Tables 6 and 7. The residual plot contains the residuals of the best calibration (lowest error) simulations for WY 2002.

For a perfect match between the simulated flows and the recorded flows, the plot of residuals would be a straight horizontal line at zero. However, hydrologic models can not yet predict streamflow as recorded by stream gages and a residual plot tends to look similar to Figures 29 and 30, with the residuals plotting on each side of zero on the y-axis. These residual plots provide tool for measuring model performance (Pebesma et al., 2004). All residual values greater than zero show the model under-simulating the recorded flow, and residual values less than zero indicate over-simulation of recorded flow. The first observation is that the Austin Creek data set goes from one extreme of under-simulating to over-simulating on the y-axis, even more so than the Smith Creek residual values (Figures 29 and 30). The Austin Creek residuals fluctuate more than the Smith Creek residuals because of the higher flows within Austin Creek and the greater differences between the base flow and the peak of storm events. Another observation is that with the large storm events, the model tends to begin by under-simulating the event and then slightly over-simulating the event as shown in the rapid fluctuation between positive values to negative values as
shown in the December, January and February storm events. This fluctuation demonstrates the model predicting peak discharge slightly too late in both Smith Creek and Austin Creek. The residual plots also illustrate that the model is simulating the discharges more closely for Smith Creek than in Austin Creek during winter months, but tends to under-simulate the values for Smith Creek more in June and July.

Just as the differences between the simulated flow and recorded flow for Austin Creek and Smith Creek can be described by descriptive statistics, so can the residuals for each creek (Tables 6 and 7). Both residual means were close to zero indicating the overall low difference between the recorded flow and simulated flows for both sub-basins. Austin Creek’s residual mean was negative (-0.19), showing that overall, the model slightly over-simulated recorded flow, hence the positive error in the calibration simulation. Smith Creek’s residual mean was positive (0.39), hence the model tends to under-simulate the recorded flow, corresponding to the negative error in the calibration simulation. The modes of both data sets were positive, indicating that for both creeks, the most common error of the model was to under-simulate the creek flow. The standard deviations and standard errors were both low with the Smith residuals having the more desired values reinforcing the observation that Smith residuals have less of a spread around zero than Austin residuals. This lower spread of residuals is not necessarily better model performance for Smith Creek than Austin Creek. The lower spread of residuals is likely due to the low flows within Smith Creek that reduce the magnitude of the time series error while not improving model performance overall.

Model performance can be improved by decreasing the residual error during the storm events with better capture of peak values and the timing of the storm events. However, I suggest that the residual analysis supports my selection of calibration parameters, with a mean residual for both data sets near 0.
5.4 Validation of Model to Austin Creek and Smith Creek Sub-basins

Model validation is the prediction of streamflow outside of the calibration timeframe to determine if the calibration parameters produce consistent results. The model was validated using meteorologic and streamflow data for WY 2003. Although validation simulations were performed for each sub-basin with my selected calibration parameters, large gaps in the recorded streamflow precluded the full validation of these sub-basins at this time. The validation simulation results plotted with the recorded streamflow illustrate the periods that lack recorded data (Figures 31 and 32). The simulation error for Austin Creek during the overlapping period of record (February 4 through September 30, 2003) is -5%. The simulation error for Smith Creek is at 3% for the overlapping timeframe (December 16, 2002 through September 30, 2003). Both errors are acceptable errors although both are higher than the calibration errors. The plots of the validation simulation results against the recorded flow show good agreement on base flow during WY 2003, but less volume for peak events, particularly in the Smith Creek basin. The model underestimates Smith Creek flow from the end of January 2003 through March 2003, and is balanced out by the over-simulation of flow through December 2002 and most of January 2003.

The amount of rainfall and volume of flow between the calibration year and validation year were very different. Rainfall totals for the Northshore climate station for WY 2002 were 1.15 m and totals for WY 2003 were 0.73 m, nearly half of the rainfall recorded in the previous year. The average flow for WY 2003 simulation for Austin Creek was 13.22 cfs with a maximum instantaneous flow of 131.75 cfs. The average flow for Smith Creek for WY 2003 simulation was 6.83 cfs with a maximum instantaneous flow of 59.12 cfs. For WY2002, Austin Creek’s average flow was 24.44 cfs and Smith Creek’s average flow was 13.32 cfs. This indicates that WY 2003 was much drier than WY 2002. In this case, the model presents reasonable results even when calibrated to a ‘wet’ year and then validated to a ‘dry’ year.
5.5 Sensitivity Analyses for Austin Creek and Smith Creek

The purpose of sensitivity simulations is to determine how much or how little the model will react to parameter change and whether these changes are expected. My sensitivity analyses focused on the main parameters of the GIS inputs (i.e., vegetation and soils) and precipitation distribution methods across the watershed (i.e., more climate station records and different interpolation methods).

Eleven sensitivity simulations were analyzed for Austin Creek and eight sensitivity simulations were analyzed for Smith Creek. The output was compared to each of the sub-basin’s calibration simulation. Comparisons were also made between the sub-basins sensitivity results highlight differences between sub-basins within the Lake Whatcom watershed and the model’s ability to capture these physical differences.

5.3.2 Soil Sensitivity Analyses

The soil sensitivity analysis is one method to determine if DHSVM is producing physically realistic results on the sub-basins. I used the two soil texture end members, bedrock and sand, to test the model’s sensitivity to soil texture. Bedrock texture typically has small storage capabilities with limited infiltration and greater volumes of surface runoff, thus increasing storm event peaks. Sand texture allows for increased infiltration that decreasing peaks from limited surface runoff, and less available storage decreasing base flow.

5.3.2.1 Soil Sensitivity Analyses for Austin Creek

The bedrock soil texture class for the Austin Creek sub-basin, reduces infiltration, thereby increasing the peaks and decreasing the base flow because bedrock greatly decreases soil storage availability (Figure 33). Total simulated flow is 62% greater than calibration flow. Because the water content was already high in the basin, the simulation began with flood conditions as evidenced by a warning message generated by DHSVM, but by the end of October, the simulated streamflow nears the calibration flow. However, with the initial flood conditions, the model does not have
the usual ‘warm up’ period, as the flood conditions quickly bring the soil water and stream levels up.

The sand simulation was different than the bedrock simulation since the sand texture produces a streamflow that was similar to the calibration simulation streamflow (where the soil texture class was predominately loam). The primary difference between the sand soil texture simulation and the calibration simulation was that the peaks are lower, and the sand simulation had an 8% decrease in the total volume of streamflow compared to the calibration simulation streamflow. Sand is expected to decrease the peaks. The simulated peaks are lower because more infiltration is occurring in the sand. I expected the model to simulate increased the base flow conditions, with greater runoff, because of the decreased soil water content (i.e., less water retained in storage). Instead, the total volume of water within the stream decreased overall, indicating that the model is not capturing the physical differences between sand and loam soil textures.

The primary reason that the model is not simulating the loam texture and sand texture differently is that the texture parameters for each soil texture are nearly the same (Table 8). In fact, the values for the exponential decrease, porosity, vertical conductivity and thermal capacity are exactly the same, and the values for pore size distribution, bubbling pressure, bulk density, and the thermal conductivity are also close in magnitude. Kabat et al. (1997) reviewed soil parameters for hydrologic models and determined that most soil parameters should be treated as calibration parameters rather than values with physical meaning. Therefore, for sand simulations to reflect realistic streamflow conditions in sandy soils, I would need to alter DHSVM soil input parameters. Currently, the input parameters provide a realistic representation of streamflow with loamy soils as opposed to sandy soils.

The different soil textures have different values of total soil water content for WY 2002 in the Austin Creek sub-basin (Table 9). These values are taken from the model’s mass balance output file. The soil water content values in the DHSVM mass balance file are given in meters per time step and are summed for the entire year to determine the total soil water content. The difference between the calibration and soil
sensitivity simulation mass balance values are presented for comparison purposes in Table 9. As expected, the mass balance error is quite low for the calibration simulation, but two orders of magnitude higher for both soil sensitivity simulations, indicating that the calibration parameters I selected do not perform adequately with a change in soil conditions.

Austin Creek sub-basin mask is comprised of 23,793 pixels sized 30 meters by 30 meters. When the total soil water content (3,996 m) of the calibration simulation is spread uniformly over the sub-basin, each pixel contains 0.17 meters of soil water. The bedrock simulation, with reduced infiltration, only contained 0.04 meters of soil water per pixel. This low amount of soil water indicates that a majority of the rainfall on the sub-basin was runoff leading to the increased streamflow (Figure 33). The sand simulation contained 0.10 meters of total soil water content nearly half the water content of the calibration simulation, as more water was lost to runoff rather than stored in the soil.

5.3.2.2 Soil Sensitivity Analyses for Smith Creek
The soil texture sensitivity results for Smith Creek sub-basin were quite different than the Austin Creek sub-basin soil texture simulations and required more analyses. The Smith Creek bedrock simulation produced high peaks and increased base flows (Figure 34). The sand simulation has nearly the same peak volumes as the calibration flow, but has greatly increased base flow, unlike the Austin Creek sand texture simulation. Both the sand and bedrock simulation results exceed the calibration simulation by over 90%.

The soil water content results within the Smith Creek pixels are similar to the Austin Creek soil water content (Table 10). The high mass balance errors for both the sand and bedrock simulations are unusual (Table 10). Multiple causes for the high error were investigated (e.g., errors in the input file, and incorrect soil grid classification). Increasing the minimum soil depth from 0.8 m to 1.7 m reduced the mass balance error (from 0.69 to 0.16) and simulated more reasonable results. By increasing the soil depth, the base flows were decreased and peaks were not as high as the previous bedrock simulation. However, increasing the soil depths is contrary to
the expected physical conditions within the Smith Creek sub-basin where soil depths are expected to be less than in Austin Creek due to the steep slopes present in the entire sub-basin (Figure 26). The channel hydraulics are expected to be different in Smith Creek as well from scouring of the streambed during debris torrents (Fox et al., 1992; Syverson, 1984).

Earlier versions of DHSVM had high errors associated with the water table jumping the height of the soil layer during saturation conditions (Wigmosta, et al., 2002). This error occurred because the soil’s saturation or un-saturation was based on the depth to the top of the water table which was the uppermost saturated soil layer. In a single time step, an entire layer could become saturated. The current version of DHSVM attempts to correct for this error with a smoothing formula for the depth to water table as a function of total soil depth, and soil water content and porosity by soil layer. My hypothesis is that the soil depth within Smith Creek was not deep enough to allow the new smoothing function to work for the bedrock and sand simulations, hence the high errors. According to on-line documentation DHSVM only simulates streamflow with soil depths greater than 1 meter and less than 10 meters (Lettenmaier, 2004). Therefore, my soil depths of less than 1 meter in the Smith Creek sub-basin increased model error during model calculations. Increasing the soil depths by over half a meter, decreased the error (Table 10), and decreased the base flow (Figure 34) which is a more realistic representation of Smith Creek sub-basin with a bedrock soil texture.

In summary, changes in the soil textures greatly increased mass balance errors not seen in the calibration simulation, confirming my parameter selection for calibration. The soil texture simulations indicate that the model contains a high level of sensitivity to the soil depths, and model performance is closely linked to the minimum values of the soil depth grid as presented in the Smith Creek soil sensitivity simulations.
5.3.2 Vegetation Sensitivity Analyses

The impact of vegetation changes within a sub-basin have long been studied with the advent of hydrologic models (e.g., Wigmosta et al. 1994; Stork et al. 1999; Berris and Harr, 1987). My sensitivity analysis is focused on two different vegetation types: ‘urban’ and ‘bare’ from the model look-up table in the input file. All the pixels classified as forest types (conifer, deciduous, forest, and shrub) were all re-classified to bare for the first simulation and urban for the second simulation. The bare simulation attempts to create a full forest harvest of tree-covered land in Smith Creek and Austin Creek sub-basins. There is no vegetation at all, just bare soil, as in a clear-cut scenario. The urban simulation attempts to capture hydrologic changes with increased urbanization in Austin Creek and Smith Creek sub-basins. The urban classification does take into account understory vegetation which is grass and low shrubs. Forest harvest is likely to occur in the Lake Whatcom watershed within the next few years (WDNR, 2003), and urbanization continues to slowly impact more area around the lake as the population of Bellingham continues to grow. Although these simulations do not take into account the all changes that occur with increased forest harvest (such as increased road networks) or increased urbanization (increased roads and impervious surfaces), these simulations do provide an insight into possible hydrologic changes and model performance by analyzing the change of the vegetation classifications within the model input file.

5.3.3.1 Vegetation Sensitivity Results for Austin Creek Sub-basin

The results of the vegetation simulation clearly show DHSVM’s lack of sensitivity to vegetation re-classification. The Austin Creek simulations present little change in flow for the bare and urban simulations (Figure 35). The vegetation simulations increased total flow by 9% for the ‘urban’ simulation, and the ‘bare’ simulation increased total streamflow by 6% over the calibration simulation. The greatest impacts on streamflow observed in the vegetation sensitivity simulations are higher peaks for winter storm events (December 14 and 16, January 27, and February 27). The winter storm peaks range from 6% to 9% higher than the calibration peaks. This result of the vegetation re-classification is expected with the increased peaks during
storm events. When vegetation is removed from a sub-basin, less water is removed or intercepted by the vegetation, which is recorded as higher peaks in the streamflow.

Corresponding decreases in evapotranspiration with less vegetation are noted in the mass balance output file (Table 11). The total evapotranspiration for the sub-basin for WY 2002 was summed from the mass balance file. Evapotranspiration for the entire watershed was 0.51 m for WY 2002. The evapotranspiration drops to 0.39 m and 0.38 m for the bare and urban simulations respectively. The evaporation is 0.01 m higher with the bare simulation because the model calculates the evaporation from saturated soils at the potential evaporation rate (Wigmosta et al., 2002). The evaporation rate decreases as the soil water content goes below saturation (Wigmosta et al., 2002). Evapotranspiration for understory is the potential evapotranspiration minus the sum of the evaporation of intercepted water and the transpiration, essentially making the rate evapotranspiration of pixels with understory less than the rate of evaporation in bare pixels (Wigmosta et al., 2002). This accounts for increase in flow for urban simulation as less water is evapotranspired than in the bare simulation.

5.3.3.2 Vegetation Sensitivity Results for Smith Creek Sub-basin

The Smith Creek simulations show slightly higher increases in flow over Austin Creek, with a 12% increase for the urban simulation, and 8% increase for the bare simulation when compared to the calibration simulation (Figure 36). The Smith Creek storm peaks also increased by 12 to 15% over the calibration peaks for the winter storm events. The higher peaks within the Smith Creek sub-basin, when compared to Austin Creek streamflow, again indicate the rapid movement of water to the stream primarily due to the steep slopes and permeability of the soils. These results are comparable to the Storck et al. (1995) study that reported a 2% average increase in streamflow peaks when 10% of the basin is harvested.

The amount of evapotranspiration also decreases in Smith Creek with the bare and urban simulations (Table 12). The calibration simulation had 0.45 m of evapotranspiration within Smith Creek watershed for WY 2002. However,
evapotranspiration was 0.33 m for the bare simulation and 0.32 m for the urban simulation.

DHSVM also demonstrated its lack of sensitivity to vegetation changes with the lack of change in the total mass balance error for the simulations. The mass balance error for the Austin Creek and the Smith Creek simulations remained constant with the calibration mass balance error. This is in stark contrast to the soil sensitivity simulations where the error greatly increases. Again, this suggests that the thin soils I created for my simulations may not allow the smoothing equation to work as mentioned above.

These results of the bare and urban simulations only present the model’s lack of sensitivity to changes in vegetation classifications as parameterized in the input file. The bare and urban classifications do not take into account all the physical changes that would occur in a watershed after forest harvest or after the spread of urbanization. After forest harvest, most watersheds have road networks left in place, which will route water differently than the natural stream system did prior to the roads being put in. Hard and Ware Creeks located in the headwaters of the Deschutes River, had increases of 27% in peaks after roads were put into the sub-basins to facilitate forest harvest (Storck et al., 1998). Thus, contributing factors to peak streamflow are both the impervious surfaces and water routing by roads and culverts.

Urbanization of a watershed is similar to expanding the road network with more roads and higher percentage of impervious surfaces, but also has the additional routing of water through storm water systems. At this time, DHSVM can not account for the routing of water through storm systems (Lettenmaier, 2004). And for this study, the impervious fraction option for vegetation was not used due to the length of time involved in making an impervious fraction grid. However, with a storm water system and impervious fraction options, the model can better capture actual urban conditions within a watershed.

5.3.2 Precipitation Sensitivity Analyses

The most sensitive meteorological parameter in the application of DHSVM is the precipitation lapse rate (Bowling and Lettenmaier, 2001; personal communication P.
Storck, 2003). The volume of streamflow simulated by the model correlates to the amount of precipitation input to the model, which is in turn, is heavily dependent on the spatial distribution of rainfall over the basins. DHSVM is sensitive to the precipitation lapse rate within Lake Whatcom watershed. The precipitation lapse rate differs dramatically between the Austin Creek and Smith Creek sub-basins, and likely varies throughout the entire Lake Whatcom watershed between sub-basins. Precipitation differences between sub-basins were found in other western Washington sub-basins, which stress the difficulties in calibrating the model for multiple basins with one precipitation lapse rate (Bowling and Lettenmaier, 2001).

The goal of the precipitation sensitivity analyses was to determine the best method for capturing temporal and spatial precipitation patterns within Lake Whatcom watershed. I attempted to find a method that would allow for one precipitation lapse rate in the model by first adding another precipitation gage, and then altering the interpolation schemes. For each simulation, I examined the changes in streamflow in Austin Creek sub-basin and in Smith Creek sub-basin, to determine the impacts of each change. I also added a third precipitation gage to Austin Creek input file to determine if a third gage would allow for a decrease in the precipitation lapse rate that approached the lapse rate in Smith Creek. If the precipitation lapse rate between the sub-basins matched, I would be closer to simulating the entire watershed with one input file.

5.3.2.1 Rainfall Gages and Precipitation Patterns in Lake Whatcom Watershed
Precipitation gages are located at many locations throughout the watershed (Figure 9). To emphasize the spatial and temporal differences of precipitation across the watershed, the total rainfall for December 2002 for three of the five gages was plotted (Figure 37). Rainfall varies greatly from station to station, although precipitation tends to increase towards the south end of the lake. The totals for the five stations for WY 2002 (calibration period for this research) also vary. A high of 1.80 ms was recorded at the Division 30 rain gage and a low of 1.07 m was recorded 10 miles away at the Geneva Intake Plant precipitation gage (Table 13). One drawback with these rainfall data is that the gages are located at or near lake level, limiting the
estimation of orographic effects within the watershed. Lake Whatcom watershed is extremely steep in places with large elevation ranges, which likely increase the orographic effect on incoming storms (Figure 2; Walker, 1995). The orographic effect can either increase the precipitation upslope or can increase the intensity of rainfall at the higher elevations (Dingman, 1994). Either one or both may be occurring in the Lake Whatcom watershed, but without data, neither effect can be confirmed.

The precipitation lapse rate was estimated using recorded data from the Sudden Valley airport (elevation: 99 m above sea level) and the Division 30 (elevation: 335 m above sea level) gages, the two closest gages to the Austin Creek sub-basin. This lapse rate of 0.0025 m/m is higher than the calibrated DHSVM lapse rate of 0.0020 m/m, suggesting that DHSVM may under-simulate precipitation in the Austin Creek sub-basin. It is possible that precipitation falling on the basin and is being routed out of the basin, or routed directly to the lake. Another possibility is that the roads within the Sudden Valley development are routing water away from the natural stream beds.

A variety of factors such as steepness of the topography, variations of wind directions and speeds, humidity, and temperature variations can also influence rainfall timing and intensity across a basin. These factors may increase the precipitation lapse rate between the Sudden Valley Airport gage and the Division 30 gage, but the general precipitation lapse rate for the entire Austin Creek sub-basin could be lower. The DHSVM precipitation lapse rate is likely capturing the average spatial distribution of rain over the Austin Creek sub-basin but not necessarily the actual precipitation as recorded by the two rain gages.

No precipitation gages currently exist within the Smith Creek sub-basin, so the accuracy of the DHSVM simulation of precipitation distribution through the Smith basin is unknown. However, the calibration of Smith Creek streamflow requires a much lower precipitation lapse in the Smith basin than in the Austin basin. This lower lapse rate indicates a rain shadow effect may be occurring in the Smith basin.
Besides varying between sub-basins, the precipitation can also vary from year to year. Precipitation over the last five years (2000 to 2004) has alternated between ‘wet’ and ‘dry’ years. The total rainfall amounts have fluctuated between 50 and 30 inches each year (Table 14). Based on these data, I calibrated DHSVM during a wet WY2002 with the Northshore met station recording a total of 1.5 m of rain. I validated the model to a dry year when the Northshore station only recorded 0.73 m of rain. As shown in the validation section, the error between the recorded flow and simulated flow slightly increased for the validation year. I adjusted DHSVM to best fit a wet year, and my parameter selection did not translate as well to a dry year.

Through the increase of concurrent recorded streamflow and meteorologic data sets, DHSVM will better capture this alternating precipitation pattern and improve the error between the wet and dry years. The best option would be to calibrate DHSVM to two years of consistent streamflow that span a wet and dry year. Then validate the model to two additional years, preferably one as a wet year and one as a dry year. Further study to determine how different weather systems distribute rainfall over the basin can augment the calibration and validation as well.

Currently, DHSVM cannot be calibrated to the entire Lake Whatcom watershed with one constant precipitation lapse rate using one climate gage precipitation data. The objective of adding more precipitation gages and altering the precipitation interpolation schemes is to determine if the model can simulate Austin Creek and Smith Creek sub-basins with one precipitation lapse rate.

5.3.2.2 Results of Multiple Precipitation Gages
To determine how DHSVM accounts for the precipitation variability, I added precipitation data from the Brannian Creek gage to the model. Brannian Creek gage, located at the south end of the watershed (Figure 9), recorded a higher rainfall of 1.66 meters for WY2002, whereas the Northshore Climate station only recorded 1.15 meters (Table 13). The rainfall monthly depths for the Northshore Climate station near Smith Creek tend to be lower than the Brannian Hatchery monthly rainfall depths for WY2002 (Figure 38). Both precipitation gages recorded a majority of the rainfall during the winter months.
I also added a third precipitation gage, the City of Bellingham’s Geneva precipitation gage. This precipitation gage is located just to the north of the Austin Creek sub-basin (Figure 9). I simulated Austin Creek’s streamflow with three precipitation gages to determine if a third precipitation time series would allow for a reduction in precipitation lapse rate. As mentioned previously, if I could drop the precipitation lapse rate, I could possibly simulate both Austin Creek and Smith Creek with one model input file.

5.3.2.2.1 Results of Austin Creek Precipitation Simulations
Austin Creek is sensitive to the increased precipitation from the addition of the Brannian Hatchery gage; resulting in an 18% increase in streamflow over the calibration simulation with the additional precipitation series. With the addition of the Brannian Hatchery gage, the simulated rainfall over the Austin Creek sub-basin increased by 0.21 meters from the calibration simulation, to 1.86 meters with the Brannian Hatchery rainfall gage (Table 15). The added rainfall increased peaks for storm events while increasing the decay of the recession curve after the December and February storm events (Figure 39). With the second precipitation gage, DHSVM over-simulates the recorded flow, except for large winter storm events, but does capture the peak timing better, evident during the summer months (Figure 40). However, the volume of water is too much for the summer months, and the recession curve decays more slowly that what was actually recorded by the stream gage. A small decrease in the Austin Creek precipitation lapse rate may slightly improve the simulation with two precipitation gages, but too much of a decrease will lower the base flows to unacceptable levels. The addition of the Brannian Hatchery precipitation appears to increase the peaks rather than the overall volume. An increase in total volume would be needed in order to drop the precipitation lapse rate closer to the precipitation lapse rate used in Smith Creek sub-basin.

The Geneva precipitation time-series was added to the Austin Creek sub-basin input file to determine if the third precipitation gage would allow for the decrease in precipitation lapse rate by increasing the overall volume of simulated streamflow.
The result with a third precipitation gage added to the model is much the same as the second gage, with an 18% increase in flow over the calibration flow (Figure 41). Again, the increase in volume is focused on the peak events, rather than increasing the total volume. In fact, the Geneva precipitation series is nearly the same as the Northshore climate station for WY 2002 (Figure 38). Since the interpolation is still NEAREST, the model is weighting the rainfall from Geneva rather than the Northshore climate station, which did not change the results of Austin Creek simulated streamflow. The third precipitation gage slightly decreased the rainfall simulated in the Austin Creek sub-basin compared to the two precipitation gage simulation (Table 15). Adding a third precipitation gage to the model input file does not decrease the precipitation lapse rate enough to improve the calibration of streamflow (Figure 42). Decreasing the precipitation lapse rate would decrease the peaks and the base flow, worsening the match between the simulated flow and the recorded flow.

5.3.2.2.2 Results of Smith Creek Precipitation Simulations

Smith Creek showed very little change in overall streamflow with an increase of 3% with the additional precipitation gage (Figure 43). The increase was primarily during the storm event peaks. The results for Smith Creek during the summer months were similar to the annual results where the additional precipitation gage did not improve the simulated streamflow over the calibration simulation, and neither the base flow nor the peaks increased (Figure 44).

5.3.2.3 Interpolation Sensitivity of DHSVM in Austin Creek and Smith Creek Sub-basins

I simulated streamflow for Austin Creek and Smith Creek with two other interpolation methods (INVDIST and VARCRESS) using the two precipitation gages (Northshore and Brannian Hatchery), and then modeled a separate simulation of Austin Creek with both interpolation schemes and the three precipitation gages (Northshore, Brannian Hatchery, and Geneva). All simulations were compared to the calibration simulation from WY 2002.
5.3.2.3.1 Interpolation Sensitivity of DHSVM in Austin Creek

The results of the INVDIST and VARCRESS simulations were not much different than the NEAREST simulations, indicating a lack of sensitivity by DHSVM to rainfall interpolation schemes for this distribution of precipitation gages (Figure 45). Like the NEAREST simulation, both the INVDIST and VARCRESS methods increased peak flow. The INVDIST interpolation scheme had a greater impact than either the NEAREST or VARCRESS, with a 21% increase in streamflow over the calibration flow. The precipitation in the Austin Creek sub-basin was increased by 0.29 meters over the calibration simulation (Table 15). Again, these impacts recorded by the Austin Creek simulations were due to the proximity of Austin Creek sub-basin to the Brannian Hatchery precipitation gage.

5.3.2.3.2 Interpolation Sensitivity of DHSVM in Smith Creek

Smith Creek results were not as noticeable in the peak flow as seen in Austin Creek (Figure 46). The INVDIST distance simulation increased the flow by 13% and the VARCRESS increased the flow by 9%. The INVDIST distance method had the largest increase in simulated precipitation as well (Table 15). Precipitation for the calibration simulation was 1.34 meters, the precipitation for the INVDIST distance was 1.50 meters and the VARCRESS simulation had 1.46 meters of rainfall in the Smith Creek sub-basin.

Overall, the INVDIST and CRESSMAN interpolation schemes do not provide an improved simulation of either Smith Creek or Austin Creek streamflow for WY2002, as both methods tend to increase the simulation error. Since the final calibration simulation error is at -3% for Smith Creek and 1% for Austin Creek, increasing the streamflow with either the INVDIST or VARCRESS methods will not improve the calibration. Other studies suggest that simple interpolation methods such as INVDIST distance do not perform as well as geostatistical methods (such as kriging) do for rainfall distribution (Phillips et al., 1992). Based on the results of the precipitation sensitivity simulations, the NEAREST interpolation provides the best physical representation of the rainfall – runoff processes within the Lake Whatcom.
watershed. At this point, adding an additional gage does not appear to improve the simulation match to the recorded flow and would likely increase the time and effort in calibrating a streamflow of a sub-basin.
6.0 CONCLUSIONS
The original goal of this study was to calibrate DHSVM to the entire Lake Whatcom watershed. Once the model was calibrated, the surface water inputs would be quantified, and the ground water inputs could have been backed out from the lake’s mass balance equation. However, my initial attempts at calibration quickly determined that simulating the entire basin with one set of input parameters in the input file was not possible. For example, when I increased the precipitation lapse rate to reduce the simulation error in for Austin Creek, the simulation error for Smith Creek would increase to 20%. Decreasing the precipitation lapse rate would decrease the Smith Creek to acceptable levels but Austin Creek’s simulation error would drop to -16%. The objective of my research then became the separate calibration of Smith Creek and Austin Creek sub-basins. Once the sub-basins were calibrated, I focused on the precipitation sensitivity analyses to determine if adding more precipitation gage sites or changing the precipitation interpolation schemes increased Austin Creek’s volume of simulated streamflow enough to justify decreasing the lapse rate to match Smith Creek’s precipitation lapse rate. The precipitation analyses quickly illustrated that the required increase in streamflow that could justify a decrease in the precipitation lapse rate would not be possible with the current precipitation gage sites.

I did not adjust the lateral hydraulic conductivity values (the other primary calibration parameter) to match between sub-basins because the input file can be easily altered to account for the differences in soil parameters. The pixels within each sub-basin can be assigned specific numbers using ArcGIS tools. These pixel numbers can correspond to the specific soil textures with the corresponding lateral conductivities in the soil look-up table in the input file. For example, instead of the soil texture of clay, which is not used in the Lake Whatcom watershed, the clay assignment of ‘12’ can be listed as a loam with all the same parameters as loam, except for the lateral hydraulic conductivity values.
I focused my research on simulating Creek similar precipitation lapse rates for Austin Creek and Smith with the goal of providing the framework for future studies modeling the entire Lake Whatcom watershed. As with my initial attempts in modeling the entire watershed, I was unsuccessful in establishing a methodology in creating a ‘one model’ of the Lake Whatcom watershed.

However, DHSVM was calibrated to Smith Creek and Austin Creek sub-basins for the WY 2002, with a calibration error of 1% and -3%, respectively. Both simulation errors are less than the recommended maximum error of +/-5%. The validation was more problematic because of gaps within the recorded streamflow data. However, for the time frame where the simulated flow and recorded flow did overlap, the simulation error was -5% for Austin Creek and 3% for Smith Creek, again within the recommended error of +/-5%.

Sensitivity analyses provide insight to parameter influences. The soil sensitivity simulations in Smith Creek have high mass balance errors, indicating that model calculations were not performing adequately. The high mass balance error is likely due to the model over-estimating the storage, or the output. The precipitation input is not likely the primary source of error because the same precipitation values, lapse rate, and interpolation scheme are used for both calibration simulations and the soil simulations. Instead, the over-estimated streamflow is likely due to the shallow soil depths that do not allow the smoothing function to work correctly.

The vegetation sensitivity simulations did not affect streamflow other than slightly increasing storm peaks. More realistic simulations that capture vegetation removal from deforestation and urbanization would require the use of a road and sewer network within the model to appropriately model decreased infiltration and channel the changes of flow.

The added precipitation gage simulations illustrated an increase in peaks in Austin Creek with the rainfall recorded at the Brannian Hatchery and the Geneva rain gages. Smith Creek did not have the increase in peaks, primarily due to its distance from Brannian Hatchery. With the addition of three precipitation gages to the input file, the overall streamflow in Austin Creek did not increase, just the volume peaks of
storm events. And when compared to recorded flow in Austin Creek, the volume of winter storm peaks was still not enough to match the recorded volume.

I also simulated streamflow for Austin Creek and Smith Creek with two other precipitation interpolation methods (INVDIST and VARCRESS) using the two precipitation gages (Northshore and Brannian Hatchery), and then modeled a separate simulation of Austin Creek with both interpolation schemes and the three precipitation gages (Northshore, Brannian Hatchery, and Geneva). All simulations were compared to the calibration simulation from WY 2002. The INVDIST interpolation method provided the greatest increase in both Austin Creek and Smith Creek, again primarily increasing peak volumes with little change in base flow.
7.0 FUTURE WORK

Future efforts should focus on modeling the individual subbasins, rather than attempting to model the entire Lake Whatcom watershed. Many heterogeneities between the individual sub-basins are captured by DHSVM which increase the difficulty in modeling the entire watershed. I provide the following recommendations to further assist modeling studies within the Lake Whatcom watershed subbasins:

- Place one or more precipitation gage in the upper reaches of the watershed to assist with an orographic estimation.
- Improve streamflow data collection on all the primary streams in the watershed by measuring high streamflow off the bridges
- Improve sub-basin calibration and validation by simulating streamflow over multiple wet and dry years as more consistent streamflow and precipitation data become available.
8.0 REFERENCES


Table 1. Hydrologic Constant Parameters for Lake Whatcom simulations

<table>
<thead>
<tr>
<th>DHSVM Constant Parameters1</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Routing</td>
<td>NETWORK</td>
</tr>
<tr>
<td>Gradient</td>
<td>TOPOGRAPHY</td>
</tr>
<tr>
<td>Interpolation2</td>
<td>NEAREST</td>
</tr>
<tr>
<td>Number of Rows</td>
<td>596</td>
</tr>
<tr>
<td>Number of Columns</td>
<td>532</td>
</tr>
<tr>
<td>Pixel Size (m)</td>
<td>30</td>
</tr>
<tr>
<td>Time step (hour)</td>
<td>1</td>
</tr>
<tr>
<td>Initial Precipitation Lapse Rate (m/m)</td>
<td>0.0012</td>
</tr>
<tr>
<td>Temperature Lapse Rate (C/m)</td>
<td>-0.0065</td>
</tr>
<tr>
<td>Rain Threshold (oC)3</td>
<td>1</td>
</tr>
<tr>
<td>Snow Threshold (oC)4</td>
<td>0</td>
</tr>
<tr>
<td>Snow Water Capacity</td>
<td>0.03</td>
</tr>
<tr>
<td>Reference Height (m)5</td>
<td>70</td>
</tr>
<tr>
<td>Rain LAI Multiplier6</td>
<td>0.0001</td>
</tr>
<tr>
<td>Snow LAI Multiplier7</td>
<td>0.005</td>
</tr>
</tbody>
</table>

1 This is a partial list of hydrologic parameters. A complete list is available on the DHSVM webpage at.
2 Method for meteorologic interpolation. Nearest simply uses the closest gage for rainfall distribution over the mask area.
3 Rain Threshold is the temperature above which all precipitation falls as rain.
4 Snow Threshold is the temperature below which all precipitation falls as snow.
5 Reference Height is the height for meteorologic observations.
6 Rain LAI Multiplier is the multiplier for LAI to determine interception capacity for rain.
7 Snow Multiplier is the multiplier for LAI to determine the interception capacity for snow.
Table 2. Austin Creek hydrologic simulations performed using DHSVM

<table>
<thead>
<tr>
<th>Date</th>
<th>Input File Name</th>
<th>Parameter</th>
<th>Old Value</th>
<th>New Value</th>
<th>Error</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/6/2005</td>
<td>input.austin.horton</td>
<td>Initialization</td>
<td>0.0012</td>
<td>0.0012</td>
<td>-17%</td>
<td>Initialization of Austin basin</td>
</tr>
<tr>
<td>2/6/2005</td>
<td>input.austin.initial1</td>
<td>First simulation</td>
<td>0.0016</td>
<td>0.0016</td>
<td>-14%</td>
<td>Simulation with DHSVM default values</td>
</tr>
<tr>
<td>2/7/2005</td>
<td>input.austin.cal1</td>
<td>Lapse Rate</td>
<td>0.0014</td>
<td>0.0014</td>
<td>-8%</td>
<td>Good baseflow, low peaks</td>
</tr>
<tr>
<td>2/7/2005</td>
<td>input.austin.cal2</td>
<td>Lapse Rate</td>
<td>0.0016</td>
<td>0.0016</td>
<td>-8%</td>
<td>Good baseflow, slightly higher peaks</td>
</tr>
<tr>
<td>2/9/2005</td>
<td>input.austin.cal3</td>
<td>Lapse Rate</td>
<td>0.0014</td>
<td>0.0014</td>
<td>-4%</td>
<td>Good baseflow, slightly higher peaks</td>
</tr>
<tr>
<td>2/9/2005</td>
<td>input.austin.cal4</td>
<td>Lapse Rate</td>
<td>0.0016</td>
<td>0.0016</td>
<td>-8%</td>
<td>Good baseflow, slightly higher peaks</td>
</tr>
<tr>
<td>2/28/2005</td>
<td>input.austin.cal5</td>
<td>Soil Depth</td>
<td>1.2 (minimum)</td>
<td>0.8 (minimum)</td>
<td>0.6%</td>
<td>Excellent baseflow and cumulative mass balance</td>
</tr>
<tr>
<td>3/4/2005</td>
<td>input.austin.monthly</td>
<td>Lateral Conductivity</td>
<td>0.01</td>
<td>0.03</td>
<td>1%</td>
<td>Summer baseflows low</td>
</tr>
<tr>
<td>3/5/2005</td>
<td>input.austin.monthly2</td>
<td>Lateral Conductivity</td>
<td>0.03</td>
<td>0.05</td>
<td>1%</td>
<td>Summer baseflows low</td>
</tr>
<tr>
<td>3/7/2005</td>
<td>input.austin.monthly3</td>
<td>Lateral Conductivity</td>
<td>0.05</td>
<td>0.02</td>
<td>1%</td>
<td>Better summer baseflows and peaks</td>
</tr>
<tr>
<td>3/11/2005</td>
<td>input.austin.sens.sand</td>
<td>Soils</td>
<td>Changed loams to sand</td>
<td>-9%</td>
<td>Similar to calibration simulation</td>
<td></td>
</tr>
<tr>
<td>3/12/2005</td>
<td>input.austin.sens.bed</td>
<td>Soils</td>
<td>Changed loams to bedrock</td>
<td>62%</td>
<td>Extreme peaks with initial flooding</td>
<td></td>
</tr>
<tr>
<td>3/13/2005</td>
<td>input.austin.sens.gauge</td>
<td>Number of gauges</td>
<td>Added a second precipitation gauge</td>
<td>18%</td>
<td>High peaks, slight drop in recession curve</td>
<td></td>
</tr>
<tr>
<td>3/16/2005</td>
<td>input.austin.sens.invdist</td>
<td>Interpolation</td>
<td>Interpolation = inv.distance</td>
<td>21%</td>
<td>Very high peaks</td>
<td></td>
</tr>
<tr>
<td>3/16/2005</td>
<td>input.austin.sens.cress</td>
<td>Interpolation</td>
<td>Interpolation = cressman</td>
<td>18%</td>
<td>Increase in peaks</td>
<td></td>
</tr>
<tr>
<td>3/16/2005</td>
<td>input.austin.sens.urban</td>
<td>Vegetation</td>
<td>Classified tree pixels to urban</td>
<td>9%</td>
<td>Increase in peaks</td>
<td></td>
</tr>
<tr>
<td>3/16/2005</td>
<td>input.austin.sens.bare</td>
<td>Vegetation</td>
<td>Classified tree pixels to bare</td>
<td>9%</td>
<td>Increase in peaks</td>
<td></td>
</tr>
<tr>
<td>8/28/2005</td>
<td>input.austin.sens.3gage</td>
<td>Number of gauges</td>
<td>Added a third precipitation gauge</td>
<td>18%</td>
<td>Increase in peaks</td>
<td></td>
</tr>
<tr>
<td>8/28/2005</td>
<td>input.austin.sens.invdist3</td>
<td>Interpolation</td>
<td>Interpolation = inv.distance</td>
<td>13%</td>
<td>Increase in peaks</td>
<td></td>
</tr>
<tr>
<td>8/28/2005</td>
<td>input.austin.sens.cress3</td>
<td>Interpolation</td>
<td>Interpolation = cressman</td>
<td>12%</td>
<td>Increase in peaks</td>
<td></td>
</tr>
</tbody>
</table>

Highlighted row is the accepted parameters for final calibration
Bold values are calibration parameter selections
Table 3. Smith Creek hydrologic simulations using DHSVM

<table>
<thead>
<tr>
<th>Date</th>
<th>input file</th>
<th>parameter</th>
<th>old value</th>
<th>new value</th>
<th>error</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/10/2005</td>
<td>input.smith.horton</td>
<td>initialization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/11/2005</td>
<td>input.smith.cat1</td>
<td>lapse rate</td>
<td>0.0014</td>
<td>0.0014</td>
<td>.001</td>
<td>35% simulation of DHSVM default parameters</td>
</tr>
<tr>
<td>2/22/2005</td>
<td>input.smith.cat2</td>
<td>soil depth</td>
<td>1.2</td>
<td>1</td>
<td>.2</td>
<td>25% baseflow, moderate peaks</td>
</tr>
<tr>
<td>3/3/2005</td>
<td>input.smith.cat3</td>
<td>soil depth</td>
<td>6.8 (minimum)</td>
<td>1.7 (minimum)</td>
<td>.1</td>
<td>24% increased baseflow for comparison only</td>
</tr>
<tr>
<td>3/4/2005</td>
<td>input.smith.cat4</td>
<td>lapse rate</td>
<td>0.001</td>
<td>0.001</td>
<td>.001</td>
<td>16% volume too high</td>
</tr>
<tr>
<td>3/5/2005</td>
<td>input.smith.cat5</td>
<td>lapse rate</td>
<td>0.0008</td>
<td>0.0003</td>
<td>.0005</td>
<td>7% volume too low</td>
</tr>
<tr>
<td>3/6/2005</td>
<td>input.smith.cat6</td>
<td>lapse rate</td>
<td>0.0005</td>
<td>0.0005</td>
<td>.0005</td>
<td>2% good baseflow</td>
</tr>
<tr>
<td>3/7/2005</td>
<td>input.smith.cat7</td>
<td>lapse rate</td>
<td>0.0005</td>
<td>0.0004</td>
<td>.0005</td>
<td>3% good baseflow and cumulative mass balance</td>
</tr>
<tr>
<td>3/12/2005</td>
<td>input.smith.monthly</td>
<td>lateral conductivity</td>
<td>0.01</td>
<td>0.03</td>
<td>.02</td>
<td>-3% summer baseflows low, some high peaks</td>
</tr>
<tr>
<td>3/13/2005</td>
<td>input.smith.monthly2</td>
<td>lateral conductivity</td>
<td>0.03</td>
<td>0.008</td>
<td>.025</td>
<td>-3% same as .01</td>
</tr>
<tr>
<td>3/14/2005</td>
<td>input.smith.val</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3% (for overlap) missing winter months, calculated error from 12/12/02 to 9/30/03</td>
</tr>
</tbody>
</table>

Highlighted row is the accepted parameters for final calibration
Bold values are calibration parameter selections
Table 4. Calibration parameters for Austin Creek and Smith Creek

<table>
<thead>
<tr>
<th>DHSVM Calibration Parameters</th>
<th>Default Values</th>
<th>Austin Creek Calibration Values</th>
<th>Smith Creek Calibration Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation Lapse Rate(^1)</td>
<td>0.0012 m/m</td>
<td>0.0020 m/m</td>
<td>0.0004 m/m</td>
</tr>
<tr>
<td>Soil Depth(^2)</td>
<td>1.2 m to 2.5 m</td>
<td>0.8 m to 2.1 m</td>
<td>0.8 m to 2.1 m</td>
</tr>
<tr>
<td>Lateral Conductivity(^1)</td>
<td>0.01 m/s</td>
<td>0.02 m/s</td>
<td>0.03 m/s</td>
</tr>
</tbody>
</table>

\(^1\) Default values are from the initial DHSVM input file used in other DHSVM applications of western Washington sub-basins

\(^2\) Original values from the creation of the soil depth grid from the AML process

Table 5. Descriptive statistics for Austin Creek and Smith Creek recorded and simulated flows for WY2002.

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>Austin Creek</th>
<th>Smith Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Recorded</td>
<td>Simulated</td>
</tr>
<tr>
<td>Mean</td>
<td>24.24</td>
<td>24.44</td>
</tr>
<tr>
<td>Median</td>
<td>11.08</td>
<td>9.23</td>
</tr>
<tr>
<td>Mode</td>
<td>0.50</td>
<td>0.11</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>46.27</td>
<td>42.77</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>2,141</td>
<td>1,829</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>47.98</td>
<td>25.76</td>
</tr>
<tr>
<td>Skewness</td>
<td>5.96</td>
<td>4.41</td>
</tr>
<tr>
<td>Range</td>
<td>615.12</td>
<td>381.73</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.04</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>615.16</td>
<td>381.83</td>
</tr>
<tr>
<td>Sum</td>
<td>212,350</td>
<td>214,055</td>
</tr>
<tr>
<td>Count</td>
<td>8,760</td>
<td>8,760</td>
</tr>
</tbody>
</table>
Table 6. Descriptive statistics for Austin Creek residuals for best-match calibrated flows for WY2002.

<table>
<thead>
<tr>
<th>Austin Residuals</th>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-0.19</td>
<td></td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Mode</td>
<td>4.01</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>20.26</td>
<td></td>
</tr>
<tr>
<td>Sample Variance</td>
<td>410.33</td>
<td></td>
</tr>
<tr>
<td>Kurtosis</td>
<td>67.49</td>
<td></td>
</tr>
<tr>
<td>Skewness</td>
<td>5.05</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>441.53</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>-132.11</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>309.41</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>-1,705.19</td>
<td></td>
</tr>
<tr>
<td>Count</td>
<td>8760</td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Descriptive statistics for Smith Creek residuals for best-match calibrated flows for WY2002.

<table>
<thead>
<tr>
<th>Smith Residuals</th>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Mode</td>
<td>5.81</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.95</td>
<td></td>
</tr>
<tr>
<td>Sample Variance</td>
<td>99.03</td>
<td></td>
</tr>
<tr>
<td>Kurtosis</td>
<td>28.23</td>
<td></td>
</tr>
<tr>
<td>Skewness</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>171.66</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>-62.11</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>109.55</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>3,433.11</td>
<td></td>
</tr>
<tr>
<td>Count</td>
<td>8760</td>
<td></td>
</tr>
</tbody>
</table>
Table 8. Input values for soil texture simulations (soil sensitivity selections highlighted in grey)

<table>
<thead>
<tr>
<th>Soil Parameter (units)</th>
<th>SAND</th>
<th>LOAMY SAND</th>
<th>LOAM</th>
<th>BEDROCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Hydraulic Conductivity (m/s)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02 (Austin Creek)</td>
<td>0.01 (Smith Creek)</td>
</tr>
<tr>
<td>Exponential Decrease</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Maximum Infiltration (m/s)</td>
<td>2.00E-04</td>
<td>6.00E-05</td>
<td>1.00E-05</td>
<td>1.00E-05</td>
</tr>
<tr>
<td>Surface Albedo (m/s)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Number of Soil Layers</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Porosity*</td>
<td>0.43</td>
<td>0.43</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>Pore Size Distribution*</td>
<td>0.24</td>
<td>0.24</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Bubbling Pressure*</td>
<td>0.07</td>
<td>0.07</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Field Capacity*</td>
<td>0.08</td>
<td>0.08</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Bulk Density* (kg/m³)</td>
<td>1492.</td>
<td>1492.</td>
<td>1520.</td>
<td>1520.</td>
</tr>
<tr>
<td>Vertical Conductivity* (m/s)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Thermal Conductivity* (J/m³°C)</td>
<td>7.114</td>
<td>6.923</td>
<td>7.114</td>
<td>6.923</td>
</tr>
<tr>
<td>Thermal Capacity* (J/kg/K)</td>
<td>1.4e6</td>
<td>1.4e6</td>
<td>1.4e6</td>
<td>1.4e6</td>
</tr>
</tbody>
</table>

*Three values are given for each soil for the three layers of soil.
### Table 9. Soil water content for Austin Creek soil simulations for WY 2002

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mass Balance Error</th>
<th>Soil Water Content (m)</th>
<th>Water Content per Pixel (m/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.003</td>
<td>3,995.64</td>
<td>0.17</td>
</tr>
<tr>
<td>Bedrock</td>
<td>0.45</td>
<td>837.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Sand</td>
<td>0.41</td>
<td>2,279.62</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### Table 10. Soil water content for Smith Creek soil simulations for WY 2002

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mass Balance Error</th>
<th>Soil Water Content (m)</th>
<th>Water Content per Pixel (m/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.001</td>
<td>3,125.07</td>
<td>0.21</td>
</tr>
<tr>
<td>Bedrock</td>
<td>0.69</td>
<td>1,112.17</td>
<td>0.08</td>
</tr>
<tr>
<td>Sand</td>
<td>0.65</td>
<td>1,842.09</td>
<td>0.12</td>
</tr>
<tr>
<td>Increased Soil Depth for Bedrock</td>
<td>0.16</td>
<td>1,477.13</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### Table 11. Total evapotranspiration from the calibration and vegetation sensitivity simulations for WY 2002 in Austin Creek sub-basin

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mass Balance Error</th>
<th>Total Evapotranspiration (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.003</td>
<td>0.51</td>
</tr>
<tr>
<td>Bare</td>
<td>0.003</td>
<td>0.39</td>
</tr>
<tr>
<td>Urban</td>
<td>0.003</td>
<td>0.38</td>
</tr>
</tbody>
</table>
Table 12. Total evapotranspiration from the calibration and vegetation sensitivity simulations for WY 2002 in Smith Creek sub-basin

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mass Balance Error</th>
<th>Total Evapotranspiration (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.001</td>
<td>0.45</td>
</tr>
<tr>
<td>Bare</td>
<td>0.003</td>
<td>0.33</td>
</tr>
<tr>
<td>Urban</td>
<td>0.003</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table 13. Rainfall totals for various gages in Lake Whatcom Watershed during Water Year 2002.

<table>
<thead>
<tr>
<th>Gage Name</th>
<th>WY 2002 Rainfall (m)</th>
<th>% Difference from Northshore Gage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northshore Climate Station (126 m)</td>
<td>1.15</td>
<td>-</td>
</tr>
<tr>
<td>Brannian Hatchery Climate Station (96 m)</td>
<td>1.66</td>
<td>44%</td>
</tr>
<tr>
<td>Geneva Rain Gage* (93 m)</td>
<td>1.07</td>
<td>-7%</td>
</tr>
<tr>
<td>Sudden Valley Airport Rain Gage (99 m)</td>
<td>1.19</td>
<td>3%</td>
</tr>
<tr>
<td>Division 30 Rain Gage (335 m)</td>
<td>1.8</td>
<td>57%</td>
</tr>
</tbody>
</table>

* Geneva gage was missing 5 days of data, so the Northshore data were substituted for the missing Geneva data.
Table 14. Direct Weighted Precipitation on Lake Whatcom in Inches (courtesy of Dr. Mitchell, 2004)

<table>
<thead>
<tr>
<th>Month</th>
<th>2000 (inches)</th>
<th>2001 (inches)</th>
<th>2002 (inches)</th>
<th>2003 (inches)</th>
<th>2004 (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>5.39</td>
<td>2.76</td>
<td>5.90</td>
<td>0.99</td>
<td>11.85</td>
</tr>
<tr>
<td>November</td>
<td>7.73</td>
<td>3.80</td>
<td>6.04</td>
<td>4.24</td>
<td>11.18</td>
</tr>
<tr>
<td>December</td>
<td>9.05</td>
<td>4.34</td>
<td>10.19</td>
<td>5.80</td>
<td>4.31</td>
</tr>
<tr>
<td>January</td>
<td>4.54</td>
<td>4.24</td>
<td>7.98</td>
<td>6.82</td>
<td>6.85</td>
</tr>
<tr>
<td>February</td>
<td>2.94</td>
<td>1.63</td>
<td>5.61</td>
<td>2.67</td>
<td>2.38</td>
</tr>
<tr>
<td>March</td>
<td>4.56</td>
<td>4.96</td>
<td>4.53</td>
<td>5.57</td>
<td>5.05</td>
</tr>
<tr>
<td>April</td>
<td>4.75</td>
<td>3.00</td>
<td>4.02</td>
<td>3.36</td>
<td>0.67</td>
</tr>
<tr>
<td>May</td>
<td>5.13</td>
<td>2.88</td>
<td>2.49</td>
<td>2.29</td>
<td>3.27</td>
</tr>
<tr>
<td>June</td>
<td>3.06</td>
<td>3.84</td>
<td>2.55</td>
<td>1.63</td>
<td>1.91</td>
</tr>
<tr>
<td>July</td>
<td>1.50</td>
<td>1.10</td>
<td>0.85</td>
<td>0.54</td>
<td>0.30</td>
</tr>
<tr>
<td>August</td>
<td>1.43</td>
<td>2.11</td>
<td>0.33</td>
<td>0.43</td>
<td>5.24</td>
</tr>
<tr>
<td>September</td>
<td>3.30</td>
<td>1.39</td>
<td>1.68</td>
<td>1.54</td>
<td>3.14</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>53.37</strong></td>
<td><strong>36.04</strong></td>
<td><strong>52.17</strong></td>
<td><strong>35.86</strong></td>
<td><strong>56.15</strong></td>
</tr>
</tbody>
</table>

Table 15. Total Simulated Precipitation in each sub-basin for the different precipitation sensitivity simulations, WY 2002

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Smith Creek Sub-basin Simulated Precipitation (m)</th>
<th>Austin Creek Sub-basin Simulated Precipitation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Calibration</td>
<td>1.34</td>
<td>1.65</td>
</tr>
<tr>
<td>Two Precipitation Gages</td>
<td>1.38</td>
<td>1.86</td>
</tr>
<tr>
<td>INVDIST</td>
<td>1.50</td>
<td>1.94</td>
</tr>
<tr>
<td>VARCRESS</td>
<td>1.46</td>
<td>1.90</td>
</tr>
<tr>
<td>Three Precipitation Gages</td>
<td>-</td>
<td>1.84</td>
</tr>
<tr>
<td>INVDIST</td>
<td>-</td>
<td>1.83</td>
</tr>
<tr>
<td>VARCRESS</td>
<td>-</td>
<td>1.80</td>
</tr>
</tbody>
</table>
Figure 1. Location of Lake Whatcom watershed, Whatcom County.
Figure 2. Topography and streams of Lake Whatcom Watershed from the USGS 10 meter DEMs.
Figure 3. Geologic map of Lake Whatcom Watershed
Figure 4. Soil groups and infiltration rates within the Lake Whatcom Watershed from the NRCS STATSGO soils database.
Figure 5. Vegetation types in the Lake Whatcom Watershed reclassified from the USGS 1992 National Land Cover data set.
Figure 6. Hillshade representation of Lake Whatcom watershed with stream network and sub-basin masks for model analysis.
Figure 7. Soil textures for Lake Whatcom Watershed from CONUS database.
Figure 8: Soil depth modified from predicted soil depth generated by an AML process.
Figure 9: Locations of meteorologic (met) stations and precipitation gages in Lake Whatcom watershed.
Figure 10: Recorded flow for Smith Creek and Austin Creek for WY2002.

Figure 11: First simulation of Austin Creek with DHSVM default parameters for WY2002.
Simulation performed with default values of all parameters (e.g. lapse rate at 0.0012m/m, default soil depths from AML, and lateral conductivity at 0.01 m/s).

Simulated flow has excessive peaks, high base flows, and slower decaying recession curves.

Figure 12: First simulation of Smith Creek with DHSVM default parameters for WY2002.

Figure 13. Austin Creek streamflow with the annual calibration simulation with a precipitation lapse rate of 0.0020m/m.
Figure 14. Austin Creek summer flow with the annual calibration simulation with a precipitation lapse rate of 0.0020m/m.

Figure 15. Beginning of WY 2002 simulation for Austin Creek with a precipitation lapse rate of 0.0020m/m showing a decrease in lag time in ‘warming’ up the model.
Figure 16. Cumulative depth plot of precipitation, streamflow and simulated streamflow in Austin Creek sub-basin for WY 2002.

Figure 17. Smith Creek streamflow with the annual calibration simulations with a precipitation lapse rate of 0.0004 and 0.0005 m/m.
Figure 18. Smith Creek summer flow with the annual calibration simulations with a precipitation lapse rate of 0.0004 and 0.0005 m/m.

Figure 19. Cumulative depth plot of precipitation, recorded flow, and simulated flow over Smith Creek sub-basin, WY 2002.
Figure 20. Comparison of basin averaged streamflow depths with different lateral conductivities by month for Austin Creek, WY 2002.

Figure 21. Final calibration simulation of Austin Creek with precipitation lapse rate of 0.0020 m/m and lateral hydraulic conductivity of 0.02 m/s for WY 2002.
Figure 22. Final calibration simulation of Smith Creek with precipitation lapse rate of 0.0004 m/m and lateral hydraulic conductivity of 0.01 m/s for WY 2002.
Figure 23. Slope percentage in the Lake Whatcom watershed using ArcGIS spatial analysis of the watershed DEM.
Figure 24. Comparison of basin averaged streamflow depths with different lateral conductivities by month for Smith Creek, WY 2002.

Figure 25. Recorded and simulated flows with different lateral hydraulic conductivity values for Smith Creek for WY 2002.
Simulated flow with a lateral hydraulic conductivity value of 0.01 m/s provided a better representation of the recorded base flow throughout the summer.

Figure 26. Recorded and simulated flows with different lateral hydraulic conductivity values for Smith Creek for summer of 2002.
Most streamflow is between 0.04 and 61.6 cfs (i.e., base flow).

Heavy tail to the right, due to high volume of storm peaks.

Figure 27. Frequency histogram of Austin Creek’s recorded and simulated streamflow data for WY 2002 indicating the lack of normality, with an exponential decay to the right.

Most streamflow is between 0.18 cfs and 18.20 cfs (i.e., base flow).

Heavy tail to the right due to high volume of storm events.

Figure 28. Frequency histogram of Smith Creek’s recorded and simulated streamflow data for WY 2002 indicating the lack of normality, with an exponential decay to the right.
Figure 29. Hourly residuals of the calibration simulation and recorded flow for Austin Creek for WY 2002.

Figure 30. Hourly residuals of the calibration simulation and recorded flow for Smith Creek for WY 2002.
Figure 31. Validation simulation of Austin Creek for WY 2003.

Figure 32. Validation simulation of Smith Creek for WY 2003.
Figure 33. Soil texture sensitivity simulations for Austin Creek sub-basin, WY 2002

Figure 34. Soil texture sensitivity simulations for Smith Creek sub-basin, WY 2002
Figure 35. Vegetation sensitivity simulations for Austin Creek sub-basin, WY2002.

Figure 36. Vegetation sensitivity simulations for Smith Creek sub-basin, WY2002.
Figure 37. Comparison of rainfall depths at Northshore Climate Station, Brannian Hatchery Climate Station, and Geneva Rain Gage in Lake Whatcom Watershed for December 2002.

Figure 38. Rainfall totals by month for WY 2002 for the Northshore climate station, Geneva rainfall gage, and the Brannian Creek Hatchery rainfall gage.
Figure 39. Calibration simulation and two precipitation gages simulation for Austin Creek, WY 2002.

Figure 40. Calibration simulation, two precipitation gage simulation and recorded flow in Austin Creek for summer months of WY2002.
Figure 41. Simulations with two and three precipitation gages and the calibration simulation for Austin Creek, WY 2002.

Figure 42. Comparison of Austin Creek simulated flow with two and three precipitation gages and the recorded flow for WY 2002.
Figure 43. Calibration simulation and two precipitation gages simulation for Smith Creek, WY 2002.

Figure 44. Calibration simulation, two precipitation gage simulation and recorded flow in Smith Creek for summer months of WY2002.
Figure 45. Interpolation scheme simulations with calibration simulation of Austin Creek, WY2002.

Figure 46. Interpolation scheme simulations with calibration simulation of Smith Creek WY2002.
Appendix A: GIS Basin Set-up Procedures and Input Data CD

Basin Set-up documentation: BasinSetup.doc

Input Files:
1. Sample input file: input.austin.initial
2. Original met data: finalsc.0103
3. Northshore met data with Brannian Hatchery rainfall: brannian.0104
4. Northshore met data with Geneva rain gage data: geneva.0102
5. Elevation grid: elev.bin
6. Mask files: austin.bin and smith.bin
7. Stream map file: kc.map
8. Stream network file: test.net
9. Stream class file: kcadjust.classfile
10. Soil texture grid: soil.bin
11. Soil depth grid: depth1.bin
12. Vegetation grid: veg.bin

DHSVM mass balance code: FinalMassBalance.c