

**MODELING THE EFFECTS OF FOREST ROAD DENSITY ON STREAMFLOW IN
THE BLUE RIDGE MOUNTAINS**

by

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ABSTRACT

Forested watersheds have often been managed for flood mitigation. Studies have shown that forests have the potential to minimize peak flows during storm events, yet the relationship between forests and flooding is inexact. Forest roads, usually found in managed systems, can potentially magnify the effects of forest harvesting on water yields. A distributed hydrologic model (DHSVM) was calibrated for a 760 ha watershed in the Blue Ridge Mountains of North Carolina. The impacts of forest road density were evaluated by running the model using uniform input parameters but changing road densities. Road densities tested were 0.5, 1.0, 3.0, 4.3, 6.0 and 12.0 km km⁻². Results indicate that increases in road density increased average streamflows at densities ≥ 4.3 km km⁻². During small storm events, discharge was impacted at densities ≥ 6.0 km km⁻² and streamflows were impacted during large rainfall events ≥ 3.0 km km⁻² road densities. These findings indicate that forest roads can influence water yields and additional management efforts may be needed that can slow the water yield from forest roads.

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CHAPTER 1. INTRODUCTION

1.1 Background

1.1.1 Forests, Roads and Floods

In 1905, Gifford Pinchot, the first Chief of the U.S. Forest Service, wrote the following statement regarding the influence of forests on floods (Pinchot, 1905):

Rain which falls over a bare slope acts differently. It is not caught by the crowns nor held by the floor, nor is its flow into the streams hindered by the timber and the fallen waste from the trees. It does not sink into the ground more than half as readily as in the forest, as experiments have shown. The result is that a great deal of water reaches the streams in a short time, which is the reason why floods occur. It is therefore true that forests tend to prevent floods.

Pinchot's interpretation of forest hydrology, conceptualized nearly three decades before Horton's groundbreaking research on infiltration and overland flow, remains prevalent in society. More than a century later, land use practices resulting in the removal of vegetation from a site are often considered culpable for large flood events (McCutcheon, 2006).

The complexity of forest hydrology and Pinchot's ensuing ideas are easily understood when the concepts are generalized (Figure 1.1). When a raindrop falls on a forested landscape it can be intercepted by the vegetative canopy or it can fall through the canopy directly to the litter soil. Water on the tree can be evaporated back to the atmosphere, utilized by the tree, fall to the ground as throughflow, or flow along stems to the ground as stemflow. Precipitation that reaches the soil surface will evaporate, infiltrate into the soil or become overland flow. Runoff will occur in one of two situations: 1) the soil is saturated and there is no more room for water in the soil profile, or 2) the rate of precipitation exceeds the infiltration capacity and thus water is falling at a faster rate than the soil infiltration capacity (Figure 1.2 and Figure 1.3). This runoff is known as *Horton Overland Flow* (Horton, 1933). A bare soil ecosystem will act similarly to a forest except the vegetation unit of the cycle can be omitted. In this system, the vegetation cannot intercept rainfall, only a small fraction evapotranspiration will occur, roots cannot take up water from the

soil, and the litter layer is not replenished. This leaves more water available to flow directly to a stream source and can create larger streamflows during rainfall events (Cornish and Vertessy, 2001).

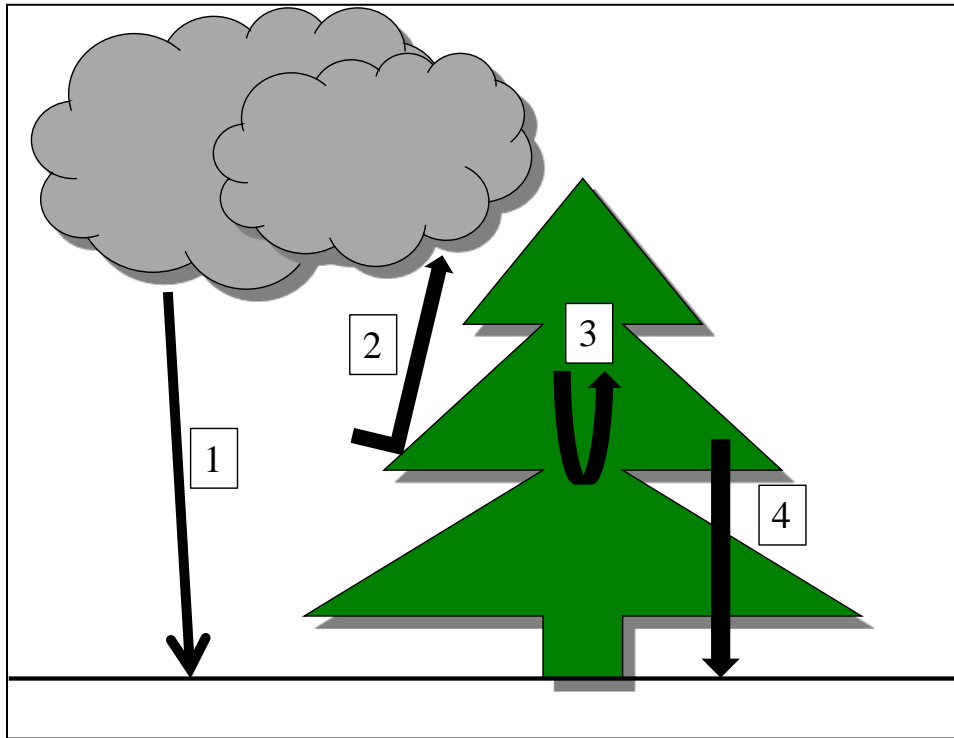


Figure 1.1 Pathways of precipitation in a forest. Precipitation can 1) fall directly on the forest floor or can interact with the vegetation. If a raindrop falls through the canopy, one of three events can occur: 2) it can be intercepted and be evaporated back to the atmosphere; 3) the water can be utilized by the tree; or 4) the water can fall back to the floor as throughfall.

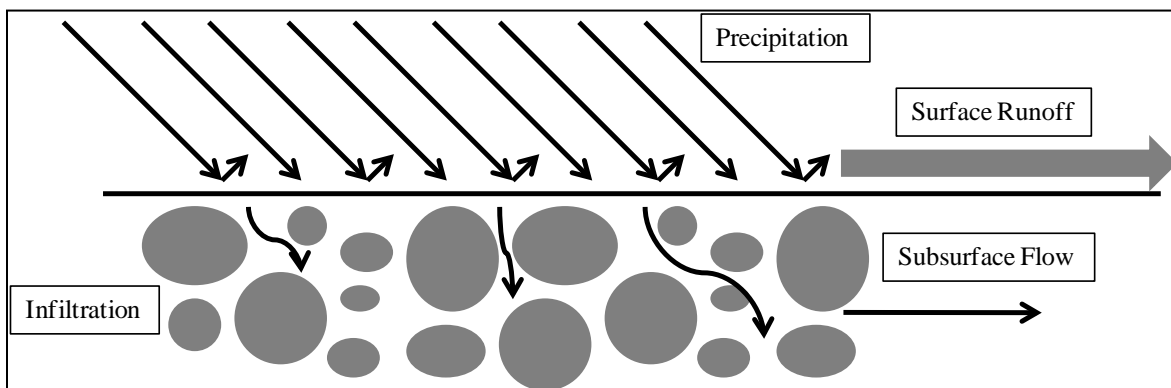


Figure 1.2 Schematic of Horton Overland Flow. In some cases, the intensity of precipitation exceeds the rate at which water can infiltrate into the soil.

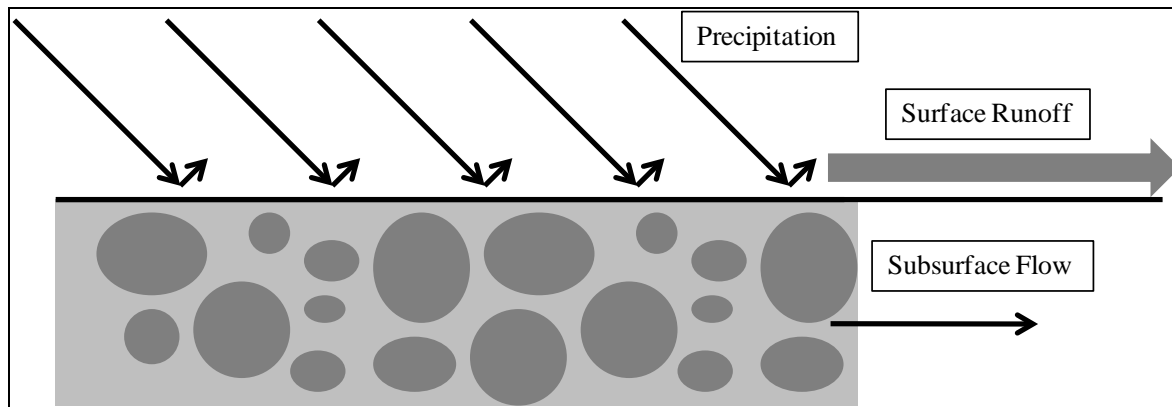


Figure 1.3 Schematic of infiltration excess runoff. Alternatively, runoff can occur when precipitation cannot infiltrate the soil due to soil saturation or frozen conditions.

The concept that forests play a role in buffering flood impacts is widely accepted. The magnitude of this effect, however, is greatly disputed. Research has shown varied responses in streamflow following forest harvesting. Guillemette et al. (2005) conducted a literature survey of 50 international basin studies in which they determined whether or not forest practices impacted peak flow. In studies looking at watersheds with the removal of greater than or equal to 50% of the total land area or basal area, non-significant increases in peak-flow stream response have been found at the Fernow in West Virginia (Reinhart et al., 1963), H.J. Andrews and Deer Creek in Oregon (Harr et al., 1975; Harr et al., 1982; Harr, 1986; Thomas and Megahan, 1998), and Alto, Texas (Blackburn et al., 1986). In studies looking at similar site treatments, significant increases in peak flow response have been found at Beaver Creek, Utah (Brown et al., 1974), Coyote Creek and H.J. Andrews, Oregon (Harr and McCorison, 1979; Harr, 1986), Coweeta, North Carolina (Douglass and Swank, 1976; Hewlett and Helvey, 1970; Swank et al., 1982), Grand Forest, Georgia (Hewlett, 1979), Upper Coastal Plain and Holly Spring, Mississippi (Ursic, 1970; Ursic, 1982; Ursic, 1991), Marcell, Minnesota (Verry et al., 1983; Verry, 1986), and Hubbard Brook, New Hampshire (Hornbeck, 1973; Hornbeck et al., 1997; Pierce et al., 1970). Many studies have found that stream discharge returns to pre-harvest conditions within five years of logging (Hewlett and Helvey, 1970; Hornbeck et al., 1970; Swank et al., 2001).

Impacts of forest harvesting on the stream hydrograph are important yet transient, since re-vegetation can occur under continued forest management. A more static issue that forest managers must consider are forest roads, which are often permanent and can affect the

surrounding ecosystem. Forest roads can influence the natural pathways of runoff. The non-vegetated road corridors can act like stream channels, intercepting overland flow and re-routing it down slope. Compacted road surfaces roads can also reduce infiltration, enabling a larger volume of water to channel along the road. The increased volume of water and sediment from the road surface can negatively impact the health and vitality of the ecosystem. In a particular catchment, a road segment may act as a barrier, corridor, sink, or source for both water and sediments (Jones, 2000). All of these functions can alter the stream hydrograph, both in quantity and in timing.

The construction of roads in national forests has been very controversial, especially during the recent decades. In 1999, Bengston and Fan found that U.S. citizens viewed forest roads as favorable, citing recreational and commodity benefits as potential uses. Despite these public views, there was increasing public and political pressure to ban construction of forest roads on “roadless” areas in the forest service (Bengston and Fan, 1999). The debates continued with the enactment of the Roadless Area Conservation Act of 2007, which was designed to protect and preserve the socio-ecological benefits of healthy watersheds. Cited benefits included the lowering the potential of flooding for downstream communities, conservation of wildlife habitat, protection of clean drinking water, and recreational opportunities (Roadless Area Conservation Act of 2007).

The ample environmental concerns over the construction of forest roads include forest fragmentation, increased sedimentation and thus decreased water and stream quality, increased fire hazards and invasive species dispersal. As of 2007, there were approximately 386,000 miles of roads located within the national forest system (Forest Service, 2008). The 2008 fiscal year budget for the US Forest Service appropriated over \$225,000,000 to the management of the road network; which was an 8 percent increase from the 2007 budget (Forest Service, 2008). Due to mounting importance and scrutiny of forest roads, it is critical for forest roads to be properly designed, installed, and maintained.

1.1.2 Flooding in the Blue Ridge Mountains

Flooding is a notable concern, especially when the potential socioeconomic impacts are considered. In 2008, three major storms cost the American public over \$2.5 billion in damages (Federal Emergency Management Association, 2009). As the costs of flood damage put their strain on society, the censure for responsibility intensifies. Highly publicized flood events often support the public misconception that forest harvesting practices are the sole cause of severe flooding (McCutcheon, 2006). In the U.S., this is usually evident in the Pacific Northwest, where heavy rains and steep slopes facilitate large floods and landslides (Johnson et al., 1997). Anthropogenic versus natural causality of flooding is commonly debated in the region, which has a history of both intensive forestry practices and grassroots environmental movements (Cutter, 2009; Streater, 2009).

The dispute over forestry and flooding is not limited to the Pacific Northwest. In the Southern Appalachians, a mountainous region in the southeastern U.S., wide scale harvesting dates back to the early 19th century. By 1835, an estimated forty sawmills were running in the area that would become West Virginia (Yarnell, 1998). Harvesting in the area has continued, and in the fiscal year 2007, 163,500 MBF of timber were harvested from national forests in the southeastern U.S. (Forest Service, 2009). Approximately 78% of the area in the Blue Ridge Mountains is forested (Taylor and Kurtz, 2008) and society continues to debate the impacts that management activities may have on their welfare. For instance, extensive flooding occurred in southern West Virginia and Southwestern Virginia in July 2001. National Weather Service stations recorded maximum rainfall intensities of 50 mm/hr and damages were estimated to be around \$150 million (Eisenbies et al., 2007). Following this event, numerous counties and citizens filed civil suits against logging and mining companies, insisting that the corporations to take responsibility for the floods (Recht, 2007).

As a result of the flood devastation, West Virginia governor Bob Wise created a Flood Investigation Advisory Committee. The team was designed to evaluate the impacts of logging and mining on flooding. In 2002 the Flood Advisory Technical Taskforce (FATT) recommendations were released. The comprehensive report detailed guidelines for mining and logging activities and was aimed at reducing their environmental impact. In regards to forestry,

the report suggested stricter regulation of harvesting practices and firmer enforcement of the West Virginia forestry Best Management Practices (Flood Advisory Technical Taskforce, 2002).

1.1.3 Using Modeling as a Research Tool

In recent decades, modeling has become more widely used both in helping to understand the components of the hydrologic cycle and in predicting hydrologic responses to potential anthropogenic impacts. Every hydrology model is designed for specific simulation goals. The first available watershed model, The Stanford Watershed Model (later termed the Hydrologic Simulation Program-FORTRAN), was developed in the 1960s as a joint venture between Harvard and Stanford Universities and the U.S. Army Corps of Engineers (Bedient et al., 2008). Additional watershed models were subsequently developed, including HEC-HMS (Center, 2009), the Natural Resource Conservation Service's NRCS TR-55 (Cronshey et al., 1986), GAMES (Dickinson et al., 1992) and AGNPS (Mostaghimi et al., 1997). Several models can be used for modeling flow in forested watersheds. Some examples include FORWADY (Seely and Kimmins, 1997), DRAINMOD (Natural Resources Conservation Service, 1980), CRHM (Pomeroy et al., 2007), RHESSys (Tague and Band, 2004), WaSiM-ETH (Schulla and Jasper, 2007), WEPP (Watershed Erosion Prediction Project 1995), TOPMODEL (Beven et al., 1993) and DHSVM (Wigmosta et al., 1994).

Hydrologic watershed models have three major operational considerations that can be used to characterize the models. First, they can either be a lumped or distributed model. A lumped model considers the physical characteristics of the watershed to be uniform, which allows for simplicity when running the model. Distributed models are more complex as they account for the watershed as it physically occurs in the landscape. This can create problems with data collection, model calibration and verification. Second, a model can examine streamflow response over time (continuous) or for one event of interest (event). Finally, a model can be physically based, meaning that it has a static initial set of conditions determined by input parameters or previous model runs. If not static, the model can be stochastic and the conditions are dynamic and follow a probability distribution (Bedient et al., 2008).

1.2 Objectives

This study originated from litigious issues surrounding forest management activities, such as harvesting and road construction, and how they might affect flood events. Since many hydrologic models now have the power to accommodate to the complexity of forested ecosystems, a modeling approach was selected. Specifically, the Distributed Hydrology-Soil-Vegetation Model was used to predict the impacts of forest road density on stream discharge. The DHSVM model was chosen because it has better capabilities for modeling different road designs and densities. The specific objectives of this research were to:

- 1) Determine whether or not DHSVM could be calibrated for use in the Southern Appalachian Mountains; and
- 2) Assess the impacts of forest road density on stream discharge for
 - a. Mean monthly streamflow
 - b. Peak flow in response to flood events

Literature Cited

- Bedient, P. B., W.C. Huber, and B.E. Vieux. 2008. Hydrologic Simulation Models. P 312-355 in *Hydrology and Floodplain Analysis*. Upper Saddle River, NJ, Prentice Hall. 795 p.
- Bengston, D. N. and D. P. Fan. 1999. The public debate about roads on the national forests. *Journal of Forestry*. 97(8): 4-10.
- Beven, K., P. Quinn, R. Romanowicz, J. Freer, J. Fisher, and R. Lamb. 1993. TOPMODEL and GRIDATE. In *CRES Technical Report TR 110 (2nd Edition)*. Centre for Research on Environmental Systems and Statistics, Lancaster University, Lancaster, UK.
- Blackburn, W.H., J.C. Wood, and M.G. DeHaven. 1986. Storm flow and sediment losses from site-prepared forestland in East Texas. *Water Resources Research*. 22: 776-784.
- Brown, H.E., M.B. Baker, Jr., J.J. Rogers, W.P. Clary, J.L. Kovner, F.R. Larson, C.C. Avery, and R.E. Campbell. 1974. *Opportunities for Increasing Water Yields and Other Multiple Use Values on Ponderosa Pine Forest Lands*. USDA Forest Services Research Paper RM-129. 36 p.
- Center, H. E. 2009. *HEC-HMS: Hydrologic Modeling System*. USACOE. Davis, CA. 310 p.

- Cornish, P.M. and R.A. Vertessy. 2001. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest. *Journal of Hydrology*. 242: 43-63.
- Cronshey, R., R.H. McCuen, N. Miller, W. Rawls, S. Robbins, and D. Woodward. 1986. *Urban Hydrology for Small Watersheds*. US NRCS TR-55. 164p.
- Cutter, J. 2009. *Commercial Logging Behind Severe Floods in Washington State*. Available online at <http://www.pslweb.org/>; last accessed Dec. 12, 2009.
- Dickinson, W. T., R.P. Rudra, D.N. Sharma, and S.M. Ahmed. 1992. Planning Sediment Monitoring Programs Using a Watershed Model. P 343-352 in *Erosion and Sediment Transport Monitoring Programs in River Basins, Proceedings of the Oslo Symposium*. Oslo, Norway.
- Douglass, J.E., and W.T. Swank. 1976. Multiple Use in Southern Appalachian Hardwoods-A 10 Year Case History. P. 425-436 in *Division I Proc. XVI IUFRO World Conference*. Norway.
- Eisenbies, M. H., W.M. Aust, J.A. Burger, and M.B. Adams. 2007. Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians-A review. *Forest Ecology and Management*. 242: 77-98.
- Flood Advisory Technical Taskforce. 2002. *Runoff Analysis of Seng, Scrabble, and Sycamore Creeks*. Charleston, WV. 123 p.
- Federal Emergency Management Association. 2009. *Significant Flood Events: 1978-June 20, 2009*. F. E. M. Agency. Washington, D.C.
- Forest Service. 2008. Fiscal Year 2008 President's Budget Overview. *USDA Forest Service*. Washington, D.C. 60 p.
- Forest Service. 2009. Timber Sold and Harvest Report Summaries. *USDA Forest Service*. Available online at <http://www.fs.fed.us/forestmanagement/reports/>; accessed Feb. 2010.
- Guillemette, F., A.P. Plamondon, M. Prévost, and D. Lévesque. 2005. Rainfall generated stormflow response to clearcutting a boreal forest: peak flow comparison with 50 world-wide basin studies. *Journal of Hydrology*. 302: 137-153.
- Harr, R.D., W.C. Harper, J.T. Krygier, and F.S. Hsieh. 1975. Changes in storm hydrographs after road building and clear-cutting on the Oregon Coast Range. *Water Resources Research*. 11: 436-444.

- Harr, R.D. and F.M. McCorison. 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. *Water Resources Research*. 15: 90-94.
- Harr, R.D., A. Levno, and R. Mersereau. 1982. Streamflow changes after logging 130-year-old Douglas-fir in two small watersheds. *Water Resources Research*. 18: 637-644.
- Harr, R.D. 1986. Effects of clearcutting on rain-on-snow runoff in Western Oregon: a new look at old studies. *Water Resources Research*. 22: 1095-1100.
- Hewlett, J.D. and J.D. Helvey. 1970. Effects of forest clear-felling on the storm hydrograph. *Water Resources Research*. 6: 768-782.
- Hewlett, J.D. 1979. *Forrest Water Quality-An Experiment in Harvesting and Regenerating Piedmont Forest*. G.F.R. Paper. University of Georgia. 22 p.
- Hornbeck, J. W., R. S. Pierce, and C.A. Federer. 1970. Streamflow changes after forest clearing in New England. *Water Resources Research*. 6: 1124-1132.
- Hornbeck, J. W. 1973. Stormwater flow from hardwood forested and cleared watersheds in New Hampshire. *Water Resources Research* 9: 346-354.
- Hornbeck, J. W., C. W. Martin, and C. Eagar. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest. *Canadian Journal of Forest Research*. 27: 2043-2052.
- Horton, R.E. 1933. The Role of Infiltration in the Hydrologic Cycle. In *Transactions of American Geophysical Union Fourteenth Annual Meeting*. National Research Council, Washington, D.C.
- Johnson, S. L., G.E. Grant, F.J. Swanson, and B.C. Wemple. 1997. Lessons From a Flood: An Integrated View of the February 1996 Flood in the McKenzie River Basin. In *The Pacific Northwest Flood of 1996: Causes, Effects and Consequenses. Proceedings of the American Institute of Hydrology and Oregon Water Resources Research Institute Flood Conference*. Portland, OR.
- Jones, J. A. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research*. 36: 2621-2642.

- McCutcheon, S.C. 2006. Hydrology of Eastern U.S. Forested Mountain Watersheds: Rigorous Testing of the Curve Number Method for Flood Analysis. In *Testimony to the West Virginia Forest Management Review Commission*. University of Georgia. 11 p.
- Mostaghimi, S., S.W. Park, R.A. Cooke, and S.Y. Wang. 1997. Assessment of management alternatives on a small agricultural watershed. *Water Resources Research*. 31(8): 1867-1878.
- Natural Resources Conservation Service. 1980. *Drainmod: Methods for Design and Evaluation of Drainage-Water Management Systems for Soils with High Water Tables*. US NRCS South National Technical Research Center, Fort Worth, TX.
- Pierce, R. S., J.W. Hornbeck, G.E. Likens, and F.H. Borman. 1970. Effect of elimination of vegetation on stream water quantity and quality. *International Association of Hydrological Science Publications*. 96: 311-328.
- Pinchot, G. 1905. *A Primer of Forestry. Part II: Practical Forestry*. USDA Bureau of Forestry Bulletin 24.
- Pomeroy, J. W., D.M. Gray, T. Brown, N.R. Hedstrom, W.L. Quinton, R.J. Granger, and S.K. Carey. 2007. The Cold Regions Hydrological Model, a platform for basing process representation and model structure on physical evidence. *Hydrologic Processes*. 21(19): 2650-2667.
- Recht, A. M. 2007. Flood Litigation-Coal River Watershed. West Virginia Court of Appeals. Raleigh County, WV. Civil Action No. 01-C-797. 31 p.
- Reinhart, K.G., A.R. Eschner, and G.R. Trimble, Jr. 1963. *Effect on Streamflow of Four Forest Practices*. USDA Forest Service Research Paper NE-1.
- Roadless Area Conservation Act of 2007. S. 1478, 110th Cong. (2007).
- Schulla, J. and K. Jasper. 2007. *Model Description: Water balance Simulation Model ETH, The Hydrological Model System WaSiM-ETH*. WaSiM Tech. Rep. 181 p.
- Seely, B., and J.P. Kimmins. 1997. *A Forest Hydrology Model for Simulating the Effect of Stand Management and Climate Change on Forest Water Dynamics*. The University of British Columbia Department of Forest Sciences FESR Group. 15 p.
- Streater, S. 2009. Increased frequency of landslides remains largely ignored despite risks. *New York Times*. Mar. 19, 2009: Energy & Environment.

- Swank, W., J.E. Douglass, and G.B. Cunningham. 1982. Changes in Water Yield and Storm Hydrograph Following Commercial Clearcutting on a Southern Appalachian Catchment. P. 584-593 in *Proceedings of the Symposium on Hydrological Research Basins*. Landeshydrologie, Bern, Switzerland.
- Swank, W. T., J. M. Vose, and K.J. Elliott. 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management*. 143: 163-178.
- Tague, C. L. and L.E. Band. 2004. RHESSys: Regional Hydro-Ecologic Simulation System-an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient. *Earth Interactions*. 8(19): 42.
- Taylor, J.L. and R. Kurtz. 2008. Blue Ridge Mountains. In *Land Cover Trends*. US Geological Survey. Available online at <http://landcoverrends.usgs.gov/>; accessed Jun 2009.
- Thomas, R. B. and W. F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. *Water Resources Research*. 34: 3393-3403.
- Ursic, S.J. 1970. *Hydrologic Effects of Prescribed Burning and Deadening Upland Hardwoods in Northern Mississippi*. USDA Forest Service Research Paper SO-54. 15 p.
- Ursic, S.J. 1982. Hydrologic Changes After Replacing Hardwoods With Southern Pine P. 735-746 in *Proceedings of the Symposium on Hydrologic Research Basins*. Landeshydrologie, Bern, Switzerland.
- Ursic, S. J. 1991. Hydrologic effects of clearcutting and stripcutting loblolly pine in the coastal plain. *Water Resources Bulletin*. 27: 925-937.
- Verry, E. S., J.R. Lewis, and K.N. Brooks. 1983. Aspen clearcutting increases snowmelt and storm flow peaks in north central Minnesota. *Water Resources Bulletin*. 19: 59-67.
- Verry, E. S. 1986. Forest harvesting and water: The Lake States experience. *Water Resources Bulletin*. 22(6): 1039-1047.
- Watershed Erosion Prediction Project. 1995. *Hillslope Profile and Watershed Model Documentation*. USDA National Soil Erosion Research Laboratory. 10 p.
- Wigmosta, M. S., L. W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resources Research*. 30: 1665-1679.

Yarnell, S. L. 1998. *The Southern Appalachians: A History of the Landscape*. USDA Forest Service General Technical Report SRS-18. 52 p.

CHAPTER 2. LITERATURE REVIEW

2.1 A History of Hydrology Research at Coweeta

The USDA Forest Service Coweeta Hydrology Research Station (now the Coweeta Long Term Ecological Research (LTER) Station) was established in 1933 with the intent to study streamflow and erosion in an ecological context (Douglass and Hoover, 1988). The 2185 ha Coweeta basin is located in the Blue Ridge Mountains of western North Carolina. The research station has a long history of paired watershed research studies, and some representative examples are described below. More detailed accounts of watershed research at the Coweeta LTER can be found in Douglass and Swank (1972 and 1975) and Swank et al. (1988).

In 1970, Swank and Helvey looked at the impacts of clear-cut harvesting and vegetative regrowth on streamflow in the Coweeta watershed. Two small (16.1 and 43.7 ha) watersheds were studied, the smaller of which had an initial clear-cut in 1940. This was followed by natural regeneration for 23 years and concluded with a second clear-cut. The larger watershed was clear-cut in 1963 and was also allowed to naturally regenerate. In both watersheds, all trees were harvested and left on the ground, and soil disturbance was minimal. The results indicated increases in water yield following harvesting and lower rates of streamflow response as vegetation regrowth occurred. In the watershed containing the two cuttings, increases in stream discharge declined at a much faster rate following the second harvest than they did after the first cutting. The authors attributed this variation in streamflow response to prolific sprouting and rapid canopy development that occurred subsequent to the second harvest (Swank and Helvey, 1970). In 1981, the study by Swank and Helvey (1970) was expanded. The extended study confirmed that the regrowth of vegetation was the primary determinant of water yields. The authors also suggested that “percent reduction in basal area is an effective predictor of streamflow increase in the first year following treatment.” However, not all streamflow trends could be explained through vegetation growth and removal. Precipitation and basin characteristics were also considered to be predictors of the irregularities of water yield response to treatment (Swift and Swank, 1981).

A similar study began in 1976 on Coweeta Watershed 7. Access roads were constructed (2.95 km total) before clear-cutting and cable yarding of the 59 ha watershed in 1977. Storms

greater than 2 cm in volume were used as an analysis of streamflow response. In the initial year after harvest, streamflow increased by 26 cm (28%) over pre-treatment conditions. By the fourth year of study, flow was 12 cm (13%) above baseline. Results were consistent with other studies and discrepancies in streamflow were considered a function of rapid forest regeneration (Swank et al., 1982). The effects of clear-cutting and cable yarding on the storm hydrograph were also investigated in the study, and it was found that the watershed had greater responses to smaller storm events. The authors suggested that this could have been a function of the linear response relationship used in the model. They unsuccessfully attempted to create a non-linear model to define the relationship between treatment and streamflow response (Swank et al., 1982). The study was updated almost two decades later to further investigate the effects of cable yarding (Swank et al., 2001). It was found that increases in streamflow initially decreased at a rate of 5 to 7 cm year⁻¹ until the 5th year following treatment. When the forest reached a successional age of 15 years, a significant increase in water yield occurred, followed by a significant decrease. Afterward, streamflow leveled off below baseline conditions, although insignificantly. The authors attributed the initial increase to stem exclusion and mortality in the stand. The decrease in flow was puzzling, but was thought to be a result of species conversion in the forest. The longer-term study showed that clear-cutting with cable yarding had little long term effects on water yield (Swank et al., 2001).

Harvesting a watershed is not the only way to impact the water yield in a catchment. In 1968, Swank and Miner looked at the implications of converting a native hardwood forest to white pine. Two Coweeta watersheds were clear-cut and planted with white pine (*Pinus strobus*) seedlings in 1956 and 1957. Competing hardwood vegetation was chemically and mechanically suppressed on both watersheds. Results indicated an initial increase in streamflow following hardwood harvesting, followed by decreases in streamflow additions. After six years of study, streamflow rates fell below pre-treatment levels. Streamflow levels continued to drop ten years after planting. The authors attributed the decreased water yields to larger evapotranspiration rates of evergreen white pines (*Pinus strobus*) during the deciduous species' dormant season and to increased interception of precipitation of by the pines. They hypothesized that streamflow levels would continue to decline in the ensuing years (Swank and Miner, 1968). This hypothesis was verified by Swank and Douglass in 1974. The continuation of the study showed that the white

pine (*Pinus strobus*) covered catchments reduced streamflow until crown closure occurred (approximately 16-17 years following planting), after which stream discharge stabilized at a rate of 20% less than that expected under hardwood conditions (Swank and Douglass, 1974). Twenty years later, water yield from the converted pine watershed was still lower in storm volume, peak flow rate, and low flow conditions (Swank and Vose, 1994).

Not all species conversions result in such long term alterations of streamflows. In 1958, merchantable timber from 8.9 ha Coweeta Watershed 6 was removed and replaced with fescue grass. Under non-fertilized conditions, the grass had trouble surviving and ground cover was essentially bare soil. Under these conditions, streamflow increased. However, when fertilization occurred and grass cover was viable, stream discharge was similar to forested conditions. As shrubs re-vegetated, flow returned even closer to the original, forested yields (Hibbert, 1969; Burt and Swank, 1992). This suggested that grass and shrub cover had similar water uses to hardwood forests.

The Coweeta watershed studies have not focused solely on forest management effects on water yield. Many investigations have looked at how harvesting may influence the ecology of an ecosystem in other fashions. For instance, forest harvesting may increase temperatures in streams, adversely affecting stream vegetation and micro- and macro-fauna (Swift, 1982). Many studies also suggest that forest management can affect stream chemistry. Swank and Vose (1994) showed that streamflow from white pine forests had less calcium, potassium, magnesium, and sodium cations than streamflow from hardwood watersheds. Scientists have also been studying the impacts of road building and sediment erosion on water quality (Riedel and Vose, 2002; Riedel et al., 2007).

2.2 Effects of Forest Management on Runoff

2.2.1 Removal of Vegetation

The removal of vegetation from a watershed can greatly affect the water budget of the catchment, particularly if the removal is permanent. The presence of vegetation primarily affects streamflow through evapotranspiration processes and by the interception of precipitation. If

vegetation is removed, the leaf area index (LAI) of a watershed will decline, thus reducing evapotranspiration (ET). The decreased ET can lead to increases in soil moisture, especially during the growing season, when ET in a forested ecosystem would be most prevalent. Heightened soil moisture can lead to increased peak flows and baseflows in the catchment (Hewlett and Hibbert, 1963; Ziemer, 1981).

For decades, scientists have shown that reductions in ET can lead to increases in streamflow. In 1966, Hibbert reviewed 39 paired-catchment studies from across the United States and concluded that reductions of forest cover led to increased water yield. From the studies, it was concluded that for every percent reduction in forest cover, streamflow increased by a maximum of 4.5 mm per year. None of the 39 studies reported a decrease in water yield following the removal of vegetation. The review also concluded that the increase in water yield was greatest in the year following disturbance, that the afforestation of a site decreased water yield, and that watershed response to treatment was highly variable (Hibbert, 1966).

In 1982, Hibbert's review was updated, with the new analysis comparing 94 catchment studies (Bosch and Hewlett, 1982). In no cases did the review detect a reduction in water yield following harvest, although the review noted differences in response based upon vegetative cover. For example, coniferous forests had a larger influence on water yield than deciduous forests. A 10% change in forest cover resulted in an annual water yield change for coniferous forests of approximately 40 mm and only 25 mm for deciduous forests (Bosch and Hewlett, 1982). Jones and Post (2004) further examined the effect of the removal of vegetation type on stream discharge. They compared studies from 14 sites in the conifer-dominated forests of the Pacific Northwest and the mixed deciduous forests of the East Coast. The authors found that, for the first five years following harvest, changes in maximum daily flow were 6 to 8 mm for coniferous forests and 2 to 3 mm for deciduous forests (Jones and Post, 2004).

Studies have concluded that harvesting will increase streamflow for approximately five years following forest removal (Hewlett and Helvey, 1970; Hornbeck et al., 1970; Kochenderfer et al., 1990; Swank et al., 2001). Swank et al. (2001) analyzed long-term changes in streamflow following clear-cutting in a 59 ha catchment in the Coweeta watershed located in the southern

Appalachians. They found that streamflow increased by 28% in the first year following harvest but decreased in the ensuing years. The study also found that streamflow had returned to baseline conditions within five years of the harvest (Swank et al., 2001). The authors attributed the initial change in streamflow to be a function of reduced evapotranspiration. As vegetation re-growth occurred, the impact of harvesting was lessened (Swank et al., 2001). When a portion of the Hubbard Brook Experimental Forest was clear-cut and treated with herbicides, researchers noticed an increase in average annual water yield of 40% in the year following harvest (Hornbeck et al., 1970). Like Swank et al. (2001), the authors attributed the initial change in streamflow to be a function of reduced evapotranspiration (Hornbeck et al., 1970). In an analysis of watershed response data at the Fernow Experimental Forest, Kochenderfer et al. (1990) found that stream discharge increased following patch clear-cuts, clear-cutting, selection cutting, and harvesting plus herbicide treatment. In all cases except those including herbicide treatments, streamflow returned to initial conditions within five years (Kochenderfer et al., 1990). Hewlett and Helvey (1970) conducted a study in which a 108 ac catchment in the Coweeta LTER was clear-cut to determine the effects of vegetation removal on storm runoff. The authors found that in the year following harvest, stormflow volume increased by 11% and peak discharge increased by 7% (Hewlett and Helvey, 1970).

Response of a stream to vegetation removal is dependent upon numerous contributing variables, including, but not limited to, climatic conditions and the season. In areas dominated by rainfall precipitation, such as the Coweeta LTER, seasonal distribution of water yields is varied. In his review of 39 paired catchment studies, Hibbert (1966) found small increases in water yield during the growing season, while large increases in water yield occurred throughout the year. This did not hold true for all watersheds, and the disagreement between seasonal and treatment water yields was attributed to watershed features, such as slope, aspect, and soil depth (Hibbert, 1966). Many studies do find that streamflow fluxes are larger during the growing season. In two deforested West Virginia watersheds, it was found that streamflow increased by 254 mm annually, with most of the increases occurring during the late growing season (Patric, 1973). Hibbert (1966) also found that Fernow Experimental watershed studies noted water yield increases during the growing season. These were ascribed to the decrease in evapotranspiration resulting from the removed vegetation (Hibbert, 1966). In their review of 14 paired catchment

studies, Jones and Post (2004) noticed that “forest effects on streamflow are strongly seasonal.” In deciduous forests, the authors found that absolute and relative changes in streamflow were more likely to occur in the warmer growing season months. Exceptions occurred at the Coweeta basin, where streamflow response paired Watersheds 13 and 14 were not associated with any season and in paired Watersheds 7 and 34, where relative streamflow changes occurred during colder months (Jones and Post, 2004). Seasonal streamflow response to vegetative reduction was also found in the central Appalachians. Significant increases in growing season peak flow were found in comparison to no changes in dormant season flows. Therefore, the authors concluded that the hydrologic response was a mechanism of the vegetative removal and not one of compaction or disturbance of soil during the harvesting process (Kochenderfer et al., 1997).

Hibbert (1966) examined data from Coweeta and the Fernow and suggested that the percent reduction in forest cover is not proportional to the first year stream yield increases. This implied that other variables, such as climate, slope, and aspect influenced stream discharge. Kochenderfer et al. (2007) further suggested this based on analysis of long-term streamflow data from the Fernow Experimental Forest. The authors examined data from 7 of the experimental watersheds and analyzed streamflow and precipitation records dating as far back as 1951. Using a model to determine the most influential factors in predicting peak streamflow, the authors found that storm characteristics such as duration, intensity, and volume influenced the variability in streamflow, while disturbance history had minimal influence (Kochenderfer et al., 2007). A 1982 study from Fernow found similar results, suggesting that the depth of rainfall and initial streamflow velocity accounted for over 85% of the variability in peak discharge (Brewer et al., 1982). Sturdevant-Rees et al. (2001) looked at the effect of a large hurricane event on flooding in the central Appalachians. The study found that antecedent soil moisture was a significant factor in determining peak discharge and that the amount of vegetative cover was of little importance (Sturdevant-Rees et al., 2001).

For sites having long term water yield measurements, the data suggest increases in harvest area cause larger stream discharges. At the Coweeta and Fraser Experimental Forests, early findings found linear relationships between the percent reduction in vegetative cover and the magnitude of stream discharge (Hibbert, 1966). In 1971, Patric and Reinhart reported on a

study to compare the effects of deforestation on stream discharge. In West Virginia, the upper half of one watershed was deforested while the lower half of a paired catchment was clear-cut. Three years later, both watersheds were completely deforested. The researchers noted a 15.2 cm increase in average water yield from the half deforested watershed and a 25.4 cm increase after complete deforestation (Patric and Reinhart, 1971). In a study comparing four different harvesting treatment types on stream parameters, Reinhart et al. (1963) concluded that a clear-cut had the largest impact on stream discharge, followed by diameter limit cut, extensive selection, and intensive selection.

Other studies have suggested that the area harvested is proportional to stream discharge. In a review of 95 catchment studies, Stednick (1996) found that different regions of the United States had varying harvesting thresholds after which detectable changes in streamflow discharge were observed. The threshold was lowest for the Rocky Mountains (15%) and largest for the Eastern Coastal Plains and Piedmont (45%). Other thresholds included 20% for the Appalachian Mountains and 25% for the Pacific Coast. For the Appalachian Mountain region, each 10% increase in area harvested resulted in an increased annual water yield of 28 mm (Stednick, 1996). Kochenderfer et al. (1990) summarized the effects of various harvesting treatments on streamflow response in the Fernow Experimental Forest. The authors found that stream discharge was directly related to the amount of vegetation that was removed. The authors also discovered that vegetation suppression in addition to removal created larger and more sustained impacts on streamflow (Kochenderfer et al., 1990).

2.2.2 Forest Roads

The issue of forest roads has become increasingly scrutinized. While an important component for research, transportation, recreation, and business purposes, forest roads can pose a threat to the surrounding ecosystem. Such threats include loss of space, unmanaged recreation, spread of invasive species, and spread of wildland fire (Grace and Clinton, 2007). One of the most sensitive areas to forest roads, however, is the riparian ecosystem. Forest roads have the ability to alter water movement and contribute sediment to streams. Understanding the road ecosystem can help forest managers achieve goals while coexisting with the natural environment (Gucinski et al., 2001).

Forest roads can potentially affect the natural movement and extent of runoff by redistributing the water through the road network. A road can affect the hydrology of a forested ecosystem through three different processes:

- 1) *Interception of Subsurface Flow*: the water table rises above the road cut and subsurface flow seeps into the road network and drainage system and is channeled down the road;
- 2) *Infiltration Excess Runoff*: the compacted road surface decreases the infiltration capacity of the soil and the excess water becomes runoff;
and
- 3) *Overland Flow*: the road and drainage system intercepts overland flow and re-routes it from the hillslope through the road network.

Scenario three is less likely to occur in a forested ecosystem, as infiltration rates are often high for forest floors and overland flow is not a primary mechanism in forest hydrology. This continues to hold true during many storm events (Bates, 2000). For sediments, a road segment may act as a barrier, corridor, sink, or source for both water and sediments (Jones et al., 2000).

Numerous studies have attempted to determine the effects of forest harvesting and road construction on stream discharge. However, it can be difficult to separate the two effects because harvesting and road construction often occur simultaneously. Thus, results are often conflicting due to the multitude of ways that roads may interact with the hydrology of a forest. Such factors include the location and design of the forest road, associated harvesting operations, watershed characteristics, antecedent soil and stream conditions, and storm characteristics (Thomas and Megahan, 1998). Ziemer (1981) conducted a study at Caspar Creek, California to investigate the impacts of forest roads on peak flow. From 1971 to 1973, 67% of the 424 ha South Fork watershed was harvested. The watershed contained approximately 15% impervious surface, 5% in roads and 10% in skid trails and landings. Over the study period, the author found that road construction resulted in no measured change in storm flow (Ziemer, 1981). A study by Rothacher (1970) looked at road and road plus harvesting effects on water yield at the H.J. Andrews

Experimental Forest in western Oregon. The study found similar results to Ziemer (1981) and concluded that the construction of forest roads did not significantly increase mean discharge in the study watersheds (Rothacher, 1970).

Additional research agrees with Rothacher (1970) and Ziemer (1981). Wright et al. (1990) studied a 424 ha coastal watershed in northern California in which 4.5% of the total area consisted of road networks. The authors concluded that road construction did not significantly increase total volume, quick-flow volume, peak flows, or lag-times in the study catchments (Wright et al., 1990). King and Tennyson (1984) found similar results in a study located in the Nezperce National Forest in north-central Idaho. The small, study watersheds (28 ha to 148 ha) had road compaction over 1.8 to 4.3% of the total catchment area. Overall, the study found no significant streamflow response to the constructed road networks. In one watershed, the 25% exceedance flow increased while the 5% exceedance flow decreased in another watershed. Exceedance flow is the streamflow that is met or exceeded a specified percent of the time (in this study, 25% and 5%). The increase in flow was attributed to the road's midslope location, which diverted subsurface flow to the stream as surface flow, with a shorter lag time. The decrease in exceedance flow occurred on the watershed that had the highest density of roads (King and Tennyson, 1984).

In contrast, studies have found that stream discharge is affected by road construction. Harr (1979) states that the collective results of watershed studies imply that roads have positive, negative, and neutral impacts on water yields. This was exemplified in a study conducted on small watersheds in the Oregon Coast Range where forest roads had no impact on peak discharge, except when they occupied greater than 12% of the total area of the watershed. Over the short, one year study period, the authors found that roads decreased the average volume of quick-flow, increased delayed flow volume, and had inconsistent effects on time to peak and overall volume of the storm hydrograph (Harr et al., 1975). Jones (2000) compared ten basins in the Western Cascade Range in Oregon to determine peak discharge responses to forest removal, re-growth, and road construction. Jones found that roads increased peak discharge in events with >1 year return periods by 13 to 36%. It was noted that this was primarily through the interception of subsurface flow by the deep road cuts as opposed to the interception and re-routing of

overland flow. The author also suggested that the configuration of roads along a hillslope may play an important role in the magnitude of impact on stream discharge (Jones, 2000).

The investigation of the effects of forest roads on streamflow can be controversial. In 1996, Jones and Grant conducted a study in a 100 ha watershed in western Oregon. The road density in the catchment was 6%, which was well below Harr et al.'s (1975) suggested threshold of 12%. Four years following road construction, storm runoff was increased and peak flows were 20% higher than base conditions, although this was not considered statistically significant. After patch clear-cutting on the same watershed, the authors found that water yield increased by 50% in the first five years following treatment. In the subsequent twenty years, discharges were still 25 to 40% greater than pre-treatment conditions. Jones and Grant attributed the increases in water yield to the increased interception of subsurface moisture and the modification of flow paths by forest roads (Jones and Grant, 1996). The approach used by Jones and Grant was later disputed by Thomas and Megahan (1998) for using an incorrect approach to analyze the discharge data. The model used by Jones and Grant used percent increases in the differences of the logarithms of peak discharges, thereby inflating the magnitude of actual change in water yield. Using the model presented by Thomas and Megahan (1998), no treatment effect was detected in the same watershed after 10 years following patch clear-cutting. This also suggests that water yield is impacted by the removal of vegetation as opposed to changes in flow routing due to roads (Thomas and Megahan, 1998).

More recently, the advancement of computer models has allowed the scientific community to parse out the effects of forest roads on streamflow. Bowling and Lettenmaier (1997) used a Distributed Hydrology Soil Vegetation Model (DHSVM) to simulate the effects of forest roads on streamflow in two catchments in western Washington. The drainage areas ranged from 2.3 to 2.8 km² and the road lengths were 10.7 and 11.4 km, respectively. The authors found that over the 11 year simulation phase, roads networks increased the ten year return period flood by 8 to 10%. With mature vegetation, it was found that forest roads could increase ten-year return peak flow rates by as much as 22% (Bowling and Lettenmaier, 1997). The authors discovered that roads redistribute water throughout the basin, resulting in drier zones directly beneath the road (due to compaction) and saturated zones in areas surrounding culvert drainage

points (Bowling and Lettenmaier, 1997). Cuo et al. (2006) also used DHSVM to study the effects of roads on evapotranspiration, soil moisture, depth to water table, and stream discharge on the Pang Khum Experimental Watershed in northern Thailand. The 93.7 ha basin had compaction from road construction over approximately 1.2% of the area. Based upon model results, the authors found that the effects of road networks on the measured variables were small and/or negligible. Stream discharge was found to increase with the presence of road networks, but only by 3% (Cuo et al., 2006).

2.3 Watershed Modeling

2.3.1 Hydrologic Models

In recent decades, models have become a prominent research tool in forest hydrology. Computing advancements have made it possible to apply hydrologic models specifically to forested watersheds. Such tools can be extremely helpful, since paired watershed studies can be expensive and labor intensive. The modeling environment gives the researcher a platform to simulate multiple scenarios over one watershed. Detailed below are descriptions of some current hydrologic models that can be applied to forested landscapes.

WRENSS

The Water Resources Evaluation of Non-Point Silvicultural Sources (WRENSS) was developed by the US EPA in 1980 with the overarching goal of estimating the effects of silvicultural practices on water yield and quality (Swanson, 2004). The model is restricted in power by the small number of outputs, although this creates simplicity for the user (Beckers et al., 2009).

TOPMODEL

TOPMODEL is a simplistic, topography-based hydrologic model that was developed in the 1970's (Beven, 1997). It is an open source model, which gives the modeler the flexibility to adjust the model to the needs of the project. There are two main underlying assumptions required for model consistency with the TOPMODEL approach: 1) The water table changes can be

predicted by a uniform subsurface model over a unit area (a), draining at a point; and 2) the topographic slope determines the hydraulic gradient of the subsurface zone (Beven, 1997).

ForWaDy

Forest Water Dynamics, or ForWaDy, can be used in a forested environment to solve a water budget under set climatic and vegetative conditions. It was designed for ease of use, so data requirements and input parameters are minimal (Seely and Kimmins, 1997). Beckers et al. (2009) list it as a “medium-complexity” water balance model. Model advantages include the potential linkage with forest growth models, while a major disadvantage of ForWaDy is the lack of experimental use (Beckers et al., 2009). Seebacher (2007) used ForWaDy to model a water stress index as linked with Western Redcedar growth. The author found the model to be sensitive to climatic variables such as solar radiation, precipitation, and temperature (Seebacher, 2007).

WaSim-ETH

The Water Simulation Model-ETH (WaSim-ETH) is a complex distributed hydrologic model that is unique in its consideration of snow hydrology, lake and groundwater processes, and channel routing (Beckers et al., 2009; Schulla and Jasper, 2007). In simulating the hydrology of a mountainous Swiss catchment, Gurtz et al. (2003) found that WaSim-ETH was acceptable in replicating in situ hydrologic measurements and in modeling flood events.

RHESSys

The Regional Hydro-Ecological Simulation System (RHESSys) is a distributed hydro-ecological model that simulates the cycling of water, carbon and nutrients (Tague and Band, 2004). The intermediary complexity of the model requires climatic, spatial, vegetative, soils, and land-use history inputs. Applications of the model include predictions of streamflow and soil moisture fluxes under changing land use (Tague and Band, 2004). Beckers et al. (2009) list drawbacks of RHESSys to be the level of difficulty for users and the high parameter inputs. However, these downfalls can be offset by the ability of the model to function both hydrologically and ecologically.

DHSVM

The Distributed Hydrology Vegetation Model (DHSVM) is highly complex, but functionally powerful model (Beckers et al., 2009). It is described in more detail in the following section.

2.3.2 The Distributed Hydrology Soil Vegetation Model

The Distributed Soil Hydrology Vegetation Model (DHSVM) is a physically based model that represents watershed processes at the scale of a digital elevation model (DEM) (Wigmosta et al., 2002). The use of distributed models is becoming increasingly important in hydrologic predictions because they allow the user to utilize available spatial data for both input and testing. DHSVM has been used to analyze the effects of land use change, harvesting, and road networks on streamflow in forested, mountainous environments throughout the world (Bowling and Lettenmaier, 1997; Bowling et al., 2000; Cuo et al., 2006; Doten and Lettenmaier, 2004; Doten et al., 2006; VanShaar et al., 2002). It has also been used in hydrologic modeling (Haddeland and Lettenmaier, 1995; Kenward and Lettenmaier, 1997; Westrick et al., 2002; Wigmosta et al., 1994; Wigmosta and Lettenmaier, 1999) and to look at the interactions between climate and climate change and hydrology (Arola and Lettenmaier, 1996; Leung and Wigmosta, 1999; Wigmosta et al., 1995).

DHSVM works by explicitly calculating the energy and water budgets for a catchment at the scale of a grid cell. DHSVM integrates user-defined inputs for meteorological, soil, vegetation, and stream and road morphology data to model evapotranspiration, snow influx and efflux, and the movement of unsaturated soil moisture, saturated subsurface flow, overland flow, and channel flow. This is completed for each grid cell at a specified time step. Outputs of the model include but are not limited to water yield, soil moisture, overland flow, and evapotranspiration. More detailed information can be found in Wigmosta et al. 1994 and 2002.

Since DHSVM requires a high number of inputs, calibration of the model for parameters that cannot be measured is necessary. Bowling and Lettenmaier (1997) used a calibration period of 3 years for their study on the effect of forest road systems on forested catchments in the Pacific Northwest. When calibrating the model for discharge, the authors had to adjust LAI,

lateral hydraulic conductivity, deep layer soil depth, height of road cuts, and decrease in lateral hydraulic conductivity. In general, the model under predicted the base flows and over predicted storm peaks (Bowling and Lettenmaier, 1997).

Cuo et al. (2006) used DHSVM to simulate the effects of road networks on hydrological processes in Northern Thailand. During calibration, the authors found that the model adequately replicated soil moisture and depth but only accurately simulated streamflow for two of the three calibration years. This was attributed to year to year changes in land cover that were not reproduced in the model (Cuo et al., 2006). In an early presentation of DHSVM, Wigmosta et al. (1994) present model calibration data for a forested basin in Montana. For discharge, the model had a daily simulation RMSE of 1.2 mm and a R^2 of 0.95. The authors also found that DHSVM slightly over predicted hydrograph recession for the growing season and under predicted low flow during the dormant season (Wigmosta et al., 1994).

Literature Cited

- Arola, A. and D. Lettenmaier. 1996. Effects of subgrid spatial heterogeneity on GCM-scale land surface energy and moisture fluxes. *Journal of Climate*. 9: 1339-1349.
- Bates, N.S. 2000. *Hydrological Effects of Forest Harvesting on Headwater Watersheds in West Virginia*. B.Sc. Princeton University. Princeton, NJ.
- Beckers, J., B. Smerdon, T. Redding, A. Anderson, R. Pike, and A.T. Werner. 2009. Hydrologic models for forest management applications Part 1: Model Selection. *Watershed Management Bulletin*. 13(1): 35-44.
- Beven, K. 1997. TOPMODEL: A critique. *Hydrological Processes*. 11: 1069-1085.
- Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*. 55: 3-23.
- Bowling, L. C. and D. P. Lettenmaier. 1997. *Evaluation of the Effects of Forest Roads on Streamflow in Hard and Ware Creeks, Washington*. University of Washington Water Resources Series 155. 202 p.

- Bowling, L. C., P. Storck, and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. *Water Resources Research*. 36(11): 3223-3240.
- Brewer, M.S., R. Lee, and J.D. Helvey. 1982. Predicting peak storm flow from an undisturbed watershed in the central Appalachians. *Water Resources Bulletin*. 18(5): 755-759.
- Burt, T.P. and W.T. Swank. 1992. Flow frequency responses to hardwood-to-grass conversion and subsequent succession. *Hydrological Processes*. 6: 179-188.
- Cuo, L., T. W. Giambelluca, A.D. Ziegler, and M.A. Nullet. 2006. Use of the distributed hydrology soil vegetation model to study road effects on hydrological processes in Pang Khum Experimental Watershed, northern Thailand. *Forest Ecology and Management*. 224: 81-94.
- Doten, C. O. and D. P. Lettenmaier. 2004. *Prediction of Sediment Erosion and Transport with the Distributed Hydrology-Soil-Vegetation Model*. University of Washington Water Resources Series 178. 70 p.
- Doten, C. O., L. C. Bowling, J.S. Lanini, E.P. Maurer, and D.P. Lettenmaier. 2006. A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds. *Water Resources Research*. 42: 15.
- Douglass, J.E. and W.T. Swank. 1972. *Streamflow Modification Through Management of Eastern Forests*. USDA Forest Service Research Paper SE-94. 18 p.
- Douglass, J.E. and W.T. Swank. 1975. *Effects of Management Practices on Water Quality and Quantity: Coweeta Hydrologic Laboratory, North Carolina*. USDA Forest Service General Technical Report NE-13. 13 p.
- Douglass, J. E. and M. D. Hoover. 1988. History of Coweeta. P. 17-31 in *Forestry Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Grace, J.M. and B.D. Clinton. 2007. Protecting soil and water in forest road management. *Transactions of the American Society of Agricultural and Biological Engineers*. 50(5): 1579-1584.
- Gucinski, H., M.J. Furniss, R.J. Ziemer, and M.H. Brookes. 2001. *Forest Roads: A Synthesis of Information*. USDA Forest Service General Technical Report PNW-GTR-509. 120 p.

- Gurtz, J., M. Zappa, K. Jasper, H. Lang, M. Verbunt, A. Badoux, and T. Vitvar. 2003. A comparative study in modeling runoff and its components in two mountainous catchments. *Hydrological Processes*. 17: 297-311.
- Haddeland, I. and D. Lettenmaier. 1995. *Hydrologic Modeling of Boreal Forest Ecosystems*. University of Washington Water Resources Series Technical Report 143. 138 p.
- Harr, R.D., W.C. Harper, J.T. Krygier, and F.S. Hsieh. 1975. Changes in storm hydrographs after road building and clear-cutting on the Oregon Coast Range. *Water Resources Research*. 11: 436-444.
- Harr, R.D. 1979. Effects of timber harvest on streamflow in the rain-dominated portion of the Pacific northwest. In *Workshop on Scheduling Timber Harvest for Hydrologic Concerns*. USDA Forest Service Pacific Northwest Region, Portland, OR.
- Hewlett, J.D. and J.D. Helvey. 1970. Effects of forest clear-felling on the storm hydrograph. *Water Resources Research*. 6: 768-782.
- Hewlett, J.D. and A.R. Hibbert. 1963. Moisture and energy conditions with a sloping soil mass during drainage. *Journal of Geophysical Research*. 68(4): 1081-1087.
- Hibbert, A. R. 1966. Forest treatment effects on water yield. In *Proceedings of a National Science Foundation Advanced Science Seminar, International Symposium on Forest Hydrology*. Pergamon Press, Oxford, NY.
- Hibbert, A.R. 1969. Water yield changes after converting a forested catchment to grass. *Water Resources Research*. 5(3): 634-640.
- Hornbeck, J. W., R. S. Pierce, and C.A. Federer. 1970. Streamflow changes after forest clearing in New England. *Water Resources Research*. 6: 1124-1132.
- Jones, J. A. and G. E. Grant 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research*. 32(4): 959-974.
- Jones, J.A. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research*. 36(9): 2621-2642.
- Jones, J. A., F. J. Swanson, B.C. Wemple, and K.U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology*. 14(1): 76-85.

- Jones, J. A. and D. A. Post. 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research*. 40: 19.
- Kenward, T. and D. Lettenmaier. 1997. Assessment of required accuracy of digital elevation data for hydrologic modeling. University of Washington Water Resources Research Technical Report 153. 131 p.
- King, J. G. and L. C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in North Central Idaho. *Forest Ecology and Management*. 224: 81-94.
- Kochenderfer, J.N., P.J. Edwards, and J.D. Helvey. 1990. Land management and water yield in the Appalachians. P 523 in *Watershed Planning and Analysis in Action, Symposium Proceedings of IR Conference*. ASCE. 10 p.
- Kochenderfer, J.N., P.J. Edwards, and F.Wood. 1997. Hydrologic impacts of logging an Appalachian watershed using West Virginia's Best Management Practices. *Northern Journal of Applied Forestry*. 14(4): 207-218.
- Kochenderfer, J.N., M.B. Adams, G.W. Miller, and J. D. Helvey. 2007. *Factors Affecting Large Peakflows on Appalachian Watersheds: Lessons from the Fernow Experimental Forest*. USDA Forest Service Research Paper NRS-3. 24 p.
- Leung, L. R. and M. S. Wigmosta. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest. *Journal of the American Water Resources Association*. 35(6): 1463-1471.
- Patric, J. H. and K. G. Reinhart. 1971. Hydrologic effects of deforesting two mountain watersheds in West Virginia. *Water Resources Research*. 7(5): 1182-1188.
- Patric, J. H. 1973. *Deforestation Effects on Soil Moisture, Streamflow, and Water Balance in the Central Appalachians*. USDA Forest Service Research Paper NE-259. 12 p.
- Reinhart, K.G., A.R. Eschner, and G.R. Trimble, Jr. 1963. *Effect on Streamflow of Four Forest Practices*. USDA Forest Service Research Paper NE-1. 80 p.
- Ridel, M.S. and J.M. Vose. 2002. Forest road erosion, sediment transport, and model validation in the southern Appalachians. In *Proceedings, Second Federal Interagency Hydrologic Modeling Conference*. United States Advisory Committee on Water Information. 13 p.

- Ridel, M.S., L.W. Swift, J.M. Vose, and B.D. Clinton. 2007. Forest road erosion research at the Coweeta Hydrologic Laboratory. P 197 in *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference*. USDA Forest Service Pacific Northwest Research Station. 8 p.
- Rothacher, J. 1970. Increases in water yield following clear-cut logging in the Pacific Northwest. *Water Resources Research*. 6(2): 653-658.
- Schulla, J., and K. Jasper. 2007. *Model Description: Water balance Simulation Model ETH, The Hydrological Model System WaSiM-ETH*. WaSiM Tech. Rep. 181 p.
- Seebacher, T.M. 2007. *Western Redcedar Dieback: Possible Links to Climate Change and Implications for Forest Management on Vancouver Island, B.C.* M.Sc. Thesis, The University of British Columbia, Vancouver, BC. 136 p.
- Seely, B. and J.P. Kimmins. 1997. *A Forest Hydrology Model for Simulating the Effect of Stand Management and Climate Change on Forest Water Dynamics*. The University of British Columbia Department of Forest Sciences FESR Group. 15 p.
- Stednick, J. D. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology*. 176: 79-95.
- Sturdevant-Rees, P., J.A. Smith, J. Morrison, and M.L. Baeck. 2001. Tropical storms and the flood hydrology of the central Appalachians. *Water Resources Research*. 37(8): 2143-2168.
- Swank, W.T. and N.H. Miner. 1968. Conversion of hardwood-covered watersheds to White Pine reduces water yield. *Water Resources Research*. 4(5): 947-954.
- Swank, W.T. and J.D. Helvey. 1970. Reduction of streamflow increases following regrowth of clearcut hardwood forest. In *Proceedings, Symposium on the Results of Research on Representative and Experimental Basins*. IASH-Unesco. Leuven, Belgium. 15 p.
- Swank, W.T. and J.E. Douglass. 1974. Streamflow greatly reduced by converting deciduous hardwood stands to pine. *Science*. 185: 857-859.
- Swank, W.T., J.E. Douglass, and G.B. Cunningham. 1982. Changes in water yield and storm hydrographs following commercial clearcutting on a Southern Appalachian catchment. P 583 in *Hydrological Research Basins and Their Use in Water Resource Planning: Proceedings of the International Symposium*. Landshydrologie. Bern, Switzerland. 12 p.

- Swank, W.T., L.W. Swift, and J.E. Douglass. 1988. Streamflow Changes Associated with Forest Cutting, Species Conversions, and Natural Disturbances. P. 297-312 in *Forest Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Swank, W.T. and J.M. Vose. 1994. Long-term hydrologic and stream chemistry responses of southern Appalachian catchments following conversion from mixed hardwoods to white pine. P 164 in *Hydrologie kleiner Einzugsgebiete: Gedenkschrift Beitrage zur Hydrologie der Schweiz*. Landolt, R. (ed.). Bern, Switzerland 35 p.
- Swank, W. T., J. M. Vose, and K.J. Elliott. 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management*. 143: 163-178.
- Swanson, R.H. 2004. The complete WRENS hydrologic model. Poster presented at *Western Snow Conference*. Richmond, B.C. 5 p.
- Swift, L.W. and W.T. Swank. 1981. Long term responses of streamflow following clearcutting and regrowth. *Hydrological Sciences Bulletin*. 26(3): 245-256.
- Swift, L.W. 1982. Duration of stream temperature increases following forest cutting in the Southern Appalachian Mountains. P 273 in *International Symposium on Hydrometeorology*. American Society of Civil Engineers. 3 p.
- Tague, C. L., and L.E. Band. 2004. RHESSys: Regional Hydro-Ecologic Simulation System-an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient. *Earth Interactions*. 8(19): 42.
- Thomas, R.B. and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. *Water Resources Research*. 32(12): 3393-3403.
- VanShaar, J. R., I. Haddeland, and D.P. Lettenmaier. 2002. Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. *Hydrological Process*. 16: 2499-2520.
- Westrick, K. J., P. Storck, and C.F. Mass. 2002. Description and evaluation of a hydrometeorological forecast system for mountainous watersheds. *Weather and Forecasting*. 17: 250-262.

- Wigmosta, M. S., L. W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resources Research*. 30: 1665-1679.
- Wigmosta, M. S., L. R. Leung, and E.J. Rykeil. 1995. Regional modelling of climate-terrestrial ecosystem interactions. *Journal of Biogeography*. 1: 453-465.
- Wigmosta, M. S. and D. P. Lettenmaier. 1999. A comparison of simplified methods for routing topographically driven subsurface flow. *Water Resources Research*. 35(1): 255-264.
- Wigmosta, M. S., B. Nijssen, and P. Storck. 2002. The Distributed Hydrology Soil Vegetation Model. P 7-42 in *Mathematical Models of Small Watershed Hydrology and Applications*. V. P. Singh and D. Frevert. Water Resources Publications.
- Wright, K. A., K. H. Sendek, R.M. Rice, and R.B. Thomas. 1990. Logging effects on streamflow: storm runoff at Casper Creek in Northwestern California. *Water Resources Research*. 26(7): 1657-1667.
- Ziemer, R.R. 1981. Storm flow response to road building and partial cutting in small streams of Northern California. *Water Resources Research*. 17(4): 907-917.

CHAPTER 3. DHSVM INPUTS AND CALCULATIONS

The distributed hydrology-soil-vegetation model (DHSVM) is a highly parameterized model that requires extensive inputs. DHSVM was selected for this project due to its ability to model road effects on hydrology, however the complexity and non-user friendly nature of the program require extensive knowledge of the inputs. Thus, this chapter (along with Appendix A) is intended to serve as a user manual for future users. The model and basic user guidelines can be downloaded from the DHSVM website interface (Land Surface Hydrology Research Group, 2006). This manual describes steps that were used to run the model specifically for the Coweeta watershed in western North Carolina.

3.1 Coweeta Spatial Data

3.1.1 Elevation

DHSVM requires a digital elevation model (DEM) in binary format. The DEM defines the grid cell scale at which the all hydrologic calculations are modeled. A DEM was obtained for the Coweeta study site, which is located in the Prentiss Quadrangle in western North Carolina. The data were obtained from the Geo Community, which offers free GIS and geospatial data to community members (GeoCommunity, 2007). The 30 m Prentiss DEM was downloaded in Spatial Data Transfer Standard (SDTS) format and converted to a raster grid. It was then converted into a 2D binary format. A finer resolution of 10 m was desired; however DHSVM requires that stream and road dimensions be contained within the grid cell. This was a noted constraint of the model. The 10 m resolution also increased model processing time increased fourfold. Thus, the 30 m resolution was considered ideal.

3.1.2 Watershed

The watershed input is a binary file that outlines the study area to be analyzed. The 760 ha Shope Fork catchment, located in the northern boundary of Coweeta, was manually delineated using ESRI ArcMap version 9.2 (Hillier, 2007). This was based on the current Coweeta boundary, the 30 m Prentiss DEM, and the internal watershed boundaries. Multiple methods of watershed delineation are possible, but it is important to verify that all cells that contribute water

to the catchment are included in the boundary of the watershed. All watershed boundary shape files were obtained from the Coweeta Hydrologic Lab. GIS input layers were then clipped to the watershed extent for model input.

3.1.3 Soil Type

Soil input parameters required by DHSVM may be obtained from an appropriate soil type map. As with elevation, the map must be in 2D binary format. Soil data for the Coweeta Basin were obtained from the Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database (Soil Survey Staff, 2008). SSURGO data were preferred over other data sources due to the fine mapping resolution (1:12,000 to 1:63,360). DHSVM usually requires coarse resolution soil data that are often aggregated by soil texture. Due to the availability of the data, soil types for Shope Fork were mapped and input based on soil series rather than soil texture (Table 3.1).

3.1.4 Soil Depth

DHSVM has been found to be very sensitive to soil depth during its hydrologic simulation process (Surfleet, 2008), so a detailed soil depth map was imperative for accuracy of the model calibration. A soil depth algorithm is present within the DHSVM pre-processing steps (see Appendix A), although the precision of this algorithm is uncertain. Surfleet (2008) found that, when compared to other estimations of soil depth, the soil depth model provided by DHSVM was the best at predicting field measurements of soil depth. However, this occurred when the weighted values and the power exponents for the soil depth variables (elevation, slope, and area) were fitted to match the field measurements. Since few field measurements were taken for this study, maximum soil depths were taken from the Macon County Soil Survey (Thomas et al., 1996). Soil depths in the Shope Fork catchment ranged from 0.43 to 2.03 m.

Table 3.1 Soil series found in the Shope Fork Catchment.

Soil Series	Taxonomic Classification
Burton*	Coarse-loamy, mixed, frigid Typic Haplumbrepts
Cashiers	Coarse-loamy, micaceous, mesic Umbric Dystrocrepts
Chandler	Coarse-loamy, micaceous, mesic Typic Dystrochrepts
Chestnut*	Coarse-loamy, mixed, mesic Typic Dystrochrepts
Cleveland*	Loamy, mixed, mesic Lithic Dystrocrepts
Cowee*	Fine-loamy, mixed, mesic Typic Hapludults
Craggey*	Loamy, mixed, frigid Lithic Haplumbrepts
Cullasaja*	Loamy-skeletal, mixed, mesic Typic Haplumbrepts
Edneyville*	Coarse-loamy, mixed, mesic Typic Dystrochrepts
Evard*	Fine-loamy, oxidic, mesic Typic Hapludults
Fannin	Fine-loamy, micaceous, mesic Typic Hapludults
Plott	Coarse-loamy, mixed, mesic Typic Haplumbrepts
Saunook	Fine-loamy, mixed, mesic, Humic Hapludults
Trimont	Fine-loamy, mixed, mesic, Humic Hapludults
Tuckasegee*	Fine-loamy, mixed mesic Typic Haplumbrepts
Wayah	Coarse-loamy, mixed, frigid Typic Haplumbrepts
Whiteside*	Fine-loamy, mixed, mesic Aquic Hapludults

*Series occurs in a complex with another series.

3.1.5 Vegetation

The cover type map file is similar to the soil map file in that it is linked to the DHSVM vegetation input parameters. Land cover data for the Coweeta basin were originally obtained from the Coweeta Geographic Network (Coweeta LTER, 2008). Data were in 2001 National Land Cover Dataset (NLCD) format. However, these data were deemed too coarse for model input. Four cover types (Table 3.2) were delineated based upon elevation and slope aspect (Bolstad et al., 198; Day et al., 1988).

Table 3.2 DHSVM cover types for the Shope Fork catchment.

Cover Type	Possible Species Present
Northern Hardwoods	<i>Acer saccharum</i> , <i>Tilia spp.</i> , <i>Betula alleghaniensis</i> , <i>Aesculus octandra</i> , <i>Acer rubrum</i>
Cove Hardwoods	<i>Liriodendron tulipifera</i> , <i>Betula lenta</i> , <i>Magnolia spp.</i> , <i>Rhododendron spp.</i>
Mixed Deciduous	<i>Quercus alba</i> , <i>Quercus rubra</i> , <i>Robinia pseudoaccacia</i> , <i>Carya spp.</i> , <i>Acer rubrum</i>
Xeric Oak-Pine	<i>Quercus coccinea</i> , <i>Quercus prinus</i> , <i>Oxydendrum arboreum</i> , <i>Pinus rigida</i> , <i>Kalmia latifolia</i>

Sources: Day et al., 1988 and Bolstad et al., 1998

3.2 Coweeta Network Files

DHSVM employs two types of networks: streams and roads. Three input files are needed for each network. Arc macro language (AML) is used to assign some of these parameters, the rest are user-defined. Coweeta stream and road shape files were downloaded from the LTER COGENT data.

3.2.1 Stream Networks

3.2.1.1 Stream Class File

The class file contains routing information for the network as it relates to each stream order. This file is downloaded from the DHSVM website (Land Surface Hydrology Research Group, 2006) and edited manually. Coweeta stream class variables were chosen based on field measurements and literature (Appendix B). At the sampling site, Shope Fork is a third order stream (Figure 3.1). The following variables are needed for the stream class file:

- 1) *Channel ID*

The channel ID is a unique identifier for each stream class. It must be a positive integer.

2) *Hydraulic Width (m)*

The hydraulic width is used to calculate the volume of storage in the stream. It corresponds to the width of the main stream channel, or the channel at bankfull discharge. This is the discharge at which flow is most effective at forming a channel and can be above or below the defined stream channel in some cases. The widths of the streams for the Coweeta Basin were based on field measurements.

3) *Hydraulic Depth (m)*

This is the depth of the stream channel. Input depths for the Coweeta Basin were based on field measurements.

4) *Friction Coefficient*

The friction coefficient refers to Manning's n for the stream channel. This input is not used during stream calculations, but DHSVM requires that the field be filled.

5) *Maximum Infiltration (m/s)*

This input is not actually used during stream routing, but DHSVM requires that the field be filled. Zero values will suffice.

3.2.1.2 Stream Map File

The stream map file links physical stream data (length, depth, width, etc.) to cell locations. It is automatically generated using the create stream network AML. Some modifications to the AML may be necessary for specific watersheds (Appendix A and Appendix B). The file contains the following information:

1) *Column Number*

This is the column number of the grid cell. It starts in the western portion of the grid.

2) *Row Number*

This is the row number of the grid cell. It starts in the northern portion of the grid. The model assigns the NW corner cell the value of 0,0.

3) *Channel ID*

The channel ID identifies the channel segment and will correspond to a value in the stream network file.

4) *Length (m)*

This is the straight distance length measurement of the channel segment.

5) *Depth (m)*

The depth refers to the stream bank height.

6) *Width (m)*

This is the width of the stream channel.

7) *Sink Indicator*

If the word *sink* appears, the model assumes that a sink is present. Water in this cell will return to the cell rather than being routed through the grid.

3.2.1.3 Stream Network File

The stream network file is similar to the stream class file in that it contains information that is common to similar segments of the stream. Like the stream map file, the stream network file is automatically generated by the create stream network AML script (Appendix A). The AML will output the following parameters:

1) *Channel ID*

The channel ID is a unique identifier for the channel segment. It will correspond to a segment in the stream map file.

2) *Segment Order*

The segment order is a code that tells the model the order of routing calculations. Segments that have a lower order are routed first and thus flow into segments of a higher order.

3) *Segment Slope ($m\ m^{-1}$)*

This is the slope of the channel segment.

4) *Channel Class ID*

This is the class of the stream channel and will refer to a class specified in the stream class file.

5) *Destination Channel ID*

This identifies the segment in which the segment will flow. The basin outlet has a destination channel ID of 0.

6) *Save Indicator*

Routing results can be saved to an output file if the word *save* appears.

3.2.2 Road Networks

The input files for road networks are almost identical to stream networks. Nevertheless, they are detailed below since there are some slight changes in the files.

3.2.2.1 Road Class File

The class file contains routing information for the network as it relates to each road order. This file is downloaded and edited manually. See Appendix B for the Coweeta Road Class file. The following variables are needed for the road class file:

1) *Channel ID*

The channel ID is a unique identifier for each road class. It must be a positive integer.

2) *Hydraulic Width (m)*

For roads, the hydraulic width refers to the dimension of the ditch along the road. In this case, it is the width of the ditch. The width of the Coweeta road classes were found using measurements taken on site.

3) *Hydraulic Depth (m)*

The hydraulic depth is the depth of the road ditch. Coweeta road network depths were based on field measurements.

4) *Friction Coefficient*

The friction coefficient refers to Manning's n for the road ditch. Manning's n is also required for the road surface; this is used as part of the mass wasting model. Values were found using Table 5.3 in Gordon et al. (2004). Class 1 roads were assumed to be coarse gravel while class 3 roads were considered fine gravel. Coweeta class 5 roads are typically closed service roads that are covered in vegetation; these were considered young trees intergrown with weeds. Lastly, class 7 roads are walkways or trails and these were assumed to be earth. Ditches were all assumed to be composed of earth.

5) *Maximum Infiltration ($m s^{-1}$)*

This is the maximum infiltration rate through the surface of the road ditch. Values were kept constant with those found in the DHSVM tutorial.

6) *Road Type*

The road type refers to the crown of the road. DHSVM allows three options: crowned, insloped, and outsloped. The default value is outsloped. Assigned road types were based off of visual observations.

7) *Road/Overland Erodibility Coefficients*

These are used in the mass wasting model and refer to the detachability of a soil particle upon raindrop impact. The road erodibility coefficients were found by using the average

watershed k values in the SSURGO revised universal soil loss equation (RUSLE) report (Soil Survey Staff, 2008).

8) *d₅₀ (m)*

d_{50} is the mean particle size diameter for the road surface. This is used in the mass wasting model. This was based on visual observation.

9) *Surface*

This input refers to the surface of the road. DHSVM allows three options: paved, unpaved, or dirt. Surface inputs were based on visual observations.

10) *Road Width (m)*

This is the road width for each class and does not include the corresponding ditch. Like the hydraulic width and depth, the road width inputs are based on field measurements.

3.2.2.2 Road Map File

The road map file links physical road data (length, depth, width, etc.) to cell locations. It is automatically generated using the create road network AML (Appendix A). The output file contains the following information:

1) *Column Number*

This is the column number of the grid cell. It starts in the western portion of the grid.

2) *Row Number*

This is the row number of the grid cell. It starts in the northern portion of the grid. The model assigns the NW corner cell the value of 0,0.

3) *Channel ID*

The channel ID identifies the road segment and will correspond to a value in the road network file.

4) *Length (m)*

This is the straight line length measurement of the road segment.

5) *Depth (m)*

The depth refers to the road ditch height.

6) *Width (m)*

This is the width of the road.

7) *Sink Indicator*

If the word *sink* appears, the model assumes that a sink is present. Water in this cell will return to the cell rather than being routed through the grid.

3.2.2.3 Road Network File

The road network file is similar to the road class file in that it contains information that is common to similar segments. Like the road map file, the road network file is automatically generated by the create road network AML script (Appendix A). The AML will output the following parameters:

1) *Channel ID*

The channel ID is a unique identifier for the channel segment. It will correspond to a segment in the road map file.

2) *Segment Order*

The segment order is a code that tells the model the order of routing calculations. Segments that have a lower order are routed first and thus flow into segments of a higher order.

3) *Segment Slope ($m\ m^{-1}$)*

This is the slope of the road segment.

4) *Channel Class ID*

This is the class of the road channel and will refer to a class specified in the road class file.

5) *Destination Channel ID*

This identifies the segment in which the segment will flow. The basin outlet has a destination channel ID of 0.

6) *Save Indicator*

Routing results can be saved to an output file if the word *save* appears.

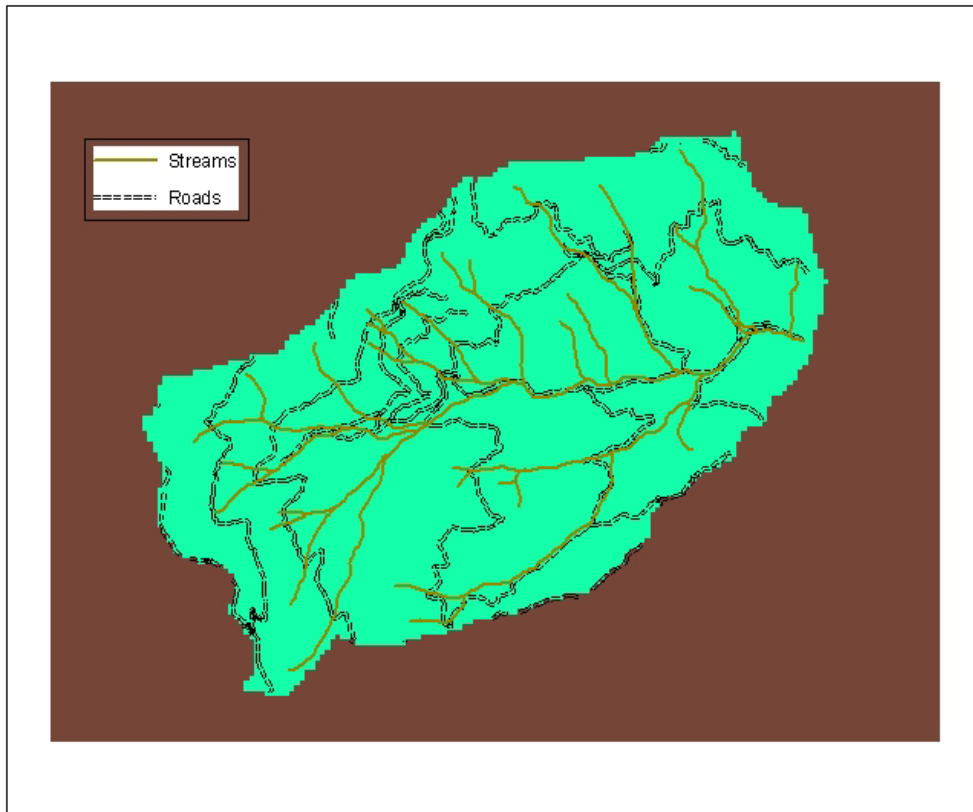


Figure 3.1 Coweeta stream and road networks. Stream networks created by CreateStreamNetwork AML, road networks provided by Coweeta.

3.3 Coweeta Meteorological Data

Meteorological data for the model must be provided and DHSVM allows a variety of formats. It will accept ASCII input, MM5, or PRISM data. The model is designed to run on an hourly timestep; a daily timestep is considered coarse and is not recommended. Many studies have used 3-hour timesteps (Bowling et al., 2000; Doten et al., 2006; LaMarche and Lettenmaier, 2001). Data were provided by the Coweeta Hydrologic Lab. One climate station was present within the boundary, as well as two rain gages. For initial testing, only one climate station was used (CS01 and RG06). Input values are used for the entire catchment and are weighted using a Cressman approach (Cressman, 1959). Data manipulations are described below.

1) *Precipitation (m)*

Hourly precipitation data for the watershed were obtained in hundredths of inches and were subsequently converted to meters. Missing values were assumed to be zero. There were no cases of missing data during a recorded rainfall event.

2) *Air Temperature ($^{\circ}\text{C}$)*

Minimum, maximum, and average hourly air temperature in degrees C were given for the climate station. Average air temperature values were used.

3) *Wind Speed (m s^{-1})*

The average hourly wind speed was obtained for the watershed. Units were already in m s^{-1} and no data manipulation was necessary.

4) *Relative Humidity (%)*

Similar to the wind speed, the hourly percent relative humidity was acquired for the watershed and no data manipulation occurred.

5) *Incoming Shortwave Radiation (W m^{-2})*

Coweeta records the hourly incoming shortwave radiation in Langley. Converting from Langley to Watt hours per square meter required a conversion factor of 11.62.

6) *Incoming Long-wave Radiation ($W m^{-2}$)*

Coweeta does not record incoming long-wave radiation, so this data had to be interpreted from the known meteorological data using the following equations (Prata, 1996). It should be noted that the subsequent calculation is for clear-sky emissivity and does not account for cloudiness, which can greatly affect incoming long-wave radiation.

$$(Eq. 1) \quad L \downarrow = \left[(1 - (1 + \xi)^{\left\{ -(1.2 + 3.0\xi)^{\frac{1}{2}} \right\}}) \right] \sigma T_0^4$$

Where:

$L \downarrow$ = incoming longwave radiation in $W m^{-2}$

σ = Stephan-Boltzmann constant and is equal to 5.67×10^{-8}

ξ = precipitable water and can be found by:

$$(Eq. 2) \quad \xi = 46.5 \frac{e_0}{T_0}$$

Where:

e_0 = actual vapor pressure in hPa and can be found by:

$$(Eq. 3) \quad e_0 = \frac{RH/100}{e_s}$$

Where:

RH = relative percent humidity

e_s = saturated vapor pressure hPa and can be found by:

$$(Eq. 4) \quad e_s = 6.11 \times 10^{\frac{7.5T}{237.7+T}}$$

Where:

T_0 = the screen level temperature in K

3.4 DHSVM Configuration File

The DHSVM configuration file relays all of the input variables to the model. It contains information on the model settings, file path names, soil and vegetation parameters, and output conditions. Many of the model variables are detailed below. See Appendix B for a complete copy of the Coweeta configuration file.

3.4.1 Model Constants

This section includes model parameters that stay constant throughout time and space during the model calculations.

1) *Ground/Snow Roughness (m)*

The roughness length refers to the height above the displacement plane (in this case, the ground) at which the mean wind speed becomes zero (Glickman, 2000). A lower roughness length indicates more interaction between the ground surface and the wind profile and thus stronger winds close to the ground. Smoother, snow covered surfaces will have a lower roughness length than forested surfaces. Davenport (1960) classified effective terrain roughness. The Coweeta vegetative cover was classified as “skimming” to “chaotic” while snow roughness was considered “smooth” since the Coweeta snow cover would rarely cover enough vegetation to consider it “featureless.”

2) *Rain/Snow Threshold (°C)*

These values set the minimum temperature at which rainfall can occur and the minimum temperature at which snowfall can occur. These temperatures are not exactly at 0°C, as one might expect. However, they are dependent upon the surface air temperature, the dew point, and the wet bulb temperature (Ahrens, 2002). The threshold values become increasingly important and complicated in the Southern and Mid-Appalachian regions, where much of the winter precipitation falls in the form of sleet and freezing rain as opposed to snow. The rain and snow thresholds were set at -1°C as opposed to 0°C to account for these forms of precipitation.

3) *Snow Water Capacity*

The liquid water holding capacity of snow is dependent upon many factors, including the regional topography, ice layer characteristics, and snow density (Singh and Singh, 2001). The impact of snowpack hydrology is not a large factor in the Coweeta basin, although some annual snowfall does occur. A rough estimate of 2.5% liquid water holding capacity at a snowpack of 0°C is suggested for low snow densities (100 to 350 kg m⁻³).

4) *Reference Height (m)*

The reference height is the height at which all meteorological observations are taken. For modeling purposes, this must be at least 10 meters above the highest canopy height. The highest canopy height was the cove hardwoods (35.5 m), so the reference height was set to 46 m.

5) *Rain/ Snow LAI Multiplier*

DHSVM models the maximum interception storage capacity using an LAI multiplier for rain, as found in Dickinson et al. (1991).

$$\text{(Eq. 5)} \quad \textit{Interception}_{max} = \textit{LAI Multiplier} \times \textit{LAI} \times \textit{Fractional Coverage}$$

LAI at Coweeta averages 6.2 m² m⁻² (Monk and Day, 1988) for overstory vegetation and maximum interception is approximately 3 mm (Helvey and Patric, 1988). Assuming 90% canopy cover, the LAI rain multiplier for Coweeta is 0.00054. DHSVM recognizes no distinction between rain and snow when modeling storage interception (Wigmosta et al., 1994).

6) *Minimum Intercepted Snow*

The minimum intercepted snow is used in the snowpack model and is not critical to the calibration of hydrologic modeling in the southern Appalachian Mountains. Storck (2000) found that the minimum amount of intercepted snow that can be melted or sublimated off the canopy to be 5 mm. Since this value was observed in the Pacific

Northwest where snowfall is much higher and snow interception is larger, this value was arbitrarily pared down to 3 mm.

7) *Temperature Lapse Rate ($^{\circ}\text{C}/\text{m}$)*

The temperature lapse rate can be set to constant or variable settings. For simplification purposes, temperature was assumed to change consistently with elevation. Gaffin et al. (2002) conducted a study in the Great Smoky Mountains National Park, which lies just west of the Coweeta Hydrologic Lab. The park has much higher elevations than the study site, but for the scope of this review it was assumed that the temperature lapse rates were approximately equal for the two areas. Gaffin et al. (2002) found the temperature lapse rates in the Great Smoky Mountains average $3.3\text{ }^{\circ}\text{F } 1000\text{ ft}^{-1}$, which converted to a lapse rate of $-0.0018\text{ }^{\circ}\text{C m}^{-1}$.

8) *Precipitation Lapse Rate (m m^{-1})*

The lapse rate for precipitation can be set to constant or variable settings. For simplification purposes, precipitation was assumed to change consistently with elevation. Swift et al. (1988) found that, in the Coweeta basin, precipitation increases with elevation on the east-west axis but the lapse rate is static along the north-south axis. For DHSVM purposes, Coweeta was assumed to have a lapse rate of 0.00025 m m^{-1} .

3.4.2 Soil Inputs

DHSVM requires numerous soil input parameters for each soil type and within each of these soil types, numerous inputs for each horizon (Refer back to Table 3.1 for soil types). All parameters are required for each individual soil type. A * indicates that the parameter is required for each soil horizon within an individual soil type.

1) *Lateral Saturated Hydraulic Conductivity (m s^{-1})*

The saturated hydraulic conductivity is the volume of unit water that will flow through a medium (saturated soil in this case) in a given unit of time. Hydraulic conductivity can be saturated or unsaturated and can be vertical or horizontal. In a clayey soil, Miwa (1999)

found that lateral hydraulic conductivity in the upper soil horizon was 6.96 m d^{-1} . Hydraulic conductivity will increase as soil particle size increases, so this value was used as a base value to determine the lateral saturated hydraulic conductivities for the Coweeta soils.

2) *Exponential Decrease*

When calculating the rate of saturated subsurface flow within the watershed, the lateral hydraulic conductivity for each soil was assumed to decrease exponentially with depth (Equation 2.48 in Wigmosta et al., 2002). Beven (1982) found that observed soil hydraulic conductivities among various studies yielded in a decay coefficient between 1 and 9. For Ohio and Pennsylvania, exponential decreases were in the order 4.0.

3) *Maximum Infiltration (m s^{-1})*

The rate at which water moves into the soil surface is known as the infiltration capacity. When the infiltration rate for a soil has reached its maximum, no more infiltration can occur and surface runoff or ponding will result. The maximum infiltration rate is dependent upon many soil characteristics, including texture, structure, and the presence of restricting layers. A rough estimate of the soil infiltration rate was found in Table 12.1 of Hillel (1982).

4) *Capillary Drive (m)*

Capillary suction (ψ) measures the adhesive forces that bind water molecules to soil particles and the cohesive forces that bind water particles to each other. Capillary suction increases with decreasing water content, since unsaturated water is held under tension. Capillary suction is dependent upon the soil moisture, soil texture, and position within the soil horizon although generic values can be determined for different soil textures. For DHSVM input, Green-Ampt infiltration parameters were used from Table 1.7 in Bedient et al. (2008).

5) *Surface Albedo*

The surface albedo is the fraction of incoming radiation that is reflected by that surface. It can be as low as 0.1 for dark surfaces and as high as 0.5 for lighter surfaces (Brady and Weil, 2004). DHSVM uses albedo when modeling snowpack hydrology. The dry surface albedos for the Shope Fork soils were found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

6) *Porosity**

Soil porosity is the percent volume of the soil bulk that is not occupied by solid particles. The porosity is extremely important in hydrologic calculations as it determines how much available pore space the soil has for water. The porosity for each soil was found using the following equation from Burger (2008):

$$(Eq. 6) \quad Total\ Porosity = \frac{2.65 - Bulk\ Density}{2.65}$$

The mean soil bulk density was found in the SSURGO *Physical Soil Properties* report (Soil Survey Staff, 2008). For soil complexes, the porosity was weighted based on the percent of map unit covered by that particular series. In the case where the map unit percents did not add to 100 percent of the area, the missing area was divided equally amongst the series in the complex. Map unit percents were found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

7) *Pore Size Distribution**

The volume of the various sizes of pores in a soil is known as the pore size distribution (Brady and Weil, 2004). Although usually expressed as a percentage of the bulk soil volume, it can also be measured using the Brooks-Corey Index, as shown in Equation 7 (Rawls et al., 1993). DHSVM uses the pore size distribution when modeling the percolation of water through the soil column.

(Eq. 7)
$$\lambda = \exp[-0.7842831 + 0.0177544(S) - 1.062498(\phi) - 0.00005304(S^2) - 0.00273493(C^2) + 1.11134946(\phi^2) - 0.03088295(S)(\phi) + 0.00026587(S^2)(\phi^2) - 0.00610522(C^2)(\phi^2) - 0.00000235(S^2)(C) + 0.00798746(C^2)(\phi) - 0.00674491(\phi^2)(C)]$$

Where:

λ = Brooks-Corey pore-size distribution index

C = percent clay (5 < % < 60)

S = percent sand (5 < % < 70)

Φ = porosity (volume fraction)

The percent clay and percent sand were found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

8) *Bubbling Pressure (m)**

The bubbling pressure refers to the air pressure that is required to force air through a porous cup. The bubbling pressure is used when calculating desorption in the model, which is part of the movement of unsaturated soil moisture. Bubbling pressure was found using the Brooks-Corey Index, as found in Table 5.3.3 in Rawls et al. (1993).

(Eq. 8)

$$h_b = \exp[5.3396738 + 0.1845038(C) - 2.48394546(\phi) - 0.00213853(C)^2 - 0.04356349(S)(\phi) - 0.61745089(C)(\phi) + 0.00143598(S)^2(\phi^2) - 0.00855375(C^2)(\phi^2) - 0.00001282(S^2)(C) + 0.00895359(C^2)(\phi) - 0.00072472(S^2)(\phi) + 0.0000054(C^2)(S) + 0.50028060(\phi^2)(C)]$$

Where:

h_b = Brooks-Corey bubbling pressure

C = percent clay (5 < % < 60)

S = percent sand (5 < % < 70)

Φ = porosity (volume fraction)

The percent clay and percent sand were found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

9) *Field Capacity**

Field capacity is the percent water held at -0.33 bars. This is the water that is available for plant uptake and is important when modeling soil moisture, which is consequently the basis of many calculations used by the model. Field capacity was found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

10) *Wilting Point**

Wilting point is the percent water in the soil that is held at -15 bars. This is water that is unavailable at plants. Like field capacity, the wilting point is also used to calculate soil moisture. The wilting point was found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

11) *Bulk Density ($kg\ m^{-3}$)**

The soil bulk density is the mass of the soil per unit volume. The bulk density was found in the SSURGO *Physical Soil Properties* report (Soil Survey Staff, 2008). The table gives the moist bulk density in $g\ cm^{-3}$. This was converted to the DHSVM required units, $kg\ m^{-3}$, by multiplying by 1000. The bulk density was found for each individual soil layer within the series and then weighted to get the bulk density for the DHSVM soil type.

12) *Vertical Conductivity ($m\ s^{-1}$)**

The vertical conductivity of the soil is the maximum rate of saturated hydraulic conductivity, or k_{sat} . This value was taken as the maximum value found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008). The data were converted to $m\ s^{-1}$.

13) *Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)**

The thermal conductivity of a soil explains the soil's ability to transmit heat, mainly through conduction and is usually defined as the quantity of heat that flows through a unit

area in a unit time under a unit temperature gradient (Jackson and Taylor, 1986). Thermal conductivity is extremely variable and is dependent on soil bulk density, particle arrangement, temperature, and, most importantly, soil volumetric water. Since thermal conductivity is time variable, the thermal conductivity of the solids was found using an equation from Bowling and Letttenmaier (1997).

$$(Eq. 9) \quad TC = \frac{S*TC_{quartz} + C*TC_{clay}}{S+C}$$

Where:

TC = Effective solids thermal conductivity

S = Percent sand fraction

C = Clay fraction

TCquartz = 8.8 W m⁻¹ K⁻¹ Thermal conductivity of quartz (Hillel, 1982)

TCclay = 2.9 W m⁻¹ K⁻¹ is the thermal conductivity of clay

The percent sand and clay fractions were found in the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

14) Thermal Capacity (J m⁻³ °K⁻¹)*

The thermal heat capacity of a soil is the change in heat content of a unit bulk volume of soil per unit change in temperature. The thermal capacity is dependent upon the soil bulk density, the solid phase, and the volumetric water and is thus variable throughout time. Most soil constituents have a heat capacity around 2.0 x 10⁶ J m⁻³ °K⁻¹ (Hillel, 1982).

15) Manning's n*

Manning's roughness coefficient (*n*) estimates the roughness of a channel material and is not typically used to describe a soil particle or the soil surface. These values were assigned based on the soil texture particle size as determined by USDA definitions (Figure 5.1.1 in Rawls et al., 1993). Manning's roughness was then determined for the particle size based on equation 12.2.2 from Shen and Julien (1993).

$$(Eq. 10) \quad n = \frac{(d_{50})^{1/6}}{21.0}$$

Where:

n = Manning's roughness coefficient for the particle

d_{50} = particle size diameter in meters

Soil texture for each layer was determined using the SSURGO *Wind Erosion and Prediction* report (Soil Survey Staff, 2008).

3.4.3 Vegetation Inputs

DHSVM requires 17 vegetation input parameters for each cover type and within each of these cover types, numerous inputs for each vegetation layer.

1) *Fractional Coverage**

The fractional coverage is essentially the canopy density. The fractional coverage is used when calculating the maximum storage interception capacity for the canopy. It is also used when calculating longwave and shortwave radiation budgets. Observed data were used and were verified using NASA Land Data Assimilation Systems (LDAS) data (Rodell, 2009).

2) *Trunk Space**

DHSVM requires an input for the fractional proportion that the trunk space exhibits in comparison to the entire tree height. It is used when calculating aerodynamic resistance. The height of the canopy top was taken to be the height of the tree (see Vegetation Input #9) and the height of the canopy bottom was taken to be the height of the trunk. Trunk height data were based on best known estimates.

$$(Eq. 11) \quad \text{Fractional Trunk Space} = \frac{\text{Height of Canopy Bottom (m)}}{\text{Height of Canopy Top (m)}}$$

3) *Aerodynamic Attenuation**

The aerodynamic attenuation index is a dimensionless extinction coefficient that is used to calculate the exponential wind profile through the overstory canopy (Wigmosta et al., 2002). The attenuation index is approximately between -0.3 to 3.0 and is dependent upon stage of growth and the density and flexibility of the canopy (Cionco, 1972). A mid-range value of 1.5 was used for each layer.

4) *Radiation Attenuation**

The radiation attenuation input is a dimensionless coefficient that is used to calculate the fraction of shortwave radiation transmitted by the overstory using a Beer's Law relationship (Wigmosta et al., 2002). To determine the attenuation coefficient (k_s) one must think about the shadow that the canopy casts upon the ground surface. In general, the leaves in a deciduous forest exhibit a random distribution of elevation angle (β), which is essentially the vertical angle of a leaf in relation to the ground. On average, deciduous trees also express randomness with respect to azimuth angle (θ), which is the leaf angle with respect to direction around the branch. Since both elevation angle and azimuth angles are randomly distributed, the Coweeta forest types have a spherical or ellipsoidal leaf distribution. This is because, if rearranged, the leaves of the trees can exhibit a similar distribution along a sphere as they would in nature (Monteith and Unsworth, 2007). It was found that many plants exhibit ellipsoidal distribution (Campbell, 1986), which gives the following equation for k_s (Campbell, 1986; Monteith and Unsworth, 2007):

$$(Eq. 12) \quad k_s(\beta) = \frac{(x^2 + \cot^2 \beta)^{0.5}}{x + 1.774(x + 1.182)^{-0.733}}$$

Where:

x = ratio of average projected areas of canopy elements on horizontal and vertical surfaces

For a spherical leaf distribution, $x = 1$ (Monteith and Unsworth, 2007). Assuming an elevation angle of 60° , $k_s = 0.86$.

5) *Maximum Snow Interception Capacity**

Snowfall interception is dependent upon branch strength under stress and the shape of the canopy as opposed to leaf shape, which is the dominating factor in rainfall interception. Falling snow will build up on a branch until the strength of the branch can no longer bear the weight of the snow or because the snow is unstable (usually due to melting). Branches can usually bear high snow water equivalent, resulting in larger snowfall interception capacities than rainfall interception capacities (Ward and Trimble, 2003). Helvey (1971) found that bare hardwoods have a rainfall interception capacity of 0.13 cm. In comparison, a fully developed Eastern White Pine (*Pinus strobus*) canopy has a rainfall interception capacity of 0.36 cm (Helvey, 1971) and a Western white pine (*Pinus monticola*) sapling has a snowfall interception capacity of about 0.25 cm (Haupt and Jeffers, 1967). Since appropriate snowfall interception capacity data are lacking for deciduous vegetation, the bare vegetation values were used to estimate the snow interception capacity for the Coweeta cover types.

6) *Maximum Release Drip Ratio**

In the Pacific Northwest, many studies have been conducted regarding snowmelt and snowpack hydrology. In the Southern Appalachians, runoff from snowmelt is not of primary concern. The maximum release drip ratio is the ratio of snow in the canopy that falls as snow (mass release) to the snow that melts off of the leaves (meltwater drip). Stork et al. (2002) found that, in the Pacific Northwest, a drip ratio of 0.4 was appropriate. For Coweeta, it was assumed that most snowfall events will be followed with periods of rapid melting and snow will primarily be removed from vegetation through meltwater drip, indicating a ratio closer to 0.2. This was assumed true for all vegetation types. Mass release will only occur if intercepted snow is greater than the specified snow water capacity (Andreadis et al., 2009).

7) *Snow Interception Efficiency**

The snow interception efficiency deals with the effectiveness of the canopy to intercept snowfall and prevent it from reaching the ground. It is dependent upon temperature and highly dependent upon wind speed. Storck et al. (2002) found that Douglas-fir in a

maritime climate exhibited a snow interception efficiency of 60%. Snow interception efficiency is known to be a maximum of 0.6 for dense conifers and decreases with canopy cover (Armstrong and Brun, 2008).

8) *Impervious Fraction*

The impervious fraction is the amount of impervious surface area present within the grid cell. All cover types were assumed to have an impervious fraction of zero.

9) *Height (m)*

DHSVM requires the maximum height for both the overstory and understory vegetation layers.

The cove-hardwoods understory is dominated by *Rhododendron spp.* which, in the mountains of North Carolina, reaches a maximum height of approximately 5 m (Lipp and Nilsen, 1997). We can assume that this is in open sunlight and that *Rhododendron spp.* found in the understory will be slightly shorter. The overstory of the cove-hardwoods is predominately *Liriodendron tulipifera*. The approximate height was found using a site index curve appropriate for the Southern Appalachians (Beck, 1962). Site index for all of the cover types was obtained from the Macon County soil survey and approximate stand ages were gathered from the Coweeta historical data.

Xeric-oak pine cover types are dominated by *Quercus spp.* in the overstory. Height was derived from a site index curve for upland oaks in the Southern Appalachian Mountains (Olson, 1959). *Kalmia latifolia* is the primary species found in the understory. It can reach heights up to 9 m (McNab and Clinton, 2003), although this is unlikely in an understory environment. Its minimum height of 2 m was a more appropriate estimate.

The mixed deciduous hardwoods overstory is dominated by *Quercus alba*, which is also considered an upland oak. Olson's (1959) site index curve for upland oaks in the Southern Appalachians was used to determine approximate overstory height. The height

of the understory, which is dominated by *Acer rubrum*, was assumed to be around 3.0 m (Walters and Yawney, 1990).

Acer saccharum is the prevailing species found in the northern hardwoods forest type. These heights were estimated using a site index curve found in Carmean (1978). The understory was considered the same as the mixed deciduous cover type.

10) Maximum/Minimum Resistance ($s\ m^{-1}$)

The stomatal resistance is the measure of a plant's ability to resist the diffusion of water out of the stomates. In other words, it is a measurement of the plant's ability to control transpiration. In a study conducted in New Hampshire and Maine, Federer (1977) found that *Acer rubrum* had a mean stomatal resistance of $3.5\ s\ cm^{-1}$ with a standard error of $0.19\ s\ cm^{-1}$. Maximum and minimum resistance were taken to be three standard errors from the mean. It should be noted that Federer's measurements included cuticle resistance, which is not normally part of stomatal resistance measurements. However, these values are usually found to be negligible (Federer, 1977). Federer also found that *Quercus coccinea* had a mean stomatal resistance of $3.2\ s\ cm^{-1}$ with $0.32\ s\ cm^{-1}$ standard error and that *Quercus alba* had a mean stomatal resistance of $3.0\ s\ cm^{-1}$ with $0.18\ s\ cm^{-1}$ standard error. *Acer saccharum* was found to have a mean stomatal resistance of $4.5\ s\ cm^{-1}$ with a standard error of $0.20\ s\ cm^{-1}$. McConathy and McLaughlin (1978) conducted a study in eastern Tennessee and found that *Liriodendron tulipifera* expressed a maximum stomatal resistance of $3.75\ s\ cm^{-1}$ while minimum values were $1.93\ s\ cm^{-1}$.

11) Moisture Threshold

When soil moisture falls below a certain water content, transpiration is restricted. This is considered to be 50 to 80% of the soil field capacity (Shuttleworth, 1993). The soil moisture threshold was calculated by taking the average field capacity under each vegetation type as found in the SSURGO data. Understory layers have less extensive root systems and were thus assumed to have lower moisture thresholds than overstory layers. The understory moisture threshold was set at 50% of field capacity while the overstory moisture threshold was determined to be at 80% soil field capacity.

12) Vapor Pressure Deficit (Pa)

At higher vapor pressures, plants require more exertion to carry water from the roots to the leaves. At a high enough vapor pressure, stomatal closure will occur. Wigmosta et al. (2002) list stomatal closure occurring around 4 kPa for most plants. The stomatal closure was used to calculate the overstory and understory canopy resistance.

13) R_{pc} ($W m^{-2}$)

R_{pc} is the fraction of shortwave radiation that is photosynthetically active (PAR) for each canopy layer. It is the light level where the stomatal resistance is twice that of the minimum stomatal resistance (Wigmosta et al., 2002). R_{pc} is usually between 10-50 $W m^{-2}$. Precise measurement is not necessary, but an accuracy of $\pm 20\%$ is optimal (Dickinson et al., 1991).

14) Root Zone Depths (m)

The root zone depths are essentially the depths of the soil layers, which were found in the SSURGO database, under the *Physical Soil Properties* report (Soil Survey Staff, 2008). The root zone depths were an estimated average.

15) Overstory/Understory Root Fraction

DHSVM requires data on the fraction of roots in each root zone for each canopy layer. After germination, *A. rubrum* extend a taproot to a depth of approximately 2 to 5 cm below the soil surface, upon which the root turns laterally. Feeder roots are extended vertically, primarily in the upper 8 cm of soil. Larger red maple trees will extend woody roots to depths of up to 80 cm (Walters and Yawney, 1990).

A. saccharum roots are “strong, oblique laterals with extensive branching” (Godman et al., 1990). More roots are contained in the upper soil layers than in the deeper soil layers. *L. tulipifera* root systems include deep taproots and wide spreading lateral roots (Beck, 1990), indicating a relatively equal proportion of roots in each soil layer. *Q. alba* initially develops a prolific taproot, but this is eventually replaced with a wide spreading fibrous root system. In a study in the Black Forest in Massachusetts, the deepest point of penetration was 1.2 m and the majority of the main branches were contained in the upper

53 cm of soil (Rogers, 1990). In comparison, *Q. coccinea* maintains a strong and deep taproot (Johnson, 1990).

16) Overstory/Understory Monthly LAI

Leaf area index, or LAI, is the proportion of vegetative surface area to ground surface area. LAI is seasonally variable, so monthly data are necessary for the model. LDAS (Rodell, 2009) provides estimated monthly LAI values for general cover types. The deciduous broadleaf forest values were found to be reasonable with southern Appalachian hardwood LAIs. A typical LAI at Coweeta averages 6.2 (Monk and Day, 1988), which was within the range of values provided by LDAS. The LDAS values were used for all of the overstory cover types.

In a study on great rhododendron in the Coweeta basin, Hille Ris Lambers and Clark (2005) found that LAI ranged from 0 to 4.28. *Rhododendron spp.* is a broadleaf evergreen and it is also assumed to have a constant LAI throughout the year. An average LAI of 2.2 was used for the shrub and urban cover types. This value was also used for *K. latifolia*. No data could be found for *A. rubrum* LAI, however a low value leaf area index for a maple-beech-birch forest in the Coweeta basin was 2.78 (Sampson et al., 1998). This was used in conjunction with the LDAS values to create monthly understory data for both the northern hardwoods and mixed deciduous forests.

17) Overstory/Understory Monthly Albedo

Monthly albedo data could not be found. Generic cover type data were found from LDAS (Rodell, 2009). These data were kept constant throughout the course of the year. Evergreen broadleaf values were used for both the *Rhododendron* and *Kalmia* understories while closed shrub-land values were used for the *Acer* understories. All overstory values were obtained from the deciduous broadleaf forest data.

3.4.4 Model State Files

DHSVM requires a number of model state files, which are files containing data on the initial conditions of the watershed. The state files are automatically generated (see Appendix A), although one text file (Initial State) should be edited according to watershed conditions. The Initial State file contains the following information:

1) *Model State Date*

This is the timestep that the model should begin to run. The Coweeta data began on 01/01/2003-03.

2) *Rows and Columns*

This line contains the number of rows in the binary input files followed by the number of columns. The information can be found in the binary files or from the raster grids.

3) *Vegetation Layers*

The number of vegetation layers should be listed. If all and/or some vegetation types have both an overstory and an understory, list 2. If all vegetation types only have an understory, put 1.

4) *Rain Interception (m)*

This is the rain interception for each vegetation layer. The number of inputs should match the number of vegetation layers listed in #3. Default DHSVM values were used.

5) *Snow Interception (m)*

Similar to the rain interception, this is the snow interception for each vegetation layer. Default DHSVM values were used.

6) *Snow Cover Mask*

Snow cover mask for the watershed. Default DHSVM value was used.

7) *Last Snowfall (days)*

The last snowfall lists the number of days since the last snowfall occurred.

8) *Liquid Water Content (m)*

Liquid water content of the top layer of snowpack. Default DHSVM value was used.

9) *Snowpack Temperature (°C)*

Temperature in degrees C of the current ground snowpack. Coweeta had no snowpack, and a value of freezing (0°C) was used.

10) *Cold Content*

Cold content of the snowpack. Default DHSVM value was used.

11) *Root Zone Layers*

Like the number of vegetation layers, this field lists the number of root zone layers. Put in the maximum number of layers in any soil type. Usually 3 is a typical number.

12) *Soil Moisture*

Volumetric soil moisture for each soil layer plus one extra layer. These values were taken from the SSURGO database (Soil Survey Staff, 2008).

13) *Soil Temperature (°C)*

The average temperature of the soil in degrees C. This was taken to be an average of the three root zone temperatures.

14) *Root Zone Temperature (°C)*

The average temperature of each soil layer in degrees C. These values were found in the SSURGO database (Soil Survey Staff, 2008).

15) *Ground Heat Storage*

Ground heat storage. Default DHSVM values were used.

16) *Runoff*

Runoff for the watershed. Default DHSVM values were used.

Literature Cited

- Ahrens, C.D. 2002. *Meteorology Today: An Introduction to Weather, Climate, and the Environment*, 7th Ed. Brooks Cole, Pacific Grove, CA. 624 p.
- Andreadis, K.M, P. Storck, and D.P. Lettenmaier. 2009. Modeling snow accumulation and ablation processes in forested environments. *Water Resources Research*. 45.
- Armstrong, R.L. and E. Brun. 2008. *Snow and Climate*. Cambridge University Press: New York, New York. 256 p.
- Beck, D.E. 1990. *Liriodendron tulipifera* L. In *Silvics of North America: Volume 2. Hardwoods*. R.M. Burns and B.H. Honkala (eds.). USDA Forest Service Agricultural Handbook 654 Volume 2. 877 p.
- Bedient, P.B., W.C. Huber, and B.E. Vieux. 2008. *Hydrology and Floodplain Analysis*, 4th ed. Pearson, Upper Saddle River, NJ. 795 p.
- Beven, K. 1982. On subsurface stormflow: an analysis of response times. *Hydrological Science Journal*. 12(4): 505-521.
- Bolstad, P.V., W. Swank, and J. Vose. 1998. Predicting Southern Appalachian overstory vegetation with digital terrain data. *Landscape Ecology*.13: 271-283.
- Bowling, L. C. and D. P. Lettenmaier. 1997. *Evaluation of the Effects of Forest Roads on Streamflow in Hard and Ware Creeks, Washington*. University of Washington Water Resources Series Technical Report 155. 202 p.
- Bowling, L.C., P. Storck, and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. *Water Resources Research*. 36(11): 3223-3240.
- Brady, N.C. and R.R. Weil. 2004. *Elements of the Nature and Properties of Soil*, 2nd Ed. Pearson, Upper Saddle River, NJ. 606 p.
- Burger, J.A. 2008. Work Unit IV. P. 4 in *Forest Soils Laboratory Manual*. Department of Forestry, Virginia Tech.

- Campbell, G.S. 1986. Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution. *Agricultural and Forest Meteorology*. 36: 317-321.
- Carmean, W.H. 1978. *Site Index Curves for Northern Hardwoods in Northern Wisconsin and Upper Michigan*. USDA Forest Service Research Paper NC-160. 16 p.
- Cionco, R.M. 1972. A wind profile index for canopy flow. *Boundary-Layer Meteorology*. 3(2): 255-263.
- Coweeta LTER. 2008. COGENT: GIS Data. *National Science Foundation*. Available online at: <http://coweeta.uga.edu/ecology/cogent.html>; last accessed Jan. 2008.
- Cressman, G.P. 1959. An operational objective analysis system. *Monthly Weather Review*. 87: 367-374.
- Davenport, A.G. 1960. Rationale for determining design wind velocities. *Journal Structural Design American Society of Civil Engineers*. 86: 39-68.
- Day, F. P., Jr., D. L. Phillips, and C.D. Monk. 1988. Forest Communities and Patterns. P. 141-149 in *Forestry Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Dickinson, R.E., A. Henderson-Sellers, C. Rosenzweig, and P.J. Sellers. 1991. Evapotranspiration models with canopy resistance for use in climate models, a review. *Agricultural and Forest Meteorology*. 54: 373-388.
- Doten, C.O., L.C. Bowling, J.S. Lanini, E.P. Maurer, and D.P. Lettenmaier. 2006. A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds. *Water Resources Research*. 42.
- Federer, C.A. 1977. Leaf resistance and xylem potential differ among broadleaved species. *Forest Science*. 23(4): 411-419.
- Gaffin, D.M., D.G. Hotz, and T.I. Getz. 2002. *An Evaluation of Temperature Variations Around the Great Smoky Mountains National Park and their Associated Synoptic Weather Patterns*. NOAA National Weather Service Forecast Office: Morristown, TN. 8 p.
- GeoCommunity. 2007. GIS Data Depot. *GeoCommunity*. Available online at: <http://data.geocomm.com>.
- Glickman, T.S. 2000. *Glossary of Meteorology*, 2nd Ed. American Meteorological Society, Washington, D.C. 850 p.

- Godman, R.M., H.W. Yawney, and C.H. Tubbs. 1990. *Acer saccharum*. Marsh. In *Silvics of North America: Volume 2: Hardwoods*. R.M. Burns and B.H. Honkala (eds.). USDA Forest Service Agricultural Handbook 654 Volume 2. 877 p.
- Gordon, N.D., B.L. Finlayson, T.A. McMahon, and C.J. Gippel. 2004. P 103 in *Stream Hydrology: An Introduction for Ecologists, 2nd Edition*. John Wiley and Sons. 444 p.
- Haupt, H.F. and B.L. Jeffers. 1967. *A System for Automatically Recording Weight Changes in Sapling Trees*. USDA Forest Service Research Note INT-71. 4 p.
- Helvey, J.D. 1971. A Summary of Rainfall Interception by Certain Conifers of North America. P 103-113 in *Proceedings of the Third International Seminar for Hydrology Professors: Biological Effects in the Hydrologic Cycle*. E.J. Monke (Ed.). Purdue University, West Lafayette, IN.
- Helvey, J.D. and J.H. Patric. 1988. Research on Interception Losses and Soil Moisture Relationships. P 129-137 in *Forest Hydrology and Ecology at Coweeta*. W.T. Swank and D.A. Crossley, Jr. (eds.). Springer-Verlag, New York, New York.
- Hillier, A., 2007. ArcGIS 9.3 Manual. *Environmental Systems Research Institute*. Available online at: http://works.bepress.com/amy_hillier/17.
- Hillel, D. 1982. P 212 in *Introduction to Soil Physics*. Academic Press: San Diego, CA. 364 p.
- Hill Ris Lambers, J. and J.S. Clark. 2005. The benefits of seed banking for red maple (*Acer rubrum*): maximizing seedling recruitment. *Canadian Journal of Forest Research*. 35: 806-813.
- Jackson, R.D. and S.A. Taylor. 1986. Thermal Conductivity and Diffusivity. P 945-956 in *Methods of Soil Analysis: Part 1-Physical and Mineralogical Methods*. Klute, A. (ed). Soil Science Society of America, Madison, WI. 1358 p.
- Johnson, P.S. 1990. *Quercus coccinea* Muenchh. In *Silvics of North America: Vol 2. Hardwoods*. R.M. Burns and B.H. Honkala (eds.). USDA Forest Service Agricultural Handbook 654 Volume 2. 877 p.
- Lamarche, J.L. and D.P. Lettenmaier. 2001. Effects of forest roads on flood flows in the Deschutes River, Washington. *Earth Surface Processes and Landforms*. 26: 115-134.

- Land Surface Hydrology Research Group. 2006. The distributed hydrology soil vegetation model. *The University of Washington Civil and Environmental Engineering*. Available online at: <http://www.hydro.washington.edu/Lettenmaier/models.php>; last accessed Mar. 2010.
- Lipp, C.C. and E.T. Nilsen. 1997. The impact of subcanopy light environment on the hydraulic vulnerability of *Rhododendron maximum* to freeze-thaw cycles and draught. *Plant, Cell, and Environment*. 20: 1264-1272.
- McConathy, R.K. and S.B. McLaughlin. 1978. *Transpirational Relationships of Tulip-poplar*. Oak Ridge National Laboratory Environmental Sciences Division. Oak Ridge, TN. 22 p.
- McNab, W.H. and B.D. Clinton. 2003. *Kalmia latifolia* L. In *Wildland Shrubs of the United States and its Territories*. Francis, J.K. (ed.). USDA Forest Service General Technical Report IIF-WB-1.
- Miwa, Masato. 1999. P 66 in *Physical and Hydrological Responses of an Intensively Managed Loblolly Pine Plantation to Forest Harvesting and Site Preparation*. Ph.D. dissertation, Virginia Polytechnic and State University. Blacksburg, VA. 172 p.
- Monk, C.D. and F.P. Day, Jr. 1988. Biomass, Primary Production, and Selected Nutrient Budgets for Undisturbed Watersheds. P 151-159 in *Forestry Hydrology and Ecology at Coweeta*. W.T. Swank and D.A. Crossley, Jr. (eds.). Springer-Verlag, New York, New York.
- Monteith, J. and M. Unsworth. 2007. P 116-123 in *Principles of Environmental Physics, 3rd Ed.* Academic Press, Burlington, MA. 440 p.
- Olson, D.J., Jr. 1959. *Site Index Curves for Upland Oak in the Southeast*. USDA Forest Service Research Note SE-125. 2 p.
- Prata, A.J. 1996. A new long-wave formula for estimating downward clear-sky radiation at the surface. *Quarterly Journal of the Royal Meteorological Society*. 122: 1127-1151.
- Rawls, W., L.R. Ahuja, D.L. Brakensiek, and A. Shirmohammadi. 1993. Infiltration and Soil Water Movement. Ch 5 in *Handbook of Hydrology*. Maidment, D.L. (ed.). McGraw-Hill, New York, New York. 1424 p.
- Rodell, M. 2009. LDAS Vegetation Parameters Mapped to UMD Classification Scheme. *NASA Land Data Assimilation System*. Available online at: <http://ldas.gsfc.nasa.gov/>; last accessed Jun. 2009.

- Rogers, R. 1990. *Quercus alba* L. In *Silvics of North America: Volume 2: Hardwoods*. R.M. Burns and B.H. Honkala (eds.). USDA Forest Service Agricultural Handbook 654 Volume 2. 877 p.
- Sampson, D.A., J.M. Vose, and H.L. Allen. 1998. A conceptual approach to stand management using leaf area index as the integral of site structure, physiological function, and resource supply. P 447-451 In *Proceedings of the Ninth Biennial Southern Silvicultural Research Conference*. USDA Forest Service. Asheville, NC.
- Shen, H.W. and P.Y. Julien. 1993. Erosion and Sediment Transport. Ch. 12 in *Handbook of Hydrology*. Maidment, D.L. (ed). McGraw Hill, New York, New York. 1424 p.
- Shuttleworth, W.J. 1993. Evaporation. Ch 4 in *Handbook of Hydrology*. Maidment, D.L. (ed.). McGraw-Hill, New York, New York. 1424 p.
- Singh, P. and V.P. Singh. 2001. P 319 in *Snow and Glacier Hydrology*. Water Science and Technology Library. Springer, New York, New York. 756 p.
- Soil Survey Staff. 2008. US General Soil Map (SSURGO) for Macon County, North Carolina. *USDA Natural Resources Conservation Service*. Available online at <http://soildatamart.nrcs.usda.gov>.
- Storck, P. 2000. *Trees, Snow, and Flooding: An Investigation of Forest Canopy Effects on Snow Accumulation and Melt at the Plot and Watershed Scales in the Pacific Northwest*. University of Washington Water Resources Series Technical Report 161. 195 p.
- Storck, P., D.P. Lettenmaier, and S.M. Bolton. 2002. Measure of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resources Research*. 38(11).
- Surfleet, C. G. 2008. *Uncertainty in Forest Road Hydrologic Modeling and Catchment Scale Assessment of Forest Road Sediment Yield*. Ph.D. dissertation, Oregon State University, Corvallis, OR, 275 p.
- Swift, L. W., Jr., G. B. Cunningham, and J.B. Douglass. 1988. Climatology and Hydrology. P 35-55 in *Forest Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Thomas, D. J., T. N. Vrana, H.O. Schmitt, W.T. Schaefer, and S.A. Browning. 1996. *Soil Survey of Macon County, North Carolina*. US NRCS. U.S. Government Printing Office. 322 p.

- Walters, R.S. and H.W. Yawney. 1990. *Acer rubrum* L. In *Silvics of North America: Vol 2. Hardwoods*. R.M. Burns and B.H. Honkala (eds.). USDA Forest Service Agricultural Handbook 654 Volume 2. 877 p.
- Ward, A.D. and S.W. Trimble. 2003. *Environmental Hydrology, 2nd Ed.* Lewis Publishers: Boca Raton, FL.475 p.
- Wigmosta, M.S., L.W. Vail, D.P. Lettenmaier. 1994. A distributed hydrology-soil-vegetation model for complex terrain. *Water Resources Research*. 30(6): 1665-1679.
- Wigmosta, M. S., B. Nijssen, and P. Storck. 2002. The Distributed Hydrology Soil Vegetation Model. P 7-42 in *Mathematical Models of Small Watershed Hydrology and Applications*. V. P. Singh and D. Frevert. Water Resources Publications.

CHAPTER 4. MODELING THE EFFECTS OF FOREST ROAD DENSITY ON STREAMFLOW IN THE BLUE RIDGE MOUNTAINS

Abstract

Forested watersheds have often been managed for flood mitigation. Studies indicate that forests can potentially minimize peak flows during storm events, yet the relationship between forests and flooding is complex. Forest roads, usually found in managed systems, can potentially magnify the effects of forest harvesting on water yields. A distributed hydrology, soil, vegetation model (DHSVM) was calibrated for a 760 ha watershed in the Blue Ridge Mountains of North Carolina. The impacts of forest road density were modeled using uniform input parameters but changing road densities. Road densities tested were 0.5, 1.0, 3.0, 4.3, 6.0 and 12.0 km km⁻². Results indicate that increases in road density increased average streamflows at densities ≥ 4.3 km km⁻². During small storm events, discharge was impacted at ≥ 6.0 km km⁻² and streamflow was impacted during large rainfall events ≥ 3.0 km km⁻² road densities. These findings indicate that higher forest road densities can influence water yields and management efforts may be needed that can reduce the water yield from forest roads. The data also indicate that using the minimal road density necessitated by the land use can have positive effects.

Keywords: Forest roads, flooding, DHSVM, hydrology

4.1 Introduction

Throughout the Blue Ridge Mountains, the impacts of forest harvesting on downstream flooding have been intensely debated. In July 2001, extensive flooding occurred in southern West Virginia and Southwestern Virginia. National Weather Service stations recorded maximum rainfall intensities of 50 mm hr^{-1} and subsequent damages were approximately \$150 million (Eisenbies et al., 2007). County governments and citizens filed civil suits against forest product and mining companies, urging the corporations to take responsibility for the floods. Ultimately, the courts found the industries to be innocent of any wrongdoing (Recht, 2007). However, as a result of the 2001 floods, West Virginia Governor Bob Wise created a Flood Investigation Advisory Committee, which was designed to evaluate the impacts of logging and mining on flooding. In 2002 the Flood Advisory Technical Taskforce (FATT) recommendations were released. The comprehensive report detailed guidelines for mining and logging activities and was intended to reduce their environmental impact (Flood Advisory Technical Taskforce, 2002).

The scientific community often accepts the concept that forests play a role in buffering flood impacts but the magnitude of the role is disputed. Research has found varied responses in streamflow following forest harvesting. Following harvest, stream discharge often increases slightly due to decreases in evapotranspiration (Cornish and Vertessy, 2001). Many studies have found that discharge returns to pre-harvest conditions within five years of logging (Hewlett and Helvey, 1970; Hornbeck et al., 1970; Swank et al., 2001).

Impacts of forest harvesting on the stream hydrograph are important yet transient, since re-vegetation of the landscape generally occurs (Hewlett and Helvey, 1970; Kochenderfer et al., 1990). A more static issue that forest managers must consider are forest roads, which are often permanent and can affect the surrounding ecosystem. Forest roads can influence the natural pathway of runoff. The non-vegetated road corridors can act like stream channels, intercepting overland flow and re-routing it down slope. Compacted road surfaces can also reduce infiltration, enabling a larger volume of water to channel along the road (King and Tennyson, 1984). The increased volume of water and sediment from the road surface can negatively impact the health and vitality of the ecosystem. In a particular catchment, a road segment may act as a barrier,

corridor, sink, or source for both water and sediments (Jones, 2000). All of these functions can alter the stream hydrograph, both in quantity and in timing.

It can be difficult to study the effects of forest roads because road construction and installation are often concurrent with forest harvesting efforts. However, the development of complex and sophisticated hydrologic models has allowed researchers to simulate the watershed environment and effectively study the potential impacts of road networks. One such model, the Distributed Hydrology-Soil-Vegetation Model (DHSVM) has been used in numerous attempts to study various aspects of logging and road building (Bowling and Lettenmaier, 1997; Bowling et al., 2000; Cuo et al., 2006; Doten et al., 2006; La Marche and Lettenmaier, 2001; VanShaar et al., 2002).

This study was motivated by litigation surrounding forest management activities, such as harvesting and road construction, and how they might affect flood events. Since several current hydrologic models have the power to handle the complexity of forested ecosystems, a modeling approach will be used. Specifically, DHSVM will be used to predict the impacts of forest road density on stream discharge. This model was chosen because it has enhanced capabilities for modeling different road designs and densities. The specific objectives of this research are to:

- 1) Determine whether or not DHSVM can be calibrated for use in the Southern Appalachian Mountains; and
- 2) Assess the impacts of forest road density on stream discharge for
 - a. Mean monthly streamflow
 - b. Peak flow in response to flood events

4.2 Methods

The effects of different road densities on stream discharge were studied by simulating the hydrology of a small watershed (760 ha) in the Blue Ridge Mountains of North Carolina using DHSVM. The model was calibrated and validated using four years of historical data from the watershed. Road density impacts were studied by comparing the response of stream discharge at

various levels of modeled road densities while keeping all other model parameters consistent with the model calibration.

4.2.1 Basin Description

The Coweeta Long Term Ecological Research Station (LTER), originally established in 1933 as the USDA Forest Service Hydrologic Laboratory, conducts research that examines streamflow and erosion in an ecological context (Douglass and Hoover, 1988). The 2185 ha LTER is located in Macon County, North Carolina (35°03'N, 83°25'W) and is in the Blue Ridge Physiographic Province. Coweeta consists of two adjacent bowl-shaped basins; the Coweeta Basin and the Dryman Fork Basin. Due to data availability and instrument location, only the northern portion of the Coweeta Basin (the Shope Fork catchment, 760 ha) was used in this study (Figure 4.1). The elevations in the mountainous region range from 675 to 1592 meters. Sideslopes are variable, but generally range from 50 to 60% (Swank and Crossley, 1988). Precipitation is primarily in the form of rainfall (90 to 98%) and is most abundant during the winter months. Mean annual precipitation is approximately 1800 mm. Average temperatures range from winter lows of -4°C to summer highs of 23°C (Swift et al., 1988). Soils are predominately Inceptisols and Ultisols and are generally sandy loams (Swank and Crossley, 1988). In 2009, the Shope Fork catchment had a road density of 4.3 km/km². Roads included a range of road standards from graveled all weather access roads (Class I) to closed, grassed harvest roads (Class III).

4.2.2 Model Input

The Distributed Hydrology-Soil-Vegetation Model (DHSVM) is a physically based model that explicitly calculates the energy and water budgets for a catchment at the scale of a grid cell. DHSVM integrates user-defined inputs for meteorological, soil, vegetation, and stream and road morphology data to model evapotranspiration, snow influx and efflux, and the movement of unsaturated soil moisture, saturated subsurface flow, overland flow, and channel flow. This is completed for each grid cell at a specified time step. More detailed information can be found in Wigmosta et al. 1994 and 2002.

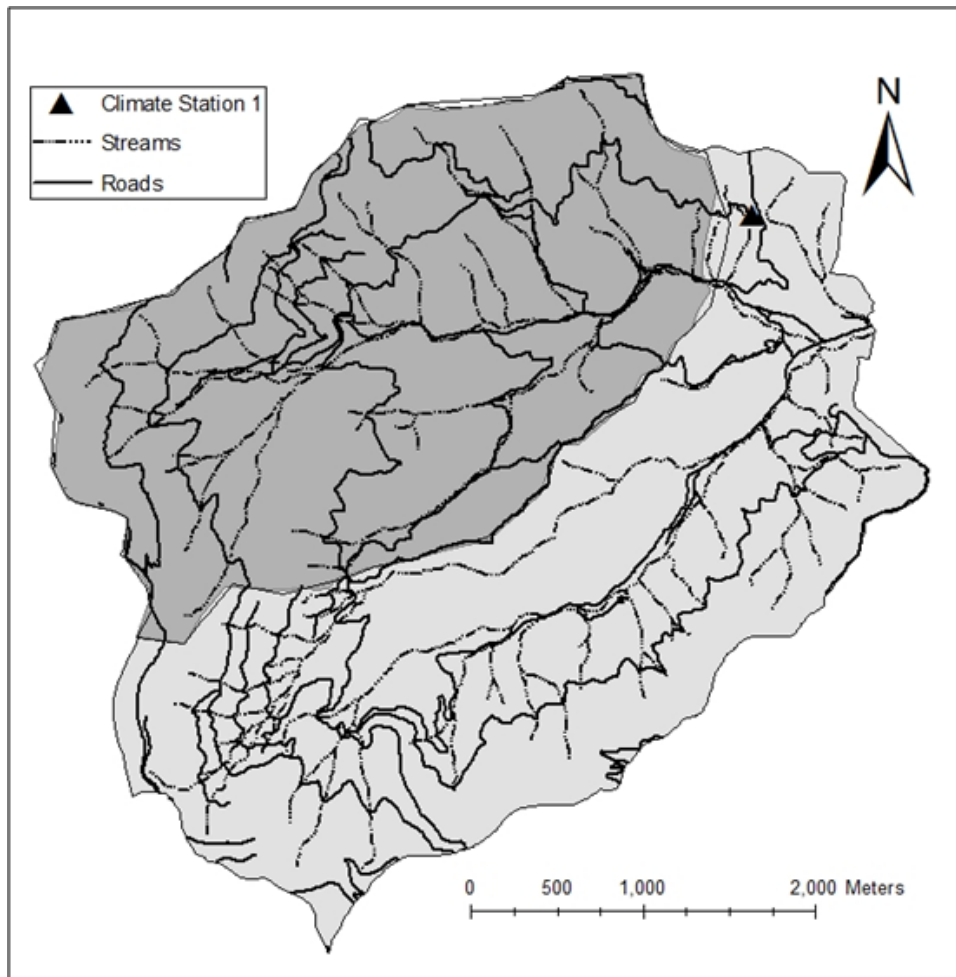


Figure 4.1 The 760 ha Shope Fork catchment (dark gray) used in the DHSVM evaluations is located in the northern portion of the Coweeta Basin (light gray).

DHSVM requires elevation, soil type, soil depth, and vegetation inputs for the study catchment in two dimensional binary format. A 30 m digital elevation model (DEM) was obtained for the Coweeta study site, which is located in the Prentiss Quadrangle (GeoCommunity, 2007). The Shope Fork catchment, located within the northern limits of Coweeta, was manually delineated using ArcMap (Hillier, 2007). This was based on the current Coweeta boundary, the 30 m Prentiss DEM, and the internal watershed boundaries. All watershed boundary shapefiles were obtained from the Coweeta Hydrologic Lab. Soil data for the Coweeta Basin were obtained from the Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database (Soil Survey Staff, 2008). SSURGO data were preferentially used rather than other data sources due to the fine mapping scale (1:12,000 to

1:63,360). Fourteen soil classes were defined and soil textures ranged from sandy clay loams to sandy and gravelly loams (Table 4.1). DHSVM is very sensitive to soil depth during its hydrologic simulation process (Surfleet, 2008) and a detailed soil depth map was imperative for accurate calibration of the model. A soil depth algorithm is present within the DHSVM pre-processing steps, although the precision of this algorithm is debatable. Surfleet (2008) found that, when compared to other estimations of soil depth, the model provided by DHSVM was the best at predicting the observed field measurements of soil depth. However, accurate results only occurred when the weighted values and the power exponents for the soil depth variables (elevation, slope, and area) were fitted to match the field measurements. Since few field measurements were available for this study, the soil depth inputs were based on the maximum soil depth values found in the Macon County, North Carolina Soil Survey (Thomas et al., 1996). Cover types were determined using tools found in ArcGIS. Four forest cover types were delineated based upon elevation, moisture regime, and aspect (Day et al., 1988) (Table 4.2). DHSVM employs two types of network files: streams and roads. Arc macro language (AML) was used to assign some of the parameters needed for the model, the rest were user-defined. Coweeta stream and road shapefiles were downloaded from the LTER COGENT dataset (Coweeta LTER, 2008).

Theoretically, all inputs and parameters to DHSVM can be physically measured. However, not all physical data can reasonably be collected at resolutions needed to satisfy model requirements. Such was the case with this study, and data were based on available historical records and literature values. In some cases, known data were combined with empirical equations to determine input values. Vegetation and soil input parameters are extensive, and descriptions were found from the DHSVM-supported website (Land Surface Hydrology Research Group, 2006) (Table 4.3 through Table 4.6).

Table 4.1 Soil mapping units in the Shope Fork catchment.

Soil Class	Taxonomic Series	Texture	Sub-Groups and Great Groups
1	Burton Craggey Rock Outcrop Complex	Sandy Loam	Humic Dystrudept
2	Cashiers	Fine Sandy Loam	Typic Dystrudept
3	Chandler	Fine Sandy Loam	Typic Dystrudept
4	Chestnut Edneyville Complex	Fine Sandy Loam	Typic Dystrudept
5	Cleveland Chestnut Complex	Sandy Loam	Lithic Dystrudept
6	Cullasaja Tuckasegee Complex	Sandy Clay Loam	Humic Dystrudept
7	Edneyville Chestnut Complex	Fine Sandy Loam	Typic Dystrudept
8	Evard Cowee	Fine Sandy Loam	Typic Hapludult
9	Fannin	Fine Sandy Loam	Typic Hapludult
10	Plott	Fine Sandy Loam	Humic Dystrudept
11	Rock Outcrop Cleveland Complex	Loam	Lithic Dystrudept
12	Saunook	Gravelly Loam	Humic Hapludult
13	Tuckasegee Whiteside Complex	Fine Sandy Loam	Humic Dystrudept
14	Wayah	Sandy Loam	Humic Dystrudept

Table 4.2 DHSVM forest cover types for the Shope Fork Catchment.

Cover Type	Representative Species
Northern Hardwoods	<i>Acer saccharum</i> , <i>Tilia spp.</i> , <i>Betula alleghaniensis</i> , <i>Aesculus octandra</i> , <i>Acer rubrum</i>
Cove Hardwoods	<i>Liriodendron tulipifera</i> , <i>Betula lenta</i> , <i>Magnolia spp.</i> , <i>Rhododendron spp.</i>
Mixed Deciduous	<i>Quercus alba</i> , <i>Quercus rubra</i> , <i>Robinia pseudoacacia</i> , <i>Carya spp.</i> , <i>Acer rubrum</i>
Xeric Oak-Pine	<i>Quercus coccinea</i> , <i>Quercus prinus</i> , <i>Oxydendrum arboreum</i> , <i>Pinus rigida</i> , <i>Kalmia latifolia</i>

Table 4.3 Description of DHSVM vegetation input parameters.

Parameter	Description	Units
Fractional coverage	Fractional coverage of the overstory	Fraction
Fractional trunk space	Fractional proportion that the trunk space exhibits in comparison to the entire tree height	Fraction
Aerodynamic attenuation coefficient for wind through the overstory	Dimensionless coefficient used to calculate the exponential wind profile through the overstory canopy	n/a
Radiation attenuation coefficient	Dimensionless coefficient used to calculate the fraction of shortwave radiation transmitted by the overstory	n/a
Height	Height of the canopy	m
Maximum/minimum stomatal resistance	Measure of a plant's ability to resist the diffusion of water out of the stomates	s m ⁻¹
Soil moisture threshold which restricts transpiration	Soil moisture at which plant transpiration no longer occurs	Fraction
Vapor pressure deficit threshold which causes stomatal closure	Vapor pressure at which stomates begin to close	Pa
Rpc	Fraction of shortwave radiation that is photosynthetically active (PAR)	W m ⁻²

Table 4.4 Description of DHSVM soil input parameters.

Parameter	Description	Units
Vertical/Lateral saturated hydraulic conductivity	Volume of water that will flow through the soil in a given unit of time	m s^{-1}
Exponential decrease rate of lateral saturated hydraulic conductivity	Rate at which lateral saturated hydraulic conductivity decreases with depth	n/a
Maximum infiltration rate	Rate at which water moves into the soil surface	m s^{-1}
Capillary drive	Measure of the adhesive forces that bind water molecules to soil	m
Soil surface albedo	Fraction of incoming radiation reflected by the soil surface	m s^{-1}
Manning's n	Roughness of the soil particle	n/a
Porosity	Percent volume of soil not occupied by soil particles	Fraction
Pore size distribution index	Volume of various sizes of pores in the soil	n/a
Bubbling pressure	Air pressure required to force air through the soil	m
Field capacity	Percent water held at -33 bars	Fraction
Wilting point	Percent water held at -15 bars	Fraction
Bulk density	Mass of soil per unit volume	kg m^{-3}
Soil thermal conductivity	Explains soil's ability to transmit heat	$\text{W m}^{-1} \text{K}^{-1}$
Soil thermal capacity	Change in heat content of a unit bulk volume of soil per unit change in temperature	$\text{J m}^{-3} \text{K}^{-1}$

Table 4.5 DHSVM vegetation inputs for calibration of Shope Fork catchment.

Vegetation Parameters	Range of Values	Source
% Canopy Cover	0.80 - 0.85	Rodell, 2009
% Trunk Space	0.60 - 0.76	Calculated
Aerodynamic attenuation coefficient for wind through the overstory	1.5	Cionco, 1972
Radiation attenuation coefficient	0.86	Campbell, 1986; Monteith and Unsworth, 2007
Height* (m)	16.8 - 24.4	Olson, 1959; Beck, 1962; Carmean, 1976; Walters and
	2.0 - 3.0	Yawney, 1990; Lipp and Nilsen, 1997; McNab and Clinton, 2003
Maximum/minimum stomatal resistance* (s/m)	193 - 490	Federer, 1977; McConathy and McLaughlin, 1978;
	312 - 388	
Soil moisture threshold which restricts transpiration*	0.139 - 0.152	Shuttleworth, 1980; Soil Survey Staff, 2008
	0.087 - 0.095	
Vapor pressure deficit threshold which causes stomatal closure (Pa)	4000	Wigmosta et al., 2002
Fraction of shortwave radiation that is photosynthetically active (W/m ²)	0.3	Dickinson et al., 1991

* Inputs required for both overstory and understory layers, respectively

Table 4.6 DHSVM input soil parameters for Shope Fork calibration. Refer to Table 4.1 for a description of the soil classes.

Soil Parameter	Range of Values	Source(s)
Lateral saturated hydraulic conductivity (m/s)	9.13 E-04 - 1.00 E-03	Miwa, 1999
Exponential decrease rate of lateral saturated hydraulic conductivity	4.0	Beven, 1982
Maximum infiltration rate (m/s)	3.06 E-06 - 1.39 E-06	Hillel, 1982
Capillary drive (m)	0.06 - 0.22	Bedient et al., 2008
Soil surface albedo	0.09 - 0.30	Soil Survey Staff, 2008
Manning's n	0.01 - 0.10	Shen and Julien, 1993
Porosity* (fraction)	0.42 - 0.58	Burger, 2008
Pore size distribution index*	0.272 - 0.386	Rawls et al., 1993
Bubbling pressure* (m)	0.009 - 0.884	Rawls et al., 1993
Field capacity* (fraction)	0.102 - 0.287	Soil Survey Staff, 2008
Wilting point* (fraction)	0.041 - 0.162	Soil Survey Staff, 2008
Bulk density* (kg/m ³)	937.5 - 1550.0	Soil Survey Staff, 2008
Vertical saturated hydraulic conductivity* (m/s)	9.0 E-06 - 1.1 E-05	Soil Survey Staff, 2008
Soil thermal conductivity* (W/m K)	6.27 - 8.00	Bowling and Lettenmaier, 1997
Soil thermal capacity* (J/m ³ K)	2.0 E-06	Hillel, 1982

* Inputs required for all soil layers

4.2.3 Model Calibration

The model was calibrated using an hourly time step for data collected from January 1, 2003 through October 31, 2007. Model output was compared with historical discharge data from Coweeta Weir 8. January 1, 2003 through September 30, 2003 was used for a model “warm-up” period to ensure that the model had adequate time to acquire to initial site conditions. Water Year 2004 (October 1, 2003 through September 30, 2004) was used as a calibration period in which parameter adjustments were made. Parameter validation occurred from Water Year 2005 through 2007 (October 1, 2004 through September 30, 2007). Precipitation for the calibration period totaled 1787 mm and had the characteristics of a normal precipitation year. The validation included one exceedingly wet year and two comparatively dry years (2195, 1439, and 1469 mm, respectively). Changes to input parameters were made in order to minimize differences between observed and predicted stream discharge. Alterations were made primarily to the lateral saturated

hydraulic conductivity and exponential decrease input parameters, as studies have shown DHSVM to be sensitive to these variables (Bowling and Lettenmaier, 1997; Wigmosta and Lettenmaier, 1999). Concurrent with Cuo et al. (2006), it was found that increasing the accuracy of peak flow resulted in a decrease of baseflow precision and vice versa.

Assessment of the calibration and validation was determined through analysis of the timing of the model hydrograph, volume of the hydrograph, and overall model accuracy. The correlation coefficient (R) was used to analyze the accuracy of the predicted hydrograph and unity was desired (e.g. a value of 1.0 implies a better fit than 0.5). The average volume error between the predicted and observed discharge ($\Delta V/V$) was used to look at DHSVM's ability to accurately simulate peak flows. Overall model accuracy was determined using the correlation coefficient (R^2). Again, unity in the model accuracy was desired, as this statistics describes the proportion of initial variance accounted for by the model. Other studies using DHSVM have used model efficiency (ME or E') to look at the effectiveness of the model (Beckers and Alila, 2004; Cuo et al., 2006, Thyer et al., 2004; Wigmosta and Burges, 1997). Model efficiency is a similar statistic to the correlation coefficient in that it is also a measure of variance (Nash and Sutcliffe, 1970).

4.2.4 Road Density Experiment

Forest roads densities in managed systems are typically much lower than urban roads, but can often be higher than some rural road densities. Forest road densities usually range from one to six km km^{-2} and average around three to four km km^{-2} (Bowling and Lettenmaier, 1997; Hawbaker et al., 2005; National Forests in North Carolina: Fiscal Year 2007). In some areas, a forest road density of two km km^{-2} is considered high and can even impact the survival of wildlife populations (Jones, 2000; Mech, 1989). In the United States, it is estimated that all state maintained roads have an average density of 1.2 km km^{-2} (Forman, 2000). Meanwhile, urban locations have much higher road densities than forested and rural areas. A suburban road density in a small town may average ten or twelve km km^{-2} and areas in very urban metropolises can approach 100% impervious cover.

A stated objective of this study was to evaluate the effects of forest road density on the stream hydrograph. Treatment densities were designed to mimic typical forest road densities in order to predict potential impacts of road density on stream discharge and flooding. In 2009, the density of the Shope Fork road network was 4.3 km km⁻². Six road densities between 0.5 and 12.0 km km⁻² were modeled with three unique replications at each density (Table 4.7). Treatments two through five represent the high and low ranges of forest road densities while treatments one and six were included to show the difference between rural and urban road densities.

Table 4.7 Treatment densities for Shope Fork road density experiment.

Treatment	Road Density (km km ⁻²)	Road Length (km)	% Area in Roads	Replications
1	0.5	3.9	0.3	3
2	1.0	7.8	0.5	3
3	3.0	23.5	1.2	3
Control (4)*	4.3	33.7	1.8	3
5	6.0	47.0	2.6	3
6	12.0	94.0	5.6	3

* Road density of the Coweeta LTER as of 2009.

Since the experiment was conducted in a modeling environment, treatment replications were done in the form of different road layouts at each treatment density. Determining the impact of road density on stream discharge is difficult because multiple road factors can affect watershed processes. Such road impact factors included the spatial location of the road with relation to streams, the gradient or slope of the road, the surfacing material of the road, road design features (such as insloped, outsloped, and crowned roads), the water control features of the road, number of stream crossings, and length of the road. Bernard (2006) developed an approach to determine the impact of road networks on sedimentation potential. Road position, slope, and class were given weighted values based on potential impacts to the watershed (Figure 4.2). These effects were then amalgamated into one *Final Erosion Factor*. A *Final Watershed Road Impact Factor* (RIF) is found by integrating road segment length into the model (Figure 4.3).

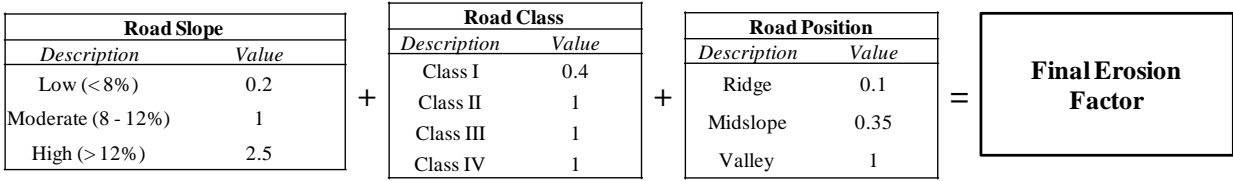


Figure 4.2 The Final Erosion Factor is based on weighted values of the impact factors, which include road position, slope, and class (Modified from Bernard, 2006).

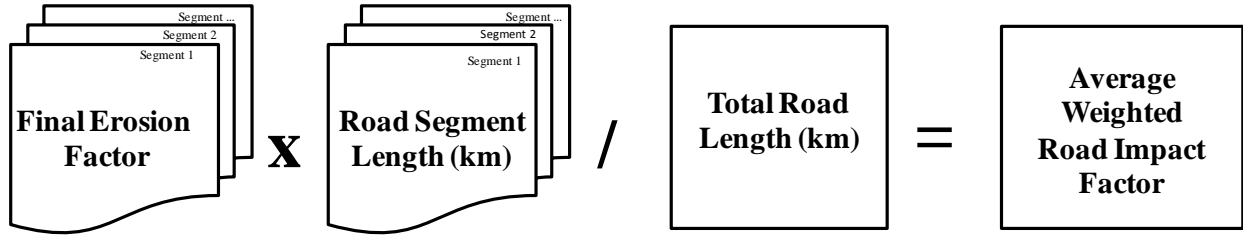


Figure 4.3 The Final Watershed Road Impact Factor (RIF) is a weighted value for the watershed based on the Final Erosion Factor and the length of roads in the watershed (Modified from Bernard, 2006).

For the purposes of this project, the Final Watershed Road Impact Factors (RIF) were used as a basic index to control for the confounding effects of road impact factors. The RIF for the current Shope Fork catchment was determined using data from Coweeta and ArcGIS algorithms. Pre-construction road design was completed in an ArcGIS setting and in a “realistic” fashion with an attempt to provide access to the various sub-watersheds within the site. After the layout was completed, the road classes were altered in order to keep the RIF for each network constant with the control (Table 4.8). The number of intermittent stream crossings was not accounted for during the design of the road layouts and as can be assumed that as density increases in a watershed, the number of stream crossings will also increase (Table 4.9).

Table 4.8 Final Watershed Road Impact Factors (RIF) for each treatment in the Shope Fork road density experiment.

Treatment	Replication	Road Density km km ⁻²	% Area in Roads	RIF	% Deviation From Control
1	1	0.5	0.3	0.630	-2.4
1	2	0.5	0.3	0.630	-2.4
1	3	0.5	0.3	0.741	8.7
2	1	1.0	0.5	0.668	1.4
2	2	1.0	0.5	0.671	1.7
2	3	1.0	0.5	0.636	-1.8
3	1	3.0	1.2	0.667	1.3
3	2	3.0	1.2	0.679	2.5
3	3	3.0	1.2	0.685	3.1
Control (4)*	1	4.3	1.8	0.654	-
4	2	4.3	1.8	0.665	1.1
4	3	4.3	1.8	0.678	2.4
5	1	6.0	2.6	0.626	-2.8
5	2	6.0	2.6	0.684	3
5	3	6.0	2.6	0.666	1.2
6	1	12.0	5.6	0.635	-1.9
6	2	12.0	5.6	0.623	-3.1
6	3	12.0	5.6	0.622	-3.2

* Road density and layout of the Coweeta LTER as of 2009.

Table 4.9 Number of stream crossings per treatment in the Shope Fork catchment.

Treatment	Replication	Road Density (km km ⁻²)	% Area in Roads	# of Stream Crossings	# Deviation From Control
1	1	0.5	0.3	14	-48
1	2	0.5	0.3	9	-53
1	3	0.5	0.3	8	-54
2	1	1.0	0.5	25	-37
2	2	1.0	0.5	15	-47
2	3	1.0	0.5	22	-40
3	1	3.0	1.2	56	-6
3	2	3.0	1.2	29	-33
3	3	3.0	1.2	41	-21
Control (4)*	1	4.3	1.8	62	-
4	2	4.3	1.8	42	-20
4	3	4.3	1.8	56	-6
5	1	6.0	2.6	79	17
5	2	6.0	2.6	61	-1
5	3	6.0	2.6	80	18
6	1	12.0	5.6	134	72
6	2	12.0	5.6	116	54
6	3	12.0	5.6	122	60

* Road density and layout of the Coweeta LTER as of 2009.

The impacts of road density were analyzed by comparing monthly average streamflow between each treatment. This was done for the entire calibration and validation study period. Inspection of the model output indicated that one of the samples (Layout 1, Density 5) suffered an unidentifiable error and thus was disregarded from the study. Using Statistical Analysis Software (SAS/STAT Software, Version 9.2), the data were determined to be normal via proc univariate. A proc mixed statement with compound symmetry was used to model the covariance structure of the data. To investigate the relationship between the various treatment densities, a Tukey-Kramer analysis was conducted in SAS using the proc mixed statement.

The effect of road density on peak flows was also analyzed by looking at the number of peak flows that fell within a certain return interval during the study time. This was done on an hourly scale to capture every peak flows in the time series. Return intervals for the Shope Fork catchment were calculated using a method derived by Douglass (1974). The number of hourly peak flows in each recurrence interval was calculated, and relationships between treatment densities were again analyzed using Tukey-Kramer methods.

4.3 Results and Discussion

4.3.1 Calibration and Validation of Shope Fork Catchment

Overall, DHSVM was successful in predicting the general trends of the Shope Fork hydrograph (Figure 4.4), although both under- and over-prediction by the model occurred during peak flow conditions. $\Delta V/V$, or the average difference between the volume of modeled and observed streamflow, was high for the calibration period (Table 4.10). Error was approximately one-third of the average baseflow conditions. Model timing measures the ability of the model to predict peaks and ebbs in streamflow at the same points in time as the observed data. Analyzed using the coefficient of determination, DHSVM matched the Coweeta data almost 70% of the time. The R^2 was lower than desired as DHSVM predicted less than 50% of the initial variance of the original data.

Table 4.10 Calibration and validation statistics for Shope Fork catchment.

	Total Precip.			
WYR	(mm)	$\Delta V/V$	R	R^2
2004	1787	0.10	0.69	0.48
2005	2195	0.06	0.79	0.63
2006	1439	-0.13	0.88	0.78
2007	1469	0.07	0.89	0.80
Calibration	1787	0.10	0.69	0.48
Validation	1692	0.00	0.85	0.73

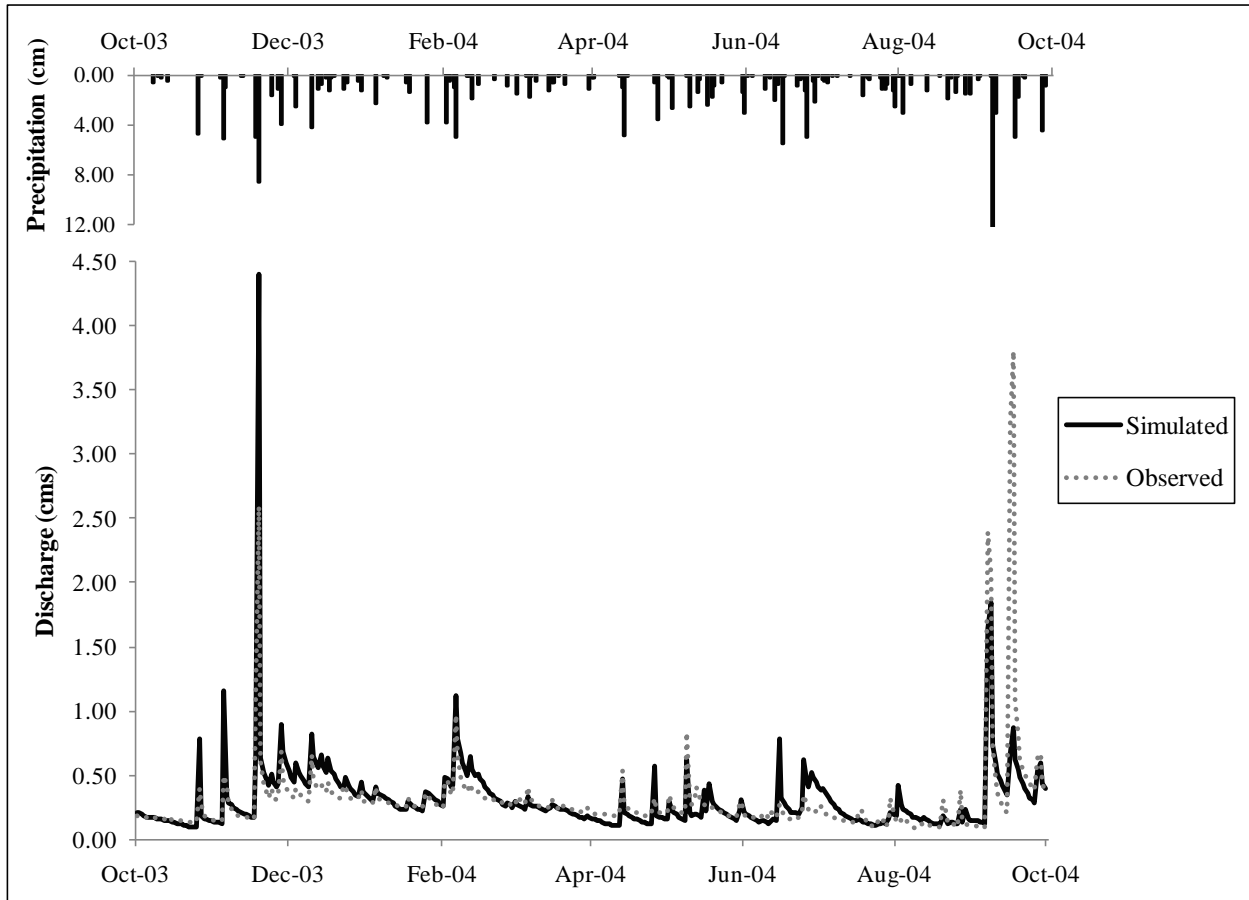


Figure 4.4 Simulated and observed streamflow and measured precipitation of Shope Fork catchment during calibration period.

The validation period was consistent with the calibration in that DHSVM predicted the general trends of the hydrograph but had trouble predicting peak flows (Figure 4.5). Although water year 2005 is representative of a higher than normal degree of tropical storm and remnant activity from the Atlantic region, the average volume error for the year was the lowest of the entire testing period (Table 4.10). Over the entire validation period, volume error averaged to be null. Timing for the validation period increased relative to the calibration ($R = 0.85$). The decrease in volume error and increase in timing accuracy created improved model efficiency during the validation period of 0.73.

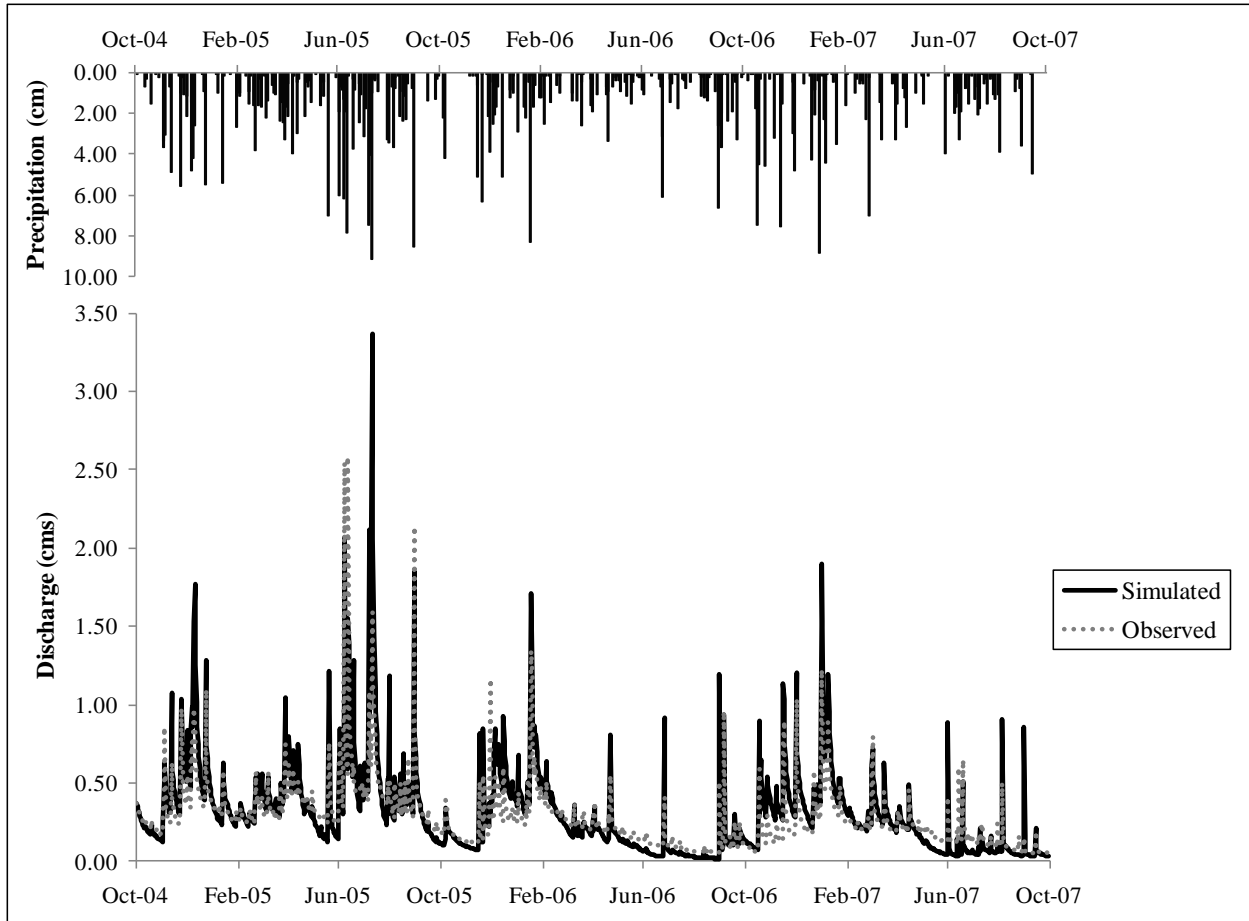


Figure 4.5 Simulated and observed discharge and measured precipitation for Shope Fork catchment during validation period.

The lack of precision when calibrating DHSVM for the Shope Fork catchment could be attributed to the following factors: (1) the difference in terrain and climate regime between typical model research applications and the study site; (2) errors in peak flow and baseflow modeling due to the lack of preferential flow pathways in the model; (3) user error while preparing the model for use; and (4) error in data input as a result of over-parameterization of the model.

DHSVM was initially created for use in steep, mountainous terrains with a winter snowpack. The topography of the Coweeta watershed is unique for the Appalachian Mountains, and its steep slopes are moderately analogous to DHSVM’s home region of the U.S. Pacific Northwest. However, the climate regime is quite different. Coweeta experiences no significant

seasonal snowpack, few rain-on-snow events, and can be affected by serious storm events in the form of hurricane remnants (as was seen during both the calibration and validation period). Much of DHSVM's efforts go into modeling the snowpack hydrology and there is likelihood that winter precipitation was incorrectly modeled. One item of note is the absence of preferential flow pathways in DHSVM calculations. Beckers and Alila (2004) found that the addition of a preferential flow model in a proprietary adaptation of DHSVM increased model accuracy in a British Columbia watershed. A similar adaptation might be applied to the Coweeta Basin, which has an extensive amount of porous saprolite (Velbel, 1988). DHSVM is a complicated model and requires many pre-processing steps before the model can be used. The numerous steps create large potentials for user error. The model also requires a large number of input parameters, some of which were complex and hard to define. Highly parameterized models can have tradeoffs, as the detail in modeling can and should result in highly accurate results. However, it can be difficult to measure and obtain values for each parameter and often values can be incorrect. It is also important to consider the possibility of equifinality, which is a downfall of highly parameterized models such as DHSVM. Equifinality is the concept that, in modeling, one outcome can be achieved through many different pathways. It can be problematic because a correct answer may be reached, but the modeling components may be incorrect. One way to overcome this ambiguity would be to use GLUE (generalized likelihood uncertainty estimation) analysis (Romanowicz and Beven, 2006).

4.3.2 Road Density Effects

Results suggest that increases in road density can create heightened streamflows and, in almost all cases, streamflow increases with an increase in road density (Figure 4.6). The few exceptions occurred in January and October, where discharge from Density 2 (1.0 km km^{-2}) was marginally higher than streamflow from Density 1 (0.5 km km^{-2}). Over the four year study period, the wet seasons were found to occur from June through December (with the exception of October). This is likely the result of the large hurricane remnants that moved through the area that, by chance, did not occur during the October months. The magnitude of average streamflow does not seem entirely dependent upon precipitation, suggesting that factors other than the volume of precipitation are important in controlling discharge. The variation in response between the treatments does not change with relation to the volume of discharge, nor with the month.

Significance of the effects of road density on stream discharge was confirmed by Analysis-of-Variance (ANOVA) using Type III sum of squares with a significance level of <0.0001 (Table 4.11).

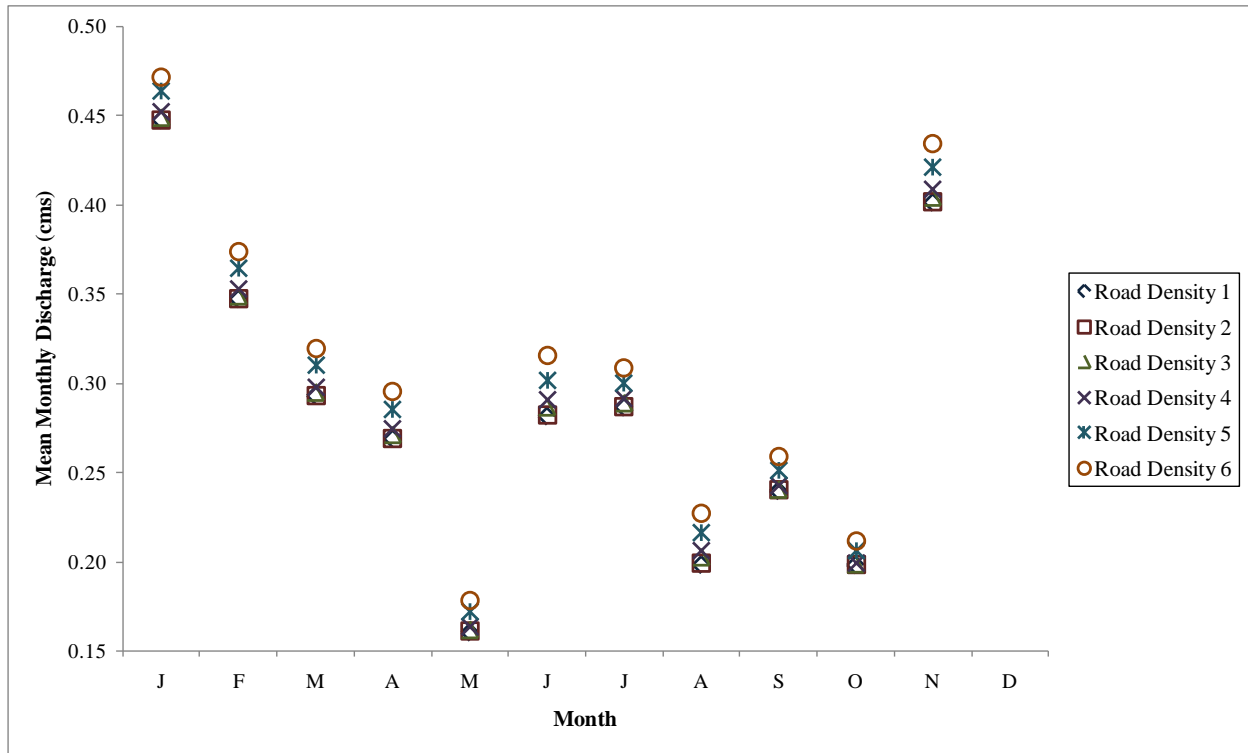


Figure 4.6 Shope Fork mean monthly discharge averaged over four-year study period. Road density 1=0.5 km km⁻²; Road density 2 = 1.0 km km⁻²; Road density 3 = 3.0 km km⁻²; Road density 4 = 4.3 km km⁻²; Road density 5=6.0 km km⁻²; Road density 6 = 12.0 km km⁻²

DHSVM results indicate a significant change in streamflow at road densities ≥ 4.3 km km⁻² (Table 4.12). Highly significant differences occurred at the 6.0 km km⁻² and 12.0 km km⁻² densities. These results suggest that streams have an altered response when forest road densities reach 4.3 km km⁻² and that it is desirable to keep maximum road densities between 3.0 and 4.3 km km⁻², and are consistent with the literature. Using DHSVM to model the effects of roads on streamflow, Bowling and Lettenmaier (1997) found that road densities of 3.7 and 4.9 km km⁻² increased streamflow of ten year floods by 8 and 10%, respectively. While significant differences in streamflow were detected at a density of 4.3 km km⁻² in the Coweeta watershed, larger changes in average monthly discharge were only seen at higher densities. An increase of

5% in discharge was first detected at a density of 6.0 km km⁻² and increases greater than 10% were not identified until road density reached 12.0 km km⁻² (Table 4.13).

Table 4.11 Abbreviated Analysis-of-Variance statistics for average monthly streamflow for the Shope Fork catchment.

Effect	DF	F-Value	p-Value
Density	5	102.28	<.0001
Month	11	177668	<.0001
Density*Month	55	17.76	<.0001

Table 4.12 Tukey-Kramer test results for significant difference between treatments for monthly and average monthly data.

Treatment	1	2	3	4	5	6
1		NS	NS	S	S*	S*
2	NS		NS	S	S*	S*
3	NS	NS		NS	S*	S*
4	S	S	NS		S*	S*
5	S*	S*	S*	S*		S*
6	S*	S*	S*	S*	S*	

NS: No significant difference between treatments; S: significant difference at $\alpha = 0.01$; S*: significant difference at $\alpha < 0.0001$

Table 4.13 Percent streamflow deviation of treatments from the Shope Fork catchment as modeled with no road coverage.

Month	% Deviation from No Roads					
	Density 1 (0.5 km km ⁻²)	Density 2 (1.0 km km ⁻²)	Density 3 (3.0 km km ⁻²)	Density 4 (4.3 km km ⁻²)	Density 5 (6.0 km km ⁻²)	Density 6 (12.0 km km ⁻²)
Jan	0.0	-0.1	0.2	1.0	3.6	5.3
Feb	0.0	0.0	0.3	1.4	5.0	7.5
Mar	0.0	0.1	0.5	1.6	5.7	8.9
Apr	0.1	0.1	0.8	2.0	6.2	9.9
May	0.0	0.1	0.6	1.6	6.9	11.0
Jun	0.3	0.4	1.9	3.5	7.4	12.2
Jul	0.1	0.2	0.8	1.7	4.8	7.7
Aug	0.3	0.5	2.2	3.9	9.2	14.8
Sep	0.1	0.1	0.3	1.2	4.7	8.1
Oct	0.0	-0.1	0.0	0.5	3.8	6.5
Nov	0.2	0.2	0.8	1.9	5.0	8.2
Dec	0.0	0.0	0.4	1.4	3.7	5.8
Annual						
Mean	0.1	0.1	0.7	1.8	5.5	8.8

4.3.3 Peak Flows

The relationship between road density and peak flow was investigated by analyzing stream response following a large and small rainfall event. A storm was defined as any event where no precipitation fell four hours prior to or following the event (Swift et al., 1988). The storms were chosen randomly based on maximum rainfall intensity and total precipitation volume. The two storm events are detailed in Table 4.14.

Figure 4.7 illustrates the relationship between road density and stream discharge following an April 2005 storm event of 4.83 mm. Data were analyzed one hour prior to rainfall and six hours following precipitation cessation. Prior to the storm, baseflow response to the larger density road networks was already higher than the lower densities. During this storm, the

larger density networks created heightened peak flows. Statistical analysis of inverse-squared transformed data suggested that density, hour, and density by hour interaction effects were all statistically significant (

Table 4.15).

Table 4.14 Description of the large and small storm events which received detailed analysis.

Storm Size	Date of Storm	Duration of Event (hours)	Maximum Intensity (mm/hr)	Total Rainfall (mm)
Small	4/12/2005	5	2.29	4.83
Large	12/31/2006	13	24.13	87.12

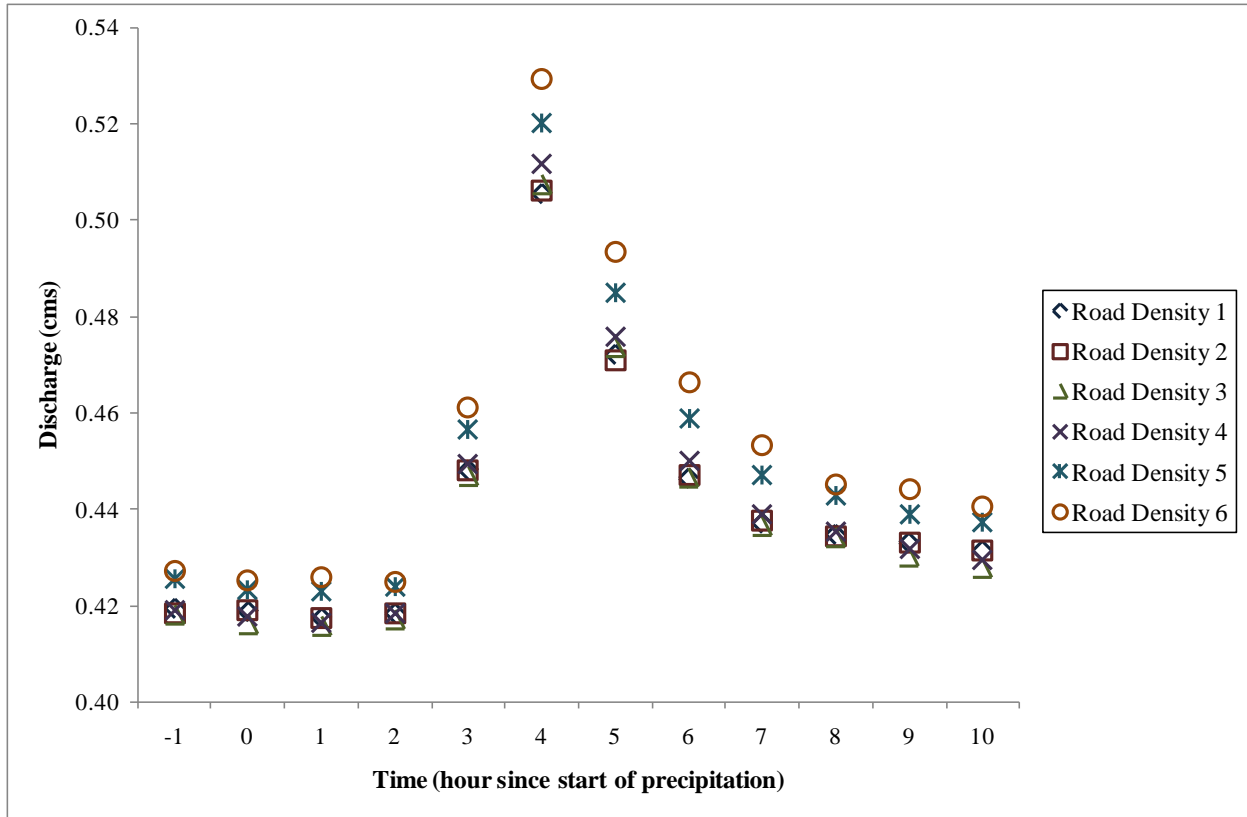


Figure 4.7 Shope Fork mean hourly discharge during April 2005 rainfall event. Density 1=0.5 km km⁻²; Density 2 = 1.0 km km⁻²; Density 3 = 3.0 km km⁻²; Density 4 = 4.3 km km⁻²; Density 5=6.0 km km⁻²; Density 6 = 12.0 km km⁻²

Table 4.15 Abbreviated ANOVA for April 2005 rainfall event in the Shope Fork catchment.

Effect	DF	F-Value	p-Value
Density	5	51.97	<.0001
Hour	11	3937.34	<.0001
Density*Hour	55	2.57	<.0001

Tukey-Kramer results suggest that there was a highly significant difference in stream discharge at densities of 6.0 km km⁻² or greater (Table 4.16). This was a slight change from the monthly data, as a significant change was detected at 4.3 km km⁻². For this small rainfall event, there was no significant difference between stream discharge at road densities of 6.0 or 12.0 km km⁻². This suggests that increasing the road density from 6.0 to 12.0 km km⁻² does not create significant differences in water yield during small storm events. In forested watersheds, such as

Coweeta, roads impact the natural hydrology predominately through subsurface interception, as overland flow in these systems is usually minimal. These results imply that smaller road densities do not intercept enough flow to significantly alter the hydrology of the watershed during a small storm. Increasing the road density increases the likelihood that flow will be intercepted and thus increases the impact of the roads on the storm hydrograph.

Table 4.16 Tukey-Kramer test results for significant difference between treatments during April 2005 rainfall event for the Shope Fork catchment.

Treatment	1	2	3	4	5	6
1		NS	NS	NS	S*	S*
2	NS		NS	NS	S*	S*
3	NS	NS		NS	S*	S*
4	NS	NS	NS		S*	S*
5	S*	S*	S*	S*		NS
6	S*	S*	S*	S*	NS	

NS: No significant difference between treatments; S: significant difference at $\alpha = 0.05$; S*: significant difference at $\alpha < 0.0001$

The larger, December 2006 storm event yielded similar results to the April 2005 storm in that increased road density created inflated peak flows (Figure 4.8). At higher densities, the peak flows lasted slightly longer, creating a slight lag in the falling limb of the hydrograph. As conditions returned to baseflow, density had a lower impact on discharge. Statistical analysis shows that road density, time, and density by time interaction were all significant (Table 4.17). Pair-wise comparison analysis shows much different outcomes than the small storm event. The results indicate a highly significant change in stream responses when road density reached 3.0 km km⁻² (Table 4.18). Some studies have found that peak flow response to logging and roads do not change significantly during large storm events (Rothacher, 1970; Ziemer, 1981). However, the modeled results indicate that small increases in road density can impact the storm hydrograph during large events (Table 4.19). This is likely the result of a higher degree of soil saturation, resulting in an increase in road interception of subsurface flow. Overland flow is modeled during DHSVM simulation, and no overland routing occurred during this storm event.

Table 4.17 Abbreviated ANOVA for December 2006 rainfall event in the Shope Fork catchment.

Effect	DF	F-Value	p-Value
Density	5	96.83	<.0001
Hour	25	7997.59	<.0001
Density*Hour	125	9.18	<.0001

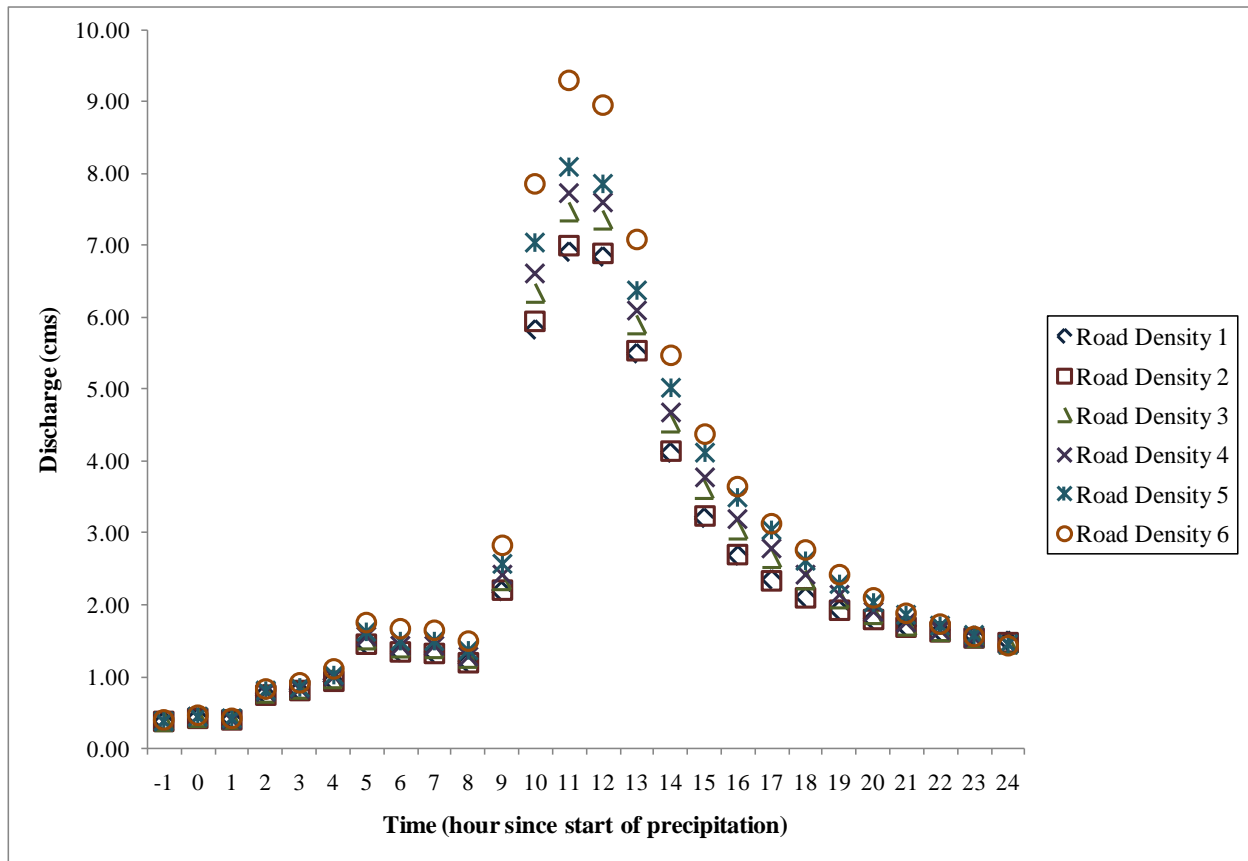


Figure 4.8 Shope Fork mean hourly discharge during December 2006 rainfall event. Density 1=0.5 km km⁻²; Density 2 = 1.0 km km⁻²; Density 3 = 3.0 km km⁻²; Density 4 = 4.3 km km⁻²; Density 5=6.0 km km⁻²; Density 6 = 12.0 km km⁻²

Table 4.18 Tukey-Kramer test results for significant difference between treatments during December 2006 rainfall event.

Treatment	1	2	3	4	5	6
1		NS	S*	S*	S*	S*
2	NS		S*	S*	S*	S*
3	S*	S*		NS	S*	S*
4	S*	S*	NS		S	S*

5	S*	S*	S*	S		S*
6	S*	S*	S*	S*	S*	

NS: No significant difference between treatments; S: significant difference at $\alpha = 0.05$; S*: significant difference at $\alpha < 0.0001$

Table 4.19 Percent deviation from no road density for each treatment for a large and small storm event.

Storm Size	% Deviation from No Roads					
	Density 1	Density 2	Density 3	Density 4	Density 5	Density 6
Small	0.7	0.8	1.1	2.0	3.6	5.5
Large	2.3	3.6	10.4	14.2	19.8	37.5

An increase in the number of hourly peak flows for each return interval was concurrent with increases in road density. However, no time by treatment trend was detected. For all return intervals, significant increases in the number of peak flows occurred at 3.0 or 4.3 km km⁻². These densities were not found to be significantly different from one another for all return intervals.

Table 4.20 Number of peak hours of flow for each treatment density for all return periods for the Shope Fork catchment.

Return Interval (years)	Max Discharge (cms)	# of Peak Flow Hours					
		Density 1	Density 2	Density 3	Density 4	Density 5	Density 6
2.33	2.17	205	209	229	237	262	303
5	3.00	115	117	125	132	146	172
10	3.81	71	73	78	83	97	118
20	4.82	37	39	49	51	58	74
30	5.44	28	28	35	36	43	55
40	5.91	21	22	26	29	32	46
50	6.39	13	14	20	22	25	36

4.4 Summary and Conclusions

A distributed hydrology model was calibrated for use in forested watersheds in the Blue Ridge Mountains. Using historical data from the Coweeta LTER, literature, and calculations, calibration and validation of the model was met with moderate success. The calibrated period

(Water Year 2004) had model accuracy (R^2) of 0.48 while the three-year validation period (Water Years 2005-2007) had a higher overall accuracy of 0.73. In other studies using DHSVM, model accuracies (R^2) have been recorded from 0.61 to 0.96 (Beckers and Alila, 2004; Leung et al., 1996; Thyer et al., 2004; Whitaker et al., 2003; Wigmosta and Burges, 1997). The high accuracy of the validation period suggests that DHSVM has potential for use in the Blue Ridge Mountains.

DHSVM was designed for use in mountainous terrains and has primarily been applied to studies in the Pacific Northwest (Beckers and Alila, 2004; Bowling and Lettenmaier, 2001; Lamarche and Lettenmaier, 1998), although this is beginning to change (Cuo et al., 2006). The Blue Ridge Mountains are dissimilar from DHSVM's native study sites in that snowpack and snowmelt have negligible contributions to the hydrologic budget. While studies have found high model accuracy using DHSVM, it should be understood that these experiments are primarily located in mountainous, snowpack-dominated systems. Taking DHSVM out of its natural environment and calibrating to an R^2 of 0.73 should be considered successful.

DHSVM requires numerous input parameters and this study was conducted using little to no field collected data. Accuracy might be improved with field sampling, and a sensitivity analysis could be used to determine what parameters would be worth collecting. DHSVM has been shown to be sensitive to the lateral saturated hydraulic conductivity and exponential decrease input parameters (Bowling and Lettenmaier, 1997; Wigmosta and Lettenmaier, 1999); although these variables were altered with no positive outcome. It may be possible that the Appalachian Mountains have a different set of sensitive parameters. Accuracy of model calibration could also be improved by increasing the time span of the study. This analysis was restricted due to data availability at the hourly time step and a coarser time step may be more feasible for longer studies.

The model accuracy found for the Blue Ridge Mountains using literature values suggests that DHSVM might have success in other regions with long-term hydrologic records. Data and sources presented in this study can be broadened and be applied outside of the Coweeta watershed. As of now, DHSVM is used solely as a research tool. Attempts have been made to

create a more user-friendly interface for the model. Such advances, along with readily available parameter data, could make DHSVM extremely useful for management of forested watersheds.

Using DHSVM as a controlled environment, we were able to model the impacts of road density on stream discharge. This process was complex, as road density is not independent from other road features and confounding effects were present. Although we attempted to account for confounding effects, we realize that they are a constraint in the study. The modeled results suggest that mean monthly stream discharge will be impacted when forested road density reaches and surpasses 4.3 km km^{-2} . Seasonal changes in the stream hydrograph have been detected following vegetation removal (Hibbert, 1966; Patric, 1973). No monthly effects were noted in this study and it is believed that reduction in evapotranspiration due to vegetation losses were not an important component of changes in streamflow. This is consistent with the literature, which suggests that changes in streamflow in the Appalachian Mountains are detectable after 20% of the vegetation has been removed (Stednick, 1996). The largest area covered by roads in this study was 5.6%.

This study found that effects on streamflow began when 1.8% of the watershed area was in roads. This fell within the range of values in the literature, which suggest that streamflow may be impacted at road densities from 1.8 to 15% (Harr, 1979; Ziemer, 1981; King and Tennyson, 1984; Wright et al., 1990). In the Shope Fork catchment, significant changes were detected as road density increased beyond 1.8%, which suggests that road managers should be cautious when road density reaches and exceeds this threshold. The effects on streamflow in this watershed are thought to be a function of intercepted subsurface flow and increased runoff on the road surfaces, both of which have been shown to increase streamflow in forested areas with roads (Ziemer, 1981; Jones, 2000).

During a rainfall event producing 4.8 mm of rainfall over 5 hours, modeled output showed that stream discharge was impacted at densities $\geq 6.0 \text{ km km}^{-2}$. For larger rainfall event (87.1 mm over 13 hours), streamflow was impacted at road densities $\geq 3.0 \text{ km km}^{-2}$. The difference between the road density thresholds during large and small storms can be attributed to differences in infiltration excess runoff from the roads and intercepted subsurface flow.

Precipitation rates are lower during small storms and may not exceed infiltration rates, allowing more water to percolate into the soil. The opposite is true for a large storm, where an excess of water may build up on road surfaces. Streamflow will be thus impacted at lower densities during larger storms, due to increased amounts of runoff from road surfaces. The same principle applies to the interception of subsurface flow by road cuts. In the variable source area concept (Hewlett and Hibbert, 1963), the area in a watershed that contributes to streamflow is dependent on factors such as antecedent moisture conditions and precipitation rates and volume. Smaller storms tend to have smaller source areas while larger storms usually have larger contributing areas. For the smaller storm, it is possible that many of the roads were not located in the area that was contributing to the stream hydrograph. Increasing the area increases the likelihood that roads will be present, even at smaller densities.

The number of hourly peak flows during the study period was also analyzed, and these were separated by the return interval of the flow. For all return intervals, streamflow was first impacted between 3.0 and 4.3 km km⁻². In contrary to the individual rainfall events, there was no noticeable distinction between recurrence interval and the road density threshold. This test, however, only looked at the difference in frequency of peak flows and not the difference in magnitude. Increasing the road density might not change the possibility of an event occurring, but may affect the magnitude of discharge and thus possible damages due to flooding.

Since only one small and one large rainfall event was analyzed for this study, it is recommended that these results be further investigated. It is also noted that, while DHSVM allows for many road features to be controlled, such as road surface and cut slope, it does not allow for water control features. The installation of BMPs such as water bars, culverts, and broad based dips can be used as important mitigation tools.

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Literature Cited

- Beck, D.E. 1990. *Liriodendron tulipifera* L. In *Silvics of North America: Volume 2. Hardwoods*. R.M. Burns and B.H. Honkala (eds.). USDA Forest Service Agricultural Handbook 654 Volume 2. 877 p.
- Beckers, J. and Y. Alila. 2004. A model of rapid preferential hillslope runoff contributions to peak flow generation in a temperate rain forest watershed. *Water Resources Research* 40.
- Bedient, P.B., W.C. Huber, and B.E. Vieux. 2008. *Hydrology and Floodplain Analysis, 4th ed.* Pearson, Upper Saddle River, NJ. 795 p.
- Bernard, A. M. 2006. *Geospatial Modeling of Forest Road Networks and Their Effects on Stream Macroinvertebrate Communities*. M.Sc. Virginia Polytechnic Institute and State University. Blacksburg, VA.
- Beven, K. 1982. On subsurface stormflow: an analysis of response times. *Hydrological Science Journal*. 12(4): 505-521.
- Bowling, L. C. and D. P. Lettenmaier. 1997. *Evaluation of the Effects of Forest Roads on Streamflow in Hard and Ware Creeks, Washington*. University of Washington Water Resources Series 155. 202 p.
- Bowling, L. C., P. Storck, and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. *Water Resources Research*. 36(11): 3223-3240.
- Burger, J.A. 2008. Work Unit IV. P. 4 in *Forest Soils Laboratory Manual*. Department of Forestry, Virginia Tech.
- Coweeta LTER. 2008. COGENT: GIS Data. *National Science Foundation*. Available online at: <http://coweeta.uga.edu/ecology/cogent.html>; last accessed Jan. 2008.
- Cuo, L., T. W. Giambelluca, A.D. Ziegler, and M.A. Nullet. 2006. Use of the distributed hydrology soil vegetation model to study road effects on hydrological processes in Pang Khum Experimental Watershed, northern Thailand. *Forest Ecology and Management*. 224: 81-94.
- Day, F. P., Jr., D. L. Phillips, and C.D. Monk. 1988. Forest Communities and Patterns. P. 141-149 in *Forestry Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.

- Doten, C.O., L.C. Bowling, J.S. Lanini, E.P. Maurer, and D.P. Lettenmaier. 2006. A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds. *Water Resources Research*. 42.
- Douglass, J. E. and M. D. Hoover. 1988. History of Coweeta. P. 17-31 in *Forestry Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Cornish, P.M. and R.A. Vertessy. 2001. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest. *Journal of Hydrology*. 242: 43-63.
- Eisenbies, M. H., W.M. Aust, J.A. Burger, and M.B. Adams. 2007. Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians-A review. *Forest Ecology and Management*. 242: 77-98.
- Federer, C.A. 1977. Leaf resistance and xylem potential differ among broadleaved species. *Forest Science*. 23(4): 411-419.
- Flood Advisory Technical Taskforce. 2002. *Runoff Analysis of Seng, Scrabble, and Sycamore Creeks*. Charleston, WV. 123 p.
- Forman, R. T. 2000. Estimate of the area affected ecologically by the road system in the United States. *Conservation Biology*. 14(1): 31-35.
- GeoCommunity. 2007. GIS Data Depot. *GeoCommunity*. Available online at: <http://data.geocomm.com>.
- Harr, R.D. 1979. Effects of timber harvest on streamflow in the rain-dominated portion of the Pacific northwest. In *Workshop on Scheduling Timber Harvest for Hydrologic Concerns*. USDA Forest Service Pacific Northwest Region, Portland, OR.
- Hawbaker, T. J., V. C. Radeloff, R.B. Hammer, and M.K. Clayton. 2005. Road density and landscape pattern in relation to housing density, land ownership, land cover, and soils. *Landscape Ecology*. 20: 609-625.
- Hewlett, J.D. and A.R. Hibbert. 1963. Moisture and energy conditions with a sloping soil mass during drainage. *Journal of Geophysical Research*. 68(4): 1081-1087.
- Hewlett, J.D. and J.D. Helvey. 1970. Effects of forest clear-felling on the storm hydrograph. *Water Resources Research*. 6: 768-782.

- Hibbert, A. R. 1966. Forest treatment effects on water yield. In *Proceedings of a National Science Foundation Advanced Science Seminar, International Symposium on Forest Hydrology*. Pergamon Press, Oxford, NY.
- Hillel, D. 1982. P 212 in *Introduction to Soil Physics*. Academic Press: San Diego, CA. 364 p.
- Hillier, A., 2007. ArcGIS 9.3 Manual. *Environmental Systems Research Institute*. Available online at: http://works.bepress.com/amy_hillier/17.
- Hornbeck, J. W., R. S. Pierce, and C.A. Federer. 1970. Streamflow changes after forest clearing in New England. *Water Resources Research*. 6: 1124-1132.
- Jones, J. A. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research*. 36: 2621-2642.
- King, J. G. and L. C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in North Central Idaho. *Forest Ecology and Management*. 224: 81-94.
- Kochenderfer, J.N., P.J. Edwards, and J.D. Helvey. 1990. Land management and water yield in the Appalachians. P 523 in *Watershed Planning and Analysis in Action, Symposium Proceedings of IR Conference*. ASCE. 10 p.
- La Marche, J.L. and D.P. Lettenmaier. 2001. Effects of forest roads on flood flows in the Deschutes River, Washington. *Earth Surface Processes and Landforms*. 26: 115-134.
- Land Surface Hydrology Research Group. 2006. The distributed hydrology soil vegetation model. *The University of Washington Civil and Environmental Engineering*. Available online at: <http://www.hydro.washington.edu/Lettenmaier/models.php>; last accessed Mar. 2010.
- Leung, L. R., M. S. Wigmosta, S.J. Ghan, D.J. Epstein, and L.W. Vail. 1996. Application of a subgrid orographic precipitation/surface hydrology scheme to a mountain watershed. *Journal of Geophysical Research*. 101(D8): 12803-12817.
- Lipp, C.C. and E.T. Nilsen. 1997. The impact of subcanopy light environment on the hydraulic vulnerability of *Rhododendron maximum* to freeze-thaw cycles and draught. *Plant, Cell, and Environment*. 20: 1264-1272.
- McConathy, R.K. and S.B. McLaughlin. 1978. *Transpirational Relationships of Tulip-poplar*. Oak Ridge National Laboratory Environmental Sciences Division. Oak Ridge, TN. 22 p.

- McNab, W.H. and B.D. Clinton. 2003. *Kalmia latifolia* L. In *Wildland Shrubs of the United States and its Territories*. Francis, J.K. (ed.). USDA Forest Service General Technical Report IIF-WB-1.
- Mech, L. D. 1989. Wolf population survival in an area of high road density. *American Midland Naturalist*. 121(2): 387-389.
- Miwa, Masato. 1999. P 66 in *Physical and Hydrological Responses of an Intensively Managed Loblolly Pine Plantation to Forest Harvesting and Site Preparation*. Ph.D. dissertation, Virginia Polytechnic and State University. Blacksburg, VA. 172 p.
- Monteith, J. and M. Unsworth. 2007. P 116-123 in *Principles of Environmental Physics, 3rd Ed.* Academic Press, Burlington, MA. 440 p.
- Nash, J. E. and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I-A discussion of principles. *Journal of Hydrology*. 10: 282-290.
- National Forests in North Carolina: Fiscal Year 2007. 2008. USDA Forest Service. Asheville, NC.
- Olson, D.J., Jr. 1959. *Site Index Curves for Upland Oak in the Southeast*. USDA Forest Service Research Note SE-125. 2 p.
- Patric, J. H. 1973. *Deforestation Effects on Soil Moisture, Streamflow, and Water Balance in the Central Appalachians*. USDA Forest Service Research Paper NE-259. 12 p.
- Rawls, W., L.R. Ahuja, D.L. Brakensiek, and A. Shirmohammadi. 1993. Infiltration and Soil Water Movement. Ch 5 in *Handbook of Hydrology*. Maidment, D.L. (ed.). McGraw-Hill, New York, New York. 1424 p.
- Recht, A. M. 2007. Flood Litigation-Coal River Watershed. West Virginia Court of Appeals. Raleigh County, WV. Civil Action No. 01-C-797. 31 p.
- Rodell, M. 2009. LDAS Vegetation Parameters Mapped to UMD Classification Scheme. *NASA Land Data Assimilation System*. Available online at: <http://ldas.gsfc.nasa.gov/>; last accessed Jun. 2009.
- Romanowicz, R.J. and K.J. Beven. 2006. Comments on generalized likelihood uncertainty estimation. *Reliability Engineering and System Safety*. 91: 1315-1321.
- Rothacher, J. 1970. Increases in water yield following clear-cut logging in the Pacific Northwest. *Water Resources Research*. 6(2): 653-658.
- SAS/STAT Software Version 9.2. Copyright, SAS Institute Inc. Cary, NC.

- Shen, H.W. and P.Y. Julien. 1993. Erosion and Sediment Transport. Ch. 12 in *Handbook of Hydrology*. Maidment, D.L. (ed). McGraw Hill, New York, New York. 1424 p.
- Shuttleworth, W.J. 1993. Evaporation. Ch 4 in *Handbook of Hydrology*. Maidment, D.L. (ed.). McGraw-Hill, New York, New York. 1424 p.
- Soil Survey Staff. 2008. US General Soil Map (SSURGO) for Macon County, North Carolina. *USDA Natural Resources Conservation Service*. Available online at <http://soildatamart.nrcs.usda.gov>.
- Stednick, J. D. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology*. 176: 79-95.
- Surfleet, C.G. 2008. *Uncertainty in Forest Road Hydrologic Modeling and Catchment Scale Assesment of Forest Road Sediment Yield*. Ph.D. dissertation, Oregon State University, Corvallis, OR. 275 p.
- Swank, W. T. and D. A. Crosley, Jr. 1988. Introduction and Site Description. P. 3-16 in *Forest Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Swank, W. T., J. M. Vose, and K.J. Elliott. 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management*. 143: 163-178.
- Swift, L. W., Jr., G. B. Cunningham, and J.B. Douglass. 1988. Climatology and Hydrology. P. 35-55 in *Forest Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Thomas, D. J., T. N. Vrana, H.O. Schmitt, W.T. Schaefer, and S.A. Browning. 1996. *Soil Survey of Macon County, North Carolina*. US NRCS. U.S. Government Printing Office. 322 p.
- Thyer, M., J. Beckers, D. Spittlehouse, Y. Alila, and R. Winkler. 2004. Diagnosing a distributed hydrologic model for two high-elevation forested catchments based on detailed stand- and basin-scale data. *Water Resources Research*. 40:20.
- VanShaar, J.R., I. Haddeland, and D.P. Lettenmaier. 2002. Effects of land-cover change on the hydrological response of interior Columbia River basin forested catchments. *Hydrological Process*. 16: 2499-2520.

- Velbel, M.A. 1988. Weathering and Soil-Forming Processes. P. 93-102 in *Forest Hydrology and Ecology at Coweeta*. W. T. Swank and D. A. Crosley, Jr. (eds.). Springer-Verlag, New York, New York.
- Walters, R.S. and H.W. Yawney. 1990. *Acer rubrum* L. In *Silvics of North America: Vol 2. Hardwoods*. R.M. Burns and B.H. Honkala (eds.). USDA Forest Service Agricultural Handbook 654 Volume 2. 877 p.
- Whitaker, A., Y. Alila, J. Beckers, and D. Toews. 2003. Application of the distributed hydrology soil vegetation model to Redfish Creek, British Columbia: model evaluation using internal catchment data. *Hydrological Processes*. 17: 199-224.
- Wigmosta, M. S., L. W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resources Research*. 30: 1665-1679.
- Wigmosta, M. S. and D. P. Lettenmaier. 1999. A comparison of simplified methods for routing topographically driven subsurface flow. *Water Resources Research*. 35(1): 255-264.
- Wigmosta, M. S. and S. J. Burges. 1997. An adaptive modeling and monitoring approach to describe the hydrologic behavior of small catchments. *Journal of Hydrology*. 202: 48-77.
- Wigmosta, M. S., B. Nijssen, and P. Storck. 2002. The Distributed Hydrology Soil Vegetation Model. P 7-42 in *Mathematical Models of Small Watershed Hydrology and Applications*. V. P. Singh and D. Frevert. Water Resources Publications.
- Ziemer, R. 1981. Storm flow response to road building and partial cutting in small streams of Northern California. *Water Resources Research*. 17(4): 907-917.

CHAPTER 5. CONCLUSIONS

This project examined the impacts of forest road density on stream discharge in the Coweeta watershed.

5.1 DHSVM Calibration

DHSVM was calibrated for Water Year 2004 (Oct. 1, 2003 to Sep. 30, 2004) and was validated for Water Years 2005 through 2007. Calibration was met with moderate success. Model accuracy was found to be 0.48 for the calibration period. Model efficiencies for DHSVM have been recorded from 0.61 to 0.96 (Beckers and Alila, 2004; Leung et al., 1996; Thyer et al., 2004; Whitaker et al., 2003; Wigmosta and Burges, 1997). The model accuracy takes into account both the volume error and the timing of the hydrograph. Efforts were made to increase the accuracy of the Shope Fork model output. DHSVM has been shown to be sensitive to the lateral saturated hydraulic conductivity and exponential decrease input parameters (Bowling and Lettenmaier, 1997; Wigmosta and Lettenmaier, 1999); these variables were altered with no positive outcome.

The validation was more successful and the overall model efficiency for this time period was 0.73. A more reliable model would measure model efficiency above 0.85. While this value was not attained for this particular study, it is suggested that the model can still be used in the region. In order to do so, field measurements should be employed in order produce more reliable input parameters. It is also recommended that normal precipitation years be used for model calibration and validation, as the above and below average precipitation years used in this particular model validation may have hindered success.

DHSVM was designed for use in mountainous terrains and has primarily been applied to studies in the Pacific Northwest (Beckers and Alila, 2004; Bowling and Lettenmaier, 2001; Lamarche and Lettenmaier, 1998), although this is beginning to change (Cuo et al., 2006). The Blue Ridge Mountains of are dissimilar from DHSVM's native study sites in that snowpack and snowmelt have negligible contributions to the hydrologic budget. While studies have found high model accuracy using DHSVM, it should be understood that these experiments are primarily

located in mountainous, snowpack-dominated systems. Taking DHSVM out of its natural environment and calibrating to an R^2 of 0.73 should be considered successful.

DHSVM is a highly parameterized model, yet a goal of this project was to determine if the model could be useful to the average watershed manager. Thus, intensive field studies to determine accurate input values were not conducted. Rather, parameters were found using readily available data from weather stations, online databases, and literature. This proved to take months longer than expected and some values are uncertain estimates. This raises the possibility of equifinality in highly parameterized models, which may have been likely during the Coweeta calibration process. The model also requires extensive knowledge in GIS and computer programming, which is unlikely for many watershed managers. Attempts have been made to create a user-friendly interface. Such advancements could create ease for watershed managers and potentially move DHSVM from a research model to a management tool.

The high accuracy of the validation period suggests that DHSVM has potential for use in the Blue Ridge Mountains. DHSVM requires numerous input parameters and this study was conducted using little to no field collected data. Accuracy might be improved with field sampling, and a sensitivity analysis could be used to determine what parameters would be worth collecting. Accuracy of model calibration could also be improved by increasing the time span of the study. This analysis was restricted due to data availability at the hourly time step and a coarser time step may be more feasible for longer studies. The model accuracy found for the Blue Ridge Mountains using literature values suggests that DHSVM might have success in other regions with long-term hydrologic records. Data and sources presented in this study can be broadened and be applied outside of the Coweeta watershed.

5.2 Effects of Road Density on Streamflow

The second objective of this project was to explore the relationship between forest road density and stream discharge. It was hypothesized that increases in road density would increase stream discharge. This is based on three underlying theories:

- 1) roads can intercept subsurface flow when the water table elevation rises above the road surface;
- 2) overland flow can be intercepted by the road network thus increasing peak discharge;
- 3) the compacted surface of a road can decrease infiltration and create heightened infiltration excess runoff.

Using DHSVM as a controlled environment, we were able to model the impacts of road density on stream discharge. This process was complex, as road density is not independent from other road features and confounding effects were present. These were accounted for as much as possible using a method created by Bernard (2006). The method uses weighted values for factors such as road slope, topographic position, class, and length to create an overall impact value on the watershed. The impact value for each treatment was kept close to constant for each treatment and this was assumed to control for outside factors. However, the treatment variation in slope, topographic position, and road class were a noted constraint in the study.

The modeled results suggest that mean monthly stream discharge will be impacted when forested road density reaches and surpasses 4.3 km km^{-2} . Seasonal changes in the stream hydrograph have been detected following vegetation removal (Hibbert, 1966; Patric, 1973). No monthly effects were noted in this study and it is believed that reduction in evapotranspiration due to vegetation losses were not an important component of changes in streamflow. This is consistent with the literature, which suggests that changes in streamflow in the Appalachian Mountains are detectable after 20% of the vegetation has been removed (Stednick, 1996). The largest area covered by roads in this study was 5.6%.

This study found that effects on streamflow began when 1.8% of the watershed area was in roads. This fell within the range of values in the literature, which suggest that streamflow may be impacted at road densities from 1.8 to 15% (Harr, 1979; Ziemer, 1981; King and Tennyson, 1984; Wright et al., 1990). In the Shope Fork catchment, significant changes were detected as road density increased beyond 1.8%, which suggests that road managers should be cautious when road density reaches and exceeds this threshold. The effects on streamflow in this watershed are thought to be a function of intercepted subsurface flow and increased runoff on the

road surfaces, both of which have been shown to increase streamflow in forested areas with roads (Ziemer, 1981; Jones, 2000).

During a rainfall event producing 4.8 mm of rainfall over 5 hours, modeled output showed that stream discharge was impacted at densities $\geq 6.0 \text{ km km}^{-2}$. For larger rainfall event (87.1 mm over 13 hours), streamflow was impacted at road densities $\geq 3.0 \text{ km km}^{-2}$. The difference between the road density thresholds during large and small storms can be attributed to differences in infiltration excess runoff from the roads and intercepted subsurface flow. Precipitation rates are lower during small storms and may not exceed infiltration rates, allowing more water to percolate into the soil. The opposite is true for a large storm, where an excess of water may build up on road surfaces. Streamflow will be thus impacted at lower densities during larger storms, due to increased amounts of runoff from road surfaces. The same principle applies to the interception of subsurface flow by road cuts. In the variable source area concept (Hewlett and Hibbert, 1963), the area in a watershed that contributes to streamflow is dependent on factors such as antecedent moisture conditions and precipitation rates and volume. Smaller storms tend to have smaller source areas while larger storms usually have larger contributing areas. For the smaller storm, it is possible that many of the roads were not located in the area that was contributing to the stream hydrograph. Increasing the area increases the likelihood that roads will be present, even at smaller densities.

The number of hourly peak flows during the study period was also analyzed, and these were separated by the return interval of the flow. For all return intervals, streamflow was first impacted between 3.0 and 4.3 km km^{-2} . In contrary to the individual rainfall events, there was no noticeable distinction between recurrence interval and the road density threshold. This test, however, only looked at the difference in frequency of peak flows and not the difference in magnitude. Increasing the road density might not change the possibility of an event occurring, but may affect the magnitude of discharge and thus possible damages due to flooding.

Since only one small and one large rainfall event was analyzed for this study, it is recommended that these results be further investigated. It is also noted that, while DHSVM allows for many road features to be controlled, such as road surface and cut slope, it does not

allow for water control features. The installation of BMPs such as water bars, culverts, and broad based dips can be used as important mitigation tools, as was suggested by Eisenbies et al., 2007.

The modeled results suggest that stream discharge can be impacted when forested road density reaches 4.3 km km^{-2} . This is the current road density of the Shope Fork watershed. It is possible that streamflow might be currently impacted in the watershed and this should be considered. During storm events, it was found that road densities greater than 6.0 km km^{-2} created significant increases in streamflow during a small event, while stream discharge was impacted at a density of 3.0 km km^{-2} during a large rainfall events. The latter density is extremely small for a managed watershed and allows for very little access to the area. Since only one small and one large rainfall event was analyzed for this study, it is recommended that these results be further investigated. It is also noted that, while DHSVM allows for many road features to be controlled, such as road surface and cut slope, it does not consider water control features. The installation of BMPs such as water bars, culverts, and broad based dips can be used as important mitigation tools

5.3 DHSVM

The Distributed Hydrology-Soil-Vegetation Model (DHSVM) is a physically based model that explicitly calculates the energy and water budgets for a catchment at the scale of a grid cell. DHSVM integrates user-defined inputs for meteorological, soil, vegetation, and stream and road morphology data to model evapotranspiration, snow influx and efflux, and the movement of unsaturated soil moisture, saturated subsurface flow, overland flow, and channel flow. This is completed for each grid cell at a specified time step. It is a complex and powerful model (Beckers et al., 2009). More detailed information can be found in Wigmosta et al. 1994 and 2002.

DHSVM has been used to analyze the effects of land use change, harvesting, and road networks on streamflow in forested, mountainous environments throughout the world (Bowling and Lettenmaier, 1997; Bowling et al., 2000; Cuo et al., 2006; Doten and Lettenmaier, 2004; Doten et al., 2006; VanShaar et al., 2002). It has also been used in hydrologic modeling

(Haddeland and Lettenmaier, 1995; Kenward and Lettenmaier, 1997; Westrick et al., 2002; Wigmosta et al., 1994; Wigmosta and Lettenmaier, 1999) and to look at the interactions between climate and climate change and hydrology (Arola and Lettenmaier, 1996; Leung and Wigmosta, 1999; Wigmosta et al., 1995).

The distributed hydrology-soil-vegetation model has the potential to be an extremely useful research tool, if used properly. The model is extremely powerful in that it has the potential to model numerous components of the hydrologic cycle, including overland flow, subsurface flow, and flow from culverts. Because the physical model attempts to account for all of the natural components of the hydrologic cycle, the inputs are numerous, overwhelming, and potentially unnecessary. The ambiguity and specificity of parameters make almost impossible to correctly input all variables. Models with high inputs also run the risk of equifinality, which occurs when outcomes are correctly predicted but the processes by which the predictions are made are incorrect. The data and processing steps provided in this thesis are intended to serve as a base for use of DHSVM in the Appalachian Mountains. Much work could be done to create a user-friendly platform for the model with readily available input parameters. DHSVM has potential for widespread application and could be useful to a variety of land management scenarios. Work should be continued to move DHSVM from a scientifically, research based model to one that can be beneficial to the broader public.

Literature Cited

- Arola, A. and D. Lettenmaier. 1996. Effects of subgrid spatial heterogeneity on GCM-scale land surface energy and moisture fluxes. *Journal of Climate*. 9: 1339-1349.
- Beckers, J. and Y. Alila. 2004. A model of rapid preferential hillslope runoff contributions to peak flow generation in a temperate rain forest watershed. *Water Resources Research*. 40.
- Beckers, J., B. Smerdon, T. Redding, A. Anderson, R. Pike, and A.T. Werner. 2009. Hydrologic models for forest management applications Part 1: Model Selection. *Watershed Management Bulletin*. 13(1): 35-44.

- Bernard, A. M. 2006. *Geospatial Modeling of Forest Road Networks and Their Effects on, Stream Macroinvertebrate Communities*. M.Sc. Virginia Polytechnic Institute and State University. Blacksburg, VA.
- Bowling, L. C. and D. P. Lettenmaier. 1997. *Evaluation of the Effects of Forest Roads on Streamflow in Hard and Ware Creeks, Washington*. University of Washington Water Resources Series 155. 202 p.
- Bowling, L. C., P. Storck, and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. *Water Resources Research*. 36(11): 3223-3240.
- Campbell, G.S. 1986. Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution. *Agricultural and Forest Meteorology*. 36: 317-321.
- Carmean, W.H. 1978. *Site Index Curves for Northern Hardwoods in Northern Wisconsin and Upper Michigan*. USDA Forest Service Research Paper NC-160. 16 p.
- Cionco, R.M. 1972. A wind profile index for canopy flow. *Boundary-Layer Meteorology*. 3(2): 255-263.
- Cuo, L., T. W. Giambelluca, A.D. Ziegler, and M.A. Nullet. 2006. Use of the distributed hydrology soil vegetation model to study road effects on hydrological processes in Pang Khum Experimental Watershed, northern Thailand. *Forest Ecology and Management*. 224: 81-94.
- Dickinson, R.E., A. Henderson-Sellers, C. Rosenzweig, and P.J. Sellers. 1991. Evapotranspiration models with canopy resistance for use in climate models, a review. *Agricultural and Forest Meteorology*. 54: 373-388.
- Doten, C. O. and D. P. Lettenmaier. 2004. *Prediction of Sediment Erosion and Transport with the Distributed Hydrology-Soil-Vegetation Model*. University of Washington Water Resources Series 178. 70 p.
- Doten, C. O., L. C. Bowling, J.S. Lanini, E.P. Maurer, and D.P. Lettenmaier. 2006. A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds. *Water Resources Research*. 42: 15.
- Eisenbies, M.H., W.M. Aust, J.A. Burger, and M.B. Adams. 2007. Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians-A review. *Forest Ecology and Management*. 242:77-98.

- Haddeland, I. and D. Lettenmaier. 1995. *Hydrologic Modeling of Boreal Forest Ecosystems*. University of Washington Water Resources Series Technical Report 143. 138 p.
- Kenward, T. and D. Lettenmaier. 1997. Assessment of required accuracy of digital elevation data for hydrologic modeling. University of Washington Water Resources Research Technical Report 153. 131 p.
- Leung, L. R., M. S. Wigmosta, S.J. Ghan, D.J. Epstein, and L.W. Vail. 1996. Application of a subgrid orographic precipitation/surface hydrology scheme to a mountain watershed. *Journal of Geophysical Research*.101(D8): 12803-12817.
- Leung, L. R. and M. S. Wigmosta. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest. *Journal of the American Water Resources Association*. 35(6): 1463-1471.
- Thyer, M., J. Beckers, D. Spittlehouse, Y. Alila, and R. Winkler. 2004. Diagnosing a distributed hydrologic model for two high-elevation forested catchments based on detailed stand- and basin-scale data. *Water Resources Research*. 40: 20.
- VanShaar, J. R., I. Haddeland, and D.P. Lettenmaier. 2002. Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. *Hydrological Process*. 16: 2499-2520.
- Westrick, K. J., P. Storck, and C.F. Mass. 2002. Description and evaluation of a hydrometeorological forecast system for mountainous watersheds. *Weather and Forecasting*. 17: 250-262.
- Wigmosta, M. S., L. W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resources Research*. 30: 1665-1679.
- Wigmosta, M. S., L. R. Leung, and E.J. Rykeil. 1995. Regional modelling of climate-terrestrial ecosystem interactions. *Journal of Biogeography*. 1: 453-465.
- Wigmosta, M. S. and D. P. Lettenmaier. 1999. A comparison of simplified methods for routing topographically driven subsurface flow. *Water Resources Research*. 35(1): 255-264.
- Wigmosta, M. S. and S. J. Burges. 1997. An adaptive modeling and monitoring approach to describe the hydrologic behavior of small catchments. *Journal of Hydrology*. 202: 48-77.
- Wright, K. A., K. H. Sendek, R.M. Rice, and R.B. Thomas. 1990. Logging effects on streamflow: storm runoff at Casper Creek in Northwestern California. *Water Resources Research*. 26(7): 1657-1667.

Ziemer, R.R. 1981. Storm flow response to road building and partial cutting in small streams of Northern California. *Water Resources Research*. 17(4): 907-917.

APPENDIX A. RUNNING DHSVM

GIS Raster Grid Processing

DHSVM requires numerous spatial data inputs in the 2D binary format. This section describes the processes of obtaining and formatting the data as raster grids. Later steps will explain how to convert the data from raster into binary format. All GIS processes are described using ESRI ArcGIS version 9.3 techniques (Hillier, 2007). All processes and scripts are displayed in italics, names of files and folders are displayed in italics and underlined.

Digital Elevation Model Processing

DHSVM requires a digital elevation model (DEM) in binary format. The DEM will define the grid cell scale at which the all hydrologic calculations are modeled. DEM processing steps are detailed below.

1. Download the DEM

Free DEM data for most of the United States can be downloaded from the Geo Community website (GeoCommunity, 2007). Only community members may download data, but no fee is required to join. Download the desired DEM in either 30 meter or 10 meter grid cell resolution.

2. Convert from SDTS to Raster

The DEM will likely be in Spatial Data Transfer Standard (SDTS) format. SDTS is not immediately recognized by ArcMap 9.2, so the format must be changed to a raster grid. Use the following steps to convert the DEM.

- 1) In ArcCatalog, make the *ArcView 8x Tools* Toolbar visible.
- 2) *Conversion Tools Toolbar* → *SDTS Raster to Grid (dem)*

Note: Some of the grids will have z units that are in feet, not meters. It is important to check the elevation units and convert to meters if necessary.

3. Fill in Sinks

Sinks are usually caused by errors in the DEM and, if left unfilled, will cause disjunctions in water routing. Before filling, check the DRG to ensure that the sinks are errors before filling them.

Spatial Analyst Toolbox → Hydrology → Fill

4. Convert to Floating Point

If the grid is not in floating point, it must be converted. This information can be found in the DEM properties.

Spatial Analyst Toolbar → Raster Calculator: float[dem]

5. Check DEM Properties

DHSVM requires that all grids have the same properties. Take note of the following:

1. Columns and Rows
2. Cell Size
3. Extent
4. Spatial Reference (Coordinate System and Datum)

Watershed Delineation

The watershed input is a binary file that outlines the study area to be analyzed. Often the watersheds are hand-delineated from a DEM. A watershed can also be delineated based on the Hydrology Toolset in ArcGIS, as detailed in the following steps. DHSVM also requires a mask of the watershed, which is described in the ensuing watershed delineation process.

1. Run the Hydrology Toolset

DHSVM will allow you to input a pre-defined watershed boundary, but this can cause mass balance errors. It is recommended that the watershed be delineated using ArcGIS.

1. Load the DEM (*dem*)
2. Run the hydrology toolset

Spatial Analyst Toolbox → Hydrology → Flow Direction

3. To delineate a watershed, a pour point must be defined. This will be the outlet of the stream. Create a raster of one cell at the watershed outlet. If you have point data:

Conversion Tools Toolbox → To Raster → Point to Raster (weirs)

Select the desired raster grid cell

Spatial Analyst Toolbar → Raster Calculator: weirs

4. Delineate the watershed

Spatial Analyst Toolbox → Hydrology → Watershed (mask)

2. Create the Watershed Mask

The watershed grid just created is a rectangle; all of the cells outside of the watershed boundary contain no data. Nodata points cause the model to crash when in Linux, so a mask must be created where all of the cells outside the watershed contain an integer value. This will be the grid that is used when the model runs.

Spatial Analyst Toolbar → Reclassify (mask0)

3. Check Raster Properties

Check to make sure that the watershed grid properties match those of the DEM and that the grid is an unsigned integer. Properties that should be identical include:

1. Columns and Rows
2. Cell Size
3. Extent
4. Spatial Reference (Coordinate System and Datum)

Soil Grid Processing

A soil type map is extremely important for DHSVM since soil input parameters correspond with soil types defined within the map. Again, the map must be in 2D binary format. Soils data for much of the U.S. can be downloaded from the NRCS SSURGO database (Soil Survey Staff, 2008).

1. Download Soils Data

Coweeta soils data were downloaded from SSURGO (including access files).

2. Convert to Raster Format

The data will be downloaded in a vector format and should be converted to raster. When converting to raster, be sure to use a field that will allow you to identify the soil series. This will be helpful in Step 3.

Conversion Tools Toolbox → To Raster → Feature to Raster

3. Reclassify the Soil Series

DHSVM requires that the values in the raster match those in the configuration file, so all of the series need to be given a numerical number. Reclassify based on the configuration file.

Spatial Analyst Toolbar → Reclassify (soil_series)

4. Mask the Soil to the Watershed Boundary

Check to make sure that the downloaded data boundaries match those of the delineated watershed. The Coweeta soils data did not exactly match the boundary for the delineated watershed. 204 cells on the boundary had data that were assumed to be similar to their neighboring cell(s).

- 1) Convert NoData cells to a separate grid. With NoData values highlighted:

Spatial Analyst Toolbar → Raster Calculator → [soil_series]

- 2) Subtract the watershed mask (be sure to use the original mask, not the reclassified mask) from the NoData grid to get all of the cells in the watershed that have null soils values.

Spatial Analyst Toolbar → Raster Calculator → [NoData_grd]-[mask]

- 3) Convert this raster to a point file.

Conversion Tools Toolbox → From Raster → Raster to Point

- 4) Add a field to the point file and manually edit the field by highlighting points and assigning them soils values based on surrounding cells.

- 5) Convert the point file back to raster

Conversion Tools Toolbox → To Raster → Point to Raster (missing_data)

- 6) Merge the grids

Be sure to list the missing data raster first so that it overwrites the soil series grid.

*Spatial Analyst Toolbar → Raster Calculator →
merge([missing_data],[soil_series])*

5. Check Raster Properties

The values in the raster grid should match the fields in the soils section of the configuration file. Check to make sure that the soil grid properties match those of the watershed mask and DEM and that the grid is an unsigned integer. Properties that should be identical include:

1. Columns and Rows
2. Cell Size
3. Extent
4. Spatial Reference (Coordinate System and Datum)

Soil Depth Grid

The create stream network AML does have an algorithm that will generate a soil depth map, but this can create problems with rooting depths and vegetation types when running the model. Creating a soil depth map based on SSURGO data is somewhat crude, but it eliminates these errors.

1. Reclassify the Soil Type Grid

The SSURGO data or soil survey contains information on the depth of each soil series. Reclassify the soil grid based on these soil depths. Set the NoData to an average soil depth for the watershed. Since soil depths are floats instead of integers, this is best done in raster calculator. You can group your soils based on similar depths.

*Spatial Analyst Toolbar → Raster Calculator → con([soil]= 3/ [soil]=6 /
[soil]=10, 1.43)*

Continue this process until all soil series have been assigned a depth.

2. Merge Grids

Merge all of the depth grids together to create one raster of soil depth.

*Spatial Analyst Toolbar → Raster Calculator → Merge([depth1],
[depth2],...[depthn])*

3. Check Raster Properties

Check to make sure that the soil depth grid properties match those of the watershed mask, soil grid, and DEM and that the grid is in floating point. Properties that should be identical include:

1. Columns and Rows
2. Cell Size
3. Extent
4. Spatial Reference (Coordinate System and Datum)

Vegetation Grid Processing

The cover type map file is similar to the soil map file in that it is linked to the DHSVM vegetation input parameters. Land cover data can be downloaded from the National Land Cover Dataset (Multi-Resolution Land Characteristic Consortium, 2010). Coweeta data were manually defined as detailed below.

1. Define the Vegetation Types

The four Coweeta vegetation types are based on three parameters: elevation, topographic position, and aspect. The elevation grid is provided by the DEM. The aspect grid can be created by the spatial analyst tool.

1. The topographic position grid needs to be created based on the DEM and the stream raster. Assume that coves are within 200 m of streams and ridges are within 200 m of a ridgetop. Anything else (for the purpose of this study) will fall into the slope class. Create a raster grid of these three topographic positions.

Spatial Analyst Toolbar → Distance → Straight Line

2. Define the four vegetation types.
 - a. Northern Hardwoods: Elevations greater than 1220 meters in cove and slope positions. Also ridges greater than 1300 meters.
 - b. Mixed Deciduous: Northeast to northwest facing slopes and ridges of up to 760 meters and slopes of all aspects from 760 to 1220 meters.
 - c. Cove Hardwoods: Elevations less than 1220 meters in the coves.
 - d. Xeric Oak Pine: West to southwest facing ridges up to 1300 meters and west to southwest facing slopes up to 760 meters.

2. Mask the Vegetation Grid to the Soil Depth Grid

While only four vegetation types are present in the watershed, they will have different rooting depths and root fractions based on soil depth.

1. Determine new vegetation types. This needs to be done for every vegetation type and soil depth combination. There are multiple ways to do this; raster calculator is one of them.

Spatial Analyst Toolbar → *Raster Calculator* → $con([veg]=1 \ \& \ [soild] \geq 0.44, 1)$

2. Merge the vegetation types to create one vegetation grid. Make sure that the values for each vegetation type match those found in the configuration file.

Spatial Analyst Toolbar → *Raster Calculator* → $Merge([veg1], [veg2], \dots, [vegn])$

3. Check the Raster Properties

The values in the vegetation raster should match the fields in the corresponding section of the configuration file. Check to make sure that the vegetation grid properties match those of the watershed mask, soil type and depth grid, and DEM and that the grid is an unsigned integer. Properties that should be identical include:

1. Columns and Rows
2. Cell Size
3. Extent
4. Spatial Reference (Coordinate System and Datum)

GIS Vector Grid Processing

DHSVM employs two types of networks: streams and roads. Three files are made from these vector networks (See Appendix A) and they require some processing in order to do so.

Create Stream Networks

There are multiple ways that stream networks can be utilized by DHSVM. If stream networks are provided, they need to be in coverage format. This file is then used in the Create Stream Network (CSN) AML to output the stream class, network, and map files that will be ultimately used by DHSVM. If stream networks are not provided, they can be created by the AML. The following process includes steps for both.

1. Create ArcInfo Folder

DHSVM requires a folder in which all of the spatial files are stored. Name this folder (*arcinfo*) and keep in mind that Linux is case-sensitive.

2. If a Stream Network Shapefile is Provided, Convert to Coverage

- 1) Clip the shapefile to the watershed boundary.
- 2) Convert from shapefile to coverage. Be sure to use arc instead of route.
Conversion Tools Toolbox → To Coverage → Feature Class to Coverage
- 3) Copy into the *arcinfo* folder.

3. Initial Inputs for Running CSN AML

The initial input files for creating stream networks are:

1. DEM- raster grid in meters, sinks must be filled and be in floating point
2. A. Mask- raster grid of watershed
B. Mouth- raster grid (point) of basin outlet
3. A. Soil depth grid
B. Maximum and minimum soil depth in meters. Also need the source area in square meters.
4. A. Stream network-coverage file
B. Source area (square meters) for beginning of stream networks

4. Gather the Initial Input Files

- 1) The DEM input is the DEM that we have been working with (*dem*). The sinks have already been filled, and it should already be in floating point.

- 2) We are using the watershed mask to run the networks (*mask*)
- 3) We are using the soil depth grid that we created earlier (*soild*)
- 4) We want the AML to create a stream network for us based on the DEM. To do this, a source area must be specified. The best way to find an accurate source area is to run a flow accumulation in ArcMap to see what the approximate cell accumulation is at stream inception.

Spatial Analyst Toolbar → Hydrology → Flow Direction

Spatial Analyst Toolbar → Hydrology → Flow Accumulation

For Coweeta, most streams start at a source area of 20 cells. For a 30m resolution, this is a source area of 18000 m². The AML will create some non-existent streams, this will require subsequent editing.

- 5) We are going to provide a stream network for the model. The Coweeta stream network was downloaded as a shapefile. This can be clipped to the study watershed and converted to a coverage file. To find the source area, run the hydrology toolset on the DEM. Then overlay the Coweeta stream network to see what the cell flow accumulation is where the streams are first starting. The average is around 250 cells, which equals a source area of 25000 m².

5. Make Changes to the CSN AML Scripts

Some parts of the AMLs have been written specifically for the tutorial settings. These should be changed to ensure more accurate model outputs.

1) Stream Classes (CSN.AML)

The channel classes, hydraulic depths and widths, and effective widths are all hardwired into the AML. These should be individualized based on the watershed. The AML will group stream segments into classes based on the segment slope and the segment mean source area. These groups are then assigned similar characteristics, such as hydraulic depth and width and effective width. The classes are hardwired into the java code and should be individualized based on the watershed. For the initial run, keep these classes as they are.

1. Cell Size (AddAat2.java)

The area of the cell (or the grid resolution) is hardwired into the java code. The tutorial runs on a 150m grid cell and we are running on a 30m grid cell.

Original Code:

```
int area=22500, halfarea = 11250; // CRUDE WAY TO SET CELL SIZE
```

New Code:

```
int area=900, halfarea = 450; // CRUDE WAY TO SET CELL SIZE
```

6. Run CSN

- 1) This step is performed in ArcInfo. Assuming that we are using our created soil depth grid and created stream network, input the following:

```
&workspace <workspace location>
```

```
&amlpath <location of aml scripts>
```

```
&run CSN-EIS <dem> <mask> <soil depth> <stream coverage>
```

```
MOUTH/MASK {minimum source area, meters} {minimum soil depth, meters} {maximum soil depth, meters}
```

Example:

```
&workspace e:\coveeta\calibration4\arcinfo
```

```
&amlpath c:\amlscrip
```

```
&run CSN-EIS cowdem cowmask soild streams MASK
```

- 2) If using a created soil depth grid but no stream network input, use this instead:

```
&run CSN-EIS <dem> <mask> <soil depth> <stream coverage>MASK  
{minimum source area, meters}
```

```
&run CSN-EIS cowdem cowmask soild streams MASK 18000
```

- 3) To have DHSVM create a soil grid but not the stream network, input the following (the same is true for cases where a soil depth grid and stream network are both needed):

```
&run CSN-EIS <dem> <mask> <soil depth> <stream coverage>MASK  
{minimum source area, meters} {minimum soil depth, meters} {maximum  
soil depth, meters}
```

```
&run CSN-EIS cowdem cowmask soild streams MASK 18000 0.2 2.5
```

7. Edit the Stream Networks

- 1) Edit unnecessary stream arcs. Since the stream network was created by a computer, it will likely input streams that are not actually there. If you know the stream location, edit the file by deleting the stream arcs. This needs to be done by converting the coverage file to a shapefile and manually editing the shapefile.

*Conversion Tools Toolbox → To Shapefile → Feature Class to Shapefile
Editor Toolbar → Start Editing*

You can also look at the attribute table to see the channel classes that the AML has assigned the stream segments.

- 2) Update all segment lengths in the attribute table.

Editor Toolbar → Start Editing → Calculate Geometry

- 3) Edit stream classes. If you haven't already done so, update the stream classes in the create stream network AML.

- 4) Convert stream network back to coverage. Be sure to use arc instead of route.

Conversion Tools Toolbox → To Coverage → Feature Class to Coverage

- 5) Delete and save files. Delete all files created by the AML using arcinfo. Copy the new stream coverage file into the arcinfo folder.

8. Re-Run

- 1) Re-run the stream network script in ArcInfo (with edited stream classes). This time we do not need to specify a source area since we are using our own stream network file.

- 2) &workspace e:\coveeta\calibration4\arcinfo

- 3) &amlpath c:\amlscripts

- 4) *&run CSN-EIS <dem> <mask> <soil depth> <stream coverage>
MOUTH/MASK{minimum source area, meters} {minimum soil depth, meters}
{maximum soil depth, meters}*

Example:

&run CSN-EIS cowdem cowmask soild streams MASK

Create Road Networks

DHSVM does not require road networks to run, but they can increase the accuracy of the model output. A road network must be provided. Culvert files can be either provided or created using an AML. Be sure that the fixroads program is properly compiled. This is extremely important in ensuring that the roads are simulated correctly.

1. If a Stream Network Shapefile is Provided, Convert to Coverage

- 1) Clip the shapefile to the watershed boundary.
- 2) DHSVM requires that you manually input classes. Make sure to title the field “class.” Do this by creating a new field and then editing the attribute table. Skip this step for streams.

Attribute Table → Options → Add Field

Editor Toolbar → Start Editing

- 3) Convert from shapefile to coverage. Be sure to use arc instead of route.

Conversion Tools Toolbox → To Coverage → Feature Class to Coverage

- 4) Copy into the arcinfo folder.

2. Initial Inputs for Running CRN AML

The initial input files for creating road networks are:

1. DEM- raster grid in meters, sinks must be filled and be in floating point
2. Mask- raster grid of watershed
3. Road network-coverage file
4. Culvert coverage file

3. Gather the Initial Input Files

- 1) The DEM input is the DEM that we have been working with (dem). The sinks have already been filled, and it should already be in floating point.
- 2) We are using the soil depth grid that we created earlier (soild)
- 3) The road network and culvert coverage files

4. Make Changes to the CRN AML Scripts

Only the create road network AML needs to be edited. The road class widths and depths should be edited depending on watershed data.

5. Run Road Break AML

- 1) The road break AML overlays the culverts into the roads, creating sinks at all culvert locations. It runs in ArcInfo.

```
&workspace e:/coveeta/calibration4/arcinfo
```

```
&amlpath c:/amlscripts
```

```
&run roadbreak <dem> <streams> <roads> <culverts>
```

Example:

```
&run roadbreak cowdem cowstreams cowroads cowculverts
```

- 2) If using basin edges, run the script again.

```
&run roadbreak <dem> <streams> <roads> <edges>
```

Example:

```
&run roadbreak cowdem cowstreams cowroads cowedges
```

6. Run CRN

This is done in ArcInfo. Be sure that the fix roads program is correctly compiled.

```
&workspace f:\coveeta\calibration\arcinfo
```

```
&amlpath c:\amlscripts
```

```
&run CRN <dem> <soil depth> <road network>
```

Example:

```
&run CRN-SFD cowdem soild cowroads
```

Create Culverts

Culverts should, at a minimum, be located where all roads and streams intersect. If you do not have a culvert file, one can be created. Steps one and two describe culvert processing using ArcMap and the ArcIntersect AML, respectively.

1. Creating Culverts Using ArcMap

This will not create culverts at basin edges (see step 2).

- 1) Convert stream and road networks to raster grids.

Conversion Tools Toolbox → To Raster → Feature Class to Raster

- 2) Find cells where streams and roads intersect.

*Spatial Analyst Toolbar Raster Calculator →
con([streams]&[roads],1)*

- 3) Convert raster to point file.

Conversion Tools Toolbox → From Raster → Raster to Point

- 4) Edit the point file. There will be many points that are not actually located at stream crossings. These should be deleted. All other points should be moved to the direct location where the stream and road coverage file cross. You can do this by snapping, but snapping can be unreliable. The best way is to move them by zooming in as far as possible and manually moving the points.

Editor Toolbar → Start Editing

- 5) Convert the point file to a coverage file to get final culvert file.

Conversion Tools Toolbox → To Coverage → Feature Class to Coverage

- 6) Copy the culvert coverage file into the arcinfo folder.

2. Create Culverts Using ArcIntersect

Culverts can also be created using the arcintersect AML. This can create culverts at basin edges, if desired.

- 1) Create a coverage file of the basin. Call this "basinedge." To do this, convert the raster to a shapefile. Create a new polyline shapefile in arccatalog. Edit the new shapefile by snapping to the edges and vertices of the basin polygon. Convert the polyline shapefile to a coverage file.

Conversion Tools Toolbox → From Raster → Raster to Polygon

Editor Toolbar → Start Editing

Conversion Tools Toolbox → To Coverage → Feature Class to Coverage

- 2) Create culverts at locations where roads and streams intersect. Do this in arcinfo.

&workspace e:\GIS\30mdata\culverts

&amlpath c:\amlscripts

&run arcintersect <roads> <streams> <culverts>

Example:

&run arcintersect cowroads cowstreams culverts

- 3) Create sinks where roads exit the basin using arcintersect.

&run arcintersect <roads> <basinedge> <edges>

Example:

&run arcintersect cowroads basinedge edges

- 4) Edit the culvert and edge files per step 1-4. This requires conversion to shapefile then back to coverage. Make sure that the coverage file has a defined coordinate system.
- 5) Copy roads, culverts and edges files into arcinfo folder.

Check Stream and Road Network Output Files

1. Class Files

Class files are not automatically generated by the AML. They must be manually edited and copied into the arcinfo folder. See the sections on stream and road networks for a description of the input fields.

2. Network Files

Check to make sure that the network files do not contain any errors. Look for errors such as unusually large slope or all zeros in the destination channel ID.

- 1) *Channel ID*- unique identifier for channel segment.
- 2) *Segment Order*- determines order for routing computations. Segments with a lower order are routed first and segments receiving inflow from other segments must have a higher order from any of the other segments from which inflow is received.
- 3) *Segment Slope (m/m)*- slope of arc.
- 4) *Segment Length (m)*- length of arc.

- 5) *Channel Class ID*- identifier for channel class.
- 6) *Destination Channel ID*- identifier of the segment to which this segment flows (basin outlet is 0).
- 7) *Save Indicator*- routing results for this segment will be placed in the output file if the keyword SAVE appears in this field.
- 8) *Segment Name*- segment name in the output file.

3. Map Files

Check to make sure that the network files do not contain any errors. Look for large or negative cut bank heights.

- 1) *Column Number*- grid cell column number.
- 2) *Row Number*- grid cell row number.
- 3) *Channel ID*- channel segment identifier, which must be one of those specified in the file with the stream network.
- 4) *Length (m)*- straight line length of the channel segment lying within the cell.
- 5) *Depth (m)*- stream bank height.
- 6) *Width (m)*- effective stream channel width.
- 7) *Save Indicator*- outflow for this segment will be placed in the output file if the keyword SINK appears in this field

4. Save Indicators

In order for output to be saved at a particular location, save indicators must be inserted into the stream and road network and map files. In the network file, the basin outlet will have a destination channel ID of 0.

Running DHSVM

1. Before Beginning

- 1) Master folder should contain the following folders:

arcinfo: contains all GIS data

configfiles: contains configfiles to initialize DHSVM

metfiles: meteorological station data

modelstate: initial state files created by supporting code (initially empty)

output: output directory

programs: supporting programs (check DHSVM website for necessary files)

- 2) Raster grids should all have the same extent, resolution, and projection. A DEM, watershed mask, soil, and vegetation grid are all required. Nodata values will cause errors, so be sure to convert all values outside the watershed boundary to an integer. This will include creating a second mask file. A soil depth grid can be created, but is not necessary. A later script will create one if needed. All grids should be in the *arcinfo* folder.
- 3) Stream and road class files should be in the *arcinfo* folder and should be edited for the watershed.
- 4) The configuration file should be completed and be in the *configfiles* folder.
- 5) All met station data should be in text format and be in the *metfiles* folder.

2. Convert Raster Grids to ASCII (Windows)

- 1) Reclassify all grids (DEM, both mask files, soil, and vegetation) to ASCII using ArcMap.

Conversion Tools Toolbox → *From Raster* → *Raster to ASCII*

Save: filename.dos.txt

- 2) The grids are now in dos format and need to be converted to UNIX. This needs to be done for each ASCII file and can be done using the command prompt.

>*copy filename.dos.txt filename.txt*

>*dos2unix filename.txt*

- 3) There will be two copies of each file. One in dos format (*filename.dos.txt*) and one in UNIX text format (*filename.txt*).

3. Convert ASCII Files to Binary (Linux)

1. Remove headers from all ASCII files (*filename.txt*). This can be done using Kwrite. Make sure that each file does not have any -9999 values.
2. Open the Linux command prompt to convert from ASCII to binary. You should be in the *arcinfo* folder. Once again, this should be done for each file. You will

need the number of rows and the number of columns for the watershed. This can be found from the raster in ArcMap or in the header of the text files. The script changes based on the grid data (floating point or integer). Floating point grids use *float* (DEM, soil depth) and integer grids use *char* (mask, soil, vegetation).

```
$ myconvert ascii float filename.txt filename.bin #rows #columns
```

4. Create Initial State Files (Linux)

The initial state files allow the model to restart under initial conditions. Be sure to be in the programs folder. Edit this file if necessary.

```
$ MakeModelStateBin InitialState.txt
```

5. Create Stream Network Inputs (Windows)

See Section B.2.1 on creating stream networks

6. Create Road Network Inputs (Windows)

See Section B.2.2 on creating road networks

7. Convert Soil Depth to Binary (Windows and Linux)

Follow the same steps in parts 2 and 3 for the soil depth grid. If the grid was not generated by the stream network AML, be sure to check whether it is floating point or integer before converting from ASCII to binary.

8. Create Initial Channel State Files (Linux)

- 1) Open the Linux command prompt and navigate to the programs folder. Make the script executable.

```
$ chmod 755 MakeChannelState.scr
```

- 2) Make the channel state. The starting depth is in meters and should be changed based on the initial conditions in the watershed. The date and time string should match that defined in the Initial State text file.

```
$ ./MakeChannelState.scr ../arcinfo/streamnetwork.dat starting depth  
date/time string
```

Example: `./MakeChannelState.scr ../arcinfo/streamnetwork.dat 0.25`
`10.01.1990.03.00.00`

9. Run DHSVM (Linux)

From the config files folder:

`$ dhsvm3 config file name`

Example: `$ dhsvm3 INPUT.rainycr`

Literature Cited

GeoCommunity. 2007. GIS Data Depot. *GeoCommunity*. Available online at:
<http://data.geocomm.com>.

Hillier, A., 2007. ArcGIS 9.3 Manual. *Environmental Systems Research Institute*. Available
online at: http://works.bepress.com/amy_hillier/17.

Multi-Resolution Land Characteristics Consortium. 2010. National Land Cover Database. *U.S.*
Department of the Interior Geological Survey. Available online at www.mlrc.gov/.

Soil Survey Staff. 2008. U.S. General Soil Map (SSURGO) for Macon County, North Carolina.
USDA Natural Resources Conservation Service. Available online at
<http://soildatamart.nrcs.usda.gov>.

APPENDIX B. EXAMPLE INPUT FILES

Shope Fork Configuration File

```
#####  
#DHSVM INPUT FILE FORMAT  
#####  
# OPTIONS SECTION  
#####  
[OPTIONS]                                # Model Options  
Format = BIN                             # BIN, BYTESWAP or NETCDF  
Extent = BASIN                           # POINT or BASIN  
Gradient = WATERTABLE                    # TOPOGRAPHY or WATERTABLE  
Flow Routing = NETWORK                   # UNIT_HYDROGRAPH or NETWORK  
Sensible Heat Flux = FALSE               # TRUE or FALSE  
Sediment = FALSE                         # TRUE or FALSE  
Sediment Input File =                   # path for sediment configuration file  
Overland Routing = CONVENTIONAL          # CONVENTIONAL or KINEMATIC  
Interpolation = VARCRESS                 # NEAREST or INVDIST or VARCRESS  
MM5 = FALSE                              # TRUE or FALSE  
QPF = FALSE                              # TRUE or FALSE  
PRISM = FALSE                            # TRUE or FALSE  
PRISM data path =                        # path for PRISM files  
PRISM data extension =                   # file extension for PRISM files  
Canopy radiation attenuation mode = FIXED # FIXED or VARIABLE  
Shading = FALSE                          # TRUE or FALSE  
Shading data path =                      # path for shading files  
Shading data extension =                 # file extension for shading files  
Skyview data path =                     # path for skyview file;  
                                           # for use with shading only  
Snotel = FALSE                           # TRUE or FALSE  
Outside = FALSE                          # TRUE or FALSE  
Rhoverride = FALSE                       # TRUE or FALSE
```

```

Precipitation Source = STATION                # STATION or RADAR
Wind Source = STATION                        # STATION or MODEL
Temperature lapse rate = CONSTANT           # CONSTANT or VARIABLE
Precipitation lapse rate = CONSTANT         # CONSTANT, MAP, or VARIABLE
Infiltration = STATIC                       # STATIC or DYNAMIC
Cressman radius = 10                        # in model pixels
Cressman stations = 2                       # number of stations
#####
# MODEL AREA SECTION
#####
[AREA]                                       # Model area
Coordinate System = UTM                     # UTM or USER_DEFINED Albers
Extreme North = 3883947.106                 # Coordinate for northern edge of grid
Extreme West = 273977.382                   # Coordinate for western edge of grid
Center Latitude = 35.06                     # Central parallel of basin
Center Longitude = 83.45                    # Central meridian of basin
Time Zone Meridian = -75                    # Time zone meridian for area
Number of Rows = 130                       # Number of rows
Number of Columns = 175                     # Number of columns
Grid spacing = 30                           # Grid resolution in m
#####
# TIME SECTION
#####
[TIME]                                       # Model period cod
Time Step = 1                               # Model time step (hours)
# spin up
#Model Start = 01/01/2003-03                # Model start time (MM/DD/YYYY-HH)
#Model End = 12/31/2003-23
#Validation
Model Start = 01/01/2003-03                 # Model start time (MM/DD/YYYY-HH)
Model End = 12/31/2007-23

```

```

#####
# CONSTANTS SECTION
#####
[CONSTANTS]                # Model constants
Ground Roughness = 1.5      # Roughness of soil surface (m)
Snow Roughness = 0.03      # Roughness of snow surface (m)
Rain Threshold = -1.0      # Minimum temperature at which rain
                            # occurs (C) minor decrease in snow from 0
Snow Threshold = -1.0      # Maximum temperature at which snow
                            # occurs (C)
Snow Water Capacity = 0.025 # Snow liquid water holding capacity
                            # (fraction)
Reference Height = 46.0    # Reference height (m)
Rain LAI Multiplier = 0.00054 # LAI Multiplier for rain interception
Snow LAI Multiplier = 0.00054 # LAI Multiplier for snow interception
Min Intercepted Snow = 0.003 # Intercepted snow that can only be
                            # melted (m)
Outside Basin Value = 0    # Value in mask that indicates outside
                            # the basin
Temperature Lapse Rate = -0.0018 # Temperature lapse rate (C/m)
Precipitation Lapse Rate = 0.00025 # Precipitation lapse rate (m/m)
#####
# TERRAIN INFORMATION SECTION
#####
[TERRAIN]                    # Terrain information
DEM File = ../arcinfo/cowdem.bin # path for DEM file
Basin Mask File = ../arcinfo/cowmask0.bin # path for mask file
#####
# ROUTING SECTION
#####

```



```

[ROUTING]                                # Routing information. This section is
                                           # only relevant if the Extent = BASIN

##### STREAM NETWORK#####
# The following three fields are only used if Flow Routing = NETWORK
Stream Map File = ../arcinfo/stream.map.dat      # path for stream map file
Stream Network File = ../arcinfo/stream.network.dat  # path for stream network file
Stream Class File = ../arcinfo/stream.class.dat    # path for stream class file
##### ROAD NETWORK #####
# The following three fields are only used if Flow Routing = NETWORK and there is a road
#network
#Scenario 1 - all existing roads
Road Map File = ../arcinfo/road.map.dat          # path for road map file
Road Network File = ../arcinfo/road.network.dat  # path for road network file
Road Class File= ../arcinfo/road.class.dat      # path for road class file
##### UNIT HYDROGRAPH #####
# The following two fields are only used if Flow Routing = UNIT_HYDROGRAPH
Travel Time File =                             # path for travel time file
Unit Hydrograph File =                         # path for unit hydrograph file
#####
# METEOROLOGY SECTION
#####
[METEOROLOGY]                               # Meteorological stations
Number of Stations = 1                       # Number of meteorological stations
# The following set of lines is to be repeated for each station, with the one
# replaced by 2, 3, etc.
Station Name 1 = Coweeta_Exp_Station         # Name for station 1
North Coordinate 1 = 3883144.19              # North coordinate of station 1
East Coordinate  = 278111.694                # East coordinate of station 1
Elevation 1 = 685.5                          # Elevation of station 1 in m
Station File1 = ../metfiles/01              # path for station 1 file

```

MM5

The following block only needs to be filled out if MM5 = TRUE. In that case this is the
#ONLY block that needs to be filled out

MM5 Start = # Start of MM5 file (MM/DD/YYYY-HH),

MM5 Rows =

MM5 Cols =

MM5 Extreme North =

MM5 Extreme West =

MM5 DY =

MM5 met files

MM5 Temperature File =

MM5 Humidity File =

MM5 Wind Speed File=

MM5 Shortwave File =

MM5 Longwave File =

MM5 Pressure File =

MM5 Precipitation File =

MM5 Terrain File =

MM5 Temp Lapse File =

For each soil layer make a key-entry pair as below (n = 1, ..,Number of Soil Layers)

MM5 Soil Temperature File 0 =

MM5 Soil Temperature File 1 =

MM5 Soil Temperature File 2 =

RADAR

The following block only needs to be filled out if Precipitation Source = RADAR.

Radar Start =

Radar File =

Radar Extreme North =

Radar Extreme West =

Radar Number of Rows =

Radar Number of Columns =

```

Radar Grid Spacing =
##### Wind #####
# The following block only needs to be filled out if Wind Source = MODEL
Number of Wind Maps =
Wind File Basename =
Wind Map Met Stations =
##### Precipitation lapse rate #####
# The following block only needs to be filled out if Precipitation lapse rate = MAP
Precipitation lapse rate =
#####
# SOILS INFORMATION SECTION
#####
[SOILS]                # Soil information
Soil Map File = ../arcinfo/cowsoil.bin    # minimum depth 0.43 maximum depth 2.03
Soil Depth File = ../arcinfo/soild.bin
Number of Soil Types = 15
##### SOIL 1 #####
Soil Description 1 = BURTON CRAGGEY ROCK
Lateral Conductivity 1 = 1.75e-3
Exponential Decrease 1 = 4.0
Maximum Infiltration 1 = 2.78e-6
Capillary Drive 1 = 0.11
Surface Albedo 1 = 0.09
Mannings n 1 = 0.011
Number of Soil Layers 1 = 3
Porosity 1 = 0.49  0.42  0.42
Pore Size Distribution 1 = 0.403  0.393  0.393
Bubbling Pressure 1 = 0.035  0.056  0.056
Field Capacity 1 = 0.221  0.188  0.188
Wilting Point 1 = 0.193  0.041  0.041
Bulk Density 1 = 1357.5 1550.0 1550.0

```

Vertical Conductivity 1 = 2.63e-5 1.54e-5 1.54e-5

Thermal Conductivity 1 = 7.77 7.92 7.92

Thermal Capacity 1 = 2.0e6 2.0e6 2.0e6

SOIL 2

Soil Description 2 = CASHIERS

Lateral Conductivity 2 = 1.75e-3

Exponential Decrease 2 = 4.0

Maximum Infiltration 2 = 1.94e-6

Capillary Drive 2 = 0.17

Surface Albedo 2 = 0.16

Mannings n 2 = 0.011

Number of Soil Layers 2 = 3

Porosity 2 = 0.47 0.47 0.47

Pore Size Distribution 2 = 0.375 0.375 0.375

Bubbling Pressure 2 = 0.040 0.031 0.031

Field Capacity 2 = 0.183 0.146 0.138

Wilting Point 2 = 0.125 0.064 0.058

Bulk Density 2 = 1400.0 1400.0 1400.0

Vertical Conductivity 2 = 2.8e-5 2.8e-5 2.8e-5

Thermal Conductivity 2 = 7.88 7.92 7.92

Thermal Capacity 2 = 2.0e6 2.0e6 2.0e6

SOIL 3

Soil Description 3 = CHANDLER

Lateral Conductivity 3 = 1.75e-3

Exponential Decrease 3 = 4.0

Maximum Infiltration 3 = 1.94e-6

Capillary Drive 3 = 0.17

Surface Albedo 3 = 0.23

Mannings n 3 = 0.011

Number of Soil Layers 3 = 3

Porosity 3 = 0.47 0.47 0.47

Pore Size Distribution 3 = 0.375 0.369 0.369

Bubbling Pressure 3 = 0.040 0.138 0.138

Field Capacity 3 = 0.165 0.202 0.202

Wilting Point 3 = 0.098 0.061 0.061

Bulk Density 3 = 1400.0 1400.0 1400.0

Vertical Conductivity 3 = 2.8e-5 2.8e-5 2.8e-5

Thermal Conductivity 3 = 7.88 7.61 7.61

Thermal Capacity 3 = 2.0e6 2.0e6 2.0e6

SOIL 4

Soil Description 4 = CHESTNUT EDNEYVILLE

Lateral Conductivity 4 = 1.75e-3

Exponential Decrease 4 = 4.0

Maximum Infiltration 4 = 1.94e-6

Capillary Drive 4 = 0.17

Surface Albedo 4 = 0.23

Mannings n 4 = 0.011

Number of Soil Layers 4 = 3

Porosity 4 = 0.44 0.44 0.43

Pore Size Distribution 4 = 0.381 0.362 0.379

Bubbling Pressure 4 = 0.046 0.139 0.038

Field Capacity 4 = 0.191 0.163 0.152

Wilting Point 4 = 0.122 0.092 0.070

Bulk Density 4 = 1486.3 1486.3 1500.0

Vertical Conductivity 4 = 2.8e-5 2.8e-5 2.8e-5

Thermal Conductivity 4 = 7.88 7.53 7.88

Thermal Capacity 4 = 2.0e6 2.0e6 2.0e6

SOIL 5

Soil Description 5 = CLEVELAND CHESTNUT

Lateral Conductivity 5 = 1.75e-3

Exponential Decrease 5 = 4.0

Maximum Infiltration 5 = 2.78e-6

Capillary Drive 5 = 0.17
 Surface Albedo 5 = 0.19
 Mannings n 5 = 0.011
 Number of Soil Layers 5 = 3
 Porosity 5 = 0.47 0.47 0.47
 Pore Size Distribution 5 = 0.367 0.356 0.356
 Bubbling Pressure 5 = 0.028 0.167 0.167
 Field Capacity 5 = 0.188 0.185 0.185
 Wilting Point 5 = 0.113 0.075 0.075
 Bulk Density 5 = 1406.3 1406.3 1406.3
 Vertical Conductivity 5 = 2.3e-5 2.3e-5 2.3e-5
 Thermal Conductivity 5 = 7.86 7.41 7.41
 Thermal Capacity 5 = 2.0e6 2.0e6 2.0e6

SOIL 6

Soil Description 6 = CULLASAJA TUCKASEGEE
 Lateral Conductivity 6 = 4.03e-4
 Exponential Decrease 6 = 4.0
 Maximum Infiltration 6 = 1.39e-6
 Capillary Drive 6 = 0.22
 Surface Albedo 6 = 0.16
 Mannings n 6 = 0.011
 Number of Soil Layers 6 = 3
 Porosity 6 = 0.65 0.53 0.50
 Pore Size Distribution 6 = 0.292 0.336 0.351
 Bubbling Pressure 6 = 0.009 0.099 0.031
 Field Capacity 6 = 0.214 0.147 0.102
 Wilting Point 6 = 0.144 0.083 0.057
 Bulk Density 6 = 937.5 1250.0 1325.0
 Vertical Conductivity 6 = 2.8e-5 2.8e-5 2.8e-5
 Thermal Conductivity 6 = 7.36 7.35 7.77
 Thermal Capacity 6 = 2.0e6 2.0e6 2.0e6

SOIL 7

Soil Description 7 = EDNEYVILLE CHESTNUT

Lateral Conductivity 7 = 1.75e-3

Exponential Decrease 7 = 4.0

Maximum Infiltration 7 = 1.94e-6

Capillary Drive 7 = 0.17

Surface Albedo 7 = 0.23

Mannings n 7 = 0.010

Number of Soil Layers 7 = 3

Porosity 7 = 0.44 0.44 0.43

Pore Size Distribution 7 = 0.383 0.365 0.379

Bubbling Pressure 7 = 0.050 0.105 0.038

Field Capacity 7 = 0.185 0.160 0.153

Wilting Point 7 = 0.112 0.082 0.070

Bulk Density 7 = 1491.3 1491.3 1500.0

Vertical Conductivity 7 = 2.80e-5 2.80e-5 2.07e-5

Thermal Conductivity 7 = 7.88 7.63 7.88

Thermal Capacity 7 = 2.0e6 2.0e6 2.0e6

SOIL 8

Soil Description 8 = EVARD COWEE

Lateral Conductivity 8 = 1.75e-3

Exponential Decrease 8 = 4.0

Maximum Infiltration 8 = 1.94e-6

Capillary Drive 8 = 0.17

Surface Albedo 8 = 0.23

Mannings n 8 = 0.010

Number of Soil Layers 8 = 3

Porosity 8 = 0.46 0.47 0.51

Pore Size Distribution 8 = 0.368 0.272 0.304

Bubbling Pressure 8 = 0.198 0.175 0.033

Field Capacity 8 = 0.198 0.231 0.200

Wilting Point 8 = 0.114 0.143 0.116

Bulk Density 8 = 1441.3 1400.0 1300.0

Vertical Conductivity 8 = 2.8e-5 9.0e-6 8.3e-6

Thermal Conductivity 8 = 7.84 6.90 7.35

Thermal Capacity 8 = 2.0e6 2.0e6 2.0e6

SOIL 9

Soil Description 9 = FANNIN

Lateral Conductivity 9 = 1.75e-3

Exponential Decrease 9 = 4.0

Maximum Infiltration 9 = 1.94e-6

Capillary Drive 9 = 0.17

Surface Albedo 9 = 0.30

Mannings n 9 = 0.010

Number of Soil Layers 9 = 3

Porosity 9 = 0.47 0.47 0.47

Pore Size Distribution 9 = 0.350 0.283 0.350

Bubbling Pressure 9 = 0.034 0.884 0.174

Field Capacity 9 = 0.212 0.287 0.214

Wilting Point 9 = 0.126 0.152 0.076

Bulk Density 9 = 1400.0 1400.0 1400.0

Vertical Conductivity 9 = 2.8e-5 9.0e-6 9.0e-6

Thermal Conductivity 9 = 7.70 6.27 7.31

Thermal Capacity 9 = 2.0e6 2.0e6 2.0e6

SOIL 10

Soil Description 10 = PLOTT

Lateral Conductivity10 = 1.75e-3

Exponential Decrease 10 = 4.0

Maximum Infiltration 10 = 1.94e-6

Capillary Drive 10 = 0.17

Surface Albedo 10 = 0.16

Mannings n 10 = 0.010

Number of Soil Layers 10 = 3
Porosity 10 = 0.44 0.47 0.44
Pore Size Distribution 10 = 0.353 0.356 0.385
Bubbling Pressure 10 = 0.014 0.106 0.036
Field Capacity 10 = 0.213 0.156 0.110
Wilting Point 10 = 0.140 0.070 0.045
Bulk Density 10 = 1100.0 1300.0 1400.0
Vertical Conductivity 10 = 2.8e-5 2.8e-5 2.8e-5
Thermal Conductivity 10 = 7.92 7.53 8.00
Thermal Capacity 10 = 2.0e6 2.0e6 2.0e6

SOIL 11

Soil Description 11 = ROCK CLEVELAND
Lateral Conductivity 11 = 9.13e-4
Exponential Decrease 11 = 4.0
Maximum Infiltration 11 = 1.67e-6
Capillary Drive 11 = 0.09
Surface Albedo 11 = 0.16
Mannings n 11 = 0.010

Number of Soil Layers 11 = 3
Porosity 11 = 0.49 0.49 0.49
Pore Size Distribution 11 = 0.357 0.357 0.357
Bubbling Pressure 11 = 0.126 0.126 0.126
Field Capacity 11 = 0.185 0.185 0.185
Wilting Point 11 = 0.081 0.081 0.081
Bulk Density 11 = 1350.0 1350.0 1350.0
Vertical Conductivity 11 = 1.12e-5 1.12e-5 1.12e-5
Thermal Conductivity 11 = 7.49 7.49 7.49
Thermal Capacity 11 = 2.0e6 2.0e6 2.0e6

SOIL 12

Soil Description 12 = SAUNOOK
Lateral Conductivity 12 = 8.03e-3

Exponential Decrease 12 = 4.0
 Maximum Infiltration 12 = 3.06e-6
 Capillary Drive 12 = 0.06
 Surface Albedo 12 = 0.16
 Mannings n 12 = 0.010
 Number of Soil Layers 12 = 3
 Porosity 12 = 0.58 0.51 0.47
 Pore Size Distribution 12 = 0.364 0.272 0.386
 Bubbling Pressure 12 = 0.191 0.175 0.038
 Field Capacity 12 = 0.227 0.226 0.110
 Wilting Point 12 = 0.125 0.118 0.052
 Bulk Density 12 = 1475.0 1400.0 1475.0
 Vertical Conductivity 12 = 2.8e-5 9.0e-5 2.8e-5
 Thermal Conductivity 12 = 7.44 6.90 7.81
 Thermal Capacity 12 = 2.0e6 2.0e6 2.0e6

SOIL 13

Soil Description 13 = TUCKASEGEE WHITESIDE

Lateral Conductivity 13 = 1.75e-3
 Exponential Decrease 13 = 4.0
 Maximum Infiltration 13 = 1.94e-6
 Capillary Drive 13 = 0.17
 Surface Albedo 13 = 0.20
 Mannings n 13 = 0.010
 Number of Soil Layers 13 = 3
 Porosity 13 = 0.54 0.50 0.47
 Pore Size Distribution 13 = 0.349 0.305 0.306
 Bubbling Pressure 13 = 0.025 0.142 0.079
 Field Capacity 13 = 0.221 0.209 0.181
 Wilting Point 13 = 0.142 0.129 0.108
 Bulk Density 13 = 1212.5 1325.0 1412.5
 Vertical Conductivity 13 = 2.80e-5 1.85e-5 2.55e-5

Thermal Conductivity 13 = 7.76 7.00 7.26

Thermal Capacity 13 = 2.00e6 2.00e6 2.00e6

SOIL 14

Soil Description 14 = WAYAH

Lateral Conductivity 14 = 1.00e-3

Exponential Decrease 14 = 4.0

Maximum Infiltration 14 = 2.78e-6

Capillary Drive 14 = 0.11

Surface Albedo 14 = 0.09

Mannings n 14 = 0.010

Number of Soil Layers 14 = 3

Porosity 14 = 0.58 0.45 0.42

Pore Size Distribution 14 = 0.351 0.381 0.410

Bubbling Pressure 14 = 0.013 0.037 0.054

Field Capacity 14 = 0.235 0.141 0.113

Wilting Point 14 = 0.162 0.065 0.046

Bulk Density 14 = 1100.0 1450.0 1525.0

Vertical Conductivity 14 = 2.8e-5 2.8e-5 2.8e-5

Thermal Conductivity 14 = 7.90 7.92 8.07

Thermal Capacity 14 = 2.0e6 2.0e6 2.0e6

SOIL 15

Soil Description 15 = BLANK

Lateral Conductivity 15 = 9.13e-4

Exponential Decrease 15 = 4.0

Maximum Infiltration 15 = 1.67e-6

Capillary Drive 15 = 0.09

Surface Albedo 15 = 0.16

Mannings n 15 = 0.010

Number of Soil Layers 15 = 3

Porosity 15 = 0.49 0.49 0.49

Pore Size Distribution 15 = 0.357 0.357 0.357

Bubbling Pressure 15 = 0.126 0.126 0.126
Field Capacity 15 = 0.185 0.185 0.185
Wilting Point 15 = 0.081 0.081 0.081
Bulk Density 15 = 1350.0 1350.0 1350.0
Vertical Conductivity 15 = 1.12e-5 1.12e-5 1.12e-5
Thermal Conductivity 15 = 7.49 7.49 7.49
Thermal Capacity 15 = 2.0e6 2.0e6 2.0e6

#####

VEGETATION INFORMATION SECTION

#####

[VEGETATION]

Vegetation Map File = ../arcinfo/cowveg.bin

Number of Vegetation Types = 16

VEGETATION 1

Vegetation Description 1 = NORTHERN HARDWOOD VERY SHALLOW

Overstory Present 1 = TRUE

Understory Present 1 = TRUE

Fractional Coverage 1 = 0.85

Trunk Space 1 = 0.60

Aerodynamic Attenuation 1 = 1.5

Radiation Attenuation 1 = 0.86

Hemi Fract Coverage 1 =

Clumping Factor 1 =

Leaf Angle A 1 =

Leaf Angle B 1 =

Scattering Parameter 1 =

Max Snow Int Capacity 1 = 0.005

Mass Release Drip Ratio 1 = 0.2

Snow Interception Eff 1 = 0.3

Impervious Fraction 1 = 0.0

Height 1 = 16.8 3.0

Maximum Resistance 1 = 490.0 388.0
 Minimum Resistance 1 = 410.0 312.0
 Moisture Threshold 1 = 0.139 0.087
 Vapor Pressure Deficit 1 = 4000.0 4000.0
 R_{pc} 1 = 0.3 0.3
 Number of Root Zones 1 = 3
 Root Zone Depths 1 = 0.10 0.13 0.19
 Overstory Root Fraction 1 = 0.50 0.30 0.20
 Understory Root Fraction 1 = 0.60 0.40 0.00
 Overstory Monthly LAI 1 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 1 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 1 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 1 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 2 #####
 Vegetation Description 2 = MIXED DECIDUOUS VERY SHALLOW
 Overstory Present 2 = TRUE
 Understory Present 2 = TRUE
 Fractional Coverage 2 = 0.85
 Trunk Space 2 = 0.76
 Aerodynamic Attenuation 2 = 1.5
 Radiation Attenuation 2 = 0.86
 Hemi Fract Coverage 2 =
 Clumping Factor 2 =
 Leaf Angle A 2 =
 Leaf Angle B 2 =
 Scattering Parameter 2 =
 Max Snow Int Capacity 2 = 0.005
 Mass Release Drip Ratio 2 = 0.2
 Snow Interception Eff 2 = 0.3
 Impervious Fraction 2 = 0.0
 Height 2 = 24.4 3.0

Maximum Resistance 2 = 336.0 388.0
 Minimum Resistance 2 = 264.0 312.0
 Moisture Threshold 2 = 0.152 0.095
 Vapor Pressure Deficit 2 = 4000.0 4000.0
 Rpc 2 = 0.3 0.3
 Number of Root Zones 2 = 3
 Root Zone Depths 2 = 0.10 0.13 0.19
 Overstory Root Fraction 2 = 0.40 0.30 0.30
 Understory Root Fraction 2 = 0.60 0.40 0.00
 Overstory Monthly LAI 2 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 2 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 2 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 2 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 ##### VEGETATION 3 #####
 Vegetation Description 3 = COVE HARDWOODS VERY SHALLOW
 Overstory Present 3 = TRUE
 Understory Present 3 = TRUE
 Fractional Coverage 3 = 0.90
 Trunk Space 3 = 0.86
 Aerodynamic Attenuation 3 = 1.5
 Radiation Attenuation 3 = 0.86
 Hemi Fract Coverage 3 =
 Clumping Factor 3 =
 Leaf Angle A 3 =
 Leaf Angle B 3 =
 Scattering Parameter 3 =
 Max Snow Int Capacity 3 = 0.005
 Mass Release Drip Ratio 3 = 0.2
 Snow Interception Eff 3 = 0.3
 Impervious Fraction 3 = 0.0
 Height 3 = 35.4 3.0

Maximum Resistance 3 = 375.0 388.0
 Minimum Resistance 3 = 193.0 312.0
 Moisture Threshold 3 = 0.109 0.068
 Vapor Pressure Deficit 3 = 4000.0 4000.0
 Rpc 3 = 0.3 0.3
 Number of Root Zones 3 = 3
 Root Zone Depths 3 = 0.10 0.13 0.19
 Overstory Root Fraction 3 = 0.40 0.30 0.30
 Understory Root Fraction 3 = 0.60 0.40 0.00
 Overstory Monthly LAI 3 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 3 = 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20
 Overstory Monthly Alb 3 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 3 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 4 #####
 Vegetation Description 4 = XERIC OAK PINE VERY SHALLOW
 Overstory Present 4 = TRUE
 Understory Present 4 = TRUE
 Fractional Coverage 4 = 0.80
 Trunk Space 4 = 0.74
 Aerodynamic Attenuation 4 = 1.5
 Radiation Attenuation 4 = 0.86
 Hemi Fract Coverage 4 =
 Clumping Factor 4 =
 Leaf Angle A 4 =
 Leaf Angle B 4 =
 Scattering Parameter 4 =
 Max Snow Int Capacity 4 = 0.005
 Mass Release Drip Ratio 4 = 0.2
 Snow Interception Eff 4 = 0.4
 Impervious Fraction 4 = 0.0
 Height 4 = 16.8 2.0

Maximum Resistance 4 = 384.0 388.0
 Minimum Resistance 4 = 256.0 312.0
 Moisture Threshold 4 = 0.151 0.094
 Vapor Pressure Deficit 4 = 4000.0 4000.0
 Rpc 4 = 0.3 0.3
 Number of Root Zones 4 = 3
 Root Zone Depths 4 = 0.10 0.13 0.19
 Overstory Root Fraction 4 = 0.40 0.30 0.30
 Understory Root Fraction 4 = 0.60 0.40 0.00
 Overstory Monthly LAI 4 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 4 = 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20
 Overstory Monthly Alb 4 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 4 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 ##### VEGETATION 5 #####
 Vegetation Description 5 = NORTHERN HARDWOOD SHALLOW
 Overstory Present 5 = TRUE
 Understory Present 5 = TRUE
 Fractional Coverage 5 = 0.85
 Trunk Space 5 = 0.60
 Aerodynamic Attenuation 5 = 1.5
 Radiation Attenuation 5 = 0.86
 Hemi Fract Coverage 5 =
 Clumping Factor 5 =
 Leaf Angle A 5 =
 Leaf Angle B 5 =
 Scattering Parameter 5 =
 Max Snow Int Capacity 5 = 0.005
 Mass Release Drip Ratio 5 = 0.2
 Snow Interception Eff 5 = 0.3
 Impervious Fraction 5 = 0.0
 Height 5 = 16.8 3.0

Maximum Resistance 5 = 490.0 388.0
 Minimum Resistance 5 = 410.0 312.0
 Moisture Threshold 5 = 0.139 0.087
 Vapor Pressure Deficit5 = 4000.0 4000.0
 Rpc 5 = 0.3 0.3
 Number of Root Zones 5 = 3
 Root Zone Depths 5 = 0.18 0.28 0.44
 Overstory Root Fraction 5 = 0.60 0.30 0.10
 Understory Root Fraction 5 = 0.70 0.30 0.00
 Overstory Monthly LAI 5 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 5 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 5 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 5 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 6 #####
 Vegetation Description 6 = NORTHERN HARDWOOD
 Overstory Present 6 = TRUE
 Understory Present 6 = TRUE
 Fractional Coverage 6 = 0.85
 Trunk Space 6 = 0.60
 Aerodynamic Attenuation 6 = 1.5
 Radiation Attenuation 6 = 0.86
 Hemi Fract Coverage 6 =
 Clumping Factor 6 =
 Leaf Angle A 6 =
 Leaf Angle B 6 =
 Scattering Parameter 6 =
 Max Snow Int Capacity 6 = 0.005
 Mass Release Drip Ratio 6 = 0.2
 Snow Interception Eff 6 = 0.3
 Impervious Fraction 6 = 0.0
 Height 6 = 16.8 3.0

Maximum Resistance 6 = 490.0 388.0
 Minimum Resistance 6 = 410.0 312.0
 Moisture Threshold 6 = 0.139 0.087
 Vapor Pressure Deficit 6 = 4000.0 4000.0
 Rpc 6 = 0.3 0.3
 Number of Root Zones 6 = 3
 Root Zone Depths 6 = 0.25 0.38 0.58
 Overstory Root Fraction 6 = 0.60 0.20 0.20
 Understory Root Fraction 6 = 0.70 0.30 0.00
 Overstory Monthly LAI 6 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 6 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 6 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 6 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 7 #####
 Vegetation Description 7 = MIXED DECIDUOUS
 Overstory Present 7 = TRUE
 Understory Present 7 = TRUE
 Fractional Coverage 7 = 0.85
 Trunk Space 7 = 0.76
 Aerodynamic Attenuation 7 = 1.5
 Radiation Attenuation 7 = 0.86
 Hemi Fract Coverage 7 =
 Clumping Factor 7 =
 Leaf Angle A 7 =
 Leaf Angle B 7 =
 Scattering Parameter 7 =
 Max Snow Int Capacity 7 = 0.005
 Mass Release Drip Ratio 7 = 0.2
 Snow Interception Eff 7 = 0.3
 Impervious Fraction 7 = 0.0
 Height 7 = 24.4 3.0

Maximum Resistance 7 = 375.0 388.0
 Minimum Resistance 7 = 193.0 312.0
 Moisture Threshold 7 = 0.152 0.095
 Vapor Pressure Deficit 7 = 4000.0 4000.0
 Rpc 7 = 0.3 0.3
 Number of Root Zones 7 = 3
 Root Zone Depths 7 = 0.25 0.38 0.58
 Overstory Root Fraction 7 = 0.40 0.40 0.20
 Understory Root Fraction 7 = 0.70 0.30 0.00
 Overstory Monthly LAI 7 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 7 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 7 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 7 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 ##### VEGETATION 8 #####
 Vegetation Description 8 = XERIC OAK PINE
 Overstory Present 8 = TRUE
 Understory Present 8 = TRUE
 Fractional Coverage 8 = 0.80
 Trunk Space 8 = 0.74
 Aerodynamic Attenuation 8 = 1.5
 Radiation Attenuation 8 = 0.86
 Hemi Fract Coverage 8 =
 Clumping Factor 8 =
 Leaf Angle A 8 =
 Leaf Angle B 8 =
 Scattering Parameter 8 =
 Max Snow Int Capacity 8 = 0.005
 Mass Release Drip Ratio 8 = 0.2
 Snow Interception Eff 8 = 0.4
 Impervious Fraction 8 = 0.0
 Height 8 = 16.8 2.0

Maximum Resistance 8 = 384.0 388.0
 Minimum Resistance 8 = 256.0 312.0
 Moisture Threshold 8 = 0.151 0.094
 Vapor Pressure Deficit 8 = 4000.0 4000.0
 Rpc 8 = 0.3 0.3
 Number of Root Zones 8 = 3
 Root Zone Depths 8 = 0.25 0.38 0.58
 Overstory Root Fraction 8 = 0.40 0.30 0.30
 Understory Root Fraction 8 = 0.60 0.40 0.00
 Overstory Monthly LAI 8 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 8 = 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20
 Overstory Monthly Alb 8 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 8 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 ##### VEGETATION 9 #####
 Vegetation Description 9 = NORTHERN HARDWOOD DEEP
 Overstory Present 9 = TRUE
 Understory Present 9 = TRUE
 Fractional Coverage 9 = 0.85
 Trunk Space 9 = 0.60
 Aerodynamic Attenuation 9 = 1.5
 Radiation Attenuation 9 = 0.86
 Hemi Fract Coverage 9 =
 Clumping Factor 9 =
 Leaf Angle A 9 =
 Leaf Angle B 9 =
 Scattering Parameter 9 =
 Max Snow Int Capacity 9 = 0.005
 Mass Release Drip Ratio 9 = 0.2
 Snow Interception Eff 9 = 0.3
 Impervious Fraction 9 = 0.0
 Height 9 = 16.8 3.0

Maximum Resistance 9 = 490.0 388.0
 Minimum Resistance 9 = 410.0 312.0
 Moisture Threshold 9 = 0.139 0.087
 Vapor Pressure Deficit 9 = 4000.0 4000.0
 Rpc 9 = 0.3 0.3
 Number of Root Zones 9 = 3
 Root Zone Depths 9 = 0.35 0.58 0.79
 Overstory Root Fraction 9 = 0.60 0.20 0.20
 Understory Root Fraction 9 = 0.90 0.10 0.00
 Overstory Monthly LAI 9 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 9 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 9 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 9 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 10 #####
 Vegetation Description 10 = MIXED DECIDUOUS DEEP
 Overstory Present 10 = TRUE
 Understory Present 10 = TRUE
 Fractional Coverage 10 = 0.85
 Trunk Space 10 = 0.76
 Aerodynamic Attenuation 10 = 1.5
 Radiation Attenuation10 = 0.86
 Hemi Fract Coverage 10 =
 Clumping Factor 10 =
 Leaf Angle A 10 =
 Leaf Angle B 10 =
 Scattering Parameter 10 =
 Max Snow Int Capacity 10 = 0.005
 Mass Release Drip Ratio 10 = 0.2
 Snow Interception Eff 10 = 0.3
 Impervious Fraction10 = 0.0
 Height 10 = 24.4 3.0

Maximum Resistance 10 = 336.0 388.0
 Minimum Resistance 10 = 264.0 312.0
 Moisture Threshold 10 = 0.152 0.095
 Vapor Pressure Deficit 10 = 4000.0 4000.0
 Rpc 10 = 0.3 0.3
 Number of Root Zones 10 = 3
 Root Zone Depths 10 = 0.35 0.58 0.79
 Overstory Root Fraction 10 = 0.45 0.45 0.10
 Understory Root Fraction 10 = 0.90 0.10 0.00
 Overstory Monthly LAI10 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI10 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb10 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 10 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 ##### VEGETATION 11 #####
 Vegetation Description 11 = COVE HARDWOODS DEEP
 Overstory Present 11 = TRUE
 Understory Present 11 = TRUE
 Fractional Coverage 11 = 0.90
 Trunk Space 11 = 0.86
 Aerodynamic Attenuation 11 = 1.5
 Radiation Attenuation 11 = 0.86
 Hemi Fract Coverage 11 =
 Clumping Factor 11 =
 Leaf Angle A 11 =
 Leaf Angle B 11 =
 Scattering Parameter 11 =
 Max Snow Int Capacity 11 = 0.005
 Mass Release Drip Ratio 11 = 0.2
 Snow Interception Eff 11 = 0.3
 Impervious Fraction 11 = 0.0
 Height 11 = 35.4 3.0

Maximum Resistance 11 = 375.0 388.0
 Minimum Resistance 11 = 193.0 312.0
 Moisture Threshold 11 = 0.109 0.068
 Vapor Pressure Deficit 11 = 4000.0 4000.0
 Rpc 11 = 0.3 0.3
 Number of Root Zones 11 = 3
 Root Zone Depths 11 = 0.35 0.58 0.79
 Overstory Root Fraction 11 = 0.40 0.30 0.30
 Understory Root Fraction 11 = 0.60 0.40 0.00
 Overstory Monthly LAI 11 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 11 = 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20
 Overstory Monthly Alb 11 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 11 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 12 #####
 Vegetation Description 12 = XERIC OAK PINE DEEP
 Overstory Present 12 = TRUE
 Understory Present 12 = TRUE
 Fractional Coverage 12 = 0.80
 Trunk Space 12 = 0.74
 Aerodynamic Attenuation 12 = 1.5
 Radiation Attenuation 12 = 0.86
 Hemi Fract Coverage 12 =
 Clumping Factor12 =
 Leaf Angle A12 =
 Leaf Angle B12 =
 Scattering Parameter 12 =
 Max Snow Int Capacity12 = 0.005
 Mass Release Drip Ratio 12 = 0.2
 Snow Interception Eff12 = 0.4
 Impervious Fraction12 = 0.0
 Height 12 = 16.8 2.0

Maximum Resistance 12 = 384.0 388.0
 Minimum Resistance 12 = 256.0 312.0
 Moisture Threshold 12 = 0.151 0.094
 Vapor Pressure Deficit 12 = 4000.0 4000.0
 Rpc 12 = 0.3 0.3
 Number of Root Zones 12 = 3
 Root Zone Depths 12 = 0.35 0.58 0.79
 Overstory Root Fraction 12 = 0.40 0.30 0.30
 Understory Root Fraction 12 = 0.60 0.40 0.00
 Overstory Monthly LAI 12 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 12 = 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20
 Overstory Monthly Alb 12 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 12 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 ##### VEGETATION 13 #####
 Vegetation Description 13 = NORTHERN HARDWOOD VERY DEEP
 Overstory Present 13 = TRUE
 Understory Present 13 = TRUE
 Fractional Coverage 13 = 0.85
 Trunk Space 13 = 0.60
 Aerodynamic Attenuation 13 = 1.5
 Radiation Attenuation 13 = 0.86
 Hemi Fract Coverage 13 =
 Clumping Factor 13 =
 Leaf Angle A 13 =
 Leaf Angle B 13 =
 Scattering Parameter 13 =
 Max Snow Int Capacity 13 = 0.005
 Mass Release Drip Ratio 13 = 0.2
 Snow Interception Eff 13 = 0.3
 Impervious Fraction 13 = 0.0
 Height 13 = 16.8 3.0

Maximum Resistance 13 = 490.0 388.0
 Minimum Resistance 13 = 410.0 312.0
 Moisture Threshold 13 = 0.139 0.087
 Vapor Pressure Deficit 13 = 4000.0 4000.0
 Rpc 13 = 0.3 0.3
 Number of Root Zones 13 = 3
 Root Zone Depths 13 = 0.20 0.52 1.30
 Overstory Root Fraction 13 = 0.60 0.20 0.20
 Understory Root Fraction 13 = 0.70 0.30 0.00
 Overstory Monthly LAI 13 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 13 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 13 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 13 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 14 #####
 Vegetation Description 14 = MIXED DECIDUOUS VERY DEEP
 Overstory Present 14 = TRUE
 Understory Present 14 = TRUE
 Fractional Coverage 14 = 0.85
 Trunk Space 14 = 0.76
 Aerodynamic Attenuation 14 = 1.5
 Radiation Attenuation 14 = 0.86
 Hemi Fract Coverage 14 =
 Clumping Factor 14 =
 Leaf Angle A 14 =
 Leaf Angle B 14 =
 Scattering Parameter 14 =
 Max Snow Int Capacity 14 = 0.005
 Mass Release Drip Ratio 14 = 0.2
 Snow Interception Eff14 = 0.3
 Impervious Fraction 14 = 0.0
 Height 14 = 24.4 3.0

Maximum Resistance 14 = 336.0 388.0
 Minimum Resistance 14 = 264.0 312.0
 Moisture Threshold 14 = 0.152 0.095
 Vapor Pressure Deficit 14 = 4000.0 4000.0
 Rpc 14 = 0.3 0.3
 Number of Root Zones 14 = 3
 Root Zone Depths 14 = 0.20 0.52 1.30
 Overstory Root Fraction 14 = 0.50 0.45 0.05
 Understory Root Fraction 14 = 0.70 0.30 0.00
 Overstory Monthly LAI 14 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 14 = 0.58 0.63 0.63 0.63 0.92 1.77 2.55 2.55 1.73 0.97 0.73 0.63
 Overstory Monthly Alb 14 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 14 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 ##### VEGETATION 15 #####
 Vegetation Description 15 = COVE HARDWOOD VERY DEEP
 Overstory Present 15 = TRUE
 Understory Present 15 = TRUE
 Fractional Coverage 15 = 0.90
 Trunk Space 15 = 0.86
 Aerodynamic Attenuation 15 = 1.5
 Radiation Attenuation 15 = 0.86
 Hemi Fract Coverage 15 =
 Clumping Factor 15 =
 Leaf Angle A 15 =
 Leaf Angle B 15 =
 Scattering Parameter 15 =
 Max Snow Int Capacity 15 = 0.005
 Mass Release Drip Ratio 15 = 0.2
 Snow Interception Eff 15 = 0.3
 Impervious Fraction 15 = 0.0
 Height 15 = 35.4 3.0

Maximum Resistance 15 = 375.0 388.0
 Minimum Resistance 15 = 193.0 312.0
 Moisture Threshold 15 = 0.109 0.068
 Vapor Pressure Deficit 15 = 4000.0 4000.0
 Rpc 15 = 0.3 0.3
 Number of Root Zones 15 = 3
 Root Zone Depths 15 = 0.20 0.52 1.30
 Overstory Root Fraction 15 = 0.40 0.30 0.30
 Understory Root Fraction 15 = 0.60 0.40 0.00
 Overstory Monthly LAI 15 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 15 = 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20
 Overstory Monthly Alb 15 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 15 = 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
 ##### VEGETATION 16 #####
 Vegetation Description16 = XERIC OAK PINE VERY DEEP
 Overstory Present 16 = TRUE
 Understory Present 16 = TRUE
 Fractional Coverage 16 = 0.80
 Trunk Space 16 = 0.74
 Aerodynamic Attenuation 16 = 1.5
 Radiation Attenuation 16 = 0.86
 Hemi Fract Coverage 16 =
 Clumping Factor 16 =
 Leaf Angle A 16 =
 Leaf Angle B 16 =
 Scattering Parameter 16 =
 Max Snow Int Capacity16 = 0.005
 Mass Release Drip Ratio 16 = 0.2
 Snow Interception Eff 16 = 0.4
 Impervious Fraction 16 = 0.0
 Height 16 = 16.8 2.0

Maximum Resistance 16 = 384.0 388.0
 Minimum Resistance 16 = 256.0 312.0
 Moisture Threshold 16 = 0.151 0.094
 Vapor Pressure Deficit 16 = 4000.0 4000.0
 Rpc 16 = 0.3 0.3
 Number of Root Zones 16 = 3
 Root Zone Depths 16 = 0.20 0.52 1.30
 Overstory Root Fraction 16 = 0.40 0.30 0.30
 Understory Root Fraction 16 = 0.60 0.40 0.00
 Overstory Monthly LAI 16 = 0.52 0.52 0.87 2.11 4.51 6.77 7.17 6.51 5.04 2.17 0.87 0.52
 Understory Monthly LAI 16 = 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20 2.20
 Overstory Monthly Alb 16 = 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23
 Understory Monthly Alb 16 = 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22 0.22
 #####
 # MODEL OUTPUT SECTION
 #####
 [OUTPUT] # Information what to output when
 Output Directory = ../output/
 Initial State Directory = ../modelstate/
 ##### PIXEL DUMPS #####
 Number of Output Pixels = 0
 # For each pixel make a key-entry pair as indicated below, varying the
 # number for the output pixel (1, .. , Number of Output Pixel)
 North Coordinate 1 =
 East Coordinate 1 =
 Name 1 =
 ##### MODEL STATE #####
 Number of Model States = 0 # Number of model states to dump
 # For each model state make a key-entry pair as indicated below, varying the
 # number for the model state dump (1, .. , Number of Model States)
 State Date 1 = # Time for model state dump

MODEL MAPS

Number of Map Variables = 0 # Number of different variables for
which you want to output maps

For each of the variables make a block like the one that follows, varying
the number of the variable (n = 1, .. , Number of Map Variables)

Map Variable 1 = # ID of the variable to output

Map Layer 1 = # If the variable exists for a number
of layers, specify the layers here
with the top layer = 1

Number of Maps 1 = # Number of maps you would like to
output for this variable

Map Date 1 1 =

MODEL IMAGES

Number of Image Variables = 0 # Number of variables for which you
would like to output images

For each of the variables make a block like the one that follows, varying
the number of the variable (n = 1, .. , Number of Image Variables)

Image Variable 1 = # ID of the variable to output

Image Layer 1 = # If the variable exists for a number
of layers, specify the layers here
with the top layer = 1

Image Start 1 = # First timestep for which to output
an image

Image End 1 = # Last timestep for which to output
an image

Image Interval 1 = # Time interval between images (hours)

Image Upper Limit 1 = # All values in the output equal to or
greater than this limit will be set to 255

Image Lower Limit 1 = # All values in the output equal to or
smaller than this limit will be set to 0

```
##### GRAPHIC IMAGES #####
Number of Graphics    = 0          # Number of variables for which you
                                # would like to output images
Graphics ID 1 =          # ID of the variable to output
# WARNING Use soil moisture layers with caution, to minimize calculations during
# redraw DHSVM does not check to make sure that the assigned soil layer exists
#####
# END OF INPUT FILE
#####
```

Class Files

Stream Class File

#Class	Width	Depth	n	Inf
1	1.5	1	0.1	0
2	2.4	1.2	0.1	0
3	1	0.3	0.1	0
4	2	0.5	0.1	0
5	2	1.5	0.1	0
6	5	4	0.1	0
7	7.5	7	0.1	0
8	3.5	0.8	0.1	0
9	6	1	0.1	0

Road Class File

#Class	Width	Depth	n	Inf	Road						
					Type	Erod	Erod_ol	d50	n	surface	width
1	0.50	0.50	0.02	0.01	CROWN	500	0.26	1.0	0.028	gravel	6.00
2	0.50	0.50	0.03	0.01	CROWN	600	0.35	9.0	9.000	paved	7.93
3	0.25	0.25	0.02	0.01	OUTSLP	300	0.26	0.1	0.024	dirt	4.00
4	0.25	0.25	0.03	0.01	INSLP	300	0.35	0.1	0.015	dirt	3.93
5	0.25	0.25	0.02	0.01	OUTSLP	300	0.26	0.1	0.030	dirt	4.00
6	0.25	0.25	0.03	0.01	OUTSLP	300	0.35	0.1	0.015	dirt	2.93
7	0.15	0.15	0.02	0.01	CROWN	300	0.26	0.1	0.020	dirt	2.00
8	0.25	0.25	0.03	0.01	CROWN	300	0.35	0.1	0.015	dirt	3.93
9	0.25	0.25	0.03	0.01	CROWN	200	0.26	0.5	0.015	dirt	3.93

Map Files

Stream Map File (page 1 of 19 shown)

```
##### This file has been automatically generated #####  
##### EDIT WITH CARE!!! #####
```

```
# Generated: July 12, 2009 4:44 PM  
# Command: ROADMAPFILE OUTCOVER STREAM.MAP.DAT EFFWIDTH EFFDEPTH  
# Workspace: e:\coveeta\calibration4\arcinfo  
#  
# Col Row ID Segment Cut/Bank Cut Segment SINK?  
# Length Height Width Aspect (optional)  
# (m) (m) (m) (d)  
#  
123 13 1 14.6551 1.9285 2.0000 329.0000  
124 13 1 2.9292 1.9285 2.0000 329.0000  
124 14 1 34.9258 1.9285 2.0000 329.0000  
124 15 1 20.4084 1.9285 2.0000 329.0000  
125 15 1 15.5381 1.9285 2.0000 324.0000  
125 16 1 31.5073 1.9285 2.0000 318.0000  
126 16 1 8.6657 1.9285 2.0000 318.0000  
126 17 1 38.5777 1.9285 2.0000 322.0000  
127 18 1 35.6961 1.9285 2.0000 326.0000  
127 19 1 19.9562 1.9285 2.0000 328.0000  
128 19 1 13.9715 1.9285 2.0000 340.0000  
107 20 5 7.7160 1.9285 2.0000 319.0000  
91 20 6 23.5922 1.7627 2.0000 296.0000  
108 20 5 20.6702 1.9285 2.0000 319.0000  
128 20 1 30.7705 1.9285 2.0000 350.0000  
91 21 6 7.0817 1.7627 2.0000 302.0000  
108 21 5 27.0441 1.9285 2.0000 323.0000  
92 21 6 36.3809 1.7627 2.0000 318.0000  
109 21 5 10.1751 1.9285 2.0000 327.0000  
128 21 1 30.0065 1.9285 2.0000 1.0000  
92 22 6 16.0706 1.7627 2.0000 337.0000  
93 22 6 16.7829 1.7627 2.0000 337.0000  
109 22 5 34.4940 1.9285 2.0000 330.0000  
128 22 1 30.0078 1.9285 2.0000 1.0000  
109 23 5 14.9308 1.9285 2.0000 330.0000  
110 23 5 19.8887 1.9285 2.0000 329.0000  
128 23 1 30.1624 1.9285 2.0000 1.0000  
93 23 6 41.6605 1.7627 2.0000 323.0000  
94 24 6 30.5085 1.7627 2.0000 278.0000  
95 24 6 30.4263 1.7627 2.0000 279.0000  
96 24 6 34.1578 1.7627 2.0000 307.0000  
128 24 1 30.3869 1.9285 2.0000 351.0000  
110 24 5 35.9527 1.9285 2.0000 327.0000  
96 25 6 5.1139 1.7627 2.0000 318.0000  
97 25 6 33.3964 1.7627 2.0000 322.0000  
111 25 5 34.4792 1.9285 2.0000 330.0000  
128 25 1 30.7391 1.9285 2.0000 348.0000  
97 26 6 17.0596 1.7627 2.0000 327.0000  
111 26 5 28.7117 1.9285 2.0000 333.0000  
98 26 6 18.8154 1.7627 2.0000 327.0000  
112 26 5 4.9282 1.9285 2.0000 333.0000  
128 26 1 31.4474 1.9285 2.0000 345.0000  
98 27 6 29.1268 1.7627 2.0000 358.0000  
112 27 5 33.2028 1.9285 2.0000 335.0000
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Road Map File (page 1 of 31 shown)

```
##### This file has been automatically generated #####
EDIT WITH CARE!!! #####
# Generated: October 20, 2009 12:24 PM
# Command: ROADMAPFILE OUTCOVER TEMP.ROAD.MAP EFFWIDTH CUTDEPTH
# Workspace: f:\coveeta\density\layout1\l1d4\arcinfo
#
# Segment Cut/Bank Cut Segment
# Col Row ID Length Height Width Aspect SINK?
# (m) (m) (m) (d) (optional)
#
120 11 256 10.1447 0.5085 4.0000 276.0000
120 11 264 3.7645 0.7987 4.0000 215.0000 SINK
121 11 256 31.0568 0.7969 4.0000 285.0000
127 11 339 30.0198 0.3207 4.0000 89.0000
126 11 339 2.5856 0.3303 4.0000 90.0000 SINK
128 11 339 30.0525 0.2663 4.0000 90.0000
122 11 256 12.0637 0.7162 4.0000 285.0000 SINK
126 11 340 27.5189 0.3971 4.0000 86.0000
129 11 339 10.3822 0.2570 4.0000 106.0000
125 11 340 18.6542 0.2736 4.0000 84.0000 SINK
122 11 255 18.4868 0.4056 4.0000 277.0000 SINK
125 11 253 11.5250 0.2555 4.0000 84.0000
124 11 253 30.0740 0.2537 4.0000 86.0000
123 11 253 3.4072 0.2537 4.0000 86.0000 SINK
123 11 255 26.8335 0.2789 4.0000 278.0000
120 11 388 14.3106 0.3252 4.0000 340.0000
129 11 254 21.4707 0.2674 4.0000 291.0000
130 12 254 34.4212 0.3783 4.0000 312.0000 SINK
130 12 338 6.8443 0.3404 4.0000 132.0000
120 12 388 30.7592 0.2739 4.0000 3.0000
131 12 338 4.2343 0.2987 4.0000 133.0000
120 13 388 6.8332 0.2609 4.0000 34.0000 SINK
120 13 341 13.8854 0.7963 4.0000 245.0000 SINK
131 13 338 30.2049 0.3345 4.0000 113.0000 SINK
132 13 338 12.3346 0.4491 4.0000 100.0000
119 13 341 30.2417 0.9985 4.0000 263.0000
118 13 341 6.2240 1.0948 4.0000 262.0000
118 13 252 24.0304 0.5582 4.0000 263.0000 SINK
117 13 252 23.1870 0.4972 4.0000 267.0000
132 13 387 20.8102 0.3410 4.0000 332.0000
132 14 387 31.3166 0.3564 4.0000 342.0000 SINK
134 14 336 20.2454 0.2838 4.0000 96.0000
133 14 387 6.6117 0.2500 4.0000 286.0000
133 14 336 15.4477 0.3160 4.0000 82.0000
133 15 336 8.3519 0.2810 4.0000 90.0000 SINK
109 15 251 16.5961 0.2916 4.0000 238.0000 SINK
134 15 386 19.6046 0.3036 4.0000 326.0000 SINK
108 15 251 4.8051 0.2500 4.0000 243.0000
106 15 250 11.7550 0.9842 4.0000 333.0000
108 15 249 27.3457 0.2656 4.0000 253.0000 SINK
107 15 249 28.2688 0.3185 4.0000 266.0000
107 15 250 5.2400 0.9206 4.0000 340.0000 SINK
107 15 248 1.8160 0.4400 4.0000 261.0000
106 15 248 30.0942 0.4464 4.0000 267.0000
105 15 248 15.3182 0.3424 4.0000 263.0000
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Network Files

Stream Network File (page 1 of 2 shown)

1	1	0.25768	647.31626	4	7	
2	1	0.31969	207.13632	3	7	
3	1	0.32537	199.90082	3	25	
4	1	0.30003	331.49430	3	25	
5	1	0.23582	805.28637	4	17	
6	1	0.20089	1104.41145	4	17	
7	2	0.14451	657.47999	8	13	
8	1	0.64909	196.91922	3	15	
9	1	0.67707	144.27326	3	15	
10	13	0.00660	71.05152	9	13	
11	1	0.16422	464.00583	4	10	
12	1	0.27969	449.17942	4	14	
13	14	0.01557	210.46318	9	14	
14	15	0.06440	76.26553	9	-1	SAVE "SHOPE FORK"
15	2	0.34807	232.84001	4	22	
16	1	0.49711	315.66472	3	22	
17	2	0.18763	465.36847	8	19	
18	12	0.05226	370.21288	9	10	
19	11	0.06342	134.86069	9	18	
20	1	0.39043	396.69564	3	28	
21	1	0.29876	676.97426	4	27	
22	3	0.18722	419.79591	4	27	
23	10	0.06628	434.53916	8	19	
24	1	0.32680	615.26849	3	23	
25	2	0.23499	661.30772	4	29	
26	7	0.06278	74.33549	8	29	
27	4	0.12715	199.16404	8	26	
28	9	0.10523	156.72024	8	23	
29	8	0.14003	445.85022	8	28	
30	5	0.07930	173.59322	8	18	
31	1	0.36688	323.50796	3	34	
32	6	0.12485	558.29894	8	26	
33	1	0.35493	945.43790	4	32	
34	2	0.29556	527.31824	4	36	
35	5	0.18937	78.69696	8	32	
36	3	0.17789	430.45972	8	35	
37	1	0.46177	458.17215	4	34	
38	1	0.27882	344.71952	3	30	
39	4	0.18432	574.27406	8	30	
40	4	0.16568	221.63043	8	35	
41	1	0.36104	107.93788	3	43	
42	3	0.12313	571.51288	4	39	
43	2	0.17952	295.99287	4	42	
44	2	0.23318	538.74566	8	36	
45	1	0.52476	314.60999	3	44	
46	2	0.15306	64.45001	4	42	
47	1	0.18932	100.88954	3	46	
48	1	0.33778	114.62122	3	43	
49	1	0.30880	157.47930	2	46	
50	3	0.19738	445.34883	8	40	
51	1	0.39590	427.73518	4	44	
52	2	0.31050	187.59652	4	50	

Road Network File (page 1 of 7 shown)

1	1	0.08872	27.63280	7	0
2	1	0.28485	22.68496	5	0
3	1	0.11443	148.47075	7	0
4	1	0.03932	57.94310	1	0
5	1	0.06476	50.73960	7	0
6	1	0.30692	11.31425	7	0
7	1	0.13197	3.05069	7	0
8	1	0.05007	25.90982	3	0
9	1	0.17708	76.35820	1	0
10	1	0.04395	42.97772	5	0
11	1	0.08797	42.49444	3	0
12	1	0.16570	38.68707	3	0
13	1	0.24967	50.90720	3	0
14	1	0.15248	78.29739	7	0
15	1	0.17776	56.59436	5	0
16	1	0.06667	63.76398	7	0
17	1	0.02697	46.41499	3	0
18	1	0.10435	142.38448	3	0
19	1	0.19893	427.29435	7	0
20	1	0.03553	47.48942	7	0
21	1	0.10926	65.82020	5	0
22	1	0.06939	113.50407	5	0
23	1	0.33235	57.91962	7	0
24	1	0.14244	361.92204	3	0
25	1	0.16479	291.97568	7	0
26	1	0.01350	62.61656	7	0
27	1	0.06064	54.64989	7	0
28	1	0.00432	61.79592	7	0
29	1	0.19388	2.72813	7	0
30	1	0.17996	51.43987	7	0
31	1	0.13149	84.81630	7	0
32	1	0.08788	75.04872	1	0
33	1	0.25603	37.17635	7	0
34	1	0.21120	181.28082	7	0
35	1	0.11400	63.16022	7	0
36	1	0.15030	51.74957	7	0
37	1	0.11068	226.82203	7	0
38	1	0.13202	48.49419	7	0
39	1	0.11745	289.06658	7	0
40	1	0.09768	52.27735	3	0
41	1	0.29326	52.47758	7	0
42	1	0.04734	55.52155	7	0
43	1	0.19090	0.51859	7	0
44	1	0.17881	57.18247	7	0
45	1	0.07965	53.76257	5	0
46	1	0.15653	54.04236	7	0
47	1	0.17548	52.83736	5	0
48	1	0.15788	37.77828	7	0
49	1	0.02688	174.45061	3	0
50	1	0.06233	57.97162	7	0
51	1	0.24227	101.48568	7	0
52	1	0.30213	21.52539	7	0
53	1	0.06455	108.56444	7	0
54	1	0.05740	61.07908	5	0