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Application of a Distributed Process-Based Hydrologic Model to Estimate the Effects of Forest Road Density on Stormflows in the Southern Appalachians

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Managed forests have historically been linked to watershed protection and flood mitigation. Research indicates 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. The distributed hydrology-soil-vegetation model was successfully calibrated at an hourly time step 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 stormflow volume by as much as 17.5% when road densities increased from 0.5 to 4.3 km km^{-2} ($P < 0.05$). Overall, model simulations suggest that minimizing road density necessitated by the land use and appropriate forest road best management practices can be used to minimize impacts on stormflow.

Keywords: distributed process-based hydrologic model, forest roads, watershed modeling, forest hydrology

Forested watersheds have many ecological and socioeconomic benefits, including buffering against downstream flooding (Aitken 1914, Lull and Reinhart 1972, Gosh and Subba 1979) and protecting air and water quality (Anderson et al. 1976, Lowrance et al. 1997, Foley et al. 2005). Forest management, especially harvesting and road building, can lead to increased streamflow (both baseflow and peak flow) sedimentation (Hess 1984, Mortimer and Visser 2004). Baseflow and peak flow often increase slightly after forest harvest (Cornish and Vertessy 2001), yet in eastern hardwood forests, water yield can return to preharvest conditions within 5 years of logging (Hewlett and Helvey 1970, Hornbeck et al. 1970, Kochenderfer et al. 1990, Swank et al. 2001). In contrast, road networks, which remain on the watershed postharvest, can negatively affect watershed hydrology for longer time frames (King and Tennyson 1984, Jones et al. 2000).

Numerous studies have attempted to determine the effects of forest harvesting and road construction on streamflow (King and Tennyson 1984, Jones and Grant 1996, La Marche and Lettenmaier 2001), yet it can be difficult to separate the two actions because harvesting and road construction often occur simultaneously. Recently, 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 exclusive of forest harvesting. One such model, the distributed hydrology-soil-vegetation model (DHSVM) has been used to study the impact of roads on baseflow and peak flow, primarily in high-elevation mountains (Bowling and Lettenmaier 1997, La Marche and Lettenmaier 2001, Cuo et al. 2006). DHSVM has not yet been applied to low-elevation mountains that are devoid of a seasonal snowpack, such as the southern Appalachian Mountains. In this region, the impacts of road networks on the stream hydrograph are

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; millimeters (mm): 1 mm = 0.039 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; cubic meters (m^3): 1 m^3 = 35.3 ft^3; kilometers (km): 1 km = 0.6 mi; kilograms (kg): 1 kg = 2.2 lb; hectares (ha): 1 ha = 2.47 ac.

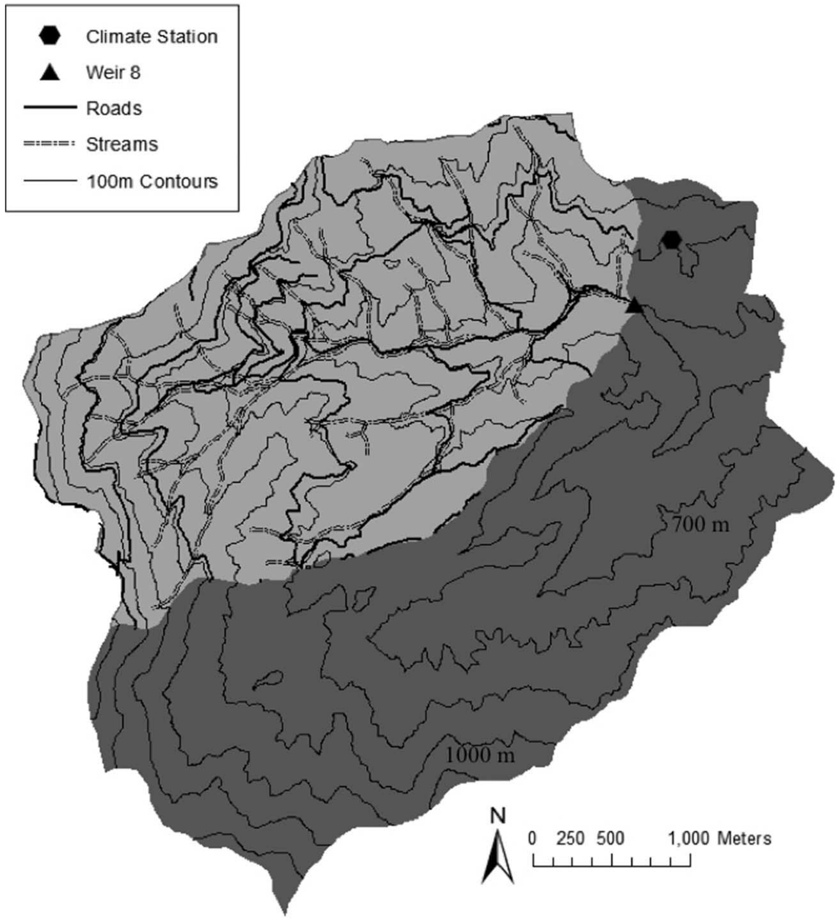

Figure 1. The 760-ha Shope Fork catchment (light gray) used in the DHSVM evaluations is located in the northern portion of the Coweeta Basin (dark gray), North Carolina.

of concern, especially given recent lawsuits and legislature surrounding forest management and downstream flooding (Pierce et al. 2002, Eisenbies et al. 2007). Despite this need, research on forest management practices and water yield in this region has focused on harvesting (Hewlett and Helvey 1970, Hornbeck et al. 1970, Kochenderfer et al. 1990, Swank et al. 2001).

This study was motivated by litigation surrounding forest management activities in the Southern Appalachian Mountains (Pierce et al. 2002, Recht 2007) and was designed to determine how forest roads may affect peak flow. Because it is both time and cost intensive to implement installation and monitoring of road networks in paired watersheds was both time and cost intensive, a modeling approach was used. Specifically, DHSVM was used because it has enhanced capabilities for incorporating road networks into its water balance equations. The two specific goals of this research were to establish whether or not DHSVM could be calibrated for use in the Southern Appalachian Mountains using easily acquired data and determine whether DHSVM is an appropriate model for land managers to apply to potential management scenarios and to assess the effects of different forest road densities on peak streamflow to recommend appropriate road density levels for land managers in the Southern Appalachians.

Methods

We studied the effect of road density on peak streamflow in the Blue Ridge Mountains of North Carolina by simulating the hydrology of a small watershed (760 ha) using the distributed hydrology model DHSVM. The model was parameterized using historical data from the USDA Forest Service Coweeta Hydrologic Laboratory, literature, and empirical equations. Using an hourly time step, we simulated watershed hydrology from Jan. 1, 2003 through Oct. 31, 2007. Although Coweeta has hydrologic records dating back to the 1930s, only 4 years of data were provided for this study due to time constraints on preparing and processing data at an hourly time step. DHSVM was calibrated by comparing modeled peak flow to observed peak flow at Coweeta Weir 8 (Figure 1). The effect of different road densities on peak flow was studied by altering the current road density at Coweeta (4.3 km km^{-2}) while holding all other input parameters constant.

Basin Description

The 2,185-ha Coweeta basin is located in Macon County, North Carolina (35°03′N and 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. Because of data availability and instrument location, only the northern portion of the Coweeta Basin (Shope Fork catchment, 760 ha) was used in this study (Figure 1). Elevations in the mountainous region range from 675 to 1,592 m. Sideslopes are variable but generally range from 50 to 60% (Swank and Crossley 1988). Precipitation is primarily in the form of rain (90–98%) and is most abundant during the winter months. Mean annual precipitation is approximately

Table 1. Soil mapping units in the Shope Fork catchment of the Coweeta Basin, North Carolina.

No.	Taxonomic class	Texture	Subgroups and great groups	% Watershed area
1	Burton Craggey Rock Outcrop	Sandy loam	Humic Dystrudept	0.1
2	Cashiers	Fine sandy loam	Typic Dystrudept	3.7
3	Chandler	Fine sandy loam	Typic Dystrudept	16.2
4	Chestnut-Edneyville	Fine sandy loam	Typic Dystrudept	<0.0
5	Cleveland-Chestnut	Sandy loam	Lithic Dystrudept	0.2
6	Cullasaja-Tuckasegee	Sandy clay loam	Humic Dystrudept	17.1
7	Edneyville-Chestnut	Fine sandy loam	Typic Dystrudept	9.9
8	Evard-Cowee	Fine sandy loam	Typic Hapludult	18.2
9	Fannin	Fine sandy loam	Typic Hapludult	11.2
10	Plott	Fine sandy loam	Humic Dystrudept	15.5
11	Rock Outcrop-Cleveland	Loam	Lithic Dystrudept	5.8
12	Saunook	Gravelly loam	Humic Hapludult	0.7
13	Tuckasegee-Whiteside	Fine sandy loam	Humic Dystrudept	1.2
14	Wayah	Sandy loam	Humic Dystrudept	0.1

1,800 mm. Average temperatures range from winter lows of −4° C to summer highs of 23° C (Swift et al. 1988). Soils are predominantly sandy loam Inceptisols and Ultisols (Swank and Crossley 1988).

In 2009, the road density of the Shope Fork catchment was 4.3 km km^{-2}. Roads include a variety of road standards ranging from graveled all-weather access roads (class I) to closed, grassed temporary harvest roads (class III) (Walbridge 1997). The nature of the research at Coweeta has resulted in well-kept road conditions generally free from erosion and gullies. Most stretches of roads are kept below the standard 10% grade. Best management practice features such as cross-drains, road surfacing (e.g., in-sloping, out-sloping, and crowning), and water diversion features (e.g., broad-based dips, turnouts, and water bars) are present throughout the study area. The roads are primarily in-sloped, and culverts or bridges are located at all major stream crossings.

Model and Input Parameters

DHSVM is a physically based model that explicitly calculates the energy and water budgets for a catchment at the scale of a grid cell, typically 10–100 m^2. 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. Digital elevation models (DEM) are used to route water across the hillslope to road ditches and stream channels. Vegetation and soil parameters are defined for each grid cell within the DEM. Each grid cell may have an overstory and understory canopy as well as a user-defined number of soil layers. Road and stream channels are modeled as "cuts" within grid cells and can receive water from precipitation, subsurface flow, or a connected channel. Flow within each channel moves from areas of higher elevation to lower elevation. DHSVM computes the water balance for each grid cell at a specified time step. Detailed model information can be found in Storck et al. (1998), Nijssen and Lettenmaier (1999), and Wigmosta et al. (1994, 2002).

DHSVM requires elevation, climate, soil, and vegetation inputs for the study catchment. A 30-m DEM was obtained for the Coweeta study site, which is located in the Prentiss Quadrangle (GeoCommunity 2007). A 30-m DEM was chosen over a 10-m DEM because of the reduced processing time; however, the courser 30-m DEM had less detail and probably introduced errors into the result due to the generalization of the landscape. The Shope Fork catchment was manually delineated using ArcMap (Hillier 2007).

Table 2. Forest cover types for the Shope Fork Catchment of the Coweeta Basin, North Carolina.

Cover type	Representative species
Northern hardwoods	*Acer saccharum*, *Tilia* spp., *Betula alleghaniensis*, *Aesculus octandra*, *Acer rubrum*
Cove hardwoods	*Liriodendron tulipifera*, *Betula lenta*, *Magnolia* spp., *Rhododendron* spp.
Mixed deciduous	*Quercus alba*, *Quercus rubra*, *Robinia pseudoacacia*, *Carya* spp., *Acer rubrum*
Xeric oak-pine	*Quercus coccinea*, *Quercus prinus*, *Oxydendrum arboreum*, *Pinus rigida*, *Kalmia latifolia*

Meteorological data were obtained from the Coweeta Climate Station 01 (Figure 1), which is located within 100 m of the outlet of the Shope Fork Catchment. DHSVM accounts for any variations in temperature and precipitation that may result from differences in elevation between the climate stations and modeled grid cells.

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 used preferentially over data from other data sources because of 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 1). DHSVM is very sensitive to soil depth process (Surfleet 2008), and a detailed soil depth map was imperative for accurate model calibration. To use information readily available to forest managers, soil depth inputs were based on the maximum soil depths found in the Macon County, North Carolina, Soil Survey (Thomas et al. 1996).

Four forest cover types were delineated as described by Day et al. (1988). Cover types were based on elevation, moisture regime, and aspect, which were delineated using ArcGIS (Table 2). DHSVM uses two types of network files: streams and roads. Arc macro language (AML) was used to assign some of the parameters needed for the model, and the rest were user-defined based on field observations and measurements. Coweeta stream and road shapefiles were downloaded from the LTER COGENT data set (Coweeta Long Term Ecological Research [LTER] 2008).

Theoretically, all inputs to and parameters in DHSVM can be physically measured. However, not all physical data can be reasonably collected at the resolutions needed to satisfy model requirements. Such was the case with this study, and data were based on available historical records, literature values, and default model settings. In some cases, known data were combined with empirical

Table 3. DHSVM input soil parameters, values, and sources used for the Shope Fork Catchment of the Coweeta Basin, North Carolina.

Soil parameter	Range of values	Source(s)
Vertical saturated hydraulic conductivity (m s^{-1})	0.02	Soil Survey Staff (2008)
Lateral saturated hydraulic conductivity (m s^{-1})	9.0E−6–2.8 E−5	Miwa (1999)
Exponential decrease of lateral saturated hydraulic conductivity	3.0	Beven (1982)
Maximum infiltration rate (m s^{-1})	1.0E−5–3.0E−5	Hillel (1982)
Capillary drive (m)	0.01	Bedient et al. (2008)
Soil surface albedo	0.09–0.30	Soil Survey Staff (2008)
Manning's *n*	0.40–0.45	Shen and Julien (1993), Rawls et al. (1993), Soil Survey Staff (2008)
Porosity*	0.36–0.65	Soil Survey Staff (2008)
Pore size distribution index*	0.27–0.41	Rawls et al. (1993), Soil Survey Staff (2008)
Bubbling pressure (m)	0.89–88.35	Rawls et al. (1993), Soil Survey Staff (2008)
Field capacity*	0.09–0.29	Soil Survey Staff (2008)
Wilting point*	0.04–0.18	Soil Survey Staff (2008)
Bulk density (kg m^{-3})*	920–1,525	Soil Survey Staff (2008)
Soil thermal conductivity (W m^{-1} K^{-1})*	18.21–37.48	Bowling and Lettenmaier (1997), Soil Survey Staff (2008)
Soil thermal capacity (J m^{-1} K^{-1})*	1.4E + 06	Hillel (1982)

* Inputs required for all soil layers.

Table 4. DHSVM vegetation input parameters, values, and sources for the Shope Fork Catchment of the Coweeta Basin, North Carolina.

Vegetation parameter	Range of values	Source(s)
% 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)*	2.0–24.4	Olson (1959), Beck (1990), Carmean (1978), Walters and Yawney (1990), Lipp and Nilsen (1997), McNab and Clinton (2003)
Maximum/minimum stomatal resistance (s m^{-1})*	193–490 312–388	Federer (1977), McConathy and McLaughlin (1978)
Soil moisture threshold which restricts transpiration*	0.139–0.152 0.087–0.095	Shuttleworth (1993), Soil Survey Staff (2008)
Vapor pressure deficit threshold which causes stomatal closure (Pa)	4,000	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.

equations to determine input values. Some input parameters and their sources are presented (Tables 3 and 4), and a detailed explanation of model inputs and justification for parameters can be found in Dymond (2010). Vegetation and soil input parameters are extensive, and descriptions are available (see Land Surface Hydrology Research Group 2006).

Model Calibration and Performance

DHSVM was calibrated for the Shope Fork Catchment using measured streamflow at the basin outlet (Coweeta Weir 8) with an hourly time step. Simulation from Jan. 1, 2003 through Sept. 30, 2003, was used for a model warm-up period to ensure that the model calibration had adequate time to acquire initial site conditions. During this time, model state variables were set equal to 0, and soil moisture was set to default model specifications (0.3 m^3 m^{-3}). Coweeta Water Year 2004 (Oct. 1, 2003 through Sept. 30, 2004) was used as a calibration period in which parameter adjustments were made. Parameter validation occurred from Water Year 2005 through 2007 (Oct. 1, 2004 through Sept. 30, 2007). Precipitation for the calibration period totaled 1,787 mm, which was approximately the average yearly precipitation of 1,800 mm (Swift et al. 1988). The validation included one exceedingly wet year and two comparatively dry years (2,195, 1,439, and 1,469 mm, respectively). Changes to input parameters were made to maximize the Nash-Sutcliffe model efficiency index (NSE) between observed and predicted streamflow. Alterations of the original input parameters focused on lateral saturated hydraulic conductivity and the exponential decrease of moisture throughout the soil profile input parameters, because studies have shown that DHSVM is 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.

Evaluation of model performance was done using the NSE. The NSE is a statistical measure that determines the relationship between the extent of residual variance and the observed variance (Nash and Sutcliffe 1970)

$$\text{NSE} = 1 - \frac{\sum(\hat{Y}_i - Y_i)^2}{\sum(Y_i - \bar{Y}_i)^2} \quad (1)$$

where $\hat{Y}_i$ is simulated streamflow, $\hat{Y}_i$ is observed streamflow, and $\bar{Y}_i$ is mean observed streamflow. Values are summed over the period of analysis. NSE values range from $-\infty$ to $+1.0$, where an NSE value of unity represents a perfect model. Values between 0.0 and 1.0 are viewed as acceptable levels of performance (Nash and Sutcliffe 1970, Moriasi et al. 2007), whereas values $<$0.4 have been deemed as satisfactory in previous hydrologic modeling studies (Ramanarayanan et al. 1997, Motovilov et al. 1999).

Additional model performance measures included the volume error and coefficient of determination. The average volume error between the predicted and observed streamflow (ΔV) was used to accurately simulate average streamflow over a period

$$\Delta V = \frac{1}{n} \sum_{i=1}^{n} \frac{V_{io} - V_{is}}{V_{io}} \quad (2)$$

where V_{io} is the observed volume of streamflow at an hourly time step, V_{is} is the simulated volume of streamflow at the corresponding time step, and n is the total number of observations. This index is relative to the magnitude of the variable streamflow where $\Delta V = 0.0$ indicates ideal model conditions. The coefficient of determination (R^2) was used to analyze predicted streamflow with respect to timing, where a value close to unity suggests a linear correlation between the observed and predicted measurements. Because ΔV and R^2 cannot test for model accuracy, they were used in conjunction with the NSE to determine overall model performance. All model performance measures were calculated at a daily time step and then averaged over the course of the calibration and validation periods.

Road Density Experiment

The primary objective of this study was to evaluate the effects of forest road density on peak flow in a small, mountainous watershed. Forest road densities in managed systems are typically much lower than those of urban roads but can often be higher than some rural road densities. Forest road densities usually range from 1 to 6 km km^{-2} and average around 3 to 4 km km^{-2} (Bowling and Lettenmaier 1997, USDA Forest Service 2001, Hawbaker et al. 2005). In some areas, a forest road density of 2 km km^{-2} is considered high and can even have an impact on the survival of wildlife populations (Mech 1989, Jones 2000). 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 10 or 12 km km^{-2}, and areas in very urban metropolises can approach 100% impervious cover.

Table 5. Road density experiment consisted of six treatments with three replications for each treatment.

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
4 (control)*	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.

To evaluate the influence of increasing forest road density on peak flow, six road density treatments ranging from 0.5 to 12.0 km km^{-2} were assigned (Table 5). These treatments represent a range of road densities commonly found in forested watersheds (1.0, 3.0, and 6.0 km km^{-2}), the road density in the Shope Fork catchment as of 2009 (4.3 km km^{-2}) and ancillary treatments representing low/rural road densities (0.5 km km^{-2}) and high/suburban road densities (12.0 km km^{-2}).

Exact treatment replications were not possible in this experiment, because running model simulations of identical road networks would result in identical output. To counter this, three road layouts were created for each treatment density. Density is not the only road parameter that may influence peak flow. With respect to road conditions, the road density, slope, road class (design features such as surfacing, grading, and water control structures), topographic position, and the number of stream crossings all have the potential to affect watershed peak flow. Because of the complexities of distinguishing among roads with multiple characteristics, Bernard (2006) developed a road impact factor to amalgamate several road parameters into an interpretable value. We adopted a similar approach, and road position, slope, and class were assigned weighted values based on potential effects on streamflow. These values were averaged over the length of the entire road network to determine the total watershed impact for the road network. For this study, the total watershed road impact factor was kept approximately consistent for each treatment. This approach was necessary because of the difficulty in keeping factors such as road slope and proximity to streams constant for each of the treatments. The number of intermittent stream crossings was not accounted for during the design of the road layouts because increasing road density inherently resulted in an increase in the number of stream crossings.

Roads were manually delineated on topographic maps and were designed according to standard road specifications (Walbridge 1997) and to provide access to subwatersheds within the catchment. The smaller road densities were designed first with subsequent increases in road density built on the existing road network. An exception to this was the low treatment densities for treatment 1, which included the existing Coweeta road network. In this case, road segments were removed from the network to achieve densities lower than those for the existing network. The first goal in designing the roads was to provide access to each subwatershed while keeping roads at below a 10% grade. The slope and topographic position for each road segment were then used to calculate the road impact factor. Road class was assigned last, so that each treatment had the

Table 6. DHSVM road input parameters used for the Shope Fork Catchment of the Coweeta Basin, North Carolina.

Road no.	Hydraulic width (m)*	Hydraulic depth (m)*	Manning's n†	Maximum infiltration (m s^{-1})‡	Road type*	Road erodibility§	d_{50} (m)*	Surface type*	Road width (m)*
1	0.5	0.5	0.02	0.01	Crowned	500	0.03	Gravel	6.00
2	0.5	0.5	0.025	0.01	Crowned	100	0.04	Paved	7.93
3	0.25	0.25	0.02	0.01	Outsloped	300	0.02	Dirt	4.00
4	0.25	0.25	0.025	0.01	Insloped	300	0.02	Dirt	3.93
5	0.25	0.25	0.02	0.01	Outsloped	300	0.03	Dirt	4.00
6	0.25	0.25	0.025	0.01	Outsloped	300	0.02	Dirt	2.93
7	0.15	0.15	0.02	0.01	Crowned	300	0.02	Dirt	2.00
8	0.25	0.25	0.025	0.01	Crowned	300	0.15	Dirt	3.93
9	0.25	0.25	0.025	0.01	Crowned	200	0.15	Dirt	3.93

* Measured parameters.
† Data from Gordon et al. (2004).
‡ DHSVM defined parameter input.
§ Data from Soil Survey Staff (2008).

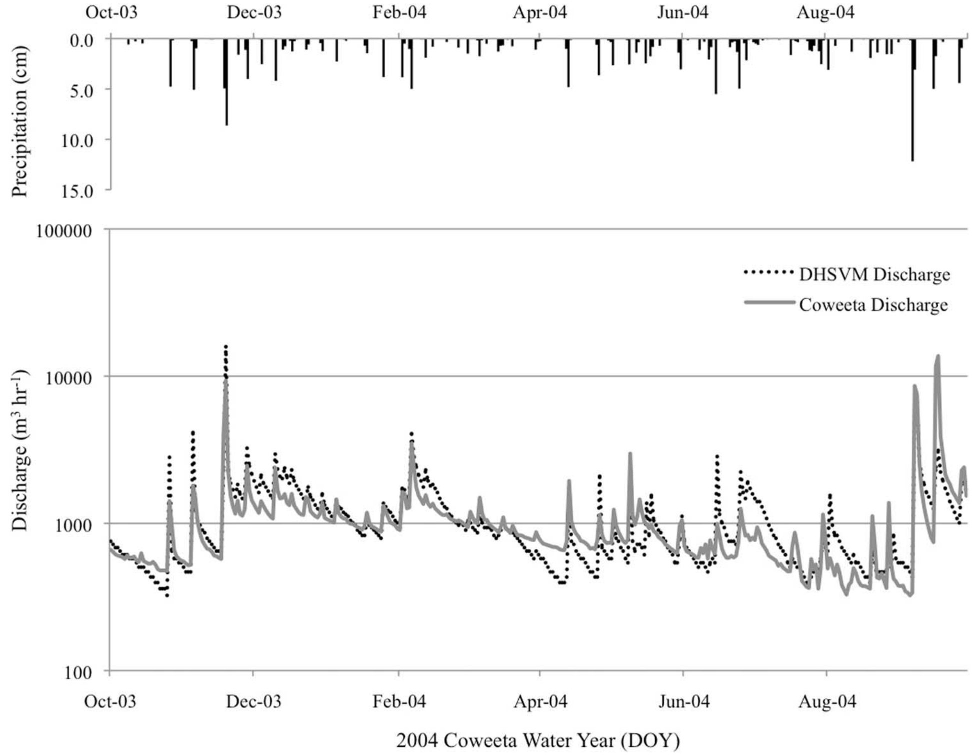

Figure 2. Daily simulated and observed streamflow and measured precipitation of Shope Fork catchment (located in the Coweeta Basin, North Carolina) during the calibration period (Coweeta Water Year 2004).

same road impact factor. Treatments were then visually transferred to ArcGIS. Road parameters such as infiltration rate, surface material, and drainage features were all specified in the model (Table 6). Some best management practices, such as culverts, surface material, and road sloping, were included in the model. Culverts were located at the intersection of road and stream segments.

The influence of road density on peak flow after storm events was analyzed by comparing peak flow between each treatment. We defined a storm event as having a recurrence interval of $>$0.4 years (Jones and Grant 1996). During the study period, five storm events with a 24-hour return interval of 2–5 years were identified for analysis. Inspection of the model output indicated that one of the treatments (treatment 5, replication 1) generated no data and, after attempts to find the error source were unsuccessful, was not regarded in the study. Using statistical analysis software (SAS Institute, Inc. 2008), the peak flow 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. Compound symmetry was used because it is a simple model that does not contain too many parameters. To investigate the relationship between the various treatment densities, a Tukey-Kramer analysis was conducted in SAS using the Proc Mixed statement.

Results

Calibration and Validation of Shope Fork Catchment

DHSVM was successful in predicting the general shapes of the Shope Fork hydrograph (Figures 2 and 3). However, large differences between peak flow in the measured and predicted hydrographs suggest that DHSVM was systematically unsuccessful in modeling the volume of peak flows in the watershed. DHSVM also struggled to adequately model the volume of baseflow during both the calibration and validation periods. In general, DHSVM overpredicted peak flow and underpredicted baseflow. The average difference between the volume of modeled and observed streamflow (ΔV) was high during the calibration period (Table 7). Although Water Year 2005 was representative of a higher than normal degree of tropical storm and remnant activity from the Atlantic region (Gray and Klotzbach 2005), the average ΔV for the year was the lowest of the entire testing period (Table 7). Over the entire validation period, ΔV averaged to be near 0, suggesting that the model was both under- and overpredicting streamflow. The NSE did not improve from the calibration to the validation period (NSE $=$ 0.44) (Table 7) and confirmed that DHSVM was satisfactory in its predictions.

Road Density Effects

The effects of road density were determined by comparing peak flow after five storms that occurred during the study period (Table 8). For each of the five storms that occurred during the study period, an increase in road density resulted in an increase in peak flow (Table 8). For a 5-year storm occurring in September 2004, peak flow increased from 20,000 m^3 $hour^{-1}$ (road density of 0.5 km km^{-1}) to 29,000 m^3 $hour^{-1}$ (road density of 12.0 km km^{-1}), an increase in peak flow of 31.4% (Figure 4). The density at which streamflow increased significantly was defined the "road density threshold," the maximum road density load that a watershed can hold at that storm level before seeing a significant impact on peak streamflow. For all storms analyzed, peak flows increased significantly ($\alpha < 0.01$) when road density reached 3.0 or 4.3 km km^{-2}. For the three smaller storms analyzed, peak flow significantly increased when road density was $\geq$4.3 km km^{-2}. In the case of the two larger storms analyzed, peak flow increased significantly when road density was $\geq$3.0 km km^{-2}. It was also found that higher road densities had a greater impact at larger peak flows (Figure 5).

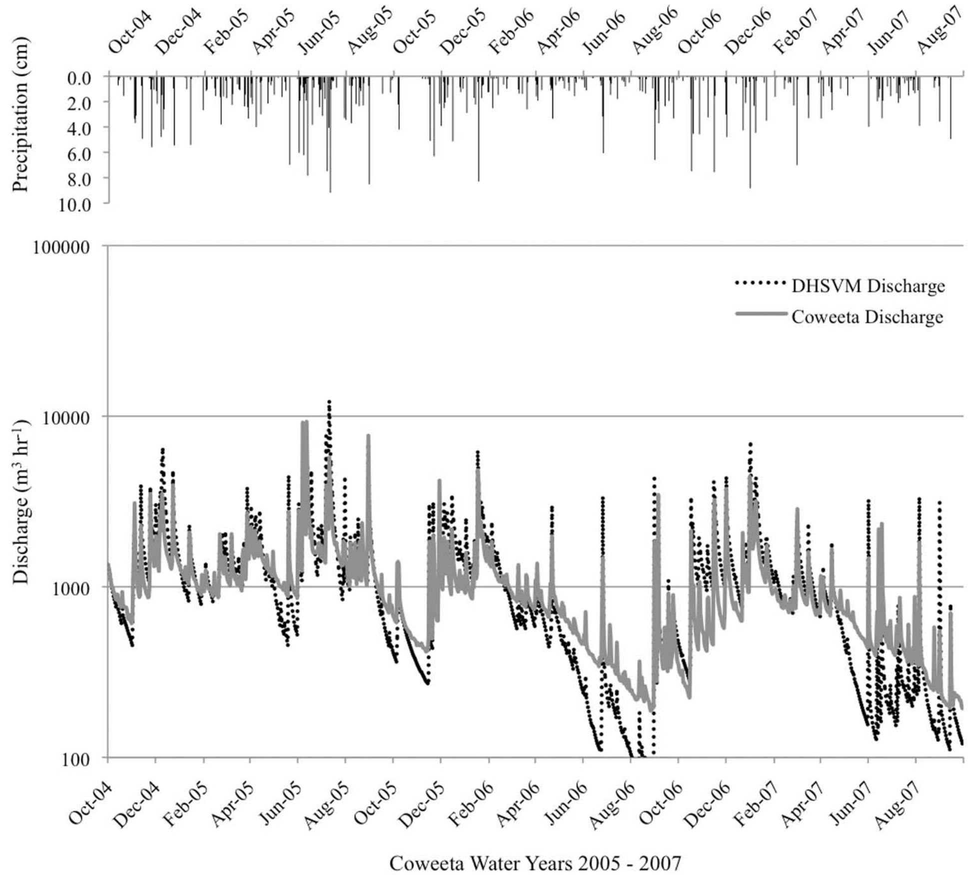

Figure 3. Daily simulated and observed streamflow and measured precipitation for Shope Fork catchment (located in the Coweeta Basin, North Carolina) during the validation period (Coweeta Water Years 2005–2007).

Table 7. Mean annual calibration and validation statistics for Shope Fork catchment of the Coweeta Basin, North Carolina.

Water year	NSE	ΔV	R^2
Calibration period			
2004	0.44	0.10	0.48
Validation period			
2005	0.41	0.06	0.63
2006	0.55	−0.13	0.78
2007	0.44	0.07	0.80
2005–2007	0.44	0.00	0.73

Discussion

We were able to calibrate and validate the DHSVM for a small, mountainous watershed in the Southern Appalachians with moderate success. DHSVM was able to correctly model the shape of a hydrograph at the Coweeta Hydrologic Laboratory Weir 8, but considerable errors were found with regard to both the timing and magnitude of streamflow.

Model Performance and Sources of Error

Model efficiencies during both the calibration and validation periods were satisfactory (NSE of 0.44 for both time periods), especially in comparison to prior applications of DHSVM in mountainous terrain. Model efficiencies of $>$0.80 have been observed (Leung et al. 1996, Wigmosta and Burges 1997, Beckers and Alila 2004, Thyer et al. 2004). Model efficiencies of $<$0.50 have been shown, although not as frequently (Leung et al. 1996, Cuo et al. 2006). Attempts were made to improve our model accuracy, but higher values for R^2 and NSE could not be obtained during parameter adjustment. A full sensitivity analysis was not conducted in this study, and it is recommended that a full sensitivity analysis of parameter inputs be conducted before further application of DHSVM in the Appalachian Mountains.

Inadequacies in model performance for the Shope Fork Catchment are attributed to one or more of the following: (1) ecological and mechanistic differences between the region where the model was developed (the US Pacific Northwest) and the Appalachian Mountains; (2) parameter inputs predominantly based on literature-derived values as opposed to observational and field-based measurements; (3) errors in meteorological and streamflow measurements; (4) shallow baseflow and stormflow at the watershed outlet; (5) lack of knowledge/data of subsurface controls on flow (e.g., soil depth, flow through shallow fracture systems, soil hydraulic properties, perennial flow) in the catchment; and (6) potential inadequate topographic resolution resulting from using a 30-m DEM.

Application to the Southern Appalachian Mountains

DHSVM was created for use in mountainous terrains that contain an annual snowpack during the winter months. One goal of this project was to determine whether this model could be used in the Appalachian Mountains. The southern Appalachians, while mountainous, are devoid of seasonal snowpack. The lack of a snowpack, however, was not determined to be a major source of model error, as DHSVM is able to correctly simulate year-round hydrology. This study used input parameters that were primarily literature derived to determine whether land managers can apply DHSVM. Our input

Table 8. Maximum stormflow and road density thresholds for five flood events in the Shope Fork Catchment (located within the Coweeta Basin, North Carolina) during October 2003 through September 2007.

				Maximum stormflow at treatment density of						
Storm date	RI (yr)	Total precipitation (mm)	Duration (h)	0.5 km km^{-2}	1.0 km km^{-2}	3.0 km km^{-2}	4.3 km km^{-2}	6.0 km km^{-2}	12.0 km km^{-2}	Threshold density (km km^{-1})
				(m^3 $hour^{-1}$)						
Nov. 19, 2003	5	135.9	23	39,240	39,600	42,120	43,200	45,000	49,320	3.0
Sept. 7, 2004	5	152.7	33	20,520	21,600	23,400	24,120	25,560	29,160	4.3
Sept. 16, 2004	1	67.3	33	10,080	10,080	10,800	11,160	11,520	12,600	4.3
June 7, 2005	1	70.6	17	28,080	28,080	30,240	31,320	33,120	37,440	3.0
June 12, 2005	1	78.2	22	9,360	9,360	10,080	10,080	10,800	11,880	4.3

RI, return interval.

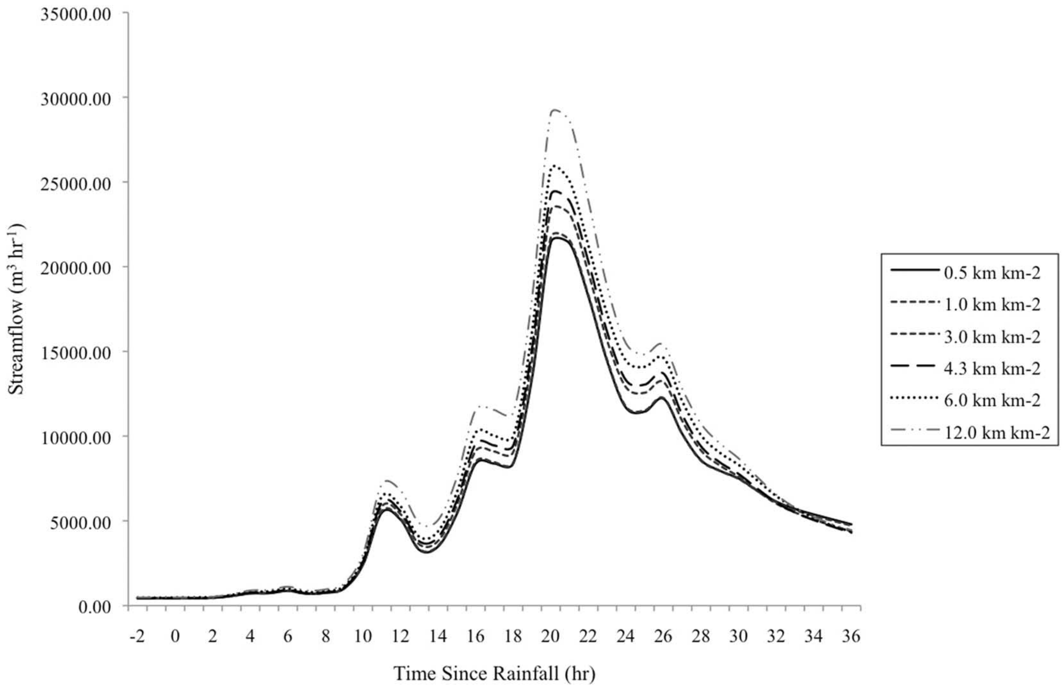

Figure 4. Hydrographs for different road density treatments after a 5-year storm starting Sept. 7, 2004.

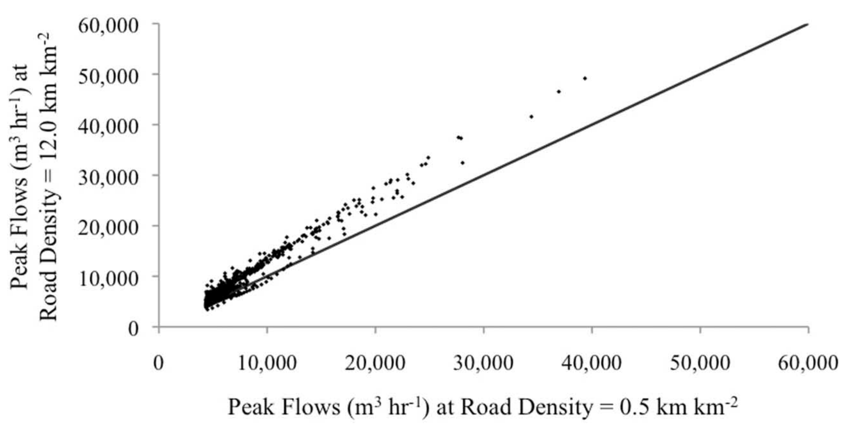

Figure 5. Peak flows for road density treatments of 0.5 km km^{-2} versus 12.0 km km^{-2}.

parameters were derived from readily available literature and online databases, which would probably be used by land managers over extensive field measurements. However, it is likely that the use of generalized input parameters contributed highly to low model efficiency.

DHSVM has been shown to have difficulty in adequately modeling subsurface flow through preferential flow pathways (Beckers and Alila 2004), which could have also contributed to variability in model performance. Preferential flow is a major component of forest hydrology in the Appalachian Mountains (Mulholland et al. 2010) and accounting for such flow paths would probably increase model efficiency. Accuracy might be improved with site-specific field sampling; sensitivity analysis could be used to determine which parameters would be most beneficial to collect. For example, 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). However, for this study, alteration of these particular variables did not improve model efficiency. 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 because of data availability at the hourly time step and a coarser time step may be more feasible for longer studies. Before application of DHSVM as a research tool in the mountains of Southern Appalachia, it is suggested that extensive model parameterization should be conducted to improve model efficiency.

DHSVM was chosen for this study because of its unique ability to incorporate forest road networks into hydrologic simulations at a watershed scale (Wigmosta et al. 1994, Storck et al. 1998, Nijssen and Lettenmaier 1999, Wigmosta et al. 2002). It was anticipated that land managers in the Southern Appalachians could use DHSVM as a tool for determining management regimes in forested watersheds. However, we recommend that DHSVM not be used as a management tool for the following three reasons: expert knowledge on uncertainty analysis is needed to ensure proper model calibration; the complexity of model inputs requires a precise understanding of every hydrologic component of the ecosystem (e.g., subsurface flow processes, plant physiology, and topographic controls on overland flow); and the complicated modeling platform requires an extensive background in multiple coding languages (e.g., AML, JAVA, and C). DHSVM is a difficult model to apply and is only appropriate for use by experts and not routine application by managers.

Influence of Road Density on Streamflow

Using DHSVM in a controlled environment, we were able to model the effects of road density on stormflow. This process was complex, because road density is not independent from other road features and confounding effects were present. The modeled results suggest that streams have an altered response when forest road densities reach 4.3 km km^{-2}, which is consistent with prior applications of the model (Bowling and Lettenmaier 1997). Although changes in the stream hydrograph have been detected after vegetation removal at the watershed scale (Hibbert 1966, Patric 1973), it is unlikely that a change in evapotranspiration due to vegetation removal from the road system was an important contributor to annual streamflow responses. This finding is consistent with the literature, which suggests that changes in stormflow in mountainous regions are detectable only after 20% of the basin area has been affected (Bosch and Hewlett 1982, Stednick, 1996). The largest area covered by roads in this study was 5.6%.

Conclusions

Despite considerable limitations on our study, we found that DHSVM could be used to model watershed hydrology in the Southern Appalachians. Before further application of the model to this region, it is recommended that a thorough sensitivity analysis of model parameters be conducted. Our NSE was satisfactory albeit lower than desired, and a study including full parameterization over a longer study period would probably yield better results. Despite the limitations, DHSVM could still be used to determine the impacts of forest road density on streamflow. It was found that the road density at the Coweeta LTER (4.3 km km^{-2} at the time of analysis) served as a threshold road density, above which streamflow increased significantly. We would like to see this analysis expanded, with more emphasis placed on the length of the study period, an increase in the study area, and an analysis of how road networks alter hydrologic flow paths after small and large rainfall events. Extensive work is needed to create a user-friendly version of DHSVM that would allow land managers to investigate the impacts of installing road networks on streamflow processes.

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