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Hydrologic impacts due to land cover change in the Yellowwood Lake watershed

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Keith Cherkauer

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HYDROLOGIC IMPACTS DUE TO LAND COVER CHANGE IN THE YELLOWWOOD LAKE WATERSHED

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ABSTRACT

Stewart, Emily M. M.S.E., Purdue University, August 2014. Hydrologic Impacts Due to Land Cover Change in Yellowwood Lake Watershed. Major Professor: Keith A. Cherkauer.

The Yellowwood Lake watershed in Southern Indiana has experienced land cover change due to forest harvest throughout the last century. A group of local stakeholders have identified sedimentation into the lake and surface erosion as major concerns for the watershed. The main objective of this study is to better understand how forest harvest methods applied within the watershed effect hydrologic and soil erosion processes. Such knowledge is required to develop a more comprehensive plan to protect the watershed.

The Distributed Hydrology-Soil-Vegetation Model (DHSVM) was used for this analysis. This is a physically based, distributed hydrology model that simulates the water and energy balance at the scale of the digital elevation model (DEM). The DHSVM sediment model also simulates hillslope erosion by overland flow and raindrop impact. A sensitivity study was conducted on the model to better understand the effect of forest thinning on the hydrology of the watershed, which was simulated by adjusting the user input fractional coverage parameter of the forest vegetation. Updates were made to the calculation of aerodynamic roughness to produce a more continuous change in displacement height with thinning forest density. Current harvest management, as prescribed by the Indiana Department of Natural Resources, was input to the model using a mixture of fractional coverage values to represent the change in canopy density due to harvest prescriptions throughout the watershed. The simulated output from the forest harvest scenario was compared to output produced using a non-harvested scenario for water years 1961-2013. The results indicate that harvest resulted in statistically significant increases to streamflow metrics related to high and low flow frequency. Flow magnitudes for 1.1 year return period flows also increased by as much as 12%. Results from the DHSVM sediment model showed that the annual sediment load into the lake increased after forest harvest. The watershed also experienced greater loss of soil in areas with steep slopes and under the clear-cut harvest prescription. It is recommended that the forest managers avoid a clear-cut prescription and harvesting on slopes steeper than 7.5% in order to reduce some of these effects.

CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction to Forest Hydrology

Proper understanding of the hydrology of an undisturbed, forested watershed is fundamental to evaluating the potential effects of vegetation changes across a landscape. Forest hydrology includes the effects of forest vegetation on the water cycle, erosion, and water quality. Under normal conditions, water that enters a forested watershed is either intercepted by vegetation or stored in the soil profile to be taken up by vegetation or enter the stream as baseflow. According to Tong and Chen (2002) a forested landscape is the most important ecosystem to regulate the water quality within a watershed. Because water availability is becoming a worldwide issue, it is critical to research the relationship between the hydrologic cycle and the environment. This chapter describes the disturbances to a forested watershed affect the streamflow regime and sedimentation within the watershed.

1.2 Hydrologic Impacts of Timber Harvest

Land use change can considerably impact the hydrology of a forested watershed. A modeling study by Pielke et al. (2002) found that deforestation significantly affects the water and energy balance as well as near-surface climate dynamics. The hydrologic impacts due to land cover change are very diverse, as they can impact many components of the hydrologic cycle. Many studies (Harr et al., 1975; Harris, 1977; Jones and Grant, 1996; Wright et al., 1990) have concluded that logging can lead to an increase in the volume of total storm runoff, resulting in changes in streamflow patterns. Deforestation initially increases total streamflow, and streamflow is slowly decreased when regrowth begins (Swank et al., 1988). In a forested watershed, harvest affects the water balance by reducing evapotranspiration and interception of precipitation (Bosch and Hewlett, 1982).

A study by Ruprecht and Schofield (1989) found that annual streamflow increased by 30% in Western Australia after replacing a native forest with agricultural plants due to decreased transpiration and interception. A reduction in interception can cause drastic increases in overland flow. As less water is intercepted by vegetation, more water is able to infiltrate into the soil profile which raises the soil moisture content. As the soil becomes saturated with infiltrated water, excess rainfall will result in increased overland flow contributing to streamflow.

The amount of water that reaches a stream by runoff is highly dependent on vegetation because of the high usage of water by plants for transpiration and surface evaporation. Timber harvest replaces deeply rooted trees with shallow rooted grasses and shrubs which transpire less and lead to more water available as runoff. Nosetto et al. (2012) found the amount of evapotranspiration is dependent on the type of land cover; concluding that woody land cover has the highest capacity for evapotranspiration.

Forest harvest has been shown to increase snow accumulation and snowmelt due to the absence of the forest canopy (Bowling et al., 2000). Clear-cuts result in an average increase in annual peak snow water equivalent of 41% according to a study in Idaho (Megahan 1983). There was no difference found in snow accumulation in a forested watershed before and after a fire removed all leaves from the trees, which suggests that aerodynamic changes across the forest canopy may be as important as interception losses (Megahan, 1983). A study by Kattelmann (1990) found that decreased shading from vegetation loss caused snow melt rates to increase by 75% compared to reference forests in the Sierra Nevada.

Many studies have been conducted using the paired watershed approach (Harr et al., 1975; Harr, 1986; Jones and Grant, 1996); however, Kurás et al. (2012) and Storck et al. (1998) both utilized the Distributed Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta 1994), to isolate the effects of vegetation in a watershed. Kurás et al. (2012) tested various harvest scenarios within a watershed in British Columbia and found that the greatest effects from harvest are shown in high return period flows. This study found that clear-cut harvest across 50% of the watershed resulted in a 9%-25% increase in peak flows compared to flows when no forest management is applied; however, a 20%-30% harvest had no statistically significant effect on the peak flow regime (Kurás et al. 2012). Storck et al. (1998) found significant differences in flow resulting from rain on snow events and snow melt in the Pacific Northwest after a clear-cut harvest. They also found middle to low elevations to be more sensitive to rain on snow events, and high elevations more sensitive to spring snow melt after forest harvest.

1.3 Impacts of Timber Harvest on Soil Loss

Land cover is also important for protecting the soil against erosion. A fully forested watershed experiences relatively little surface erosion, but timber harvest alters the canopy cover, exposing the soil to water and wind. Forests provide the maximum amount of soil protection; however, forest cover does not prevent all surface erosion. A study by Hood et al. (2002) calculated a loss of 0.14 tons/acre-year from a forested control plot in the Appalachians. It is widely accepted that timber harvest can increase the supply of sediment to surface water by accelerating the natural erosion rate of the landscape (Nelson and Booth, 2002).

Non-point source pollution is recognized as a significant source of surface water quality problems, with sediment eroded from the landscape being the major source of this pollution. Sediment transported by surface runoff can cause many problems within the transporting channels and receiving water bodies. Wood and Armitage (1997) found that fine sediments may attach to nutrients and chemicals which can contribute to eutrophication and toxicity of aquatic organisms. Suspended fine sediments which do not settle along the stream banks cause the stream to appear brown and cloudy, and also reduce the amount of sunlight reaching the stream bottom, limiting photosynthesis and oxygen produced within the stream (Novotny and Olem, 1994). Large, coarse sediments within the stream can cause channel degradation which reduces flow capacity and may increase risk of flooding and channel instability (Novotny and Olem, 1994).

The removal of vegetation reduces canopy interception of raindrops and root cohesion, which leaves the soil at increased risk for detachment. Motha et al. (2003) concluded that harvesting hillslopes can increase erosion rates one to five times over the observed rates of undisturbed hillslopes. This study separated the soil erosion contributions from logging roads and harvested and un-harvested areas within the watershed after 6% of the area was harvested in a patchwork pattern. It was found that harvested areas contributed 5%-15% of the sediment load for the entire landscape.

The landscape slope gradient may also be a good predictor of sediment losses in the watershed. A study by Liu et al. (1994) observed the natural erosion rates from three different runoff plots with slopes ranging from 9%-55% steepness. They found erosion rates increase linearly according to the sine of the slope angle, indicating that more soil is lost from steeper slopes. Additionally, slope was found to cause more soil loss on longer hillslopes than shorter slopes, as a longer slope provides more opportunity for rill erosion to develop.

Losses in forest cover reduce the aerodynamic resistance across the landscape, which increases the wind velocity over the soil surface. Iserloh et al. (2012) conducted a plot scale experiment to study the effect of wind and rain on hillslope erosion. When vegetation is removed in a watershed, soil is at risk of the impact from wind-driven raindrops over the soil surface; which increase the sediment available for transport. This experiment demonstrated that the combination of wind and rain significantly increases the amount of eroded sediment, indicating that vegetation loss may accelerate the sediment detachment rate during a rain event due in part to increased wind velocity. Wind-driven rain resulted in a 113% to 1108% increase in eroded sediment than plots that were not exposed to wind (Iserloh et al., 2012).

Vegetation not only intercepts precipitation before it reaches the soil, it also stabilizes the soil to reduce surface erosion. Istanbulluoglu et al. (2004) modeled the effect of decreased root cohesion on sediment load within a watershed in Idaho. They found that long-term sediment delivery within the watershed was dominated by large rain events in which all vulnerable soil was detached, and the threshold for these events was dictated by the vegetation root cohesion and density. These findings suggest that erosion events become more frequent after vegetation loss because less precipitation is required to cause hillslope erosion.

Land management practices can influence overland flow, infiltration rates, and erosion during rainstorm events. Many best management practices (BMPs) have been adopted to minimize the effects of surface erosion. The Indiana Department of Natural

Resources lists BMPs that must be followed for all logging activity within any Indiana State Forest (IDNR, 2001). These practices include regulations pertaining to forest roads, skid trails, stream crossings, riparian management zones, and log landings. The goal of riparian management zones is to maintain a stable forest floor and expose no more than 10% bare soil within a 20 foot strip along the tract boundary, however, trees within these zones may be harvested. These guidelines aim to reduce the effects of forest harvest on sediment detachment within the watershed.

1.4 Hydrologic Modeling of Timber Harvest

Hydrologic models have been used over the past 35 years to analyze the hydrologic effects of land cover change and timber harvest across a landscape. Various models are available to researchers which aid in the planning, development, and management of watersheds. Streamflow data is limited across the United States, and hydrologic models can produce reasonable flow rates that land managers can use to make decisions regarding land management practices. Watershed scale models provide insight into how factors such as land cover, soil type, and climate will affect changes in streamflow, loss of depth within the landscape, and water quality.

Watershed scale models are able to represent differences between vegetative cover, soil characteristics, and topography for a large study area. These models provide a means in which environmental impacts can be evaluated by changing the input parameters.

A spatially distributed model can analyze hydrologic changes by dividing the watershed area into smaller units and solving the water balance for each of these. The Distributed Hydrologic Soil Vegetation Model (DHSVM; Wigmosta 1994) divides the watershed area according to grid cells of equal, rectangular size which are distributed evenly across the watershed; the grid cells have the same resolution as the digital elevation model (DEM) of the landscape. Each grid cell within DHSVM can have unique vegetation and soil attributes. DHSVM can simulate hydrologic changes in the watershed, and has a separate mass wasting model (MWM) component which simulates mass wasting events and hillslope erosion, as well as changes in water quality related to sediment (Doten et al., 2006).

In this study DHSVM will be used to simulate the hydrologic effects of forest harvest. DHSVM has a high degree of complexity in representing heterogeneous soil and vegetation parameters within the study area (Singh and Woolhiser, 2002), which makes this model appropriate to simulate various forest management styles and their effect on streamflow and soil loss within the study area. DHSVM has been used in previous studies to examine the effects of logging in the Pacific Northwest (Bowling et al. 2000), prediction of sediment erosion and transport (Doten et al., 2006), and the effect of forest roads on flood peaks (Bowling and Lettenmaier, 2001).

1.5 Objectives and Hypotheses

The overall goal of this project is to evaluate the role of land cover on streamflow characteristics and hillslope erosion at Yellowwood Lake watershed. Sedimentation into Yellowwood Lake and surface erosion within the watershed are some of the primary concerns of the Yellowwood Lake Watershed Planning Group, a group of local residents who promote the well-being of the watershed. One top priority of the group is to reduce the sediment load in the streams by encouraging best management practices and maintaining the forest within the watershed. It is anticipated that the outcome of these objectives will be useful in developing a more comprehensive plan to protect the watershed.

The main objective of this study is to better understand the hydrologic response to forest harvest methods at the watershed scale. The Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta et al., 1994) is employed in this study to identify these effects. A better knowledge of the hydrologic response could help land use managers lessen the impacts. The following hypotheses and objectives of this project are described below.

1. Evaluate the role of forest harvest at the watershed scale on streamflow characteristics and flow metrics. *Yellowwood Lake watershed is experiencing increased high flow events due to existing forest management practices.* Studies by Harr (1981, 1986) on harvested areas in Oregon conclude that peak flows increase after clear-cutting because of greater snow accumulation before rain-on-snow events and increased surface wind, resulting in greater latent and sensible heat transfer. An additional study by Jones and Grant (1996) found peaks in streamflow increase in watersheds in western Oregon where clear-cutting is prevalent, relative to watersheds with less harvested area. Kurás et al. (2012) found significant changes in streamflow magnitudes and peak flow frequency for various forest harvest scenarios in British Columbia. It is understood that a decrease in forest cover will result in an increase in mean annual streamflow; however, these studies are focused on extreme land treatment (clear-cutting), which is an unrealistic scenario for much of the Yellowwood Lake watershed.
2. Quantify the magnitude of hillslope erosion for varying land covers throughout the Yellowwood Lake watershed. *Hillslope erosion will increase as canopy cover in the watershed decreases due to forest management.* Factors such as

detachment energy of raindrops, leaf drip, and overland flow are identified as contributing to available soil for hillslope erosion (Doten et al., 2006). A reduction in vegetative cover makes soil much more susceptible to hillslope erosion because of an increase in raindrop impact and overland flow. Sedimentation into Yellowwood Lake and surface erosion within the watershed were some of the primary concerns of the Yellowwood Lake Watershed Planning Group. A numerical simulation approach to identify the impacts of vegetation loss has not previously been applied to this drainage basin.

Little is known of the water and energy fluxes in the Yellowwood Lake watershed, but studies of forest harvest suggest the potential for significant effects on watershed hydrology (Beltran-Przekurat et al. 2011, Harris 1977), indicating that it may be of importance in this region. This study will be focused on investigating the changes in streamflow patterns and surface erosion attributed to land cover changes in the Yellowwood Lake watershed. DHSVM will be used to conduct numerical simulation experiments to quantify streamflow and erosion rates throughout the Yellowwood Lake watershed under a variety of harvest scenarios. Effectiveness of land cover to prevent soil erosion will be tested by comparing forest management strategies across the landscape. Results from the experiments will be used to aid in the creation of future watershed management strategies.

1.6 Organization of Thesis

This thesis is composed of five chapters, of which this Chapter includes the introduction and literature review. Chapter 2 includes the methodology of how the experiments were conducted. Chapter 3 discusses the results of the streamflow analysis, and Chapter 4 discusses the changes in sediment erosion due to forest harvest. Lastly, Chapter 5 discusses the conclusion from the study and makes recommendations for future forest management, as well as future work based on these results.

CHAPTER 2. METHODS

2.1 Study Area

This study was performed for the Yellowwood Lake watershed in the northwest corner of Brown County in Southern Indiana (Figure 2.1). All land in the Yellowwood Lake watershed drains into Yellowwood Lake. The watershed is contained within the larger North Fork Salt Creek-Jackson Creek (HUC 05120208050060) and Salt Creek (HUC 05120208050) watersheds, also shown in Figure 2.1. The annual average amount of precipitation in Brown County is 1021 mm, and average snowfall is 406.4 mm (Nobel et al., 1990). The total area of the watershed is 17.4 km^2, of which 80% is located in Yellowwood State Park and is managed by the Indiana Department of Natural Resources (IDNR). The watershed's landscape is mostly forested and hilly; which attracts many visitors to hike, fish, and camp. Residential development, timber harvesting on state and private land and recreational facilities are also located in the watershed.

The Division of Forestry within the Indiana Department of Natural Resources (DNR) lists a long history of timber harvest within the Yellowwood Lake watershed. The earliest recorded harvests date back to 1951, where the objective was primarily to remove low-quality species and enhance the growth of more profitable species. To date, timber management has been applied to 13.8 km^2 in the watershed. The Yellowwood Lake Watershed Management Plan (2006) suggests that timber harvest should be avoided in areas with slopes steeper than 20%, or areas designated for recreation and research because these areas are particularly sensitive to the effects of vegetation loss. They also suggest that riparian management zones show no more than 10% bare soil along the tract boundaries next to the streams and the lake.

The Yellowwood Lake Watershed Planning Group, a group of local residents and stakeholders, formed in 2000 to promote the well-being of the watershed. The group produced the Yellowwood Lake Watershed Management Plan in 2006, where they agreed that loss of vegetation and sedimentation into Yellowwood Lake are the main concerns for the watershed. In addition to the effects of land cover, invasive species, and chemical and biological contaminants are also concerns for the watershed (Yellowwood Lake Watershed Management Plan, 2006). It is anticipated that the outcomes from the analysis of the streamflow regime and sediment loss due to forest harvest will be useful in developing a more comprehensive plan to protect the watershed.

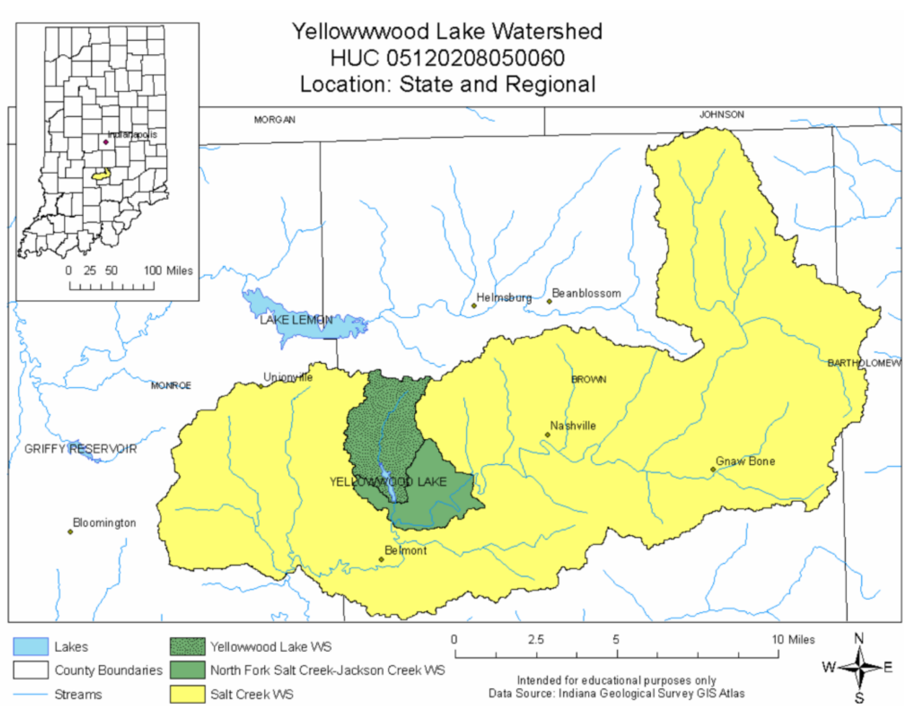


Figure 2.1: Yellowwood Lake watershed (The Yellowwood Lake Watershed Management Plan, 2006)

2.2 DHSVM

The Distributed Hydrology Soil Vegetation Model version 3.1.1 (DHSVM; Wigmosta et al., 1994) was used to simulate hydrologic and sediment processes for this study. DHSVM is a physically based, spatially distributed hydrology model that calculates the water and energy balance for each grid cell defined by the DEM at the time step of available weather data. Each grid cell is assigned vegetation characteristics and soil properties, and is hydrologically linked to other cells by surface and subsurface routing. Stream networks route water through the watershed by confining the flow to stream channels. Unsaturated soil moisture movement is calculated using Darcy's Law. Evaporation of water intercepted by the canopy is assumed to occur at the potential rate, and transpiration from vegetation is calculated using the Penman-Monteith equation. Some of these properties are illustrated in Figure 2.2. DHSVM has been used in a variety of applications such as quantifying the hydrologic effects of logging in the Pacific Northwest (Bowling et al. 2000), prediction of sediment erosion and transport (Doten et al., 2006), and the effect of forest roads on flood peaks (Bowling and Lettenmaier, 2001).

The sediment model is an optional module run within DHSVM and consists of components for mass wasting, hillslope and road erosion, and sediment transport via channel routing (Doten et al., 2006). Slope failure probabilities are calculated based on the dynamic soil saturation simulations by DHSVM. Overland flow is modeled using an explicit finite difference solution of the kinematic wave, and infiltration excess runoff is determined by DHSVM based on the maximum infiltration capacity threshold of each time step. Re-infiltration of overland flow is possible, and depends on the maximum infiltration capacity.

Sediment available for hillslope erosion is calculated based on the detachment energy of raindrops, leaf drip, and overland flow (Doten et al., 2006). Soil particle detachment via overland flow is predicted using an empirical detachment efficiency (β_{de}) where C_s is soil cohesion in kPa:

$$\beta_{de} = 0.25e^{-0.6C_s}$$

Soil particle detachment by raindrop and leaf drip impact is calculated based on the estimated precipitation momentum, calculated as a function of rainfall momentum, shown in the equation from Wicks and Bathurst (1996):

$$D_R = k_r F_W (1 - C_G)[(1 - C_C)M_R + M_D]$$

The variables in the equation for soil detached by raindrop are as follows: D_R is soil detached by raindrop impact (kg m^{-2} s^{-1}), k_r is the raindrop soil erodibility coefficient (J^{-1}), F_W is the water depth correction factor, C_G is the proportion of soil covered by ground cover, C_C is the percentage of area covered by canopy cover, M_R is the momentum squared for rain ((kg m $s^{-1})^2$ m^{-2} s^{-1}), and M_D is the momentum squared for leaf drip ((kg m $s^{-1})^2$ m^{-2} s^{-1}). The sediment model has been used in a range of applications (Lanini et al., 2009; Surfleet et al., 2014) and has been validated in field tests by Wigmosta et al. (2009) and Doten et al. (2006).

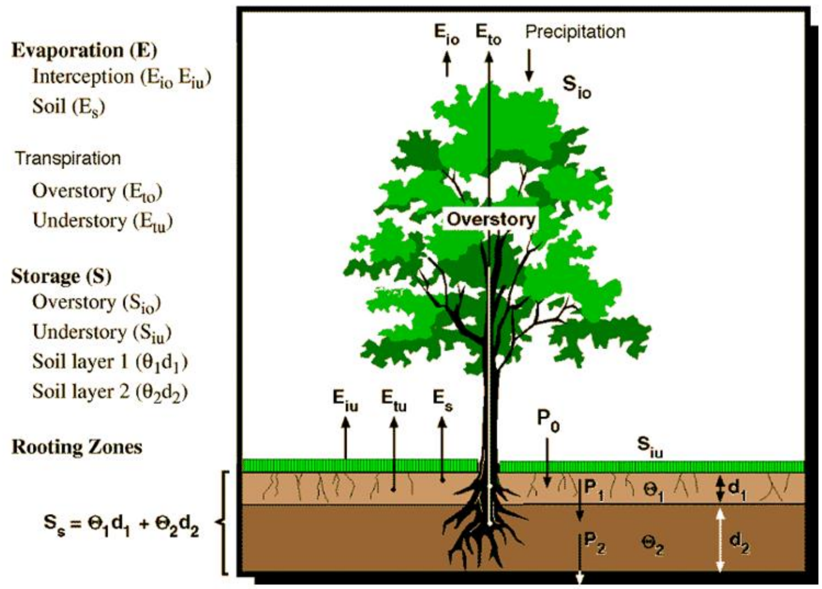


Figure 2.2: DHSVM hydrology model schematic (Wigmosta et al., 1994)

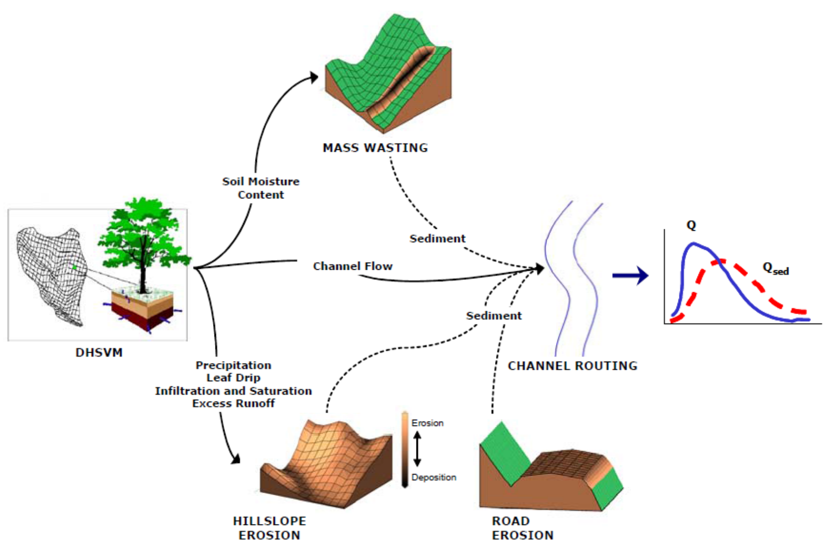


Figure 2.3: DHSVM sediment model schematic (Doten et al., 2006)

2.2.1 Data Collection

Hourly meteorological forcing data was input to DHSVM. The meteorological data requirements for DHSVM include air temperature, precipitation, relative humidity, wind speed, and incoming longwave and shortwave radiation. Daily air temperature and precipitation data were obtained from the NCDC station in Bloomington, Indiana; however, it needed to be disaggregated to a smaller temporal resolution in order to run the model at an hourly time step. Disaggregation was performed using a climate generator (CLIGEN) which generates breakpoints in the precipitation data based on observed precipitation patterns and then integrates the breakpoint intensities into hourly precipitation and temperatures (Mao et al., 2010). Hourly wind speed data for Brown County was provided by Sinha et al. (2010). The additional forcing data was generated by the Variable Infiltration Capacity (VIC) model which uses temperature, precipitation, and wind speed to calculate relative humidity and shortwave and longwave radiation, based on the MTCLIM algorithm (Kimball et al., 1997; Thornton and Running, 1999; Thornton et al., 2000).

The model was run using a digital elevation model (DEM) at a 30x30 meter resolution. The DEM was obtained from the National Elevation Dataset (USGS) and was then used to delineate the Yellowwood Lake watershed and create the stream network for the drainage area. The stream network in the watershed has a 2.2 km/km^2 drainage density, and Table 2.1 lists the model input parameters for flow routing for each stream class within the Yellowwood Lake watershed.

Table 2.1: Input parameters for the stream network

Channel Class	Hydraulic Width (m)	Hydraulic Depth (m)	Manning's N	Maximum Infiltration Rate (m/s)
1	0.25	0.20	0.150	1.0
2	0.50	0.35	0.125	1.0
3	1.00	0.50	0.110	1.0
4	2.00	0.75	0.100	1.0
5	3.00	0.75	0.090	1.0
6	4.50	1.00	0.080	1.0
7	6.00	1.25	0.070	1.0
8	8.00	1.50	0.050	1.0
9	12.00	2.00	0.025	1.0

The land use within the watershed is predominantly forest, and Table 2.2 shows the model input parameters for the deciduous forest vegetation type, since it was the primary vegetation type within the watershed. The fraction of each land use type for the watershed is listed in Table 2.3. Fractional coverage was determined from the land use dataset for the area provided by the National Land Cover Dataset (2006), shown in Figure 2.4.

Table 2.2: Input parameters for deciduous forest vegetation type. If parameters are required for each vegetation layer, the first value is for the overstory, the second for the understory. Three entries correspond to the root zones, with the entry for the top root zone first and for the bottom root zone last.

Vegetation Parameters	**Value**
Fractional Coverage	0.9
Trunk Space	0.5
Aerodynamic Attenuation	1.5
Radiation Attenuation	0.2
Maximum Snow Interception Capacity (m)	0.003
Mass Release Drip Ratio	0.4
Snow Interception Efficiency	0.6
Height (m)	20.0, 0.5
Maximum Resistance (s/m)	5000.0, 3000.0
Minimum Resistance (s/m)	150.0, 50.0
Moisture Threshold	0.33, 0.13
Vapor Pressure Deficit (Pa)	4000, 4000
Fraction of Photosynthetically Active Shortwave Radiation	30.0, 100.0
Number of Root Zones	3
Root Zone Depths (m)	0.10, 0.25, 0.40
Overstory Root Fraction	0.20, 0.40, 0.40
Understory Root Fraction	0.40, 0.60, 0.00
Overstory Monthly LAI	1.68, 1.52, 1.68, 2.90, 4.90, 5.00, 5.00, 4.60, 3.44, 3.04, 2.16, 2.00
Understory Monthly LAI	0.12, 0.12, 0.15, 0.26, 0.57, 0.85, 0.95, 0.85, 0.56, 0.21, 0.13, 0.12
Overstory Monthly Albedo	0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18
Understory Monthly Albedo	0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2

Table 2.3: Land use types within Yellowwood Lake watershed classified by the National Land Cover Dataset (2006)

Land Use Type	Percent of Watershed Area
Open Water	0.4%
Deciduous Forest	92.1%
Evergreen Forest	5.4%
Mixed Forest	0.2%
Pasture/Hay	1.3%
Row Crops	0.6%
Wetlands	0.1%

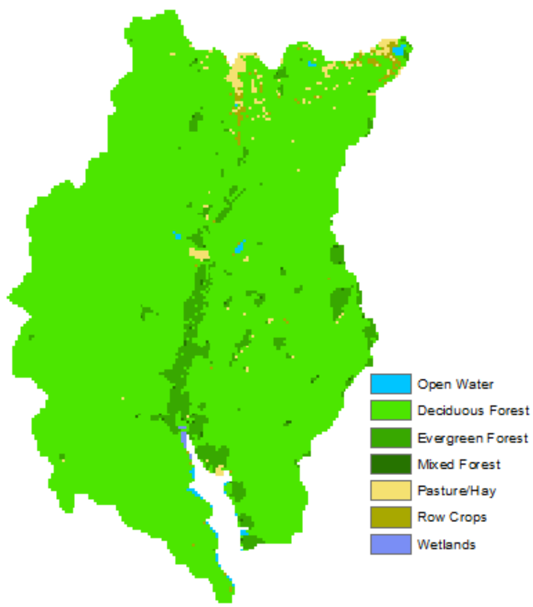


Figure 2.4: Land use types within Yellowwood Lake watershed classified by the National Land Cover Dataset (2006)

DHSVM also requires information regarding characteristics for each soil type. Soil information was obtained from the Web Soil Survey (Figure 2.5) for the watershed area, and then categorized by the model according to soil texture. All the soil in the watershed is a silty loam texture. Soil characteristics for silty loam remained constant according to values provided by literature (Noble et al., 1990) except for vertical and lateral conductivity and maximum infiltration rate, which were adjusted for model calibration (Table 2.4).

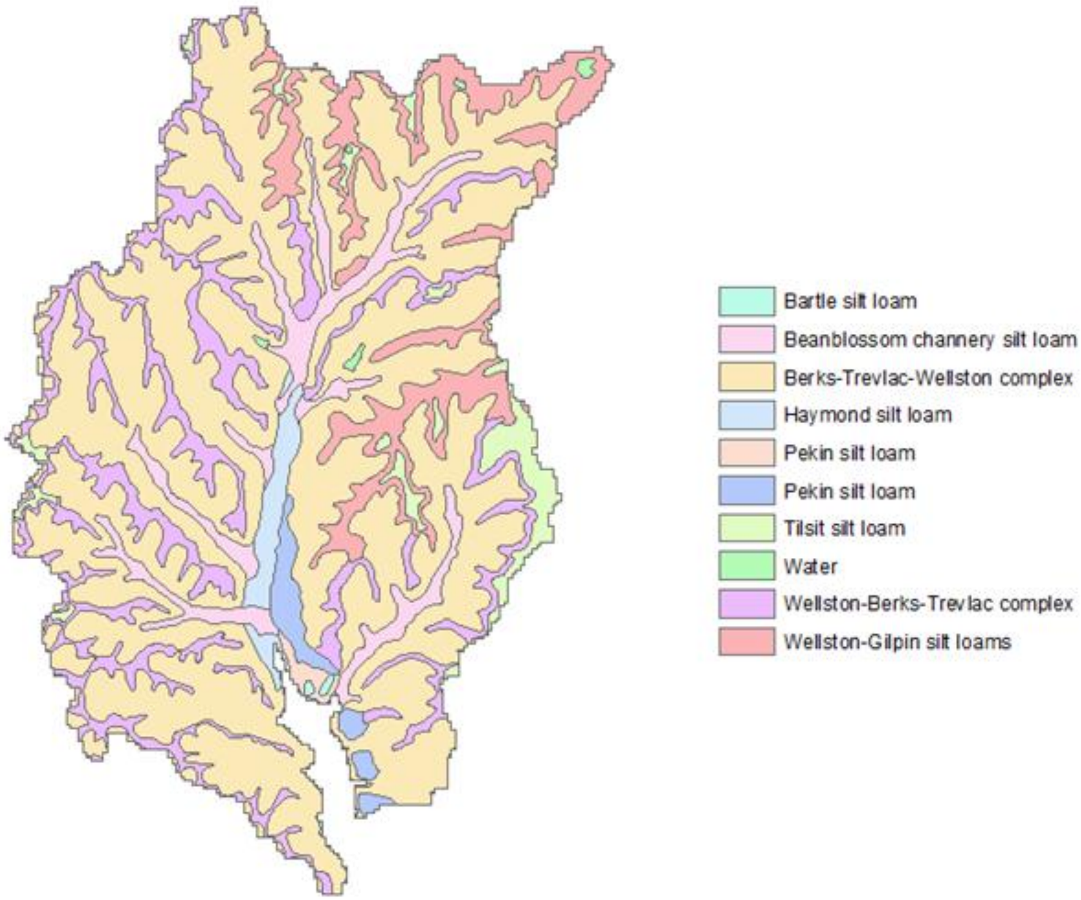


Figure 2.5: Soil series for Yellowwood Lake watershed (SSURGO)

Table 2.4: Input parameters for silty loam soil. Multiple entries correspond to the soil layers, with the entry for the top soil layer first and for the bottom soil layer last.

Soil Parameter	**Value**
Lateral Conductivity (m/s)	3.6E-5
Exponential Decrease of Lateral Conductivity	3.0
Maximum Infiltration Rate (m/s)	6.0E-6
Surface Albedo (m/s)	0.1
Number of Soil Layers	3
Porosity	0.46, 0.46, 0.46
Pore Size Distribution	0.26, 0.26, 0.26
Bubbling Pressure	0.21, 0.21, 0.21
Field Capacity	0.32, 0.32, 0.32
Wilting Point	0.12, 0.12, 0.12
Bulk Density (kg/m^3)	1330.0, 1330.0, 1330.0
Vertical Conductivity (m/s)	1.0E-5, 1.0E-5, 1.0E-5
Thermal Conductivity (W/m°C)	7.11, 6.92, 7.00
Thermal Capacity (J/m^3°C)	1.4E6, 1.4E6, 1.4E6

2.3 Model Calibration

2.3.1 Hydrology Model Calibration

Because the Yellowwood Lake watershed does not have any observed streamflow, DHSVM was applied to a similar watershed in order to calibrate the model then the calibrated parameters were transferred to the study area. The Brush Creek watershed is similar to the Yellowwood Lake watershed in location, topography, soil type, and size (Table 2.5). Climate data were obtained from the NCDC station in North Vernon, Indiana; and all additional DHSVM input data for Brush Creek were collected from the same sources as the input data for Yellowwood Lake watershed. The observed streamflow from Brush Creek was collected from USGS gage 03368000, and then compared to simulated streamflow for water years 2002-2006 for the model calibration. The model was then validated for water years 2006-2008 using streamflow from Brush Creek. DHSVM was run on an hourly time step, however, a hydrograph of average daily streamflow was calculated to be used for calibration since the USGS streamflow record are at a daily time step.

Table 2.5: Location and size of Yellowwood Lake and Brush Creek watersheds

Site	USGS Gauge Number	Latitude	Longitude	Drainage Area (km^2)	Average Annual Precipitation (mm)
Yellowwood Lake	N/A	39.2	-86.3	17.4	1021.1
Brush Creek	03368000	39.0	-85.5	29.5	1188.5

During the calibration process soil parameters for vertical and lateral hydraulic conductivity, and maximum infiltration rate were adjusted. DHSVM is most sensitive to changes in lateral hydraulic conductivity. Other soil properties were obtained from the Brown County Soil Survey (Noble et al., 1990), and were not adjusted for calibration because DHSVM is a physically based model. The soil class within the Yellowwood Lake watershed is mostly a Berks-Trevlac-Wellston silt loam complex, which has a maximum infiltration rate of 0.24 meters per day and lateral conductivity ranges between 0.37-3.65 meters per day (Noble et al. 1990); which are very close to the values chosen for the calibration parameters (Table 2.6). Many simulations were performed while changing the calibration parameter values in order to maximize the model efficiency, NS (Nash and Sutcliffe 1970).

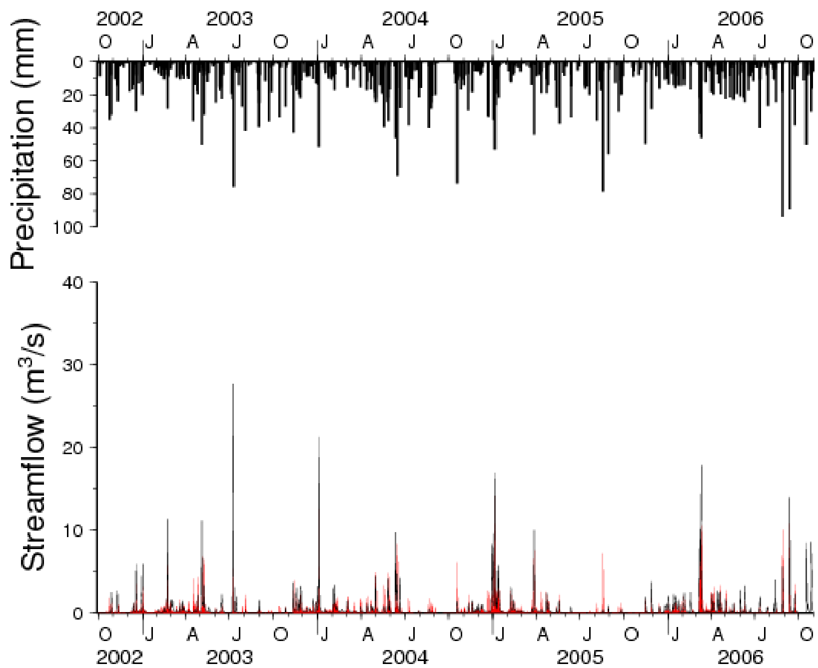


Figure 2.6: Calibration Hydrograph for Brush Creek. Black line is observed streamflow, red line is simulated streamflow

Table 2.6: Soil parameters determined from calibration

Parameter	Lateral Hydraulic Conductivity (m/day)	Vertical Hydraulic Conductivity (m/day)	Maximum Infiltration Rate (m/day)
Value	3.11	0.86	0.26

The Nash Sutcliffe Efficiency (NS, Equation 1) determines the similarity in shape and volume between the observed and simulated hydrograph based on the variance of both flows, and is particularly sensitive to differences in peak flows (Whitaker et al., 2003). The value can range from negative infinity to one, and a negative value suggests that the observed mean flow is a better predictor of observed flow than the model. The coefficient of determination (CoD, Equation 2) relates how well the observed and calculated hydrographs compare in shape depending only on timing, not volume, of flow (Whitaker et al., 2003). A successfully calibrated model should have values of NS and

CoD close to one. The values for Nash Sutcliffe Efficiency and Coefficient of Determination for the model calibration are 0.52 and 0.72, respectively.

Equation 1
$$NS = 1 - \frac{\sum_{i=1}^{N}\left(Q_{obs}^{i} - Q_{sim}^{i}\right)^2}{\sum_{i=1}^{N}(Q_{obs}^{i} - \bar{Q}_{obs}^{i})^2}$$

Equation 2
$$CoD = \frac{\sum_{i=1}^{N}(Q_{obs}^{i} - \bar{Q}_{obs})(Q_{sim}^{i} - \bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{N}\left(Q_{obs}^{i} - \bar{Q}_{obs}\right)^2 \sum_{i=1}^{N}\left(Q_{sim}^{i} - \bar{Q}_{sim}\right)^2}}$$

The streamflow hydrographs were also analyzed for total volume of flow, runoff ratio, and baseflow ratio. Figure 2.7 shows a double mass curve for the calibration time period which is constructed using the cumulative volume of flow from the calculated hydrograph. This data is plotted against the cumulative volume of flow from the gauge at Brush Creek. The linear trend in the double mass curve indicates that the streamflow from both sets of data are not significantly different from each other.

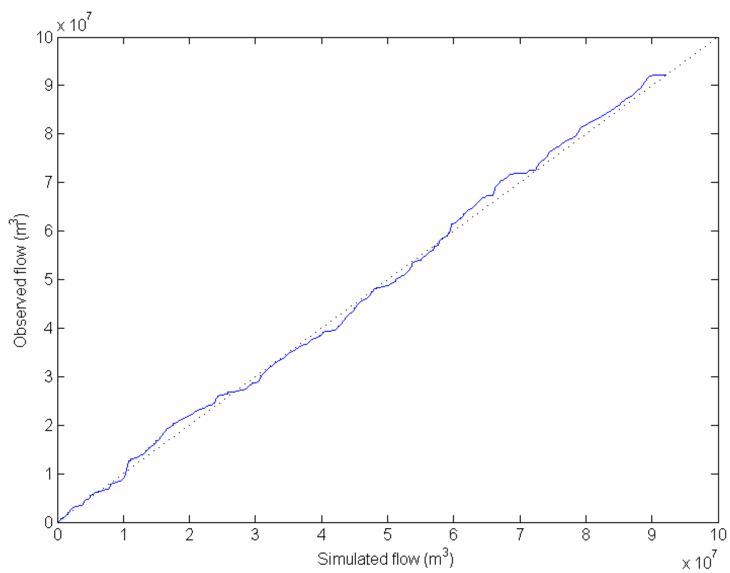


Figure 2.7: Double mass curve of observed and simulated flow. Light black line represents the 1:1 line

The runoff ratio was also calculated for observed and calculated hydrographs. The runoff ratio is the quotient of volume of flow over volume of precipitation over the watershed. This parameter represents the percentage of precipitation that becomes streamflow, and can vary between 0.01 for a very dry watershed to 0.5 for a wet watershed (Milly 1994). The runoff ratios for the observed and calculated hydrograph are 0.37 and 0.38, respectively. The similarities in runoff ratio values for the observed and simulated cases suggest that DHSVM is accurately calculating the water balance in the watershed.

Additionally, the base flow index was calculated by using PART version 2.0, a program developed by the USGS to estimate daily base flow from the streamflow record by streamflow partitioning (Rutledge 1998). PART assumes that nearly all groundwater is diverted to streams. The program scans daily observed flow data for dates that fit a requirement of antecedent recession and designates the base flow to be equal to the flow on these days. Then, the model linearly interpolates the baseflow for days with surface runoff. The base flow index is the ratio of baseflow to total streamflow. Results for the observed and simulated streamflow for the Brush Creek watershed during the calibration period are listed in Table 2.7. The results demonstrate that the model is producing reliable results for groundwater contribution to streamflow.

Table 2.7: Streamflow partition results from PART for water years 2002-2006

	Cumulative Streamflow (m)	Cumulative Base Flow (m)	Base Flow Index
Observed	1.90	0.49	0.26
Simulated	1.85	0.47	0.26

2.3.2 Model Validation

The calibration parameters were used to evaluate simulated streamflow for water years 2006-2008. Observed streamflow from Brush Creek watershed was also available for this time period, so simulated flow was again compared to the observed hydrograph (Figure 2.8). The validation simulation yielded similar statistics to the calibration run for Brush Creek. The values for NS and CoD are 0.53 and 0.74 respectively (Table 2.8). The results from the validation analysis suggest that the model is successfully calibrated. Final calibration parameters from Brush Creek were applied to the Yellowwood Lake watershed for all additional analysis.

Table 2.8: Model efficiency statistics from validation run

Metric	Value
Nash Sutcliffe Efficiency	0.53
Coefficient of Determination	0.74

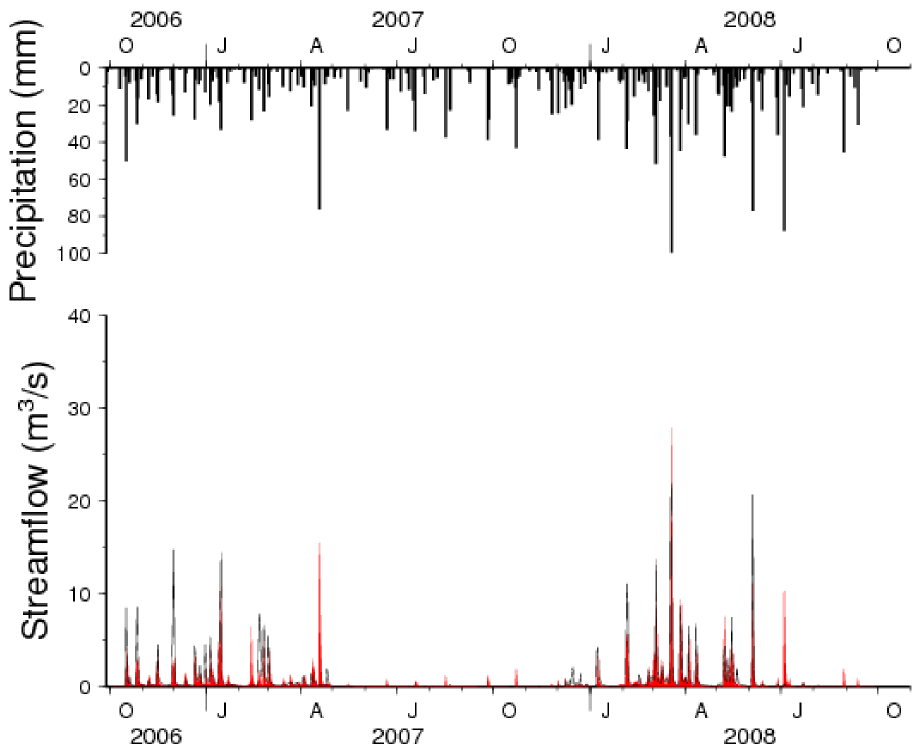


Figure 2.8: Validation hydrograph for Brush Creek. Black line is observed streamflow, red line is simulated streamflow

In addition to a validation period, the performance of the calibration parameters in the Yellowwood Lake watershed must also be evaluated to ensure the model can produce reliable results. The simulated hydrograph from the Yellowwood Lake watershed is shown in Figure 2.9. Additionally, the runoff ratio for the simulated flow is 0.27 for Yellowwood. Yellowwood has a smaller drainage area than Brush Creek and higher percentage of woody vegetation, which can lead to more evapotranspiration, and explains why streamflow and runoff ratio are lower than the results from the calibration watershed.

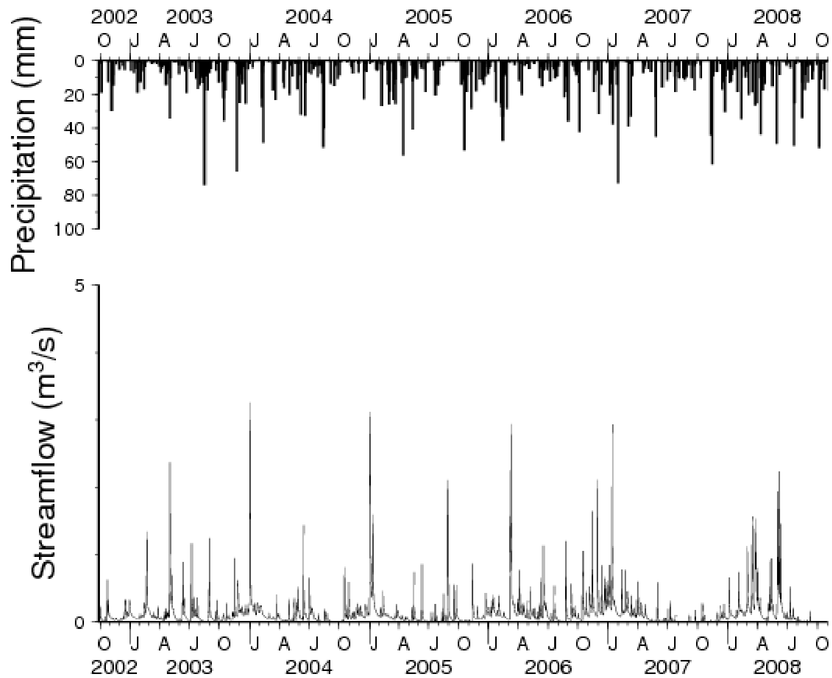


Figure 2.9: Simulated Hydrograph for Yellowwood Lake watershed

2.3.3 Sediment Model Calibration

The sediment model was evaluated to ensure that the simulated erosion rate from the DHSVM sediment model was realistic for the Yellowwood Lake watershed. No field work or weir pond installation has been done in Yellowwood to estimate hillslope erosion, thus simulation results from the Water Erosion Prediction Project (WEPP) model were used as the baseline erosion rate for which to calibrate the DHSVM sediment model before any forest management was applied.

The WEPP model was developed to predict soil detachment, transport, and deposition from water at the field scale. When the model is run continuously, rather than for a single storm, it is able to calculate the soil water content through the soil layers as well as the excess infiltration resulting from individual storms. The peak runoff rate resulting from excess infiltration is estimated using a solution to the kinematic wave equation, which in turn is used to compute the flow shear stress. The flow shear stress over the hillslope is then used in the sediment transport and detachment equations.

WEPP was developed by the United States Department of Agriculture (USDA) in 1985 to estimate erosion loads from land practices in rural environments. The physically based aspects of the model allow it to be applied to a wide range of topographies and climates since it relies on user input climate, slope, soil, and vegetation data. WEPP calculates soil erodibility in forests based on the amount of vegetative cover and the presence of any disturbances, such as forest roads or fire (Elliot, 2004). The model has been updated in order to accurately predict hillslope erosion rates from forested landscapes by adjusting the hydraulic conductivity of the soil according to vegetative cover (Elliot, 2004).

Studies have found the WEPP model to produce realistic results for sediment detachment in a variety of applications without calibration. A study by Tiwari et al. (2000) found the model predicted sediment loss at 71% efficiency for 20 sites across the country when compared against observed erosion rates. WEPP has also been applied to small watersheds in Indiana to determine best management practices based on sediment loss predictions (Cechova et al., 2010).

Simulation results from DHSVM were compared to those from WEPP for water years 2002 to 2006 using similar hillslopes and land use types to those found in the Yellowwood Lake watershed. WEPP was setup to use 30.5 meter long hillslopes with silty loam texture, a land cover of 20-year-old forests, and meteorological forcing data from Bloomington, Indiana. Slopes within the Yellowwood Lake watershed range between 0.1% and 28.0% (Figure 2.10), so annual erosion rates were simulated for representative hillslopes within that range. The WEPP model predicted an annual erosion rate of 8.97 kg/ha to 611.98 kg/ha for the sampled hillslopes. The results from WEPP were used to calculate an estimated aggregate annual erosion rate of 255.70 kg/ha by using the area within each slope category for a fully forested watershed (Table 2.9).

Table 2.9: Erosion rate output from WEPP model for varying slopes present in the Yellowwood Lake watershed

Slope	Erosion Rate (kg/ha/year)	Percent Total Area (%)	Fractional Erosion Rate (kg/ha/year)
0.1%	8.97	0.56%	0.05
1.0%	38.11	3.54%	1.35
2.5%	116.57	9.47%	11.04
4.0%	188.30	20.12%	37.88
5.0%	221.93	20.46%	45.41
7.5%	289.18	17.12%	49.52
10.0%	345.22	13.06%	45.08
12.5%	387.81	8.75%	33.95
15.0%	430.41	4.28%	18.42
17.5%	479.72	1.85%	8.89
20.0%	520.07	0.75%	3.92
25.0%	580.60	0.03%	0.17
28.0%	611.98	0.01%	0.04
		Annual Erosion Rate (kg/ha):	**255.70**

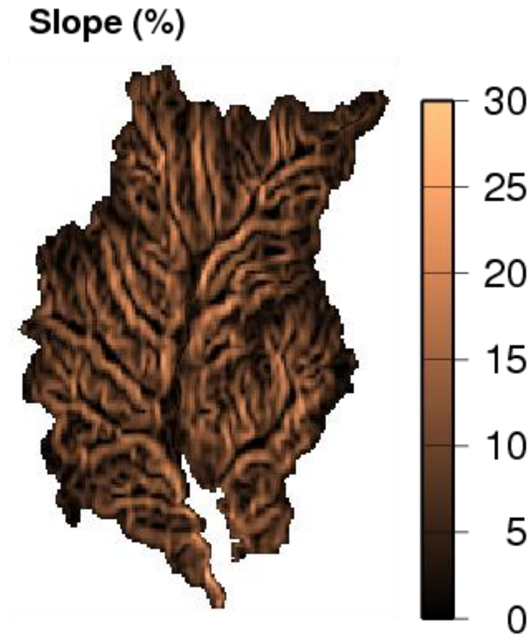


Figure 2.10: Slopes within Yellowwood Lake watershed

The constants within the equation for particle detachment and user defined soil cohesion value were adjusted within the sediment module until DHSVM produced an erosion rate similar to the erosion rate produced from the WEPP model. When the particle detachment equation is adjusted to $\beta_{de} = 0.25e^{-0.6C_s}$ and the soil cohesion value is set at 0.75 kPa, DHSVM yielded an annual erosion rate of 259.95 kg/ha which was very close to the erosion rate predicted by the WEPP model. Figure 2.11 shows the sediment load leaving the watershed during the calibration period. The annual erosion rate was calculated from the simulated sediment load by using a value of 1.33 g/cm^3 as the bulk density of silt loam (Noble et al., 1990).

The largest simulated sediment loads from Yellowwood Lake watershed during the calibration period occurred between January and August of 2004. Seasonal and antecedent conditions play a large role in sediment detachment throughout the landscape, which are evident in the Yellowwood Lake watershed. The spike in erosion in February and March of 2004 coincided with snow melt events that resulted in increased overland flow across the watershed, which increased sediment detachment. The largest spikes in sediment load occurred in June and July of 2004, when soil moisture throughout the watershed was nearly saturated. A flume experiment using simulated rainfall by Luk (1985) found that the amount of sediment washed away by storm events increases as antecedent soil moisture increased. The two largest spikes during the calibration period coincide with storms in which 60 mm. and 40 mm. of precipitation fell, respectively, and resulted in large amounts of erosion because of high antecedent soil moisture which left the soil vulnerable to detachment.

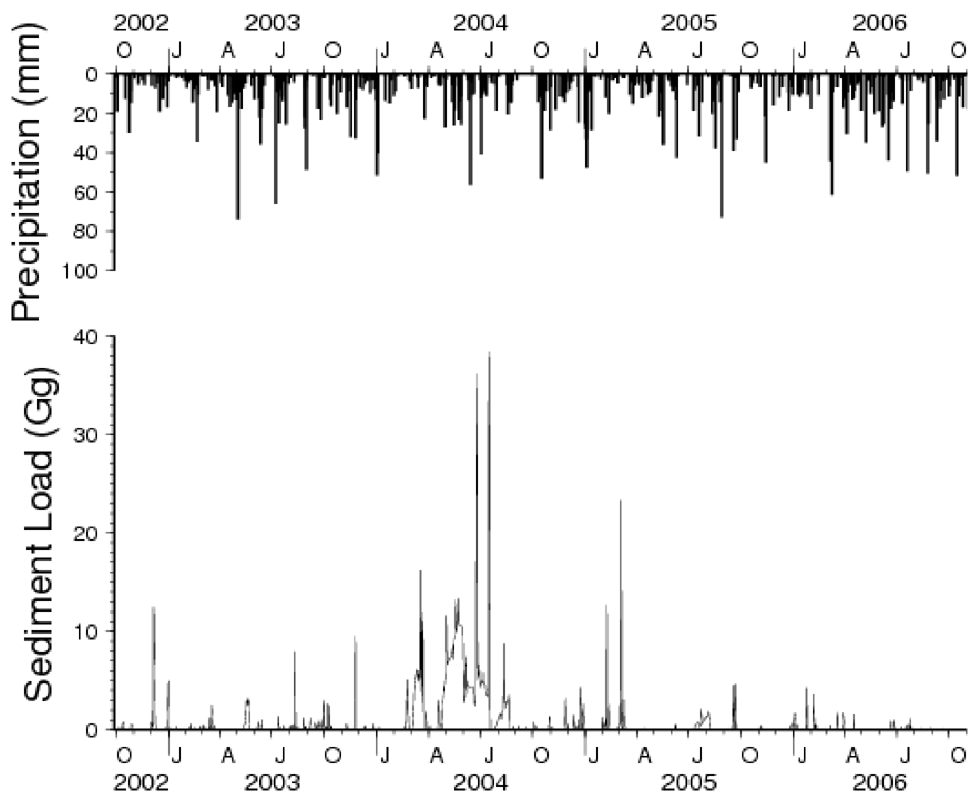


Figure 2.11: Sediment load simulated by DHSVM during sediment calibration run

2.4 DHSVM for Yellowwood Lake Watershed

DHSVM was used to simulate streamflow for forest harvest scenarios in the Yellowwood Lake watershed. Streamflow metrics and hydrographs for the simulated data were used to calculate how deforestation alters streamflow and to examine changes in high flow. The new land cover layers were created and edited in ArcGIS for each 30 meter grid cell. The land cover layers were created based on the areas, or tracts, which have been previously harvested. Figure 2.12 displays a map in which previously harvested tracts are highlighted. Timber harvest within the watershed is controlled by the Division of Forestry within the Indiana Department of Natural Resources (IDNR). The IDNR prescribes a forest management type for some tracts which range from single tree selection to a complete harvest. Preliminary analysis was conducted on the watershed to see what management styles have a significant effect on streamflow. A sub-watershed within the Yellowwood Lake watershed (Figure 2.12), which has been harvested across 49% of the drainage area, was used for the preliminary analysis of various land cover types in order to reduce computation time of the model.

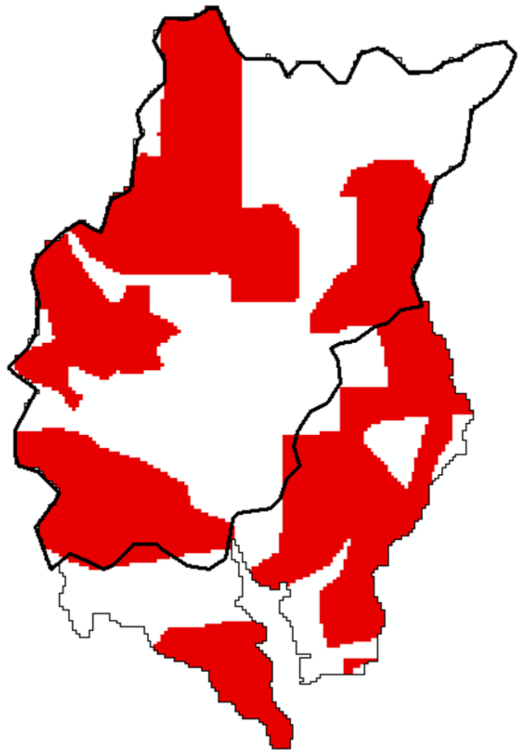


Figure 2.12: Tracts within the Yellowwood Lake watershed that have previously been harvested (red), and the sub-watershed used for the fractional coverage sensitivity analysis (dark outline)

The land cover scenarios include single tree selection, regeneration openings, intermediate, and clear-cut harvest of all highlighted tracts. Literature from the IDNR related to the harvesting of the tracts within Yellowwood describes single tree selection as the removal of low vigor, low quality trees in order to allow space for trees with higher quality stems. The regeneration openings prescription creates larger openings throughout the tract to promote growth of species that cannot reach the upper canopy themselves, so the upper canopy is removed in order to allow other trees to grow and promote diversity within the forest. Intermediate harvest consists of a uniform thinning throughout the entire tract, although the extent of the thinning may vary between tracts. Clear-cutting is the removal of the entire overstory canopy within the tract boundary.

A land cover scenario with no forest management is used as well; this data set is from NLCD 2006 in which the tracts are fully forested. Single-tree selection, regeneration openings, and intermediate forest harvest are represented in the model by varying the fractional coverage parameter for the deciduous forest within the tract area. Fractional coverage represents the percentage of area that is covered by the overstory. A decrease in the fractional coverage parameter implies a thinning of the forest density, and a fractional coverage of zero implies no overstory. A complete harvest is represented by completely removing the overstory. It is assumed that grasses and small shrubs will grow quickly after a forest harvest, so the understory remains present when any harvest is performed.

First a simulation experiment was conducted to evaluate changes in fractional coverage (i.e., canopy closure) on streamflow. All tracts that have previously been harvested were assigned the same fractional coverage, and then simulations were conducted for fractional coverage values of 0.00, 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.85, and 0.90. A fractional coverage of 0.00 (no overstory) defines a clear-cut harvest, and a fractional coverage of 0.90 (canopy openings equal 10% of the area) represents an area that is fully forested. A plot of the cumulative average daily streamflow for varying values of fractional coverage throughout water years 1962-2013 is shown in Figure 2.13 below. Preliminary tests with the fractional coverage scenarios in DHSVM identified a large shift in ET between vegetation with no overstory and a thin forest overstory with 5% fractional coverage. Smaller increases in ET are observed when fractional coverage increases from 5% to 90%. This results in a step change in hydrologic variables between no forest / overstory and very limited overstory.

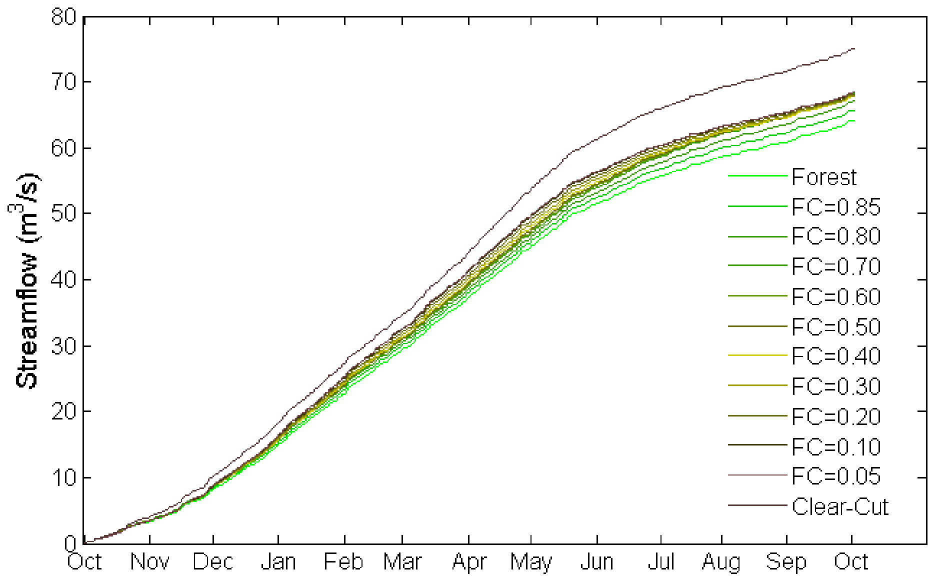


Figure 2.13: Cumulative daily streamflow for different levels of fractional coverage

2.5 Changes to Aerodynamic Resistance

The forest canopy fractional coverage was manipulated as a model input parameter in order to run the model with a variety of forest harvest scenarios. Different harvesting methods are represented in the model by changing the fractional coverage of the overstory. With changes to the overstory canopy, it is certain that evapotranspiration (ET) throughout the watershed will be affected. DHSVM uses a two-layer Penman-Monteith equation to calculate ET for each vegetation type; for which solar radiation, surface meteorology, soil moisture, soil characteristics, LAI, and stomatal resistance are all factors. The aerodynamic resistance over the vegetation is an important parameter which affects the surface meteorology within the Penman-Monteith equation. The aerodynamic resistance determines the transfer of heat and water vapor from the vegetative surface, and is very sensitive to the displacement height of the vegetation.

The displacement height is the height at which there is zero wind velocity due to vegetation obstructing wind flow, and is important in the calculation of ET because it characterizes the wind velocity profile over the landscape.

Currently, DHSVM uses a constant value of 0.63 times the vegetation height to calculate the displacement height for all vegetation types. As currently implemented, displacement height is a constant value based on tree height until all trees are removed and it is then calculated based on the height of the understory vegetation. This constant value does not represent the changing influence of the reduced canopy density on wind when forest stands are thinned, which is illustrated in Figure 2.14 where there is a large gap in ET between a fractional coverage of 0% and 5%, but fractional coverage of 5% and 10% are overlapping. As this does not reflect the actual change in wind speed due to forest thinning, changes were made to the calculation of aerodynamic roughness to produce a more continuous change in displacement height with forest density.

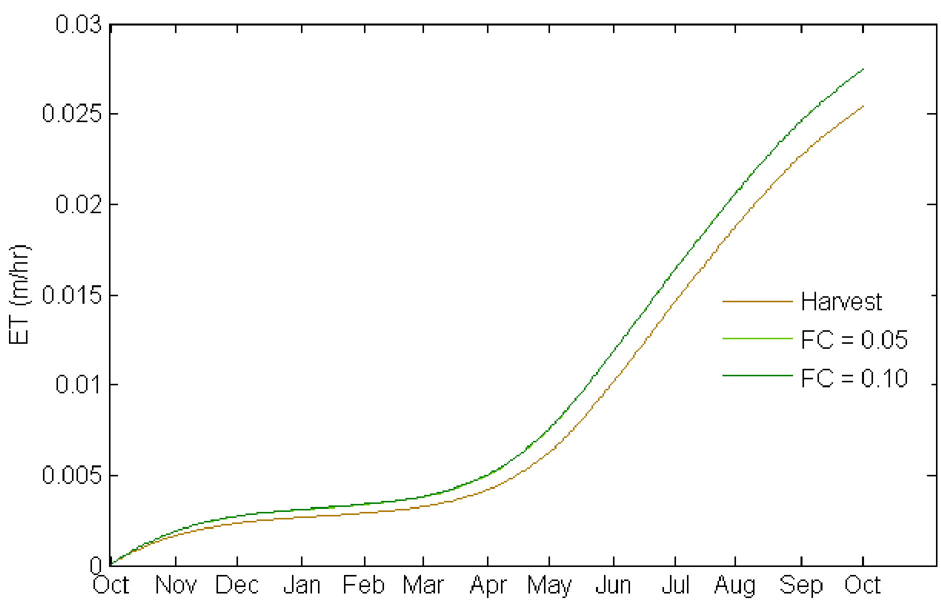


Figure 2.14: Cumulative ET for different levels of fractional coverage before changes to the aerodynamic resistance equations

There have been a few studies relating the thinning of forest areas to changes in wind speed, and these were used in modifying the aerodynamic resistance algorithm in DHSVM. A study by Novak et al. (2000) found that the displacement multiplier (d/h) decreases with decreasing tree density. In his study, Novak et al. (2000) conducted a wind tunnel study using small-scale model trees in which varying densities of forests were tested for changes to the wind and turbulence regimes and compared the results to a plot scale study conducted by Green et al. (1995). The fractional coverages for the forest scenarios tested by Novak et al. and Green et al. were calculated using the shape and density of the trees in the respective study. The results from the wind tunnel and plot scale study are shown in Table 2.10. Using the experimental results from studies by Novak et al. (2000) and Green et al. (1995), a continuous set of equations (Equation 3) was developed to represent the change in displacement height for thinned forests where x represents the fractional coverage. Figure 2.15 shows the continuous equation as well as the observed displacement multipliers from different studies. The displacement multiplier is given a value of 0.81 for all fractional coverages larger than 61% because the displacement height does not increase dramatically when aggregate fractional cover is above 61%, and this value was the largest value for displacement height that was recorded by the wind tunnel and plot study tests.

Table 2.10: Change in displacement multiplier with tree density from wind tunnel tests and a plot study

	Wind tunnel test (Novak et al., 2000)				Plot study (Green et al., 1995)		
Density (trees/ha)	839	315	138	78	625	278	156
Fractional Coverage (%)	53	20	9	5	39	19	10
d/h	0.81	0.72	0.64	0.59	0.75	0.71	0.61

Equation 3
$$d/h = \begin{cases} 14.50x - 0.14, & 0.00 < x \leq 0.05 \\ 0.09\ln(x) + 0.85, & 0.05 < x \leq 0.61 \\ 0.81, & 0.61 < x \leq 1.0 \end{cases}$$

x= Fractional Coverage

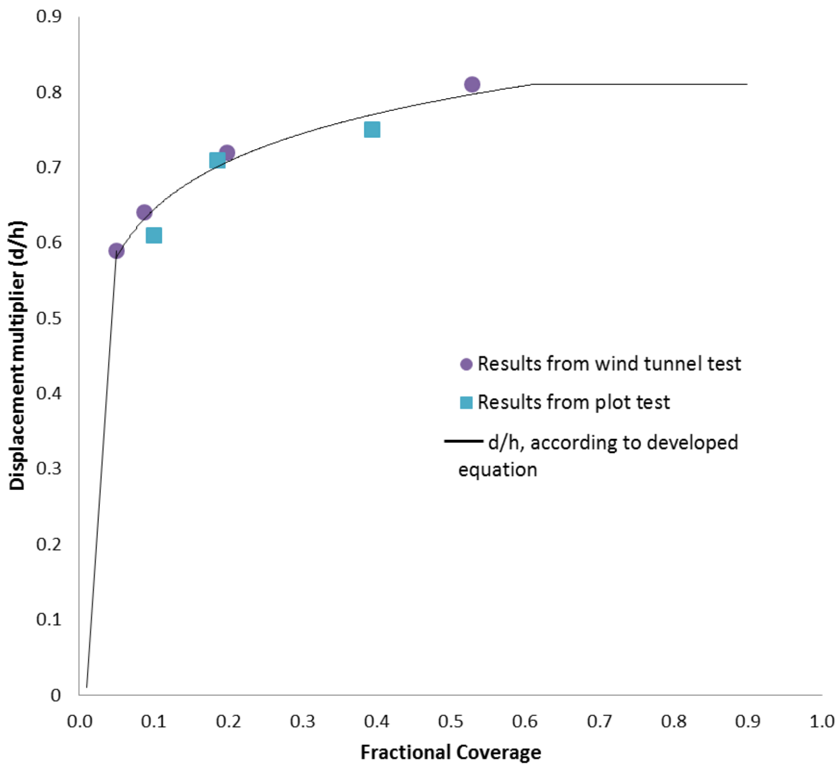


Figure 2.15: Plot of equations for displacement multiplier determined by fractional coverage

The displacement height for vegetation within Yellowwood is shown in Figure 2.16 for a variety of fractional coverage values. The displacement height is 0.32 meters when there is no overstory canopy because the model uses a constant displacement multiplier of 0.63 for the understory. The height of the understory within Yellowwood Lake watershed is modeled as a constant 0.5 meters. Figures 2.17 and 2.18 show the changes in cumulative ET and streamflow after the updates were made to the aerodynamic resistance equation. In both figures, the gap between fractional coverage of 0% and 5% is smaller than when a constant displacement multiplier was used to calculate displacement height of the overstory.

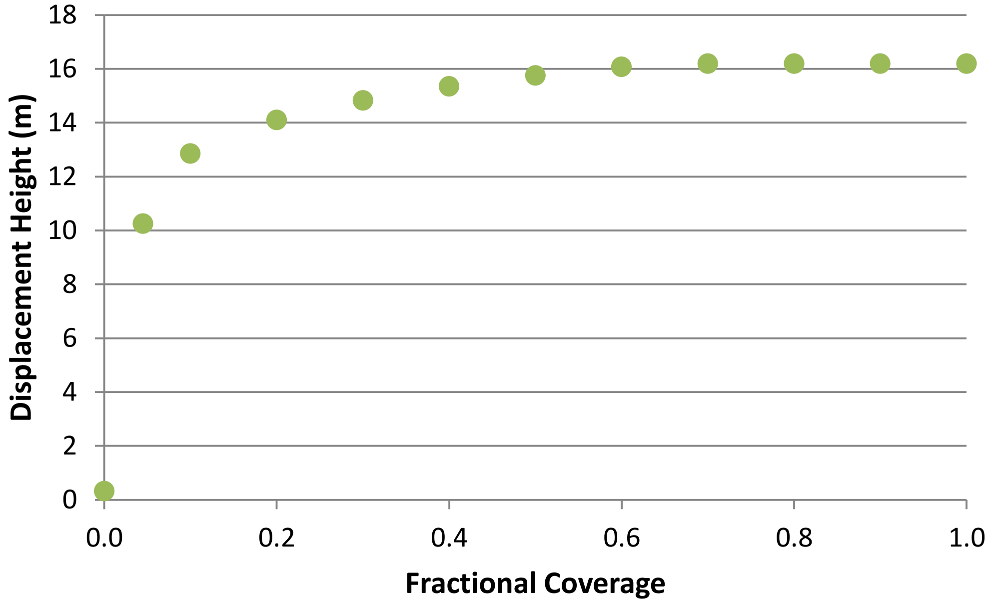


Figure 2.16: Displacement heights calculated by DHSVM for vegetation in the Yellowwood Lake watershed

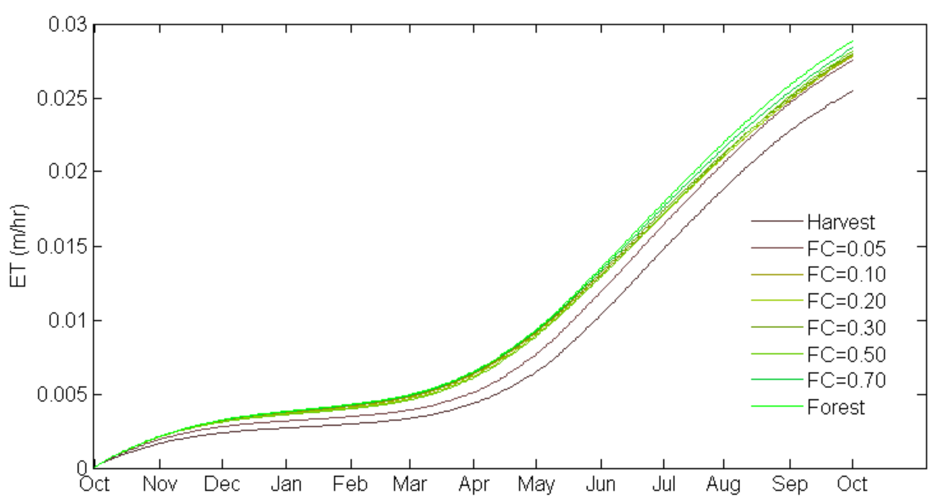


Figure 2.17: Cumulative ET for different levels of fractional coverage after changes to the aerodynamic resistance equations

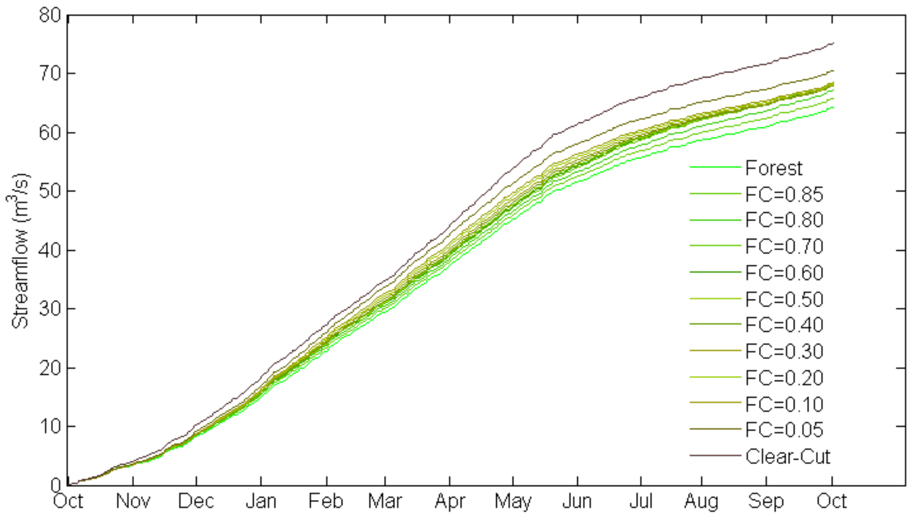


Figure 2.18: Cumulative streamflow for different levels of fractional coverage after changes to the aerodynamic resistance equations

2.6 Test for Differences in Streamflow

Parametric tests were performed to test for significant differences in central tendency in annual maximum streamflow for different land use scenarios. Streamflow from both the forested and clear-cut scenarios were tested since they exhibit the largest difference. Shifts in maximum annual streamflow were analyzed for water years 1962-2013. Before applying any tests to the data, the underlying assumptions for each test were evaluated. The F-test is a test for equal variance among the samples, and the t-test tests for equal means of the samples. The F-test and the t-test both assume that the data set is identically and independently distributed, as well as normally distributed. Figure 2.19 shows an autocorrelation and normal probability plots of the streamflow from the forested and clear-cut cases. These plots show that the data have no significant correlation and can be represented using a normal distribution.

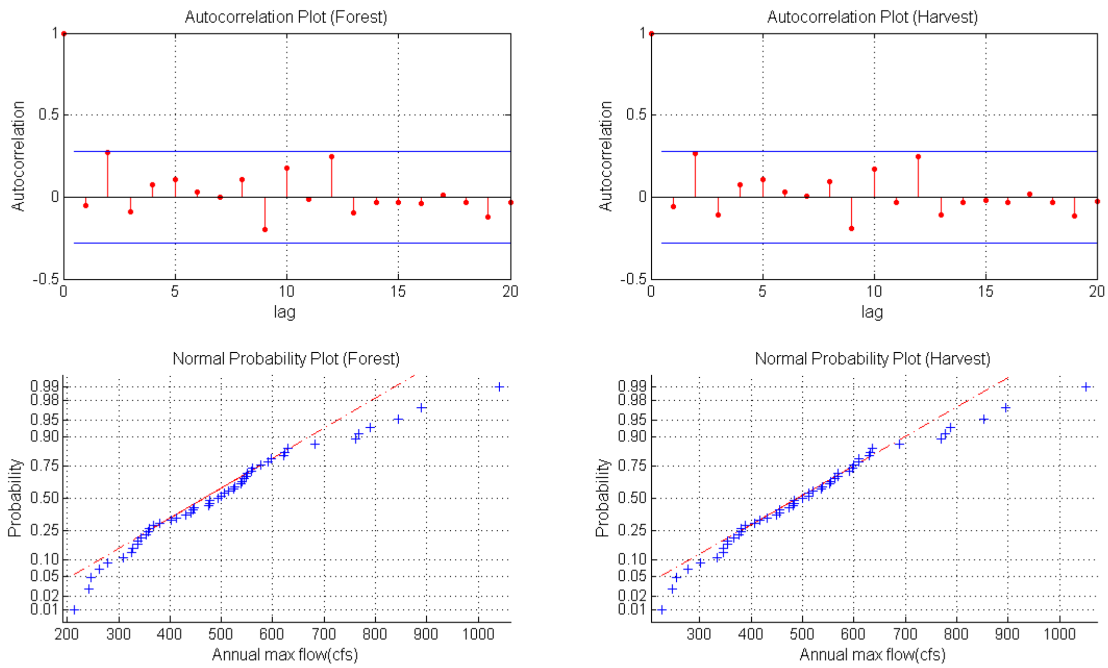


Figure 2.19: Autocorrelation and normal probability plots for the forested and harvested cases

The F-test must be conducted first to see if there is equal variance between the two data sets. The F-test is done using a 90% significance level, and the null hypothesis states that the variance of the two samples is equal. The test statistic is $f = s_x^2/s_y^2$, where s_x^2 and s_y^2 are the variances from the forested and clear-cut cases, respectively. The null hypothesis is rejected if $f \geq F_{1-\frac{\alpha}{2},n-1,m-1}$, where n and m are the sample sizes of the two data sets. The result of the F-test determines if the t-test is conducted assuming equal or unequal variances. The t-test is also conducted using a 90% significance level and the null hypothesis states the means of the two samples are equal. The test statistic for the t-test is $t = \frac{\bar{x}-\bar{y}}{\sqrt{\frac{s_x^2}{n}+\frac{s_y^2}{m}}}$ and the null hypothesis is rejected if $|t_c| > T_{1-\alpha/2,df}$. The results from the F-test and t-test are listed in Table 2.11, and did not show significant increases in maximum annual streamflow.

Table 2.11: Results from the F-test and t-test applied to the annual maximum streamflow series for the forested and clear-cut cases

	F-test	t-test
Test Statistic	1.03	-0.44
Critical Value	1.44	1.30
Reject H_o	no	no

2.6.1 Streamflow Metrics

Although the land cover scenarios did not result in a statistically significant difference in annual maximum streamflow, the changes in streamflow with each change in fractional coverage are worthy of further analysis. Konrad and Booth (2005) list metrics that are ecologically significant and accurately demonstrate hydrologic effects due to land cover change while remaining stationary in reference data sets. Table 2.12 lists the metrics selected for this analysis.

Table 2.12: Metrics used for streamflow analysis for various values of fractional coverage

Metric	Name
High Flow	Exceedance of three times median flow, frequency of events greater than 10^{th} percentile flow
Flow Distribution	Mean flow, median flow
Low Flow	90^{th} Percentile flow, 90^{th} percentile flow/median daily flow

Streamflow metrics are calculated for each of the 51 years in the simulation period using daily streamflow from the main tributary flowing into Yellowwood Lake and then averaged for all years (Table 2.13). These metrics were also tested for statistically significant differences using a t-test. The frequency of flow events above three times the median increased from 70 in the forested case to 84 events per year in the harvested case. Average streamflow increased as the overstory canopy was removed from

0.175 m^3/s to 0.205 m^3/s. The low flow metrics also shifted; the 90th percentile flow almost doubled, increasing from 0.007 m^3/s to 0.013 m^3/s when the overstory canopy was removed. The changes in streamflow metrics suggest that fractional coverage plays an important role in the streamflow regime, and will be considered when examining realistic harvest scenarios within the watershed.

Table 2.13: Streamflow metrics for change in fractional coverage for the selected sub-watershed for water years 1962-2013

Fractional Coverage	90%	85%	80%	70%	60%	50%	40%	30%	20%	10%	5%	0%
Frequency of daily flows exceeding 3xmedian	70.00	71.67	72.86	74.20	74.51	75.00	75.39	75.75	76.55	77.18	77.31	84.12
Frequency of events greater than 10th percentile flow	36.00	37.35	38.20	39.09	39.03	38.94	39.15	39.37	39.66	40.00	39.70	43.00
Mean Streamflow (m^3/s)	0.175	0.180	0.183	0.186	0.186	0.186	0.185	0.186	0.186	0.187	0.187	0.205
Median Streamflow (m^3/s)	0.048	0.050	0.052	0.053	0.053	0.052	0.052	0.052	0.052	0.053	0.053	0.065
90th percentile flow (m^3/s)	0.007	0.008	0.008	0.009	0.009	0.009	0.009	0.009	0.009	0.010	0.010	0.013
90th percentile flow/median daily flow	0.15	0.16	0.17	0.18	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.27
Annual maximum streamflow (m^3/s)	14.09	14.15	14.21	14.23	14.25	14.25	14.25	14.26	14.27	14.29	14.29	14.52

Metrics were also evaluated using ANOVA tests to account for change in high and low flows, and streamflow variation among more than two realistic harvest scenarios. ANOVA tests for each metric were run for the 51-year span of calculated metrics to test for statistically significant differences in central tendency among three or more samples, and if the samples come from the same population. The data is identically and independently distributed and normally distributed, which meets the assumptions of the ANOVA test. An ANOVA test was performed on the metrics from the forested and realistic scenarios to test for statistically significant differences between the vegetation cases.

2.7 Flood Frequency Analysis

A Gumbel probability distribution was fit to the annual maximum flow data for each vegetation scenario to construct a flood frequency diagram. These diagrams relates flood discharge values to return period to provide an estimate of the return period or recurrence interval of a given discharge level. As shown in Figure 2.20, discharge is usually plotted on the y-axis using a linear scale, and return period is plotted on the x-axis. The x-axis scale is a modified probability scale, so that the resulting flood frequency curve appears as a straight line.

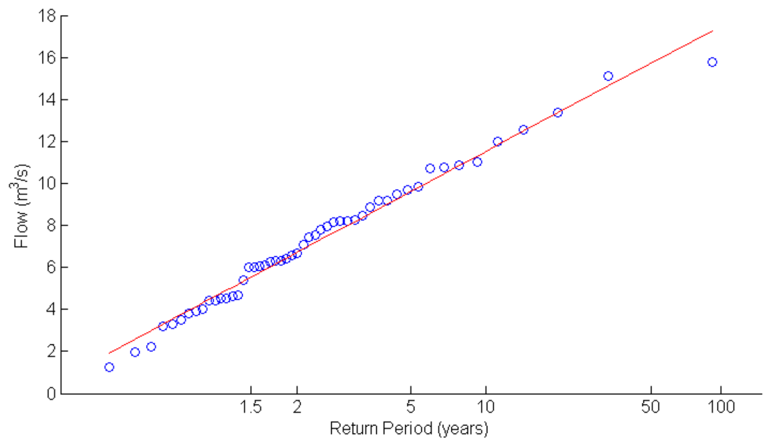


Figure 2.20: Flood frequency diagram of streamflow from the selected sub-watershed using a Gumbel distribution, using the annual maxima series from the fully forested vegetation scenario. The theoretical distribution is shown by the straight line, and the circles are the annual maxima series.

For each distribution the empirical exceedance probability, or plotting position, was calculated based on the rank of the data. Then, the standard gumbel variate and parameters were calculated to find the theoretical discharge for a certain return period. For the Gumbel distribution, the plotting position (q_i) used Gringorten's 'a' value of 0.44 because that is most appropriate for the Gumbel distribution. The formula for the plotting position is $q_i = \frac{i-a}{N+1-2a}$ where 'i' is the rank of the observed annual peak and 'N' is the number of data points being analyzed. The standard gumbel variate (y) is calculated by y= –ln(-ln(1-q)). The parameters for the Gumbel distribution are β and X_o. The method of moment estimators are $X_0 = \overline{X} - 0.5772\beta$ and $\beta = \sqrt{\frac{6\sigma^2}{\pi^2}}$.

The Kolmogorov-Smirnov (KS) test was used to evaluate the goodness of fit of the distributions. The test statistic (d2) for the KS test is the maximum value of abs(i/n-F(x)). For the Gumbel distribution, F(x)= exp(-exp-(x-x_o)/β)). The null hypothesis for the KS test states that the observed data follows the specified probability distribution. The calculated values of the test statistic are then compared to the KS critical value and the null hypothesis is rejected if d2>KS(α,N). The KS critical value is found in a look-up table. For this study alpha = 0.05 and N = 51, so the KS critical value is $1.36/\sqrt{N}$, or 0.19.

CHAPTER 3. STREAMFLOW RESULTS

3.1 Introduction

Forest harvest has been found to increase streamflow magnitudes in the Yellowwood Lake watershed due to decreased canopy interception and evapotranspiration. Changes to the fractional coverage parameter throughout the watershed were shown to affect the streamflow regime, so harvest scenarios which represent different harvest prescriptions were applied to Yellowwood Lake watershed. This is designed to mimic the actual harvest impacts, rather than evaluate the sensitivity of the model as done in the previous chapter when a constant fractional coverage was used for all previously harvested tracts. Streamflow metrics will be analyzed from different locations in the watershed to examine which areas are more prone to increased streamflow as a result of forest harvest.

3.2 Sensitivity Testing of Harvest Scenarios

The harvest scenarios tested in this study have a fractional coverage that varies depending on the forest management defined for that tract by the Indiana Department of Natural Resources. Tracts harvested in the Yellowwood watershed are categorized as one of the following: clear-cut harvest, intermediate harvest, regeneration openings harvest, single-tree selection harvest, or no harvest. Clear-cut harvest is the removal of the entire overstory canopy within the tract. Intermediate harvest consists of a uniform thinning throughout the entire tract, although the extent of the thinning may vary between tracts. Regeneration openings create larger openings throughout the tract to promote growth of species that cannot reach the upper canopy themselves, with areas of the upper canopy removed other trees species can grow and promote diversity within the forest. The IDNR describes single tree selection harvest as the removal of low vigor, low quality trees in order to allow space for trees with higher quality stems. Some tracts were not assigned a management prescription in the IDNR database, so they were assumed to have been managed using regeneration openings harvest.

It is important that the harvest scenarios that are used for the analysis accurately represent the actual harvest prescription and its effect on the streamflow regime in order to correctly represent current conditions with the model. The set of scenarios in Table 3.1 lists the fractional coverage values that were assigned for each management style for each scenario based on the recommendations from the IDNR. The five fractional coverage scenarios were designed to help determine appropriate fractional coverage values for the existing harvest types. These five scenarios will be used to simulate actual watershed conditions using the methods detailed in the previous chapter, and their effect on hydrologic parameters is assessed to determine which scenario set best represents current conditions.

Table 3.1: Fractional coverage assigned for each prescribed management style

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Clear-Cut Harvest	0%	0%	0%	0%	0%
Intermediate Harvest	50%	30%	40%	60%	20%
Regeneration Openings Harvest	70%	50%	60%	70%	50%
Single-Tree Selection Harvest	85%	80%	80%	85%	70%
No Harvest	90%	90%	90%	90%	90%

The IDNR does not list the fractional coverage of each tract before or after the prescribed management style is applied, so scenarios are developed in which a mixture of fractional coverage values are assigned to each harvest type to see which scenarios might have a measureable effect on streamflow, and which effects seem the most realistic. Single tree selection harvest is assigned a fractional coverage value ranging between 70% to 85% because only low quality stems are removed, however, there is no defined limit to the amount of trees that are cut down. The fractional coverage of regeneration openings harvest is set between 50%-70% because they typically have s-shaped openings throughout the tract of various sizes and frequency. The intermediate harvest prescription is a uniform thinning of all the trees, with thinned densities ranging between 30%-70% of fully forested coverage, so a fractional coverage from 20% to 60% seems reasonable for this harvest style. Clear-cut harvest is assigned 0% fractional coverage for all scenarios because there is no overstory after the harvest is applied. Each fractional coverage scenario will be examined for significant changes to streamflow and the effect on the water balance to decide which scenario best represents actual conditions within the watershed.

Annual streamflow metrics (described in Chapter 2) were calculated using all streamflow entering Yellowwood Lake and were averaged over the entire 51 year analysis period (Table 3.2). A t-test was applied to test for significant differences between the fully forested scenario, fractional coverage scenarios, and clear-cut scenarios for the metrics calculated during each year of the analysis period. The results from the statistical tests for each fractional coverage scenario are shown below (Table 3.3). The clear-cut scenario has significantly more frequent high flow events and increased low-flow event volumes than the forested scenario. None of the fractional coverage scenarios displayed any statistically significant difference with respect to the no-harvest case for any of the streamflow metrics, except for the frequency of events greater than 10^{th} percentile flow, which was calculated using a constant 10^{th} percentile flow from the fully forested vegetation scenario. This indicates that simulated streamflow is only sensitive to the fractional coverage scenarios for the highest flows at the watershed scale.

Table 3.2: Annual average streamflow metrics for the evaluation watershed for fully forested, clear-cut harvest, and observed harvest patterns with five scenarios of fractional coverage based on harvest type.

Metric	Forest	Clear -Cut	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Frequency of daily flows exceeding 3xmedian	71	89	76	75	76	76	76
Frequency of events greater than 10th percentile flow	36	45	39	39	39	40	39
Mean Streamflow (m^3/s)	0.235	0.277	0.249	0.245	0.248	0.250	0.246
Median Streamflow (m^3/s)	0.068	0.090	0.074	0.072	0.073	0.074	0.072
90th percentile flow (m^3/s)	0.014	0.020	0.017	0.016	0.016	0.017	0.016
90th percentile flow/median daily flow	0.215	0.350	0.262	0.255	0.258	0.262	0.257

Table 3.3: Test statistic results from comparing the clear-cut scenario and all fractional coverage scenarios to the fully forested case. Red represents a significant increase in the average annual metric. Blue represents no significant difference. There were no significant decreases.

	Fractional Coverage Scenarios					Clear-Cut
	1	2	3	4	5	
Frequency of daily flows exceeding 3 times median						
Frequency of events greater than 10th percentile flow						
Mean Streamflow						
Median Streamflow						
90th percentile flow						
90th percentile flow/median daily flow						

The results from the streamflow metric comparison determine that clear-cut harvest significantly affects the flow regime at the watershed scale, and although it is an unrealistic scenario, it demonstrates that the model is sensitive to changes in vegetation at the watershed scale. In regard to the fractional coverage scenarios, only 39.4% of the watershed had regeneration opening harvest, 2.0% had single tree selection harvest, 8.4% had intermediate harvest, and 2.5% was clear-cut harvest. Given that the majority of the landscape is still forested, and that harvest has been implemented in patches throughout the drainage area, it is not surprising that the fractional coverage scenarios had minimal effect on streamflow for the full watershed.

The aggregate value for fractional coverage over the entire watershed was calculated for each fractional coverage scenario by using the fractional coverage assigned for each harvest prescription and the area of each management type. The aggregate fractional coverage varies between 65-76% for the different harvest scenarios. Figure 3.1 shows the aggregate fractional coverage plotted against cumulative depth of water in the canopy, and Figure 3.2 shows cumulative depth of water in the soil throughout the simulation period. Scenario 3 lies between the other harvest scenarios for both depth of water in the canopy and in the soil throughout the 51 year simulation period.

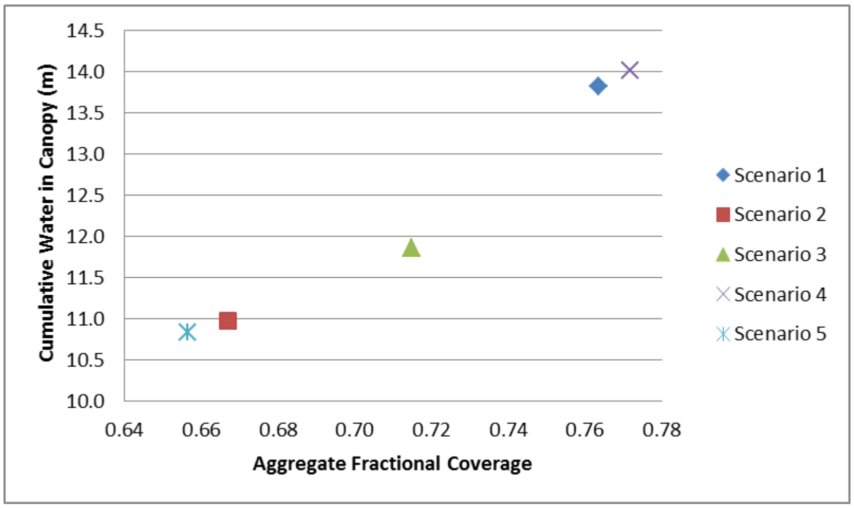


Figure 3.1: Cumulative depth of water in the canopy for each harvest scenario

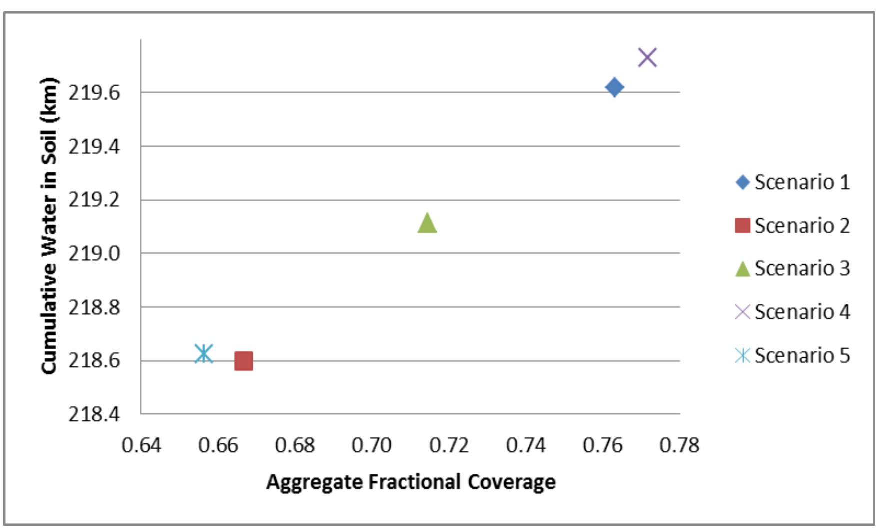


Figure 3.2: Cumulative depth of water in the soil for each harvest scenario

3.3 Sub-Watershed Analysis

Yellowwood Lake watershed was divided into sub-watersheds in order to get a better picture of the streamflow impacts from forest harvest. Smaller drainage areas are more responsive to vegetation change as the time of concentration is decreased. Additionally, the degree to which each watershed has been harvested is important to changes in streamflow, and each sub-watershed has been exposed to different amounts and mixtures of harvest types (Table 3.4). The next step in the analysis is to break the watershed into smaller sub-watersheds (Figure 3.3) that better represent headwaters which may have been significantly affected by forest harvest to date given the higher percentage of harvest within each sub-watershed. The results from the statistical tests of streamflow metrics for each sub-watershed are shown below (Table 3.5)

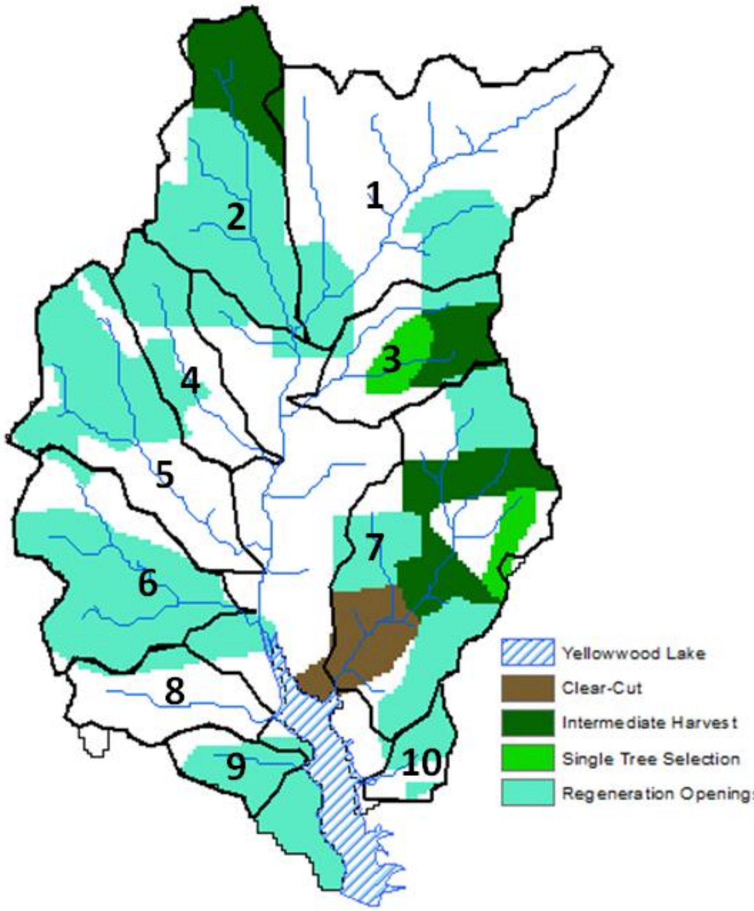
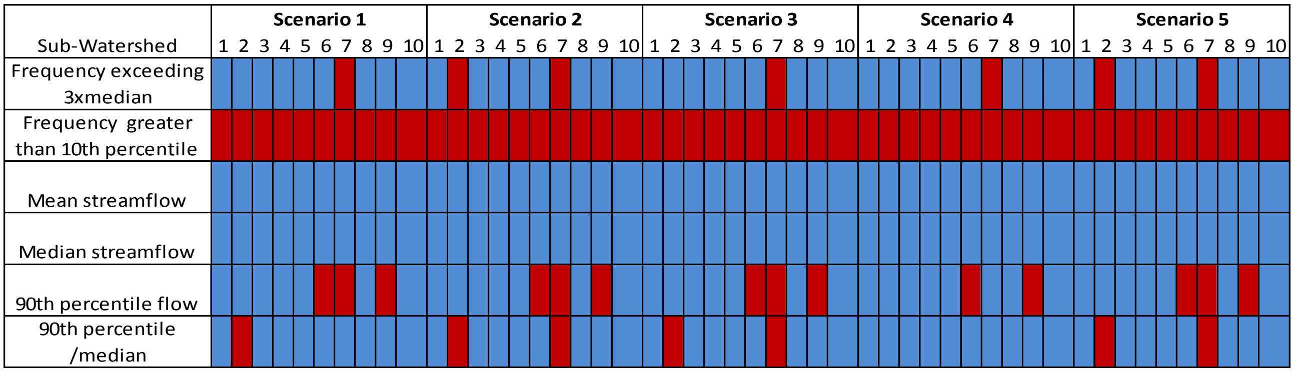


Figure 3.3: Ten sub-watersheds used for harvest analysis within the Yellowwood Lake watershed, with IDNR harvest scenarios indicated. Areas shown in white were not prescribed any harvest.

Table 3.4: Properties of the sub-watersheds in Yellowwood Lake watershed

	Watershed 1	Watershed 2	Watershed 3	Watershed 4	Watershed 5	Watershed 6	Watershed 7	Watershed 8	Watershed 9	Watershed 10
Area (km^2)	3.2	1.8	1.0	0.8	1.7	1.6	2.8	0.7	0.4	0.3
% Clear-Cut	0.0	0.0	0.0	0.0	0.0	0.0	13.9	0.0	0.0	0.0
% Intermediate Harvest	1.0	28.7	25.7	0.0	0.0	0.0	23.5	0.0	0.0	0.0
% Single Tree Selection	0.0	0.0	18.2	0.0	0.0	0.0	5.3	0.0	0.0	0.0
% Regeneration Openings	20.9	64.4	14.7	53.3	53.3	76.5	34.0	14.0	76.7	60.4
Total Percent Harvested (%)	21.9	93.2	58.6	53.3	53.3	76.5	76.7	14.0	76.7	60.4
Aggregate Fractional Coverage (%)	83.2	56.3	70.9	74.0	74.0	67.0	55.0	85.8	67.0	71.9
Max. Slope (%)	25.1	23.8	23.7	22.1	20.3	19.6	23.3	19.0	16.3	15.1
Median Slope (%)	6.5	7.0	6.6	8.2	6.7	7.1	7.1	6.5	7.0	7.4
Min. Slope (%)	0.01	0.13	0.01	0.01	0.01	0.01	0.01	0.02	0.23	0.44

Table 3.5: Statistical test results when comparing all fractional coverage scenarios to the fully forested case for all sub-watersheds. Red represents a significant increase in the average annual metric. Blue represents no significant increase.



ANOVA tests were performed on each sub-watershed to see if the extent of harvest within each sub-watershed results in more significant changes to streamflow metrics. ANOVA test results are presented for only two of the ten sub-watersheds: Watershed 8 with 14% of its area harvested (Table 3.6), and Watershed 2 with 93% of its area harvested (Table 3.7). It can be seen from the ANOVA results that metrics related to high and low flow were most likely to experience statistically significant (at a 90% confidence level) changes due to harvest, with more metrics experiencing significant changes in Watershed 2 than in Watershed 8.

From these extreme harvest cases, it can be seen that even a watershed with a relatively small percentage of forest harvest can experience significant increases in the frequency of events greater than the 10^{th} percentile of flow. This indicates that forest harvest increases the number of high flow events from the watershed which is a result of increased volume and peak rate of runoff during storm events, and that the representation of harvest techniques show significant changes to the flow regime at the sub-watershed scale.

Table 3.6: ANOVA tests for streamflow metrics in Watershed 8 (14% harvested). F-critical for each metric is 2.24.

Metric	F test statistic	Significance	Direction of change
Frequency of daily flows exceeding 3 times median	0.03	Not Significant	Increase
Frequency of events greater than 10th percentile flow	4.19	Significant	Increase
Mean streamflow	0.007	Not Significant	Increase
Median streamflow	0.009	Not Significant	Increase
90th percentile flow	0.0004	Not Significant	Increase
90th percentile flow/median daily flow	0.0006	Not Significant	Increase

Table 3.7: ANOVA tests for streamflow metrics in Watershed 2 (93% harvested). F-critical for each metric is 2.24.

Metric	F test statistic	Decision	Direction of change
Frequency of daily flows exceeding 3 times median	9.03	Significant	Increase
Frequency of events greater than 10th percentile flow	17.37	Significant	Increase
Mean streamflow	0.42	Not Significant	Increase
Median streamflow	0.72	Not Significant	Increase
90th percentile flow	1.65	Not Significant	Increase
90th percentile flow/median daily flow	2.29	Significant	Increase

Because the results from the previous sensitivity analysis found few statistically significant differences between the effects on streamflow due to differences in how fractional coverage is defined for different harvest types (Table 3.3 and Table 3.5), only one of the five scenarios will be used in the rest of the analysis to represent actual conditions (post-harvest) in the watershed. Each scenario was examined for cumulative depth of water in the canopy and in the soil throughout the simulation run to see if scenarios exhibited differences in other components of the water balance not reflected in the streamflow metrics. Scenario 3 was chosen to represent the forest management scenario. This scenario exhibits statistically significant differences in streamflow metrics related to high and low flow variability when compared to the fully forested case at the sub-watershed scale using a t-test at a 90% significance level.

3.4 Analysis of Harvest Effects

3.4.1 Daily Flow Metrics Analysis

The metrics for the chosen vegetation scenarios illustrate increasing high flow variability as the severity of harvest increases within the sub-watershed. The metrics from all the sub-watersheds using the harvest and forested vegetation scenarios are shown in Table 3.8. The severity of forest harvest is described in terms of the aggregate fractional coverage of each sub-watershed, which was calculated by using the average fractional coverage and the percent area for each harvest type. Each streamflow metric was examined for significant changes in streamflow distribution using a t-test at a 90% confidence interval, and significant increases are highlighted in red. The relative harvest management mixtures and range of topographic slopes were also considered in the analysis.

The severity of forest harvest within the sub-watersheds significantly increased some of the streamflow metrics. Watershed 7, which has an aggregate fractional coverage of 54.9% and a clear-cut prescription for 13.5% of its area, experienced a significant increase in high flow frequency and low flow magnitude after forest harvest (Table 3.5). Watershed 3, which has an aggregate fractional coverage of 70.9%, does not include a clear-cut prescription, but is otherwise similar to Watershed 7 in terms of harvest mixtures and slope. Low flow magnitude increased significantly in Watershed 7 and not Watershed 3, which suggests that clear-cut harvest significantly increases low flow magnitude. Figure 3.4 shows the change in metrics related to low flow with respect to aggregate fractional coverage and shows the significant linear trend by the dotted line, which was calculated using linear regression analysis. These plots illustrate how harvest causes larger increases to these metrics as aggregate fractional coverage decreases, or in other words harvest becomes more severe.

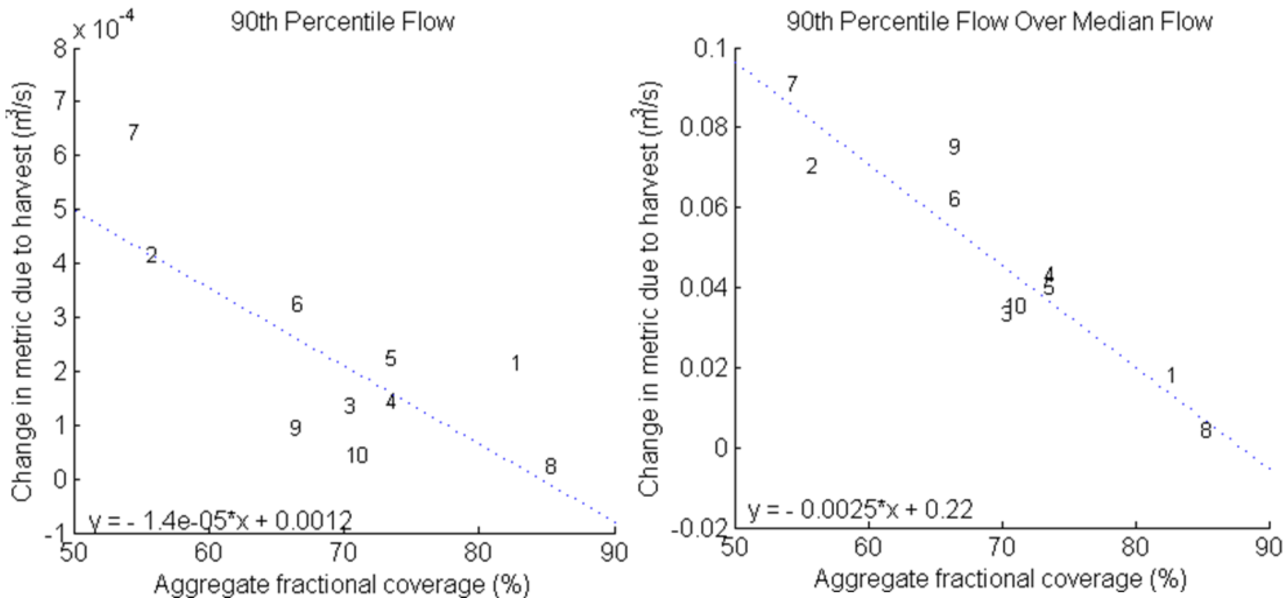


Figure 3.4: Increase in metrics related to low flow after harvest, with respect to aggregate fractional coverage. Left: 90th percentile flow, Right: 90th percentile flow over median

Sub-watersheds were also examined for slope distributions and extent of forest harvest. Watershed 4 has an aggregate fractional coverage of 74.0% and the steepest median slope (8.21%) of the sub-watersheds; however, the increase in the calculated metrics is no higher than for sub-watersheds with similar harvest mixtures and lower slope. Slope could affect the flow distribution by accelerating flow routing downstream where the landscape is particularly steep. The metrics do not indicate that slope has affected the response after harvest. The metrics for sub-watersheds with high median slopes do not increase significantly, and there is no sign of increases in the metrics pertaining to distribution of flow with respect to median slope in the sub-watershed (Figure 3.5).

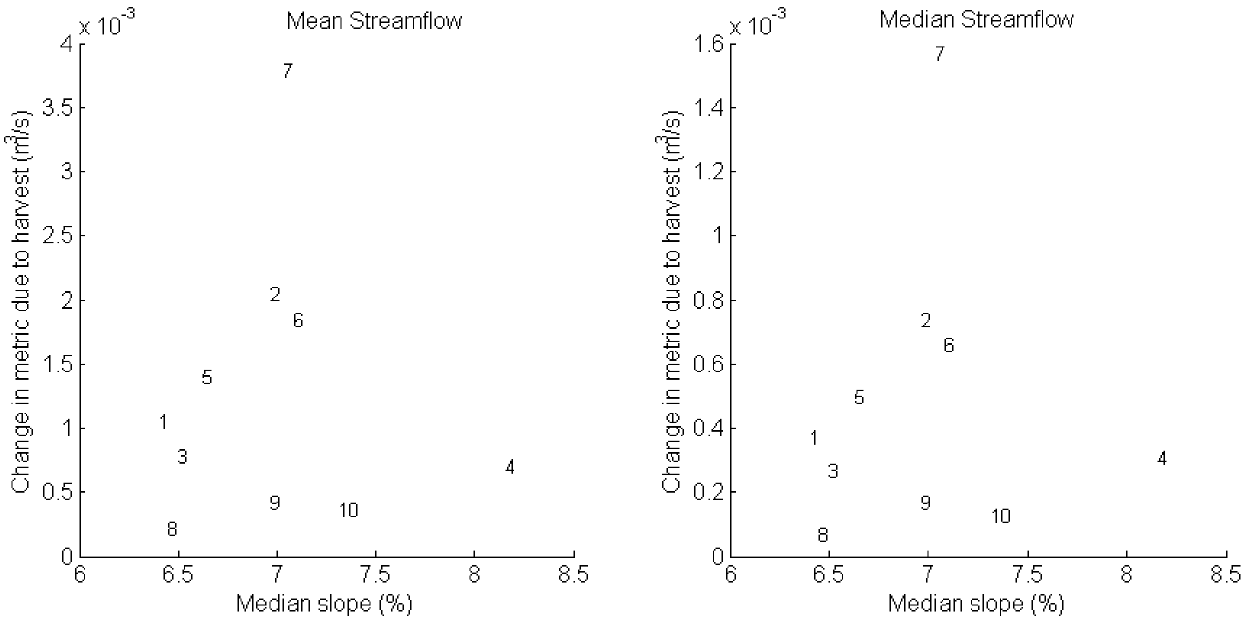


Figure 3.5: Increases in metrics related to flow distribution after harvest, with respect to median slope. Left: Mean streamflow, Right: Median streamflow

Although all sub-watersheds showed significant increases in high flow frequency after harvest, the magnitude of the increases in these metrics were also affected by the aggregate fractional coverage. Watershed 2 has the largest percentage of area that is harvested (aggregate fractional coverage is 56.3%), which resulted in a larger increase in high flow metrics than Watershed 8 (aggregate fractional coverage is 85.8%). The increasing differences in high flow metrics after harvest with respect to aggregate fractional coverage is shown below (Figure 3.6).

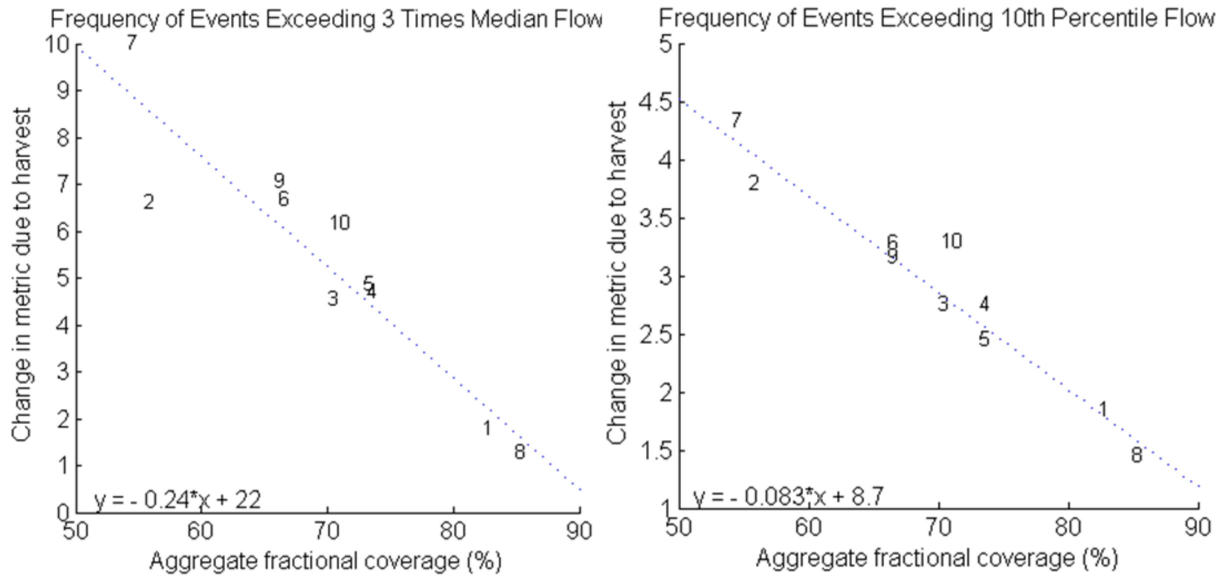


Figure 3.6: Increases in metrics related to high flow after harvest, with respect to aggregate fractional coverage. Left: Frequency of events exceeding 3 times median flow, Right: Frequency of events greater than 10th percentile flow

Streamflow metrics illustrate that low flow magnitude significantly increases if the sub-watershed is harvested to an aggregate fractional coverage of 67.0% or less. No watersheds experienced statistically significant changes in mean or median flow after harvest, but all sub-watersheds had a significant increase in high flow frequency with forest harvest as quantified using the frequency of events greater than 10th percentile flow metric.

Table 3.8: Streamflow metrics for harvested and forested sub-watersheds. Metrics highlighted in red represent a significant increase in the metric from the forested to harvested case

		Sub-watersheds									
		1	2	3	4	5	6	7	8	9	10
Frequency of daily flows exceeding 3xmedian	Harvest	69.12	74.75	74.20	70.98	78.80	80.20	81.22	79.96	85.35	87.63
	Forest	67.57	68.39	69.90	66.53	74.20	73.76	71.45	78.92	78.75	81.71
	Difference	1.55	6.35	4.29	4.45	4.61	6.43	9.76	1.04	6.61	5.92
Frequency of events greater than 10th	Harvest	37.75	40.10	38.80	39.45	39.20	39.94	41.20	37.78	39.35	39.37
	Forest	36.00	36.41	36.16	36.80	36.84	36.76	36.97	36.43	36.29	36.18
	Difference	1.74	3.69	2.65	2.65	2.35	3.18	4.23	1.35	3.06	3.20
Mean streamflow (m^3/s)	Harvest	0.0482	0.0268	0.0166	0.0127	0.0259	0.0244	0.0419	0.0107	0.0056	0.0049
	Forest	0.0472	0.0249	0.0159	0.0121	0.0246	0.0227	0.0383	0.0106	0.0053	0.0046
	Difference	0.0009	0.0019	0.0007	0.0006	0.0013	0.0018	0.0037	0.0001	0.0003	0.0003
Median streamflow (m^3/s)	Harvest	0.0148	0.0084	0.0050	0.0042	0.0073	0.0070	0.0123	0.0026	0.0014	0.0011
	Forest	0.0145	0.0077	0.0047	0.0039	0.0069	0.0064	0.0107	0.0026	0.0012	0.0010
	Difference	0.0003	0.0007	0.0002	0.0003	0.0005	0.0006	0.0016	0.0000	0.0001	0.0001
90th percentile flow(m^3/s)	Harvest	0.0033	0.0019	0.0011	0.0010	0.0015	0.0016	0.0029	0.0005	0.0003	0.0002
	Forest	0.0031	0.0015	0.0010	0.0009	0.0013	0.0013	0.0023	0.0005	0.0003	0.0002
	Difference	0.0002	0.0004	0.0001	0.0001	0.0002	0.0003	0.0006	0.0000	0.0001	0.0000
90th percentile flow/median daily flow	Harvest	0.23	0.27	0.24	0.26	0.24	0.27	0.31	0.21	0.30	0.26
	Forest	0.22	0.20	0.21	0.22	0.20	0.21	0.22	0.21	0.23	0.23
	Difference	0.02	0.07	0.03	0.04	0.04	0.06	0.09	0.00	0.07	0.03

3.4.2 Flood Frequency Results

Flood frequency diagrams were constructed using the annual maximum series for the 51 year simulation period using the harvested and fully forested vegetation scenarios. The sub-watersheds with low aggregate fractional coverage tend to yield larger increases in return period flow than watersheds of smaller harvested area. For example, Watershed 7 (aggregate fractional coverage 55.0%), experiences much larger increases in 1.1 year return period flow than Watershed 8, which has an aggregate fractional coverage of 85.8%. The increases in maximum instantaneous flows are not as dramatic for high return period flows, because the soil is already saturated and vegetation storage may be negligible compared to the high flow volumes. Figure 3.7 illustrates how increases in 1.1 year return period maximum instantaneous flow after harvest tend to be larger as aggregate fractional coverage within the drainage basin is decreased.

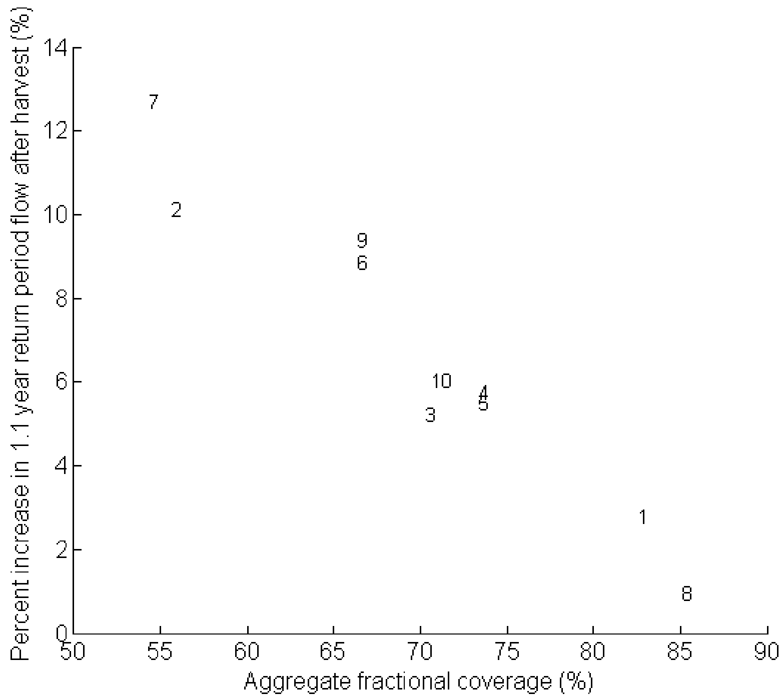


Figure 3.7: Increase in maximum instantaneous flow for a 1.1 year return period event after harvest, with respect to aggregate fractional coverage

Return period flow was also examined to determine if the range of topographic slopes throughout the sub-watershed had any effect. Watershed 4 and Watershed 5 are both 53.3% harvested by regeneration openings; however, the median slope in Watershed 4 is much higher than the slope in Watershed 5. There was an increase in 1.1 year return period flow of 5.5% and 5.2% for Watershed 4 and Watershed 5, respectively. No large impact on increase of return period flow due to topographic slope was found in this analysis.

The annual maxima series for all sub-watersheds from the harvested and fully forested vegetation scenarios are plotted (Figure 3.8), and the maximum instantaneous flood peaks for specific return periods are shown in Table 3.9. The instantaneous flood peaks from the sub-watersheds will be used to examine the effect of current management on streamflow for each of the sub-watersheds.

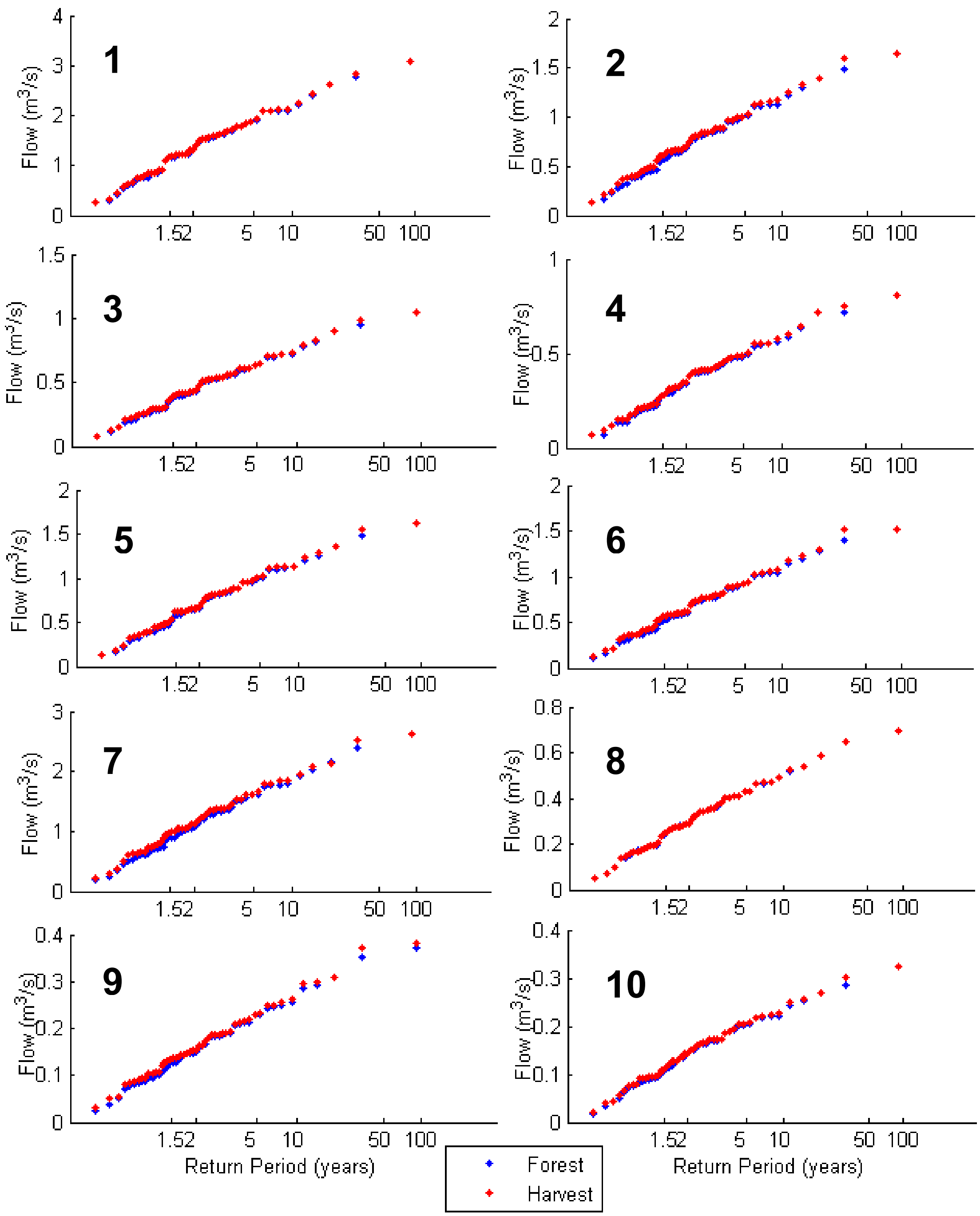


Figure 3.8: Ranked annual maxima series for all sub-watersheds in the fully forested and harvested case. Number of the respective sub-watershed is in top-left corner of each plot

Table 3.9: Maximum instantaneous return flows for the sub-watersheds for the harvested and forested cases

		Return period flow (m^3/s) 1.1 Year Flood	5 Year Flood	10 Year Flood	50 Year Flood
Watershed 1	Harvest	0.699	1.871	2.241	3.057
	Forest	0.682	1.858	2.229	3.047
	Difference	0.017	0.014	0.012	0.010
	% Increase	2.5%	0.8%	0.5%	0.3%
Watershed 2	Harvest	0.380	1.010	1.209	1.647
	Forest	0.346	0.983	1.185	1.628
	Difference	0.034	0.026	0.024	0.019
	% Increase	9.8%	2.6%	2.0%	1.2%
Watershed 3	Harvest	0.235	0.636	0.762	1.041
	Forest	0.224	0.628	0.755	1.035
	Difference	0.011	0.008	0.007	0.005
	% Increase	4.9%	1.3%	0.9%	0.5%
Watershed 4	Harvest	0.174	0.492	0.593	0.814
	Forest	0.165	0.484	0.585	0.807
	Difference	0.009	0.008	0.007	0.006
	% Increase	5.5%	1.7%	1.2%	0.7%
Watershed 5	Harvest	0.363	0.990	1.188	1.624
	Forest	0.345	0.974	1.172	1.609
	Difference	0.018	0.016	0.016	0.015
	% Increase	5.2%	1.6%	1.4%	0.9%
Watershed 6	Harvest	0.343	0.929	1.115	1.522
	Forest	0.316	0.904	1.090	1.499
	Difference	0.027	0.025	0.024	0.023
	% Increase	8.5%	2.8%	2.2%	1.5%
Watershed 7	Harvest	0.607	1.603	1.918	2.610
	Forest	0.541	1.557	1.878	2.585
	Difference	0.067	0.046	0.039	0.025
	% Increase	12.4%	3.0%	2.1%	1.0%
Watershed 8	Harvest	0.153	0.420	0.504	0.690
	Forest	0.152	0.419	0.503	0.689
	Difference	0.001	0.001	0.001	0.001
	% Increase	0.7%	0.2%	0.2%	0.1%

Table 3.9: Continued

Watershed 9	Harvest	0.083	0.227	0.272	0.372
	Forest	0.077	0.221	0.267	0.367
	Difference	0.007	0.006	0.006	0.005
	% Increase	9.1%	2.7%	2.2%	1.4%
Watershed 10	Harvest	0.074	0.198	0.238	0.325
	Forest	0.070	0.195	0.235	0.322
	Difference	0.004	0.003	0.003	0.003
	% Increase	5.7%	1.5%	1.3%	0.9%

3.5 Conclusions

Streamflow magnitudes are found to increase in Yellowwood Lake watershed as a result of forest harvest. Although impacts were limited at the scale of the whole watershed, analysis of sub-watersheds yielded interesting results.

Low flow magnitudes were seen to increase significantly if the aggregate fractional coverage within the drainage area after harvest was less than 67.0%, which corresponds to a stem density of 60% or less. The clear-cut harvest prescription results in significant increases in high flow frequency and low flow magnitude when compared to a watershed with similar cumulative harvest extent. The return period for high magnitude flows also shows a sharper increase due to the amount of harvested area within the watershed and severity of the harvest prescription. The slope gradient over the landscape was not found to have a quantifiable effect on flow variability or return period. Additionally, return period flow magnitudes increased for sub-watersheds as the aggregate fractional coverage within the sub-watersheds decreased and as harvest severity increased.

Results from this study are in agreement with many previous studies on the effect of deforestation on streamflow. Paired watershed studies have shown significant increase in peak flow magnitudes as a result of forest harvest (Harr, 1981, 1986; Jones and Grant, 1996). Additionally, Kurás et al. (2012) found significant changes in simulated streamflow magnitudes and peak flow frequency for various forest harvest scenarios using DHSVM.

The Yellowwood Lake watershed management group was concerned about increased flows entering into Yellowwood Lake which stir up sediment in the lake, and that have also been assumed to be the cause of severe channel erosion throughout the watershed. The outlets of Watershed 1 and Watershed 2 were identified by the management group as critical areas in terms of channel erosion. The results from this study found a significant increase in high flow frequency due to forest harvest in both watersheds, which could increase the rates of channel erosion at those locations, although this is true for sub-watersheds that were not found to have channel erosion. Increased frequency of high flow events can also result in increased turbidity and sediment detachment, so all sub-watersheds may be at risk for increased channel erosion.

Sub-watersheds with clear-cut prescriptions and sub-watersheds with a stem density of 60% or less after harvest were found to result in significant increases to streamflow. It is recommended to not prescribe a clear-cut harvest, and avoid harvesting to a stem density of 60% or less within the drainage area in order to avoid significant impacts to the streamflow regime.

CHAPTER 4. SEDIMENT RESULTS

4.1 Introduction

Forest harvest reduces canopy interception of raindrops and root cohesion, which leaves the soil at increased risk for detachment. Scenarios representing no-harvest and existing harvest conditions in the Yellowwood Lake watershed are input to DHSVM, and simulations are run using the erosion and sediment transport algorithms to model the changes in sediment loss due to land cover management for water years 1962 to 2013. Current harvest patterns resulted in significant increases of streamflow metrics when compared to the fully forested case (Chapter 3), and are therefore expected to result in increased erosion rates as well. The erosion rates are examined according to slope and harvest prescription at the watershed and sub-watershed scale in order to get more insight into the effect of vegetation loss and examine which areas are particularly vulnerable to sediment detachment.

4.2 Watershed Scale Erosion Results

The forested and current harvest vegetation scenarios were applied to the Yellowwood Lake watershed using DHSVM to analyze the effects of vegetation loss on soil detachment across the watershed. Soil that is transported by the stream network is deposited into Yellowwood Lake, which has resulted in a loss of depth in the lake since the early 20th Century (Yellowwood Lake Watershed Management Plan, 2006). The sediment load entering into Yellowwood Lake was calculated from all streamflow entering the lake for the entire simulation period.

Annual sediment loads into Yellowwood Lake were calculated for each year of the analysis period and tested for significant differences in mean using a t-test and variance using an f-test at a 90% significance level. Annual sediment loads increased from the non-harvested to the current harvest case (Figure 4.1), indicating that forest harvest has an effect on sedimentation into Yellowwood Lake, and soil loss throughout the watershed. The mean annual sediment load did not increase significantly, but variability in annual sediment load significantly increased (Table 4.1).

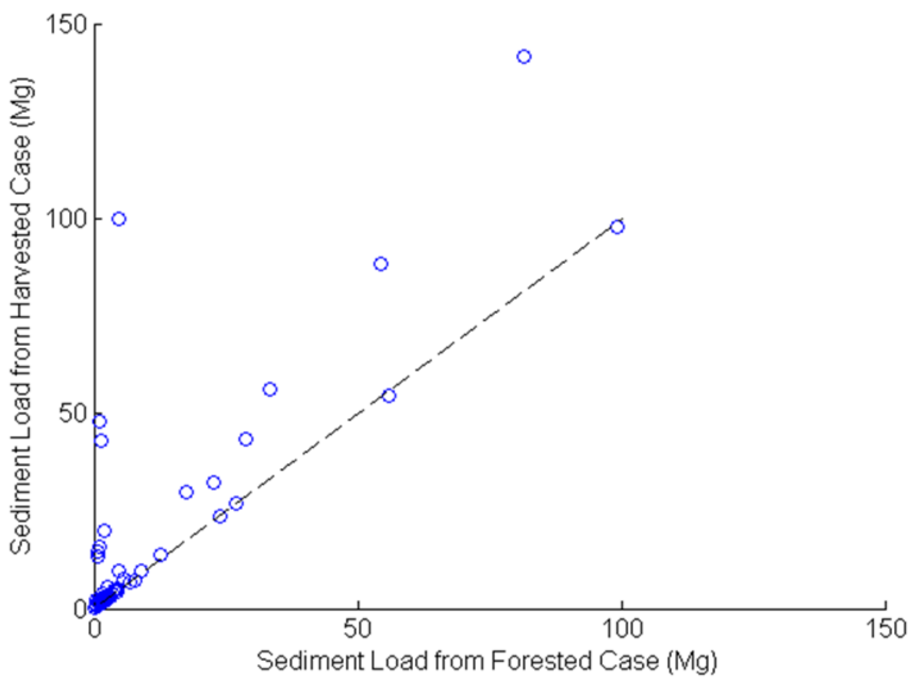


Figure 4.1: Annual sediment load for the forested and harvested cases. The dashed line is the 1:1 line

Table 4.1: Results from statistical tests of maximum annual sediment load into Yellowwood Lake for the harvested case compared to the forested case

Test	Test Statistic	Significance
F-test	2.17	Significant Increase
t-test	1.59	No Significant Increase

4.2.1 Erosion Related to Slope

In order to get a better picture of the erosion processes that are occurring, spatial output of erosion throughout the watershed was analyzed after a substantial rain event during the simulation period (Table 4.2). The cumulative change in sediment depth is provided for each pixel in the watershed, so specific areas can be identified as being prone to sediment detachment or deposition.

Table 4.2: Storm date, duration and total depth of rainfall of the storm event selected for spatial analysis.

Date	Storm Duration (hours)	Total Depth of rainfall (mm)
July 13, 1979	20	139

Erosion resulting from the storm on July 13, 1979 was analyzed to determine the distribution of pixels losing sediment according to slope. This event was selected because it is the largest rain event during the 51 year simulation period (139 mm), and provides close to 10% of the annual average precipitation in this region, so it is expected to result in substantial sediment detachment across the watershed. The slopes were divided into twelve ranges, and the results were normalized according to the area within each slope category. Figure 4.2 shows how deposition (positive) and erosion (negative) vary spatially between the harvested and non-harvested scenarios by slope range.

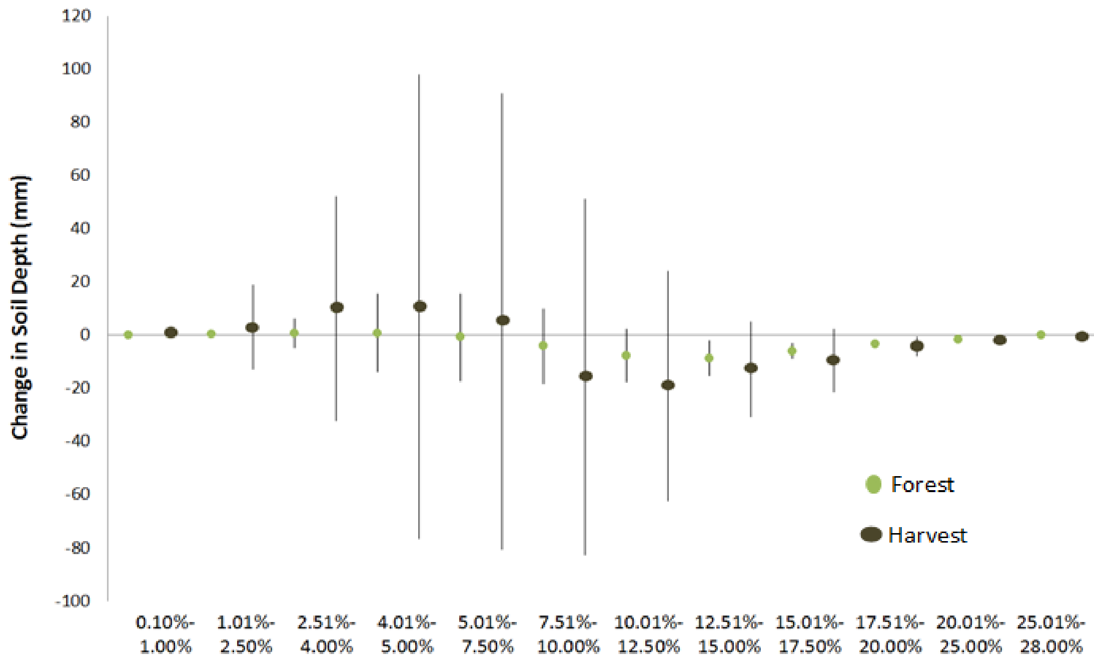


Figure 4.2: Average (green dot) and standard deviation (line) of the changes in sediment depth from the forested scenario, and average (brown dot) and standard deviation (line) of the changes in sediment depth from the harvested scenario during storm event on July 13, 1979, with respect to slope. A negative value represents a loss of soil, while a positive value indicates sediment accumulation

The results show that slopes between 7.5% and 17.5% result in the largest average loss in soil depth for both the harvest and forested case during this rain event, and the harvested case has more dramatic losses of soil compared to the forested case. Deposition also tends to be higher in the harvested case than the forested case, which may be a result of increased sediment available for deposition once harvest is applied. Areas with very small slopes (0.1-5.0%) are typically accumulating sediment, while areas with slopes steeper than 7.5% are generally losing sediment. Areas with slopes between 2.5%-12.5% have large standard deviations when compared to other slopes, implying that these areas have many pixels in which both sediment detachment and deposition is occurring, particularly once harvest is applied.

A spatial plot of the sediment loss during this substantial storm also shows that the steep slopes are the major contributor to sediment loss. Figure 4.3 shows the cumulative change in soil depth during the storm event, as well as a plot of the differences in deposition and erosion between the forested and harvested cases. A negative value represents soil erosion, while a positive value indicates sediment deposition. Many of the areas with steep slopes experience loss in soil depth (blue), indicating that these areas are very sensitive to soil detachment. The map of differences in deposition was created by calculating the difference in all pixels that are exhibiting deposition for the forested and harvested cases, and illustrates that the amount of deposition increased for most pixels after harvest was applied. Additionally, the figure of the differences in erosion shows was created by calculating the difference in all pixels that are exhibiting erosion for the forested and harvested cases, and shows that grid cells in the harvested case lost more sediment than pixels in the forested case. The spatial plots reinforce the results from Figure 4.2 which shows that erosion and deposition both increase in magnitude after forest harvest is applied.

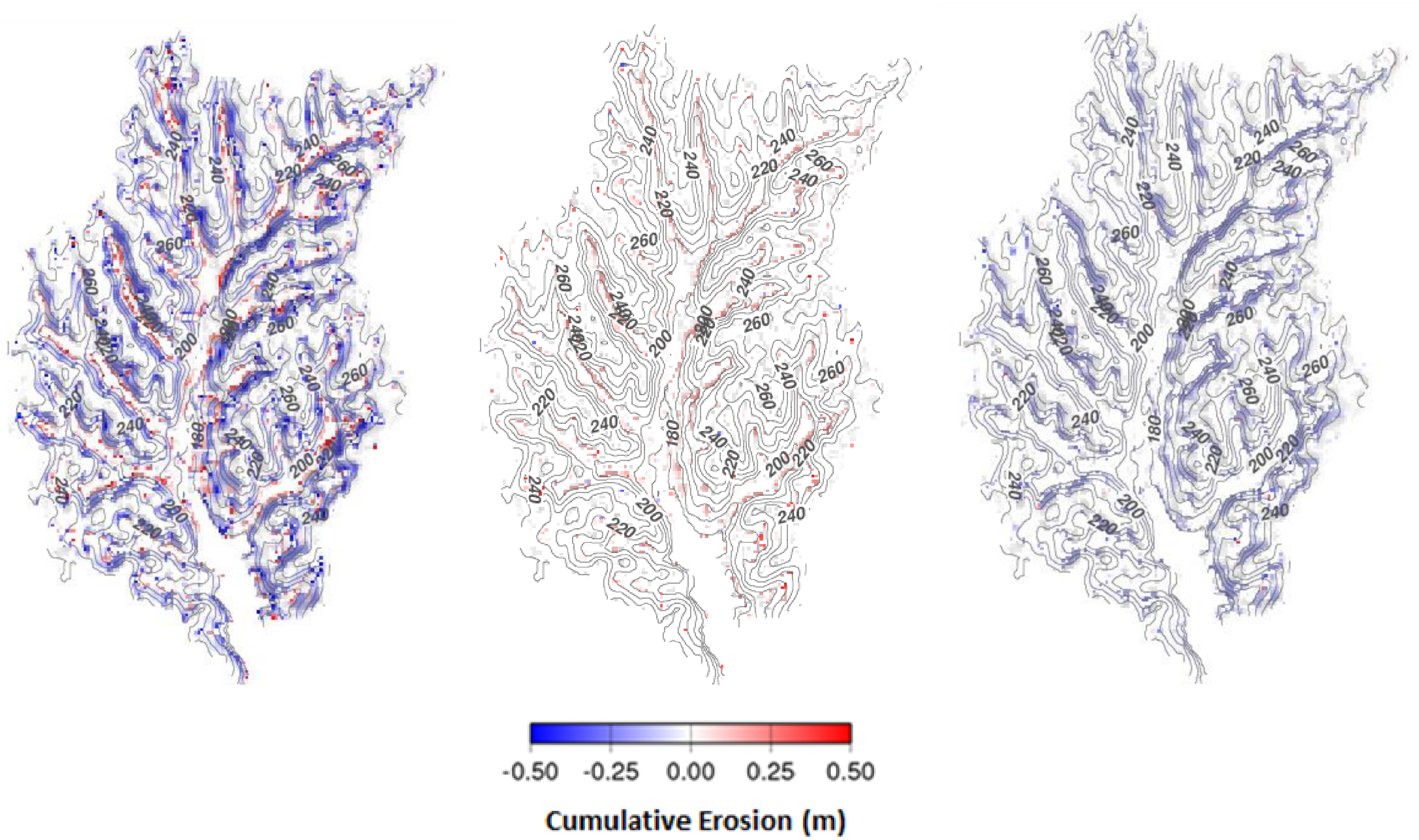


Figure 4.3: The figure on the left is the cumulative change in soil depth in the harvested case during the storm event. The figure in the middle shows the change in deposition between the harvested and forested cases. The figure on the right shows the change in erosion between the harvested and forested cases. Positive values represent deposition and negative values represent erosion

4.2.2 Erosion Related to Harvest Prescription

Canopy density also plays a large role in the erosion process, so harvest prescriptions were examined for erosion rates throughout the watershed. Approximately 57% of the watershed area is harvested, of which 75% has a harvest prescription for regeneration openings. Erosion rates for the storm on July 13, 1979 are categorized by harvest prescription in Figure 4.4. This figure shows the difference in spatial mean and standard deviation of erosion for the pixels affected by each harvest prescription after harvest is applied. There is no difference in soil loss for the pixels that were managed by single tree selection harvest, which thins the forest to a fractional coverage of 80%. Pixels which experienced regeneration openings harvest and intermediate harvest lost more soil in the harvested case, but have a large standard deviation, which suggests many of these pixels are accumulating sediment as well. The most noticeable difference in soil loss after harvest is the erosion occurring in the pixels with a clear-cut harvest. These pixels are subject to the most severe harvest prescription, and lose on average an additional 25.3 mm of soil after harvest.

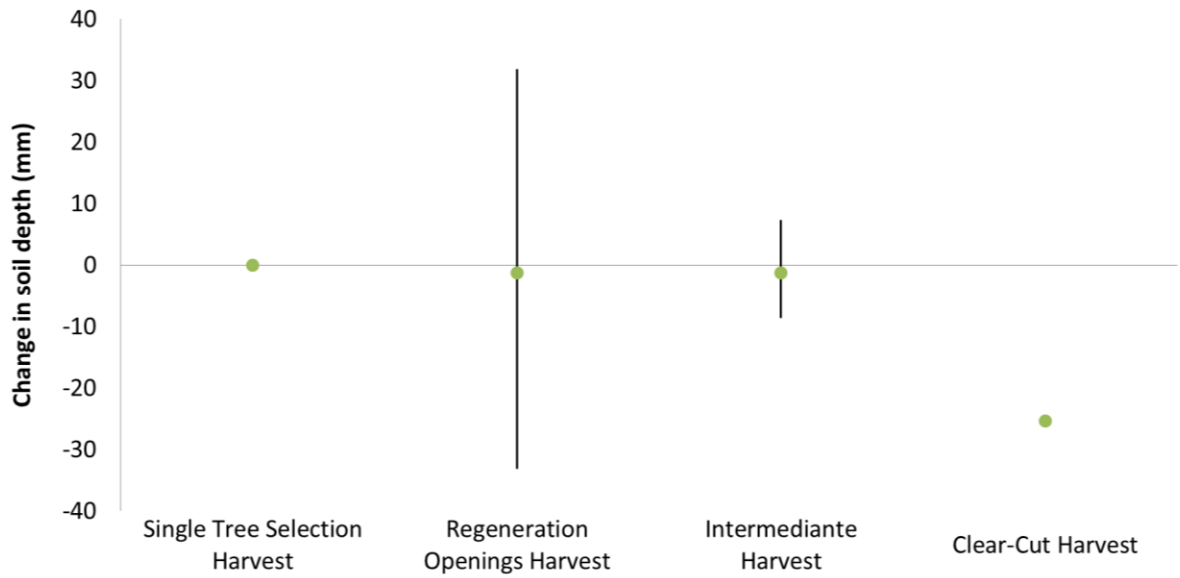


Figure 4.4: Difference in mean and standard deviation of change in soil depth of harvested and forested vegetation scenarios according to harvest prescription

4.3 Sub-Watershed Analysis

The sub-watersheds (Figure 3.3) within the Yellowwood Lake watershed were examined to look more closely into the effect of harvest prescription on sediment loss. The sub-watersheds vary in terms of area and extent of harvest, which will help identify controls on erosion losses between them. The cumulative sediment load exiting each sub-watershed, as well as the load normalized by the drainage area are listed in Table 4.3. A t-test was performed to test for significant changes in mean annual sediment load between the fully forested case and the harvested case for each sub-watershed, but none of the sub-watersheds exhibited a significant increase in sediment load after harvest was applied.

Table 4.3: Cumulative sediment loads for 51 year study period of the forested and harvested vegetation scenarios

Sub-Watershed	Aggregate Fractional Coverage after Harvest	Scenario	Cumulative Sediment Load (Mg)	Cumulative Sediment Load per Unit Area (Mg/ha)
Watershed 1	83.2%	Harvest	69.3	2170.5
		Forest	69.3	2170.5
		Difference	0.0	0.0
Watershed 2	56.3%	Harvest	123.6	7047.7
		Forest	83.4	4755.3
		Difference	40.2	2292.4
Watershed 3	70.9%	Harvest	77.3	7630.6
		Forest	62.5	6173.8
		Difference	14.8	1456.8
Watershed 4	74.0%	Harvest	61.0	7368.4
		Forest	127.1	15351.4
		Difference	-66.1	-7983.1
Watershed 5	74.0%	Harvest	120.1	7016.0
		Forest	109.7	6408.5
		Difference	10.4	607.5
Watershed 6	67.0%	Harvest	111.0	7081.3
		Forest	88.3	5630.8
		Difference	22.7	1450.4
Watershed 7	55.0%	Harvest	187.1	6732.5
		Forest	40.1	1443.9
		Difference	147.0	5288.6
Watershed 8	85.8%	Harvest	49.1	6647.7
		Forest	30.6	4142.6
		Difference	18.5	2505.1
Watershed 9	67.0%	Harvest	24.5	6746.4
		Forest	4.1	1124.9
		Difference	20.4	5621.6
Watershed 10	71.9%	Harvest	20.3	6763.4
		Forest	5.5	1835.2
		Difference	14.8	4928.3

Although there was no significant increase in sediment loads for the sub-watersheds, the changes in cumulative sediment load according to aggregate fraction coverage does indicate that sub-watersheds with a higher extent of harvest (low aggregate fractional coverage) tend to yield higher sediment loads (Figure 4.5). Watersheds 2 and 7 have the largest increases in cumulative sediment loads throughout the simulation period and a low aggregate fractional coverage, while Watershed 1 and 8, which have the highest aggregate fractional coverage, increase very little after harvest. The sediment load from Watershed 4 decreases after harvest is applied, which was not expected. This decrease in sediment load could be attributed to an increase in deposition in the low slopes of the watershed, and eroded sediment is not being routed out of the sub-watershed.

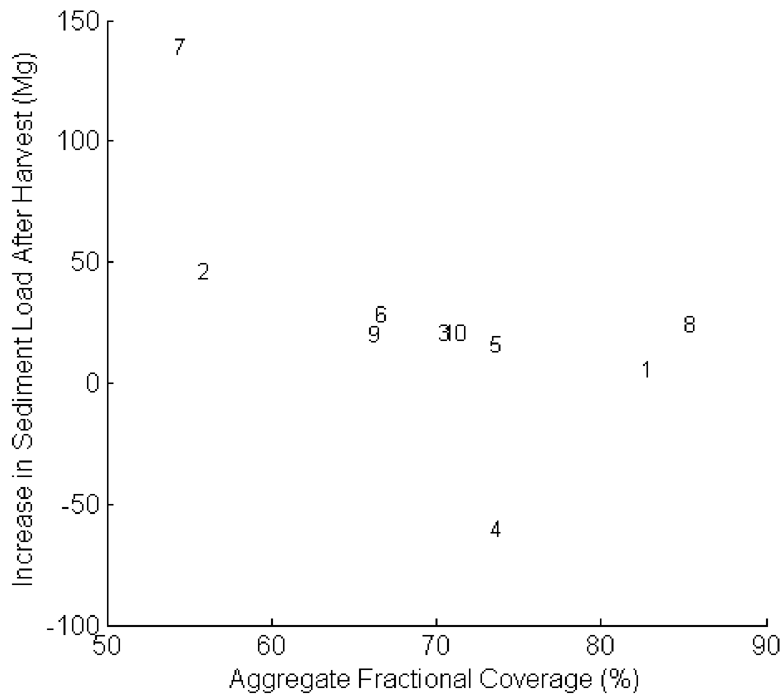


Figure 4.5: Increase in sediment load for each sub-watershed after harvest, with respect to aggregate fractional coverage

In addition to the sediment load, the amount of sediment stored in the channel after forest harvest was also analyzed. Figure 4.6 shows the linear relationship between the percent increase in sediment accumulation and aggregate fractional coverage. The results from the accumulated sediment show that lessening the aggregate fractional coverage increases the amount of detached sediment. This is not evident in the sediment load results because the transport capacity of the streamflow does not increase as available sediment increases, thus, a considerable amount of eroded sediment is stored in the stream channels until there is enough streamflow to carry it downstream.

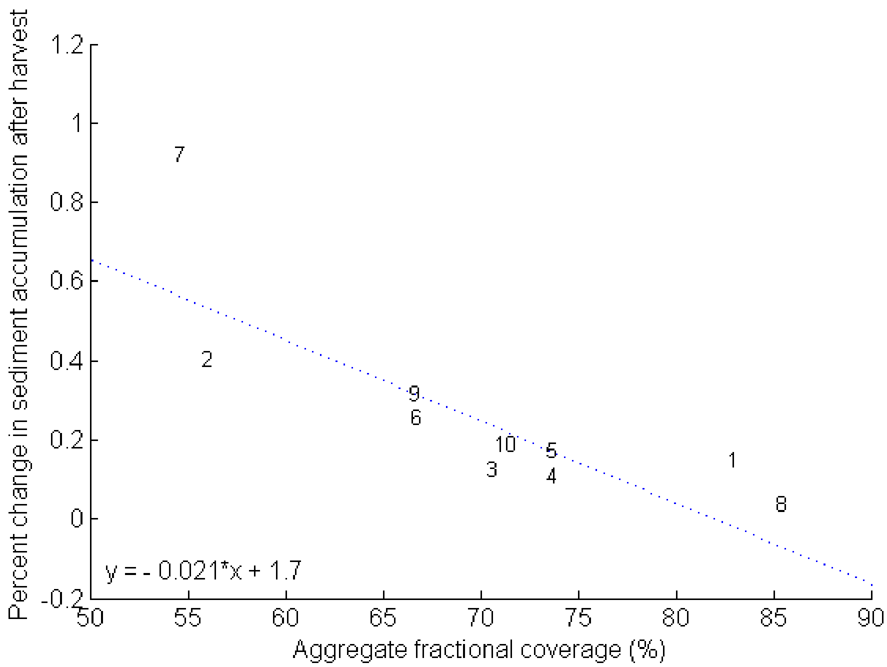


Figure 4.6: Percent increase in sediment accumulation at each sub-watershed outlet after harvest, with respect to aggregate fractional coverage

The sub-watersheds were examined for effects from slope on the sediment load from the drainage area. Watershed 4 has the steepest median slope and contributes the largest sediment load per unit area, although the aggregate fractional coverage (74.0%) is higher than other sub-watersheds. Figure 4.7 shows the cumulative sediment load from each sub-watershed with respect to median slope, but shows that steep slopes do not cause increases in sediment load after harvest is applied.

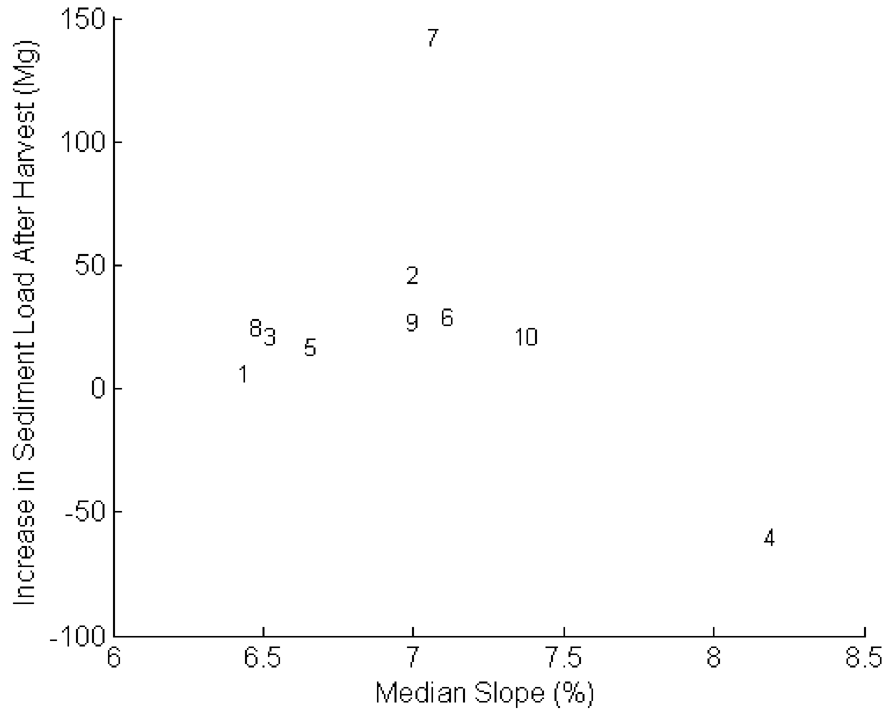


Figure 4.7: Increase in sediment load for each sub-watershed after harvest, with respect to median slope

The sub-watersheds were also analyzed for soil loss during the largest rain event during the 51 year simulation period on July 13, 1979. The mean loss in soil depth for each harvest prescription, as well as mean loss of depth of the entire drainage area are listed for each sub-watershed using the harvested and forested vegetation scenarios (Table 4.4). Each sub-watershed experiences a larger mean loss of soil in the harvested case than in the forested case. Additionally, many of the areas that were not prescribed any type of harvest lost additional soil once the harvest scenario was applied. These areas were not expected to have dramatic changes in soil loss, but increased runoff due to vegetation change higher on the slope could be the cause of extra sediment detachment in fully forested areas.

Some areas which were prescribed regeneration openings harvest resulted in less sediment loss after harvest than when the sub-watershed was fully forested during this substantial storm. Figure 4.8 shows that these areas had a very low median slope; areas which were shown to accumulate more sediment after the harvest was applied (Figure 4.3). Sediment loss after harvest seems to become more exaggerated as the slopes in the harvested areas get steeper.

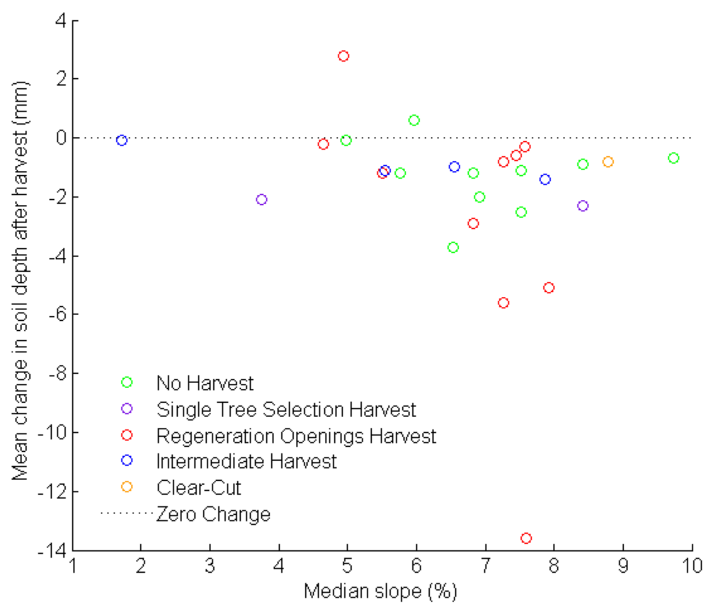


Figure 4.8: Mean change in soil depth for areas prescribed a regenerations opening harvest, with respect to slope

Table 4.4: Loss in soil according to harvest prescription due to the storm event on July 13, 1979.

Drainage Area	Harvest Prescription	Median Slope	Mean change in soil depth with harvest (mm)	Mean change in soil depth with no harvest (mm)	Mean change in depth of entire drainage area (mm)	
					Harvest	Forest
Watershed 1	No Harvest	6.83%	-65.7	-63.3	-56.7	-52.8
	Regeneration Openings Harvest	7.92%	-24.9	-14.7		
	Intermediate Harvest	1.73%	-50.4	-24.5		
Watershed 2	No Harvest	4.97%	-10.5	-10.3	-30.4	-29.2
	Regeneration Openings Harvest	7.57%	-35.2	-34.6		
	Intermediate Harvest	6.55%	-24.9	-22.9		
Watershed 3	No Harvest	7.53%	-63.52	-61.3	-81.8	-80.4
	Single Tree Selection Harvest	8.42%	-153.0	-148.4		
	Regeneration Openings Harvest	4.94%	-68.9	-74.5		
	Intermediate Harvest	5.54%	-69.1	-66.9		
Watershed 4	No Harvest	9.73%	-18.7	-17.3	-34.0	-32.4
	Regeneration Openings Harvest	7.26%	-47.62	-46.02		
Watershed 5	No Harvest	8.42%	-24.1	-22.3	-65.9	-63.7
	Regeneration Openings Harvest	5.50%	-102.6	-100.2		
Watershed 6	No Harvest	6.53%	-80.0	-72.7	-61.1	-58.5
	Regeneration Openings Harvest	7.44%	-55.5	-54.3		

Table 4.4: Continued

Watershed 7	No Harvest	5.97%	-68.5	-69.7	-69.1	-66.3
	Single Tree Selection Harvest	3.76%	-130.5	-126.3		
	Regeneration Openings Harvest	6.83%	-85.0	-79.3		
	Intermediate Harvest	7.86%	-55.9	-53.1		
	Clear-Cut Harvest	8.79%	-31.2	-29.6		
Watershed 8	No Harvest	6.92%	-26.5	-22.5	-23.3	-19.9
	Regeneration Openings Harvest	4.65%	-4.7	-4.3		
Watershed 9	No Harvest	5.76%	-50.2	-47.8	-35.0	-25.9
	Regeneration Openings Harvest	7.27%	-30.4	-19.3		
Watershed 10	No Harvest	7.52%	-58.7	-53.7	-73.5	-55.3
	Regeneration Openings Harvest	7.60%	-83.4	-56.3		

Sub-watershed 4 was chosen to examine the effect of slope on the soil loss of the individual pixels during the storm event. This watershed was chosen because the slopes range between 0.01%-22.06% inside the drainage area and it has the steepest median slope of all the watersheds. This sub-watershed is 53% harvested with a regeneration openings harvest, and has an aggregate fractional coverage of 74.0%. The pixels with regeneration openings harvest lose more soil depth than the forested pixels even though the pixels with no prescribed harvest have a steeper median slope.

The relationship between slope and elevation for the non-harvested and regeneration openings harvested areas in Watershed 4 are shown in Figure 4.9, which shows more soil loss on steeper slopes. For both management types, pixels at steep slopes are more likely to lose soil; however, there is both soil detachment and accumulation at smaller slopes. The harvested pixels show soil loss occurring at smaller slopes than in the forested pixels, which suggests vegetation loss makes slopes more vulnerable to sediment detachment. There is also higher accumulation of soil in the forested pixels. A t-test was applied to the slopes of each management type, which found the slopes exhibiting erosion to be significantly higher than slopes accumulating sediment for both management strategies (Table 4.5). This implies that steep slopes are at high risk of soil detachment when the area is forested, and loss in forest canopy appears to make slopes even more sensitive to soil loss.

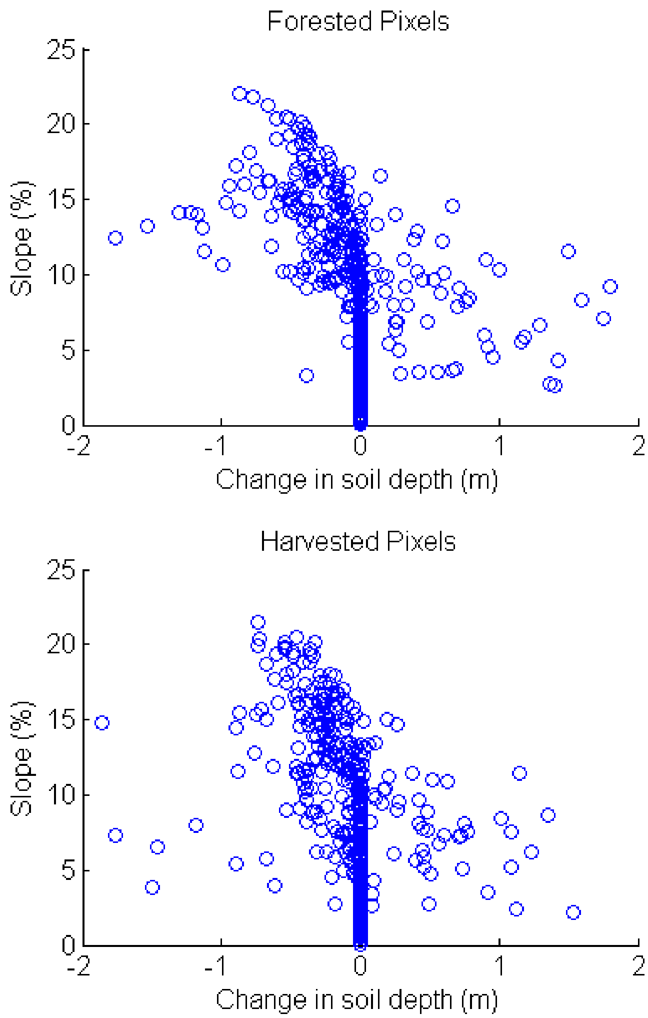


Figure 4.9: Change in soil depth with respect to slope for sub-watershed 4

Table 4.5: Results from statistical tests to find significant difference between slopes that are losing soil and slopes accumulating soil

	Forested Pixels	Regeneration Openings Harvest Pixels
t-test statistic	12.82	7.52
Decision	Significant	Significant

4.4 Conclusions

Erosion rates at the grid cell level indicate that forest management and slope increase soil detachment in the Yellowwood Lake watershed. Running the DHSVM sediment model using the fully forested and harvested vegetation scenarios demonstrated that vegetation loss resulted in a greater sediment load into Yellowwood Lake and greater loss in soil depth during the simulation period. Canopy loss also caused soil loss on sloped areas to be more exaggerated, which was evident at the watershed scale for the substantial storm event on July 13, 1979.

Analysis at the sub-watershed scale illustrated that harvested areas with steep slope are most sensitive to soil loss. Plots showing the change in soil depth with respect to slope illustrate that steep slopes are more likely to lose soil. Additionally, the sediment load exiting each sub-watershed demonstrated that forest harvest greatly increased the amount of sediment exiting most drainage areas, which is in agreement with studies by the United States Environmental Protection Agency (USEPA, 2005) who observed that the sediment load in the streams is proportional to the amount of logging that takes place over the drainage area for watersheds in New Jersey.

The Yellowwood Lake Watershed Management Group identified sediment loss due to forest management as a main concern in the watershed. The outlet of sub-watershed 2 was identified by the group as a critical area in terms of sediment concentration and channel erosion. Although DHSVM is not able to simulate channel erosion, this sub-watershed did show an increase in sediment load and mean loss of soil depth when compared to a sub-watershed with a smaller percentage of forest harvest. Despite many sub-watersheds having a harvest prescription applied over 50% of their drainage areas, no significant increases in sediment load were found in these drainage areas.

However, the sediment load from sub-watershed 7 increased more than the other sub-watersheds, which suggests that a clear-cut prescription should be avoided in order to reduce soil loss. Land managers should avoid harvesting on areas with a slope greater than 7.5%, as well as clear-cut management prescriptions, in an effort to mitigate the effect of forest harvest on the watershed.

The sediment load exiting the Yellowwood Lake watershed was expected to increase once harvest was applied, and was compared to other studies of sediment load after forest harvest. The average annual sediment load from the Yellowwood Lake watershed was 2,700 Mg/ha, which falls within the acceptable range of annual sediment load from disturbed forests as calculated by Istanbulluoglu et al. (2003). They found disturbed forests to contribute an annual sediment load between 2,600 Mg/ha to 23,500 Mg/ha, which includes the simulated annual sediment load into Yellowwood Lake calculated in this study.

Some pixels surrounding Yellowwood Lake were excluded from the sediment analysis because they had very large accumulations of soil since DHSVM does not have the capability to model flow into a lake via the shoreline. Pixels surrounding the lake were sloped toward the stream outlet into the lake; however, the sediment concentration exceeded the transport capacity of the overland flow, which resulted in the large depositions of sediment. This issue could be fixed by adding a small stream at each pixel surrounding the lake, allowing them to drain directly into the lake.

CHAPTER 5. CONCLUSIONS

5.1 Summary of Overall Conclusions

This project addressed the changes in streamflow and erosion due to forest harvest in the Yellowwood Lake watershed. The DHSVM was used for this analysis; it was calibrated and adjusted in Chapter 2 to realistically simulate the water and soil balance in the watershed. Simulated streamflow was calibrated using observed streamflow and meteorological data from a small watershed in Indiana, and simulated erosion was calibrated using output from the WEPP model for similar hillslopes. A sensitivity study was conducted on the model to better understand the effect of forest thinning on the hydrology of the watershed, which was simulated by adjusting the user input fractional coverage parameter of the forest vegetation.

In Chapter 3, it was hypothesized that forest harvest would cause increased high flow events. Streamflow metrics from the fully forested vegetation scenario were compared to metrics using harvested and clear-cut vegetation scenarios. The harvested areas were based off of previously harvested tracts within the watershed, and were represented by altering the fractional coverage of the overstory canopy according to harvest prescriptions from the Indiana Department of Natural Resources (IDNR). The forest management styles prescribed in this watershed include: no harvest, single tree selection harvest, regeneration openings harvest, intermediate harvest, and clear-cut harvest. One mixture of fractional coverage values was chosen to represent the current harvest in the watershed, which resulted in increased high flow frequency of streamflow entering into Yellowwood Lake. Streamflow from ten sub-watersheds within the Yellowwood Lake watershed were analyzed for effect of forest harvest as well, which showed more dramatic results than the watershed-scale analysis. Streamflow metrics related to high flow frequency increased significantly for all sub-watersheds, and metrics related to low flow magnitude increased significantly for all sub-watersheds that were harvested to a stem density of 60% or less. The return period flows from the sub-watersheds increased proportionally to the decrease of aggregate fractional coverage in the sub-watershed after harvest, with 1.1 year return period flows increasing by as much as 12%.

In Chapter 4, changes in land cover were also shown to exhibit a large effect on sediment loss in the watershed. The hillslope erosion component of the DHSVM sediment model captured sediment detachment from overland flow and raindrops throughout the simulation period. It was hypothesized that sediment loss would increase after forest harvest due to more overland flow and soil vulnerability to raindrops due to decreased canopy cover. The sediment load into the lake greatly increased once harvest was applied. Erosion output from a substantial storm event showed that on average, areas with prescribed harvest lost more soil once harvest was applied, with clear-cut areas experiencing the most soil loss. The watershed experienced greater loss of soil in areas of steep slope (7.5% and 17.5%) and more accumulation in low slopes (0.1-5.0%) after forest harvest. Sediment load exiting the drainage area increases as aggregate fractional coverage within the watershed decreases, so more severe harvest results in increased sediment loading. The sub-watersheds experienced an increase in average depth of soil lost during a substantial storm event, compared to soil lost in the fully forested case. Additionally, harvested areas within the sub-watersheds lost more soil during this storm event as the median slope of the respective harvested area increased. A sub-watershed was also analyzed for erosion according to slope, and it was found that the pixels that were losing soil depth had a significantly higher slope than pixels that were accumulating soil, and soil loss was occurring at lower slopes for the harvested areas than non-harvested. These results suggest that steep slopes lose more soil, and forest harvest also makes slopes more vulnerable to soil loss.

In order to lessen the effects of forest harvest in the Yellowwood Lake watershed, it is recommended that forest harvest does not occur on slopes steeper than 7.5%, and that sub-watersheds are not harvested beyond a stem density of 60% or less. Slopes steeper than 7.5% were the main contributors of soil loss during a substantial storm event, and metrics related to low flows increased significantly in sub-watersheds which were harvested to a stem density of 60% or less. The watershed that experienced significant clear-cut harvest experienced larger increases in high flow magnitudes as well as significantly increased sediment loads after harvest, so it is also recommended that clear-cut harvest is avoided in the watershed.

5.2 Recommendations for Project Improvements

Some pixels surrounding the lake had to be excluded from the erosion analysis at the grid cell level due to unrealistic simulation of sediment accumulation. DHSVM does not have the capability to model flow into a lake via the shoreline, which resulted in abnormally large accumulations of sediment along the lake shore. Pixels surrounding the lake were sloped toward the stream outlet into the lake; however, the sediment concentration exceeded the transport capacity of the overland flow, which resulted in the large depositions of sediment. Although these accumulations of sediment could be considered sedimentation into the lake, it is not appropriate to include them in the analysis of hillslope erosion. This issue could be remediated by placing a small stream in each pixel surrounding the lake to simulate more realistic flow from the watershed shoreline into Yellowwood Lake.

The discussion on the effects of sediment loss due to forest management could have been improved by including logging roads and log landings, which are present during most harvest activities. Both of these practices remove additional vegetation, and experience a lot of activity, particularly from large trucks and logging machinery. A study by Motha et al. (2003) found that logging roads contribute the majority of the sediment which results from forest harvest, which implies that there is a lot of sediment loss due to forest harvest in Yellowwood Lake watershed that was not captured by the DHSVM simulations.

The Yellowwood Lake watershed management group is also concerned about additional hillslope erosion from the construction of private properties along the northern ridge of the watershed. Many of these private land owners have cleared the forest cover in their property, which may contribute to additional sediment load and increased streamflow in addition to the effects from forest harvesting on public lands. The group is also concerned about channel erosion and channel stability along the main stream reaches in the watershed. DHSVM does not have the capability to simulate channel erosion, but did find increased high flows after harvest in the reaches that are considered at risk for channel erosion.

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