Application and Evaluation of WEPP in a Forested Watershed with Perennial Streams

by

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Abstract

Forests generally have low erosion rates unless they are disturbed by harvesting operations or road construction. These common disturbances typically cause increase in the sediment yield which is reduced after vegetation and plant litter covers the surface. To better quantify and predict sediment loads adequate watershed scale erosion simulation tools are needed. The Water Erosion Prediction Project model (WEPP version 2008.907) is calibrated using 13 storm events in 2004 for runoff and sediment yield in an undisturbed forested watershed (4.41 km^2) in East Texas having perennial streams. Although the WEPP model is not designed for application in watersheds having perennial streams, an attempt was made to validate the calibrated watershed model using observed post-harvest runoff and sediment yield from 19 storm events from 2005 to 2007. For calibration and validation, WHAT baseflow separator program is used to compare estimated runoff (subsurface and surface runoff) with corresponding simulated model runoff. Sediment rating curves developed from observed data were used to estimate sediment yield from runoff for comparison with model simulated sediment yield. WEPP performance in terms of calibration and validation of runoff and sediment yield prediction is evaluated with the correlation coefficient (R), coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE)-observation standard deviation ratio, and percent bias (PBIAS). A high value of correlation coefficient (R=0.98) is found between WEPP simulated runoff and WHAT baseflow separated runoff for the pre-harvest calibration. A high correlation coefficient (R = 0.98) indicates a positive relationship between WEPP simulated sediment and estimated sediment from runoff for pre-harvest conditions. NSE, RSR, and PBIAS statistical evaluation of model calibration is considered "very good" for runoff (NSE = 0.95, RSR = 0.22, and PBIAS = 11.67%) and ranges from "satisfactory" to "very good" for sediment yield (NSE = 0.90, RSR = 0.32, and PBIAS = 7%). In subsequent validation of post-harvest conditions, a road crossing, culvert, and forest roads were added to the pre-harvest model using field information available at the time of harvest. The resulting R between simulated runoff and WHAT baseflow separated runoff is 0.91. However, NSE, RSR, and PBIAS evaluation of WEPP performance is considered "unsatisfactory" for runoff (NSE = 0.46, RSR = 0.74, and PBIAS = 48.72%). Sediment validation results such as correlation coefficient (R = 0.91) indicated a positive linear relationship between simulated and estimated sediment from post-harvest runoff. Although the resulting R value for the linear regression is 0.91, NSE, RSR values are considered "unsatisfactory" (NSE = 0.11 and RSR = 0.94). The model failure to validate runoff and sediment for post-harvest conditions is due to major limitations of WEPP model not being intended for use in watersheds with perennial streams. Attempts to accurately simulate culvert, road crossing, and forest road surfaces in this study were not sufficient to overcome model limitations. In order to apply the WEPP model confidently in watersheds having perennial streams, model capabilities should be improved to include erosion and sedimentation occurring within the channel during baseflow conditions.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Undisturbed forests generate relatively low sediment yields since both surface runoff and erosion are negligible (Elliot et al., 2000). Consequently, forested areas are associated with water of higher quality than agricultural, urban, or industrial areas (Chang, 2006; USEPA, 1995). Forest streams formed from subsurface flow also have relatively low sediment yield (Dun, 2008). Disturbances such as clear-cutting and road construction remove the vegetative covering on soils dramatically increasing surface runoff and erosion potential (Binkley et al., 1999). Subsequent sedimentation reduces the quality of receiving water and the storage capacity of reservoir (Novotny, 2003).

Past research indicates that forest Best Management Practices (BMPs) can be highly effective at minimizing the negative water quality impacts resulting from forestry operations (McBroom et al., 2008; Beasley et al., 1988; Blackburn et al., 1986). In order to choose among available BMPs, foresters and other stakeholders need to be able to predict sediment yield following various forest operations not just at the field scale, but at the watershed level. Since the measurement of actual erosion and sediment delivery to water bodies is difficult and expensive, several models have been developed to predict average annual soil loss and sediment yield from a hillslope or watershed.

Models such as the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1965, 1978), and the Revised Universal Soil Loss Equation (RUSLE1, USDA-ARS, 1997) and RUSLE2- United States Department of Agriculture-Agricultural Research Service (USDA-ARS, 2003), have been used to evaluate average annual soil loss on a standard plot (22.1m long, 1.8m wide, and 9% slope). USLE and RUSLE are widely used field-scale models developed using data from agricultural plots in the central and eastern United States. Both models empirically predict average annual soil loss at the plot or field scale but do not compute sediment yield which means that these models do not predict the fraction of soil entering the channel. The USLE does not estimate deposition while RUSLE1 and RUSLE2 are capable of computing deposition. RUSLE2 computes rill and interrill erosion rates needed for conservation planning on all land uses (Foster et al., 2003). Newer, more robust RUSLE2 estimates for average annual soil loss generally overpredict comparative USLE predictions. The Modified Universal Soil Loss Equation (MUSLE, William, 1977) is an empirical based model and is able to predict sediment yield from large watersheds upto 1300 ha (Blaszczynski, 2003) but for only a single storm event.

Several physically based continuous simulation models have been developed by scientists from USDA for agricultural settings. Among them are the Erosion Productivity-Impact Calculator (EPIC, Williams at al., 1994) and Groundwater Loading Effects from Agricultural Management Systems (GLEAMS, Leonard et al., 1987). Both these models are field-scale models and cannot be applied to large watersheds. For example, EPIC cannot be used to represent subsurface flow or sediment routing. GLEAMS uses the erosion component of Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS, Knisel, 1980) model with some modifications (Leonard et al., 1987). One advantage of the GLEAMS model over EPIC is that it can evaluate the effects of management scenarios over a long period of time.

Aerial Nonpoint Source Watershed Environment Response Simulation (ANSWERS, 1980) is a distributed parameter model developed for agricultural watersheds and single storm events. The Agricultural Policy/Environmental eXtender (APEX, Williams et al., 2000) model runs on a daily time step and was developed primarily for assessment of BMPs in small agricultural watersheds. Recently, APEX was modified for forested watersheds (Saleh et al., 2004) to allow simulation of streamside management zones.

The Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995) is a physically-based, distributed parameter continuous simulation model originally developed for agricultural hillslopes. WEPP simulation requires numerous input parameters making it a complex mechanistic model. The model has a user interface which makes application and simulation relatively easy as a function of land cover (management), soil, climate, and slope profiles. Because of the user friendly interface, WEPP model has become a popular model for field scale modeling of erosion. WEPP has been improved to simulate erosion and deposition on an event by event, daily, monthly, or annual basis at both the hillslope and watershed scale. In WEPP 2008, perennial growth and senescence factors were added to the model to provide estimates of vegetative growth and leaf fall as they impact forest cover conditions. Parameterization using the anisotropy ratio, the ratio of lateral to vertical flow, allows simulation of subsurface lateral flow which is a dominant hydrologic process in undisturbed forest regions (Dun et al., 2009). A main limitation of the WEPP model at present is the inability to simulate instream processes of watersheds having first or second-order perennial streams (Conroy et al., 2005).

1.2 OBJECTIVES

The overall goal of this study is to test the applicability of WEPP watershed model version 2008.907 on a large forested watershed that includes both ephemeral and perennial streams to evaluate the ability of the model to predict the effects of silvicultural practices on water quality. The WEPP model is tested for expanded use by forest managers to assess and predict water quality impacts from forest management systems. The study watershed is located northeast of Houston county, TX, in the Johnson Creek watershed. In this study watershed intensively managed silvicultural practices were carried out on a 1.14 km^2 near the downstream portion of the watershed. Precipitation and streamflow data were monitored at the watershed outlet one year prior to a clearcut harvest and three years after the harvest.

Specific objectives of this study are to:

1) Set up WEPP model for a multiple hillslope watershed that includes both perennial and ephemeral stream segments.
2) Calibrate the WEPP watershed model for pre-harvest runoff and sediment yield using observed data.
3) Validate the WEPP watershed model for post-harvest runoff and sediment yield using observed data.

1.3 LITERATURE REVIEW

1.3.1 WATER QUALITY IN THE UNITED STATES

The National Erosion Reconnaissance Survey of 1934 first documented the degree of erosion caused by wind and water in the United States. This information led to the establishment of Soil Conservation Service, the forerunner of the Natural Resource Conservation Service (NRCS) (Gilley and Flanagan, 2007**.** It was estimated that about 3.9 billion metric tons of soil were lost in the United States each year through the processes of wind and water erosion (National Resources Inventory, 1987, USDA-SCS). About 70% of the total soil lost was eroded from agricultural land. In the United States, the cost of off-site and on-site soil erosion from agricultural lands amounts to greater than $44 billion per year (Pimental et al., 1995). Soil erosion has been of major concern to the long-term productivity of agricultural and forest lands and has been identified as the major cause of non-point source (NPS) pollution (Novotny, 2003). In the United States, runoff is considered as a major pollutant carrier. Sediment carried in runoff is one of the most visible NPS pollutants of streams, lakes, and estuaries (USEPA, 1995). The effects of excessive sediment loading in water bodies includes deterioration of water quality, loss of aquatic habitat, and reduction in storage capacity of reservoirs (Novotny, 2003).

About 65% of the southeastern United States is forested (Ursic, 1975). Research in the southeast has revealed that erosion rates from undisturbed forest land are less than the rates of natural erosion caused by geological processes (Patric, 1976; Beasley, 1979; Schrieber et al., 1980). Undisturbed forests have relatively low rates of erosion due to canopy cover from trees and surface cover from organic litter (Grace, 2002a). Canopy and surface cover in forest areas intercepts the maximum amount of precipitation reducing raindrop impact and soil detachment. Organic litter and debris increase the surface roughness and infiltration of soil decreasing overland flow and transport of detached soil particles (Grace, 2002a). As a consequence, higher levels of erosion can occur in a forest when surface vegetation and litter are removed by forestry operations (Binkley and Brown, 1993).

The southeastern United States supplies more than 60% of the forest products for the nation and is the largest forest timber producing region in the world (Wear and Greis, 2002; Fox et al., 2006). Many researchers have reported increased sediment levels as a result of silvicultural practices such as clearcutting, thinning, and road construction (Beasley, 1979; Van Lear et al., 1985; Miller, 1984; Beasley and Granillo, 1998; Grace 2002a). The Clean Water Act of 1977 (P.L. 95-217) emphasized the importance of NPS pollution from silvicultural practices. As a result, various forest BMPs including streamside management zones (SMZs) have been developed to reduce sediment reaching water bodies. SMZs have been shown to be an effective management practice to minimize sediment loss from forest harvesting operations (Kochenderfer and Edwards, 1990).

1.3.2 FOREST RUNOFF AND SEDIMENT STUDIES

Several field studies have been conducted at a watershed scale, with and without BMPs to evaluate the effects of silvicultural practices on storm runoff and sediment loss (Beasley et al., 1988; Blackburn et al., 1986; Miller, 1988; Wynn et al., 2000; McBroom et al., 2008). Beasley (1976) studied the contribution of subsurface flow from upper slopes in a forested watershed to channel flow on 0.054 and 0.089 ha plots. The study revealed that subsurface flow from upper slopes contributes significantly as runoff to channel flow where permeable soils overlay less permeable bedrock.

Beasley (1979) conducted another study on four small watersheds (0.7-1.0 ha) in the Coastal Plain of Northern Mississippi. Three watersheds had intensive site preparation (chopping, shearing and windrowing, and bedding) and the fourth served as an undisturbed control. Results verified that site preparation exposed the soil on the treated watersheds. Reported sediment yields for the first-year of study were 12.5, 12.8, 14.2, and 0.6 tons/ha on the chopped, sheared and windrowed, bedded, and control watersheds respectively. Second-year sediment yields from chopped, sheared and windrowed, bedded, and control watersheds decreased to 2.3, 2.2, 5.5 and 0.1 tons/ha respectively.

Beasley and Granillo (1988) measured water and sediment yields on nine small forested watersheds (2.3 to 4.0 ha) in the Gulf Coastal Plain of Arkansas from 1981 to 1985. All watersheds were assigned randomly to each of the following three treatments:

1) clearcut and mechanical site preparation, 2) selective clearcut (clearcut with SMZs), and 3) an undisturbed control. One year-pretreatment (1981) measurements were taken for all watersheds followed by four years of post-treatment data collection (1982-1985). Watershed slope was greater than one percent with the predominant soil series Tippah silt loam. Predominant hardwood species included white oaks, southern red oak, sweetgum, and hickories. All watersheds had intermittent stream flow during winter and spring seasons. The results of the first two-post treatment years for clearcut watersheds indicated significantly increased sediment and water yield compared to the control undisturbed watersheds. Selective clearcut and undisturbed watersheds had similar sediment loss and water yields for four post-treatment years. Sediment loss and water yields were statistically similar for all the watersheds after two years of post-treatment due to the rapid growth of vegetation.

Blackburn et al. (1986) compared storm flow, sediment concentration, and sediment loss between 1980 and 1985 on a study site composed of nine small watersheds (2.57 to 2.72 ha) in southwest Cherokee County in East Texas. Three replicated watersheds for each of the following treatments were compared: 1) shearing, windrowing, and burning, 2) roller chopping and burning, and 3) undisturbed control. One year after the treatment, mean storm flow from sheared watersheds was greater than from the chopped watersheds (14.6 cm versus 8.3 cm); and mean storm flow from undisturbed watersheds (2.6 cm) was less than both treated watersheds. Mean storm flow from the second year after treatment from sheared watersheds was greater than from chopped watersheds (5 cm versus 3.6 cm) and was lowest from the undisturbed watersheds (1.2 cm). No significant difference was reported in mean storm flow during the third year after treatment. However, during the fourth year after treatment, mean storm flow from sheared watersheds was greater than from the chopped watersheds (6.1 cm versus 3.5 cm) and was lowest for undisturbed watersheds (1.4 cm). First year sediment losses from sheared watersheds (2937 kg/ha) were greater than from chopped (25 kg/ha) and undisturbed watersheds (33 kg/ha). During the second year after treatment sediment losses were reduced by 97% in the sheared watersheds (79.9 kg/ha) but were still greater than from the chopped watersheds (5.5 kg/ha) and undisturbed watersheds (5.1 kg/ha). In the third year following the treatment, sediment losses from sheared watersheds (34.6 kg/ha) were greater than from chopped watersheds (5.4 kg/ha). During the fourth year after treatment, sediment losses from the sheared watersheds (165 kg/ha) were greater than from the chopped watersheds (16 kg/ha) and undisturbed watersheds (29 kg/ha). Overall, storm runoff and sediment losses during post-treatment years were greatest from sheared watersheds, intermediate from chopped watersheds, and lowest from the undisturbed watersheds.

Miller et al. (1988) conducted a study on nine small forest watersheds (4.18 to 5.91 ha) in the Quachita Mountains of Arkansas from 1981 to 1983 to observe forest harvest and site preparation effects on erosion and sedimentation. Three watersheds for each of the following three treatments were selected: 1) clearcut, 2) selective clearcut (clearcut with SMZs), and 3) undisturbed control. First-year annual sediment yield increased significantly on clearcut watersheds compared to selective clearcut and control but not in the second and third years. Clearcut to control sediment yield ratios were 20:1, 6:1, and 2.6:1 in years one, two, and three, respectively. Corresponding, sediment yield ratios from selective clearcut to control were 3:1, 2.4:1, and 1.2:1.

Lebo et al. (1998) carried out a study on a 470 ha watershed near Beaufort, North Carolina on the Coastal Plain to assess the impact of harvest operations on outflow characteristics. Outflow was monitored at three locations within the watershed from 1986 to 1994. During the study period, 60% of the watershed area was harvested and regenerated. For the three years following harvest, only minor impacts on outflow were observed, with no significant change in total suspended solids (TSS) concentrations.

Wynn et al. (2000) conducted a similar study to determine the effects of forest harvesting BMPs on surface water quality in the Virginia Coastal Plain. The following three scenarios were developed for each of the three watersheds selected: 1) clearcut without BMPs, 2) clearcut with BMPs, and 3) undisturbed control. The main BMP implemented was streamside management zones (SMZs). The clearcut watershed without SMZ had reduced storm flow volumes but did not significantly reduce peak flow. The clearcut watershed with SMZs had significantly decreased storm flow volumes with increased peak flow. The changes in storm flow volumes and peak flow was due to disturbance in subsurface flow during harvest or rapid growth of vegetation after harvest. Sediment loss from the clearcut watershed without SMZs increased significantly during storm events. However, both the clearcut watershed with SMZs and the undisturbed control watershed showed only minor changes in sediment loss that was within tolerable erosion rates of one t/ha/yr (Robichaud and Waldrop, 1994). Overall, the study concluded that forest clearcutting and site preparation with BMPs can greatly reduce sediment loss from watersheds.

Ensign and Mallin (2001) conducted a sediment yield study on two similar size watersheds (Goshen Swamp and Six Runs Creek), the latter one a control, in the Coastal Plain Swamp Forest of North Carolina. The objective was based on the hypothesis that clearcutting in the Goshen Swamp watershed would negatively impact downstream water quality. Results showed significantly higher sediment yields from the clearcut watershed following harvest compared to the control watershed even though 10 m vegetated buffer zone was left along the sides of the streams. Consequently, the study concluded that a 10 m buffer zone along streamside was insufficient to protect stream water quality.

McBroom et al. (2008) conducted a study on nine small paired watersheds and four large paired watersheds from 1999 to 2003 to evaluate the effects of silvicultural activities on runoff and sediment yield with BMPs. On small watersheds, there were three replicates of two treatments methods that included conventional and intensive, with one control in each replicate. For large watersheds, one acted as a control and three as treatments. Conventional harvesting method included clearcutting followed by pre-plant herbicide application. Intensive harvesting methods included everything in the conventional treatment with a pre-plant subsoil operation added. Treatment effects for watersheds were determined using the paired watershed approach. Runoff and sediment yields were also compared to a study of the same watersheds from the 1980s without BMPs (prior to the adoption of Texas BMPs). Results showed that total storm runoff increased significantly in the range of 0.94 to 13.73 cm following harvest on all six treated small watersheds. However, no significant runoff increase was found on the treated large watersheds. The total first-year sediment yield was significantly greater on two of the conventional and one of the intensively harvested small watersheds. The first-year sediment yield on the intensively harvested large watershed was significantly greater than that from the conventional watershed. Reductions of one-fifth of the first-year sediment yield with BMPs were reported compared to those from the 1980 study without BMPs. The study concluded that BMPs are effective means to improve water quality.

1.3.3 FOREST ROADS STUDIES

Research has shown that forest roads contribute up to 90% of sediment yield from forest lands (Megahan, 1972; Van Lear, 1995; Appelboom, 2002). Sediment from roads can flow directly to streams, causing sedimentation (Packer, 1967). Sedimentation degrades the quality of forest streams and aquatic habitat (Elliot et al., 1994). Sedimentation also clogs spawning beds, reduces the storage capacity of reservoirs, and degrades drinking water (Grace, 1998). Consequently, road management is an important element in preserving and maintaining healthy forests throughout the nation (Grace, 2002a). As demand increases for timber products and recreational use, roads must be constructed and maintained for increased access (Appelboom, 2002). This demand dramatically increases the potential for sediment production (Appelboom, 2002). The increased erosion potential from forest roads requires special considerations to reduce the environmental impact on water quality (Grace, 2002a).

Soil erosion from forest roads is primarily due to the disturbance of the roadbed. Increased potential for soil detachment and transport from forest roads is due to elimination of vegetative cover, destruction of soil structure, increased compaction and slope, interception of surface and subsurface flow, and concentrated flow (Grace, 2002a). The detachment of soil particles due to raindrop impact is a primary cause of erosion (Brooks, 2003). Once a soil particle has been detached from its position, runoff carries soil particles with increased velocity by concentrated flow through rills that are formed. To control the degree of runoff and erosion, engineers have developed road BMPs such as broad-based dips to divert water into SMZs or ditches with grassed waterways (Swift, 1985; Kochenderfer and Helvey, 1987). Ursic and Douglass (1978) and Kochenderfer and Helvey (1987) suggested using gravel on roads to reduce the amount of sediment reaching streams.

1.3.4 MODELS USED FOR SOIL EROSION

Computer simulation models are the most effective tools that have been used in the US for soil conservation planning and design to predict soil erosion from agricultural and forest areas (USDA, 2002). It is not easy to monitor the impact of various agricultural and forest management practices across all ecosystems and climatic conditions. Erosion prediction tools are used mainly to rank alternative management practices with regard to their relative impact. The major soil erosion models developed during the last four decades are summarized in Table 1.1 and discussed as follow.

Table 1.1 Summary of main differences between erosion models.

Characteristics	USLE	RUSLE	MUSLE	EPIC	ANSWERS	GLEAMS	APEX	WEPP
Temporality	Erosion simulation on an average annual basis	Erosion simulation by a period or average annual	Erosion simulation on an average annual basis	Erosion simulation on daily basis, continuous simulation	Erosion simulation by event based	Erosion simulation on daily basis, continuous simulation	Erosion simulation on daily basis, continuous simulation	Erosion simulation on event by event, monthly or annual averages
Erosion Equations	Empirical	Empirical	Empirical	Empirical	Physically based	Physically based	Physically based	Physically based
Scale	Plot	Plot	Large watersheds	Small watersheds	Small watersheds	Small watersheds	Small watersheds	Plot, hillslope, small watersheds
Applications	Croplands, rangelands, and forests	Croplands, rangelands, and forests	Croplands, rangelands, and forests	Croplands	Croplands, rangelands	Croplands	Whole farm and forests	Croplands, rangelands, and forests
Limitations	Do not account for ephemeral gullies, problems with multiple land uses, do not predict deposition and sediment yield, no spatial and temporal variation	Do not predict deposition and sediment yield.	Do not account for ephemeral gullies, problems with multiple land uses, do not predict sediment yield, no spatial and temporal variation	Not capable of simulating subsurface flow and sediment routing. Not suitable for large watersheds	Not capable for long-term simulations	Not suitable for large watersheds	Not suitable for large watersheds	Do not account for gullies or permanent channels and streams. Not suitable for large watersheds

UNIVERSAL SOIL LOSS EQUATION (USLE)

The USLE is the most commonly used soil erosion model. Wischmeier and Smith (1965) developed an empirical relationship for estimating average annual soil loss from small plots (22.1 m length and 9% slope) using 10,000 plot years of runoff and soil erosion data collected from all over the United States. The soil loss equation developed utilizes rainfall, soil, topographic, and management data as follows:

$$A = RKLSCP \tag{1}$$

where:

A = the computed average annual soil loss per unit area, tons ha^{-1}

R = the rainfall and runoff factor, ft tonsf in acre^{-1} hr^{-1} year^{-1}

K = the soil erodibility factor, tons acre hr hundreds^{-1} acre^{-1} ft^{-1} tonsf^{-1} in^{-1}

LS = the slope-length factor

C = the cover management factor

P = the erosion control practice factor; LS, C, and P are unitless.

Weichmeier (1976) recommended using the USLE for small plots. Risse et al. (1993) conducted an error assessment of USLE to measure its performance and accuracy under conditions comparable to those for which it was developed. The USLE over-predicted soil loss by 22% on plots with low observed erosion rates and under-predicted soil loss by 80% on plots with high observed erosion rates. Cover and management, C and topographic parameters, LS had the most significant effect on model efficiency. Overall, the accuracy of USLE model predictions improved with increasing observed soil loss.

Dissmeyer and Foster (1981) introduced a new procedure to estimate the cover management factor, C for forest conditions in the USLE using nine subfactors; 1) amount of bare soil, 2) canopy, 3) soil reconsolidation, 4) organic content, 5) fine roots, 6) residual binding effect, 7) on-site storage, 8) steps, and 9) contour tillage. Data from 39 undisturbed research watersheds and four plots in the southeastern U.S. were used to validate the procedure. The correlation (R^2) between predicted and observed sediment was 0.90 and the standard error was 71% of the mean measured sediment yield. Soil loss estimates were accurate for high erosion rates (1112 tons/acre) or greater.

REVISED UNIVERSAL SOIL LOSS EQUATION (RUSLE)

RUSLE (Renard et al., 1991) is the revised and updated version of the ULSE. New relationships were derived based on modern erosion theory for each of six USLE factors. The RUSLE equation is as follows:

$$A = RKLSCP \tag{2}$$

where:

A = the average annual soil loss from sheet and rill erosion (tons ha^{-1})

R = the climate erosivity factor (MJ mm ha^{-1} h^{-1})

K = the soil erodibility factor (Mg ha^{-1} MJ^{-1} mm^{-1} ha h)

L = the slope length factor

S = the slope steepness factor

C = the cover management factor

P = the support practice factor; L, S, C, and P are unitless.

R factor represents the driving force of sheet and rill and is computed using rainfall amount and intensity. K in RUSLE is a function of an average soil particle diameter and is estimated using erodibility data from around the world. The RUSLE uses four separate slope-length relationships. Three are the functions of slope steepness as in the USLE, and fourth is the function of susceptibility of the soil to rill erosion relative to interrill erosion. C factor is computed using weighted averages of soil loss ratios (SLRs). SLRs is computed as a function of five sub-factors including the prior land use, canopy cover, surface cover, surface roughness, and soil moisture. P factors were improved using fundamentals of detachment and transport theory based on flow hydraulics and sediment transport. RUSLE is a lumped parameter model that predicts soil loss at the hillslope scale (Renard et al., 1993). RUSLE empirically computes infiltration, overland flow, particle detachment, and sediment transport processes using the above six factors (equation 2).

MODIFIED UNIVERSAL SOIL LOSS EQUATION (MUSLE)

Williams (1977) and Williams and Brendt (1972) developed the lumped parameter model MUSLE using several sets of storm data from US watersheds. The R-factor from the USLE was replaced with runoff volume and peak discharge parameters to predict sediment yield from the watersheds for a single storm. The MUSLE equation, developed using English units, is as follows:

$$Y = 95\left((Qq_p)^{0.56}\right)(K)_a(LS)_a(CP)_a \qquad (3)$$

where:

Y = single storm sediment yield (tons)

Q = runoff volume (acre-feet)

q_p = peak flow (cfs)

$(K)_{a,}$ $(LS)_{a,}$ and $(CP)_a$ are area weighted average USLE/RUSLE parameters for the watersheds.

The MUSLE model can be used on small sites and watersheds that are relatively homogenous in nature. Its routing procedure does not provide any time distribution of sediment or a size distribution of sediment. MUSLE does not include flood plain erosion and channel erosion (William, 1978).

EROSION PRODUCTIVITY IMPACT CALCULATOR (EPIC)

EPIC (Williams et al., 1994) is a continuous simulation field scale erosion model that predicts soil erosion and examines the long term effects of soil erosion on soil productivity. The major processes simulated in EPIC are weather, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature variation, tillage, plant environment control, and economics. Daily runoff volume in EPIC is estimated using the Soil Conservation Service (SCS) curve number method (USDA, 1972). The water erosion model in EPIC uses an equation of the form:

$$A = X\,(K)(C)(P)(LS)(ROKF) \tag{4}$$

where:

A = the sediment yield (tons ha^{-1})

K = the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1})

C = the crop management factor

P = the erosion control practice factor

LS = the slope length and steepness factor

ROKF = the coarse fragment factor

X provides an erosivity index option (MJ mm ha^{-1} h^{-1}); C, P, LS, and ROKF are unitless.

Soil erosion is simulated using any of the following equations; USLE (Wischmeier and Smith, 1978), MUSLE (Williams, 1977), Onstad-Foster modification of USLE (Onstad and Foster, 1975), MUSS (MUSLE for small watersheds) and MUST (another version of MUSLE). The main disadvantage of the EPIC model is that it not capable of simulating subsurface flow or sediment routing.

AERIAL NONPOINT SOURCE WATERSHED ENVIRONMENT RESPONSE SIMULATION (ANSWERS)

The ANSWERS (Beasley et al., 1980) model was developed to compute runoff and soil loss from agricultural watersheds for a single event. ANSWERS is a distributed parameter model that computes spatially varying processes of runoff, infiltration, subsurface drainage, and erosion using topography, soil, and land use information. The ANSWERS model consists of a hydrologic model, a sediment detachment/transport model, and routing components essential to depict the movement of water in overland, subsurface, and channel flow. The erosion component of ANSWERS is based on the following assumptions: 1) channel erosion is insignificant, 2) sediment particles require the same amount of energy for detachment or reattachment, and 3) subsurface flows produce no sediment.

GROUNDWATER LOADING EFFECTS FROM AGRICULTURAL MANAGEMENT SYSTEMS (GLEAMS)

The GLEAMS (Leonard et al., 1987) model is a physically based continuous simulation model that simulates processes affecting water quality in an agricultural field. The hydrology component in GLEAMS simulates runoff using a modification of the SCS curve number method (Williams and LaSeur, 1976). Hydrologic computations for evapotranspiration, percolation, infiltration, and runoff are determined on a daily time step (Knisel, 1993). Storage routing through the soil profile is a function of porosity, field capacity, and saturated hydraulic conductivity. The erosion component in GLEAMS is similar to that in the CREAMS model (Knisel, 1980) which considers overland flow, channel flow, and impoundments. A modification of the Universal Soil Loss Equation (USLE) is used to estimate inter-rill and rill detachment. A modification of the Yalin equation is used to calculate sediment transport capacity (Foster et al., 1980).

AGRICULTURAL POLICY/ENVIRONMENTAL EXTENDER (APEX)

The APEX (Williams et al., 1995) model was developed for whole farm and small watershed management and assessment of BMPs. The individual field simulation component of APEX is taken from the EPIC model. A watershed can be divided into subareas with homogenous soil, land use, and management characteristics. The APEX model incorporates routing of surface runoff and sediment yield on a daily time step. Saleh et al. (2004) applied APEX to forested watersheds in Cherokee County, East Texas by modifying rainfall interception by canopy, surface litter water balance, and subsurface flow components. Management capabilities incorporated in APEX by Saleh et al. (2004) for forest conditions include drainage, SMZs, waterways, and tillage.

WATER EROSION PREDICTION PROJECT (WEPP)

WEPP hillslope model (Laflen et al., 1991) is a process based, continuous simulation model used for runoff and sediment yield prediction. It was intended for use on small agricultural fields. Later, it was extended for watersheds applications less than 260 ha where hydrology is dominated by Hortonian overland flow (where rainfall rates exceed infiltration capacity and subsurface flow is negligible) and each hillslope and channel element has a significant sediment contribution to the watershed outlet (Ascough II et al., 1995b). The WEPP hillslope model is capable of calculating spatial and temporal distributions of soil loss along the hillslope as well as sediment delivery to the stream channel (Figure 1.1) (Flanagan et. al., WEPP Documentation, 1995). It can simulate multiple soil types and land uses along a single hillslope profile. The erosion processes considered in the WEPP hillslope model includes rill and inter-rill erosion, sediment transport, and deposition.

For watershed applications, the model links all hillslopes to channels and impoundments (Figure 1.2). The WEPP watershed model is also capable of; 1) identifying zones of sediment deposition and detachment within channels, and 2) accounting for the effects of backwater on sediment detachment, transport, and deposition within channels (Ascough II et al., 1995a). The various components last updated in WEPP are presented in Table 1.2.

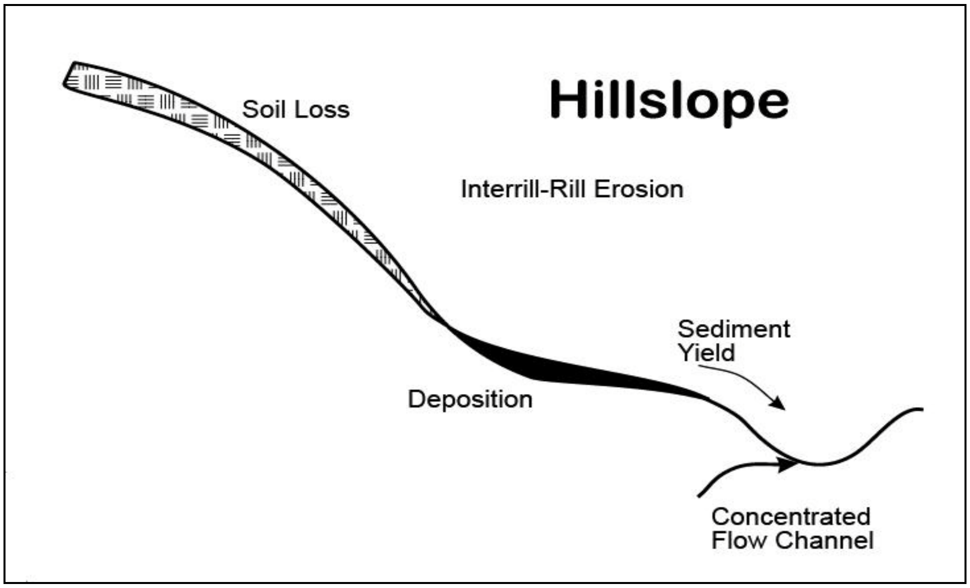

Figure 1.1 WEPP model hillslope profile showing spatial and temporal variability of soil loss and deposition along the hillslope and sediment yield into the channel. (Adapted from WEPP model documentation, 1995)

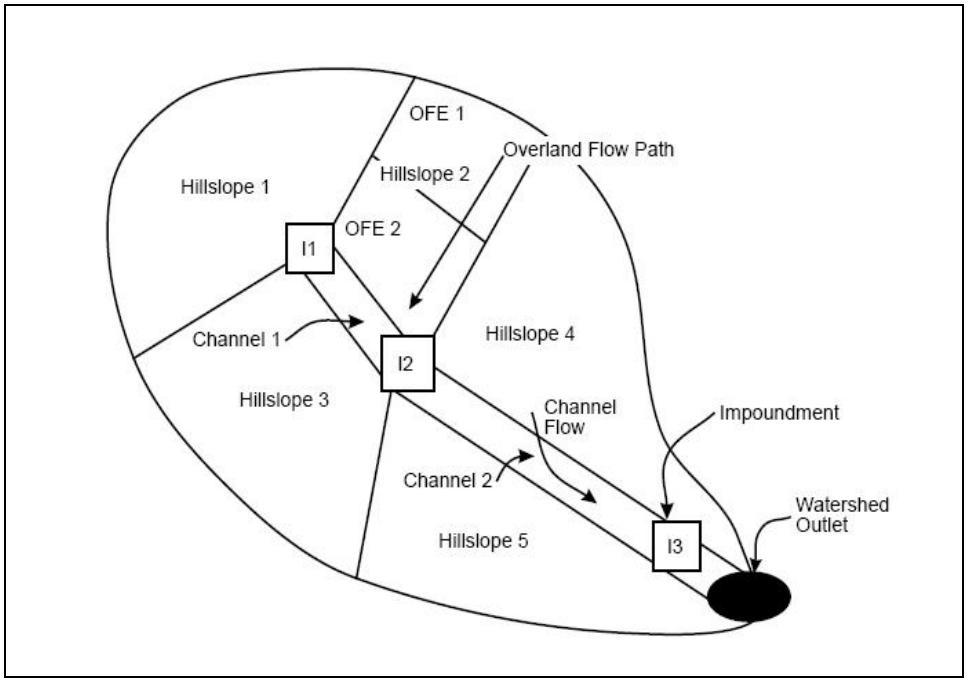

Figure 1.2 Schematic of a small watershed consisting of 5 hillslopes, 2 channels and 3 impoundments on which WEPP watershed model can be applied. OFEs are overland flow elements within which soil properties and vegetation conditions are regarded uniform and unique (Adapted from WEPP model documentation, 1995).

Table 1.2 Selected WEPP model components and year of last modification.

Model components	Last updated
Hillslope erosion component	2007
Hydrology, continuous simulation	1995
Climate generation - climate generator (CLIGEN), Breakpoint climate data generator (BPCDG)	2001, 2007
Flow hydraulics	1995
Water balance, percolation, drainage	1995
Plant growth (senescence)	2008
Soil component (forest soils)	2000
Residue decomposition and management	1995
Winter process (snow)	2008
Irrigation	2004
Channel and watershed components	1997
Impoundment components	2002
Water balance and subsurface lateral flow	2006

Source: Water Erosion Prediction Project : Development history, model capabilities and future enhancements (Flanagan et. al., 2007)

GEOSPATIAL WATER EROSION PREDICTION PROJECT (GEOWEPP)

The GeoWEPP (Renschler, 2003) is a geospatial interface for WEPP that utilizes digital elevation models (DEM) together with soils and landcover maps to delineate a watershed and analyze output within a GIS. GeoWEPP model combines WEPP version 2008.907 with Topography Parameterization software (TOPAZ) (Garbrecht and Martz, 1999) within ArcGIS 9.2 (ESRI, 2007) to predict runoff and erosion at the hillslope and watershed scale. GeoWEPP is used to create a main catchment (the watershed) as well as subcatchments based on the location of intermittent streams. The limitation of GeoWEPP is that it allows only a single soil and land use for each subcatchment. Consequently, GeoWEPP is not capable of simulating various BMPs such as SMZs.

1.3.5 SEDIMENT MODELING APPLICATIONS

1.3.5.1 MODEL EVALUATION METHODS

Hydrologic models are used frequently to simulate or predict flow and sediment on a continuous basis or for a particular event. To assess the performance of these models several test criteria are necessary. Moriasi et al (2007) conducted extensive research to establish guidelines for watershed model evaluation that focuses on streamflow, sediment, and nutrients.

Standard regression statistics determine the strength of the linear relationship between simulated and measured data. The slope and y-intercept of the best-fit regression line indicates how well simulated data match measured data (Moriasi et al., 2007). For example, a slope of one and a y-intercept of zero indicate that modeled results are in perfect agreement with measured data (Willmott, 1984). For dimensionless quantitative analysis another goodness-of-fit criteria is Nash-Sutcliffe efficiency (NSE, Nash and Sutcliffe, 1970). NSE values indicate how well the plot of observed versus simulated fits the 1:1 line. NSE with a value of 1.0 indicates a perfect match. Values between zero and one indicate an acceptable level of model performance. NSE is computed using the following equation.

$$\mathbf{NSE} = \mathbf{1} - \left[\sum_{i=1}^{n} \left(Y_{obs,\,i} - Y_{sim,\,i} \right)^2 \Big/ \sum_{i=1}^{n} \left(Y_{obs,\,i} - Y_{mean} \right)^2 \right] \tag{5}$$

where $Y_{obs,\ i}$ = i^{th} observation for the constituent being evaluated, $Y_{sim,\ i}$ = i^{th} simulated value for the constituent being evaluated, Y_{mean} = mean of observed data for the constituent being evaluated, and n = total number of observations.

An error index statistical analysis commonly used for model evaluation includes root mean square error (RMSE)-Observations standard deviation Ratio (RSR) and percent bias (PBIAS). RSR standardizes RMSE using the observed standard deviation (Legates and McCabe, 1999). RSR varies from an optimal value is zero, which indicates perfect model simulation to a larger positive value. RSR is calculated as the ratio of RMSE and standard deviation of measured data as shown below:

$$\mathbf{RSR} = \frac{\mathbf{RMSE}}{\mathbf{STDEV_{obs}}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(\mathbf{Y_{obs,\ i}} - \mathbf{Y_{sim,\ i}}\right)^{2}}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(\mathbf{Y_{obs,\ i}} - \mathbf{Y_{mean,\ i}}\right)^{2}}\right]} \tag{6}$$

PBIAS assesses the inclination of simulated data to either over-predict or under-predict (Gupta et al., 1999). Positive values indicate that the model underestimated, while negative values indicate model overestimation. The equation used for computing PBIAS is as follows:

$$\mathbf{PBIAS} = \left[\sum_{i=1}^{n}\left(\mathbf{Y_{obs,\ i}} - \mathbf{Y_{sim,\ i}}\right) * (\mathbf{100}) \Big/ \sum_{i=1}^{n}\left(\mathbf{Y_{obs,\ i}}\right)\right] \tag{7}$$

where: *PBIAS* = deviation of data being evaluated, expressed as a percent.

General model evaluation guidelines were developed (Moriasi, 2008) based on performance ratings for the recommended statistics using daily and monthly streamflow, surface runoff, sediment, and nutrients from numerous studies. The reported performance ratings developed for NSE, RSR, and PBIAS for streamflow and sediment are shown in Table 1.3.

Table 1.3 General performance ratings for recommended statistics.

Performance Rating	NSE	RSR	PBIAS	
			Streamflow	Sediment
Very Good	0.75<NSE≤1.00	0.00≤RSR≤ 0.50	PBIAS < ±10	PBIAS < ±15
Good	0.65<NSE≤0.75	0.50<RSR≤0.60	±10≤PBIAS<±15	±15≤PBIAS<±30
Satisfactory	0.50<NSE≤0.65	0.60<RSR≤0.70	±15≤PBIAS<±25	±30≤PBIAS<±55
Unsatisfactory	NSE ≤ 0.50	RSR > 0.70	PBIAS ≥± 25	PBIAS ≥ ±55

1.3.5.2 FOREST WATERSHEDS

Saleh et al. (2004) conducted a study with Agricultural Policy/Environmental eXtender (APEX) on nine small forested watersheds (2.58 to 2.74 ha) located in southwest Cherokee County in East Texas. APEX was adapted for forest conditions by introducing rainfall interception by canopy, litter, subsurface flow and routing enrichment ratios. Measured flow, sediment loss, and nutrient loss (1980-1985) from nine watersheds (W1 - W9) were used to calibrate and evaluate APEX. The following treatments were monitored at the watershed scale; 1) undisturbed control watersheds (CON), 2) clearing, shearing, windrowing, and burning (SHR), and 3) clearcutting, roller chopping, and burning (CHP). APEX was also applied to two watersheds (W2 and W4) to demonstrate the effectiveness streamside management zones (SMZs) and to estimate sediment from forest roads. Simulations for the first post-treatment year indicated six times the runoff for SHR and five times the runoff for CHP watersheds compared to CON watersheds. Simulated sediment loading was approximately 13 times for SHR and two times for CHP watersheds compared to the control. During the second post-treatment year, storm runoff and sediment loading were reduced due to vegetation growth. During the fourth and fifth post-treatment years, storm runoff and sediment loading approached to those of CON watersheds. APEX simulations also showed a decrease in runoff and sediment loss through SMZs whereas forest roads increased runoff and sediment significantly.

Wang et al. (2007) tested the APEX model on the same watersheds used by Saleh et al (2004) using storm runoff, sediment losses, and nutrient losses measured from 1999 to 2003. APEX modeling was conducted to simulate intensive silvicultural practices with best management practices (BMPs) using flow, sediment, nutrient, and herbicide loss data. Treatments modeled were 1) undisturbed control, 2) clearcut followed by herbicide site preparation and replanting (conventional), and 3) clearcut followed by herbicide site preparation, subsoil, replanting, and fertilizer application (intensive). Three watersheds were used for each treatment. The model was evaluated with NSE and coefficient of determination (R^2) with a value of 1.0 indicating a perfect match between observed and simulated values. NSE values of annual and monthly flow ranged from 0.68 to 0.94 and R^2 values from 0.69 to 0.97. Annual and monthly NSE and R^2 values ranged from 0.60 to 0.99 and from 0.68 to 0.99, respectively. Simulated annual average stream flow was within ± 7% of the observed values for each of the nine watersheds. Eight out of nine watersheds had simulated annual average sediment losses within ± 8% of the observed values. Overall, results indicated that APEX was able to predict the effects of silvicultural practices with and without BMPs. Authors suggested APEX as a useful tool for simulating water quantity and quality response to forest management.

Covert et al. (2005) compared annual runoff predictions generated by GeoWEPP model and a modified version of WEPP v98.4 (Modified WEPP) in three forested watersheds ranging from 2-9 ha located in the northwest mountain region of the United States. Wu et al., (2000) found that WEPP v98.4 over-estimated deep percolation and under-estimated subsurface flow in forest conditions. In the modified version of WEPP used by these researchers, the following two components were added; 1) a bedrock layer to limit deep percolation and increase subsurface lateral flow and 2) subsurface lateral flow added to channel flow to increase total water yield. Annual runoff predictions were assessed using index of agreement (Willmott, 1984) with 1.0 indicating a perfect fit between observed and predicted values. Results showed that, GeoWEPP significantly under-predicted total annual runoff in all watersheds whereas the Modified WEPP predicted total annual runoff in two of three watersheds with an index of agreement 0.8 and 0.9 for each. The index of agreement for the third watershed (0.3) indicated less accurate prediction of annual runoff. Further refinement of the water balance algorithms was suggested to correctly simulate hydrologic processes.

Dun et al. (2009) conducted a study in the Boise National Forest, Idaho to modify WEPP v2004.7 algorithms and subroutines to improve forest subsurface (lateral flow) hydrologic processes. Their modified version of WEPP v2008.9 incorporated the following two components; 1) a bedrock layer beneath the soil profile with user defined effective saturated hydraulic conductivity and 2) a user defined anisotropy ratio representing the dominance of horizontal (lateral) flow over vertical flow. Both modified WEPP v2008.9 and WEPP v2004.7 model were applied to a 9-ha watershed in Idaho and results were compared with measured field data. WEPP v2008.9 simulated annual water discharge (262 mm) in agreement with measured field data (275 mm) indicating the model's realistic representation of hydrologic processes in this forested watershed.

1.3.5.3 AGRICULTURAL WATERSHEDS

Baffaut et al. (1997) conducted a study with the WEPP v98.4 model to verify the behavior of watershed subdivision (subwatershed delineation) on sediment yield; and evaluated the sensitivity of channel parameters on sediment yield in a small agricultural watershed. Results from two subdivided watersheds under various delineation schemes were evaluated and compared for selected events using one year of continuous simulation. Sensitivity analyses were performed on the following channel parameters; slope, bank slope or side slope, critical shear stress, erodibility, hydraulic conductivity, and total and bare soil Manning's coefficient. Results indicated the following three elements were important for watershed discretization: 1) hillslope length, 2) number of channels, and 3) hillslope drain into top, left side or right side of the channel. For larger watersheds, an individual hillslope length not greater than 100 m was recommended. Model sensitivity analyses on channel parameters confirmed that the bare soil Manning's coefficient was the most critical parameter. The total Manning's coefficient and channel slope were found to be the next most sensitive parameters. Their study also suggested that the sensitivity of parameters on erosion varied greatly from storm to storm. For example, channel erodibility and critical shear stress were found important parameters for erosion with some storms, but for others they were unimportant.

Liu et al. (1997) compared measured runoff and sediment yields predicted values from WEPP95 in fifteen small watersheds in Chickasha (Oklahoma), Coshocton (Ohio), Holly Springs (Mississippi), Riesel (Texas), Tifton (Georgia), and Watkinsville (Georgia) ranging in size from 0.34 to 5.14 ha. Both single event and continuous simulations were conducted without calibration using default model parameters. Four precipitation parameters including precipitation, duration, peak 5-min rainfall intensity, and time to peak intensity were calculated using break point precipitation data that creates break point precipitation using actual measured data. In two watersheds total daily precipitation amount and duration were used due to unavailability of break point data. Six other daily climate parameters including maximum and minimum temperature, solar radiation, wind velocity and direction, and dew point temperature were generated by the WEPP synthetic weather generator, CLIGEN (Nicks et al., 1995). Slope input files were developed using digital topographic maps. Surface management files from WEPP95 default data were wheat, corn, soybeans, alfalfa, sorghum, rye, and peanuts. Parameters for barley and bermudagrass were derived using the Crop Parameter Intelligence Database System (Deer-Ascough et al., 1995) and by modifying the WEPP default database for wheat and rye grass. Soil characteristics including percent sand, clay, organic matter, rock fragment, and cation exchange capacity were acquired from field measurements. Baseline soil erodibility parameters including interrill, rill, and critical shear stress and effective hydraulic conductivity values were estimated using WEPP default procedures (Flanagan and Nearing, 1995) for agricultural lands. For peak runoff calculation, the EPIC (Ascough et al., 1997) method recommended for small watersheds was used. Results showed that the coefficient of determination, R^2, values between measured and predicted total runoff and sediment yields from 15 watersheds were 0.86 and 0.91 respectively. The R^2 values between measured and predicted storm event data ranged from 0.01 to 0.85 for runoff and 0.02 to 0.90 for sediment yield. WEPP predictions were found satisfactory in simulating long-term erosion rates from small watersheds using default WEPP management parameters. The use of more precise values for management parameters during individual storm events were suggested by authors.

Tiwari et al. (2000) used 1600 plot years of natural runoff plot data on agricultural fields at 20 locations over the US to validate WEPP v98.4. They included in their study most of the data that was used to develop the USLE. WEPP values for soil loss were compared with results from both USLE and RUSLE. Validation was performed against observed data to evaluate the reliability of predictions obtained from the WEPP model. Simulations were conducted across a wide variety of soil series, slope percent (3-21%), and crops. The NSE of WEPP was 0.71 compared to 0.80 and 0.72 for the USLE and RUSLE, respectively. Low values of observed soil loss were comparable with results from all three models. USLE and WEPP performed better at high ranges of soil loss in this study. Overall, USLE and RUSLE performed better than WEPP as parameters used in USLE and RUSLE were site-specific to the natural runoff plots. WEPP model simulations on the other hand were carried out without calibration. Authors suggested further refinements and modification in deriving basic input parameters for the WEPP model.

Bhuyan et al. (2003) compared the performance of WEPP, EPIC, and ANSWERS models to predict soil loss from small plots under three tillage systems (ridge-till, chisel-plow, and no-till) at Kansas State University's East Central Experimental field in Ottawa, Kansas. Models were evaluated with root mean square error (RMSE) (Thomann, 1982) and NSE (Nash and Sutcliffe, 1970) statistical methods. The optimal value for RMSE is zero which indicates that simulated values are a perfect match with observed values. NSE value range from $-\infty$ to 1.0 with 1.0 indicate a perfect match between simulated and observed values. WEPP model performed better than EPIC and ANSWERS in all tillage system comparisons. RMSE values reported for ridge till, chisel plow, and no till were 0.1183, 0.2521, and 0.0590, respectively. NSE values for ridge-till, chisel plow, and no till were 0.1055, 0.1301, and 0.6310, respectively. Authors reported that effective hydraulic conductivity, inter-rill erodibility, and critical shear values were the most sensitive parameters in the WEPP model.

Reyes et al. (2004) compared soil loss predictions from GLEAMS, RUSLE, EPIC, and WEPP models using 17 months of observed runoff and soil loss from a field scale study in Greensboro, North Carolina. Three replications of each of the following four treatments were tested: 1) conservation tillage (CT), 2) strip tillage (ST), 3) no tillage with controlled traffic (NC), and 4) no tillage with full traffic (NF). Crops grown were soybean and corn. Soil and management inputs parameters were acquired from local data, literature, and the WEPP user manual. The WEPP breakpoint climate data generator (BPCDG) was used for weather generation. Comparative results indicated that neither of the models predicted sediment yield satisfactorily. Authors attributed the relatively short data period and incorrect or incomplete estimation of parameters for the unsatisfactory results. WEPP in particular, underpredicted soil loss by 14, 29, 46, and 34% of the mean observed soil loss for the CT, ST, NC, and NF treatments, respectively.

Amore et al. (2004) evaluated the scale effect in USLE and WEPP models for prediction of sediment yield on three Sicilian basins located upstream of Ragoleto (115 km^2), Trinita (185 km^2) and Pozzillo (570 km^2) reservoirs, Italy. Each basin was subdivided into hillslopes using morphological criterion derived from Digital Terrain Maps (DTMs). As a result, the following three subdivision methods were selected for each basin: 1) fine scale, 2) gross scale and 3) an intermediate scale. Three sets of hillslopes for each basin were obtained by superimposing morphological subdivisions on the soil and land use map. Each hillslope was characterized by unique shape, topography, soil, and land use. The following were noted; 1) both models were applied to areas with slope length greater than recommended, 2) average hillslope area and length in the runoff direction for each subdivision were similar for the two smaller basins, and 3) steepness varied significantly among the three basins. Both the USLE and WEPP models showed insensitivity to hillslope area on sediment yield and did not have improved results using finer subdivisions. WEPP over-predicted sediment yield but was closer to measured values than USLE which under-predicted sediment yield. The study also revealed that relative error in respect to measured data with both the models was lower as soil erosion rates increased.

Pieri et al. (2007) simulated seven years (1999-2005) of observed runoff and sediment yield using WEPP v2006.201 on eight experimental plots in the Centonara watershed, Italy. Data for runoff, soil water and sediment, and weather were collected on an hourly basis. Crop biomass energy ratio and effective hydraulic conductivity parameters were first calibrated to simulate the hydrologic and erosion impact of three crop rotations including corn, wheat, and alfalfa-alfalfa on runoff and sediment yield reduction. Results indicated that WEPP under-predicted sediment yield in all years. Further evaluation and calibration of soil erodibility parameters including inter-rill erodibility, rill erodibility, and critical shear were suggested to improve the erosion prediction in the study area.

Pandey et al. (2008) conducted a study on a large agricultural watershed (2793 ha) in India using WEPP. Daily measured runoff and sediment yield data were collected for the monsoon season (June to September) from 1992 to 2000. The watershed was divided into seven sub-watersheds. Hillslopes were delineated within each sub-watershed using the methodology adopted by Amore et al. (2004). For weather generation, breakpoint climate data generator was used. Slope and soil files were built within the WEPP interface using DEMs and soil maps. The WEPP model was calibrated using 1996 observed runoff and sediment data. For validation, data from 1992 to 2000 excluding 1996, were used. Sensitivity analysis of the model showed that runoff was sensitive to effective hydraulic conductivity whereas sediment yield was sensitive to effective hydraulic conductivity, inter-rill erodibility, rill erodibility, and critical shear. WEPP model performance measured for sediment yield simulation resulted in coefficients of determination (R^2) from 0.81 to 0.95 and NSE from 0.78 to 0.92 which indicate WEPP model's satisfactory performance in a large agricultural watershed.

Abaci et al. (2009) carried out research on a small agricultural watershed in a sub-watershed of Clear Creek in Iowa. Authors used the WEPP v2008.907 model to provide an enhanced understanding of the long term impact on erosion from rainfall associated land use and management practices. For long-term (100-yr) continuous simulation, CLIGEN (CLImate GENerator), a synthetic weather generator was used. Model predictions were compared with field data collected from 1997 to 2007. The R^2 and the ratio of mean of predicted versus observed monthly water discharge was 0.81 and 0.78, respectively. The R^2 and ratio of mean for the monthly sediment yield was 0.92 and 0.92, respectively. Similarly, R^2 and mean for yearly water discharge was 0.84 and 0.77, respectively. The R^2 and mean for yearly sediment yield were 0.93 and 0.94, respectively. Overall results indicated that land management practices significantly influence the impact of precipitation on long term soil erosion in a small watershed.

1.4 SUMMARY OF LITERATURE REVIEW

In summary, literature on the effects of silvicultural practices and BMPs on forested watersheds indicates that BMPs are effective in the protection and improvement of water quality. The substantial challenges inherent in forestry field studies make field data collection difficult and expensive. Consequently, numerous studies have been conducted using soil erosion models to provide an effective means to evaluate effects of land use and land change on water quality. Literature indicates that numerous studies have been conducted with the WEPP model on agricultural land. However, fewer studies have been conducted with WEPP to quantify runoff and sediment yield for silvicultural practices on forested watersheds. Past WEPP studies on agricultural and forested regions helped develop the methodology used in the current study to evaluate the effects of silvicultural practices and BMPs at a watershed level in an effort to preserve forest resources and water quality. The present study contributes to the body of knowledge concerning the application of a calibrated WEPP model to evaluate the effectiveness of forest BMPs.

CHAPTER 2

METHODS

2.1 WATERSHED AND TREATMENT DESCRIPTION

The forested watershed (4.54 km^2) is located in northeast Houston county in the Johnson Creek watershed in East Texas (31.46° N, 95.26° W) (Figure 2.1). The watershed consists of both ephemeral and perennial streams. Elevation ranges from 89 to 141 m with slopes from 0 to 13%. The area has a humid subtropical climate with mean annual precipitation of 1130 mm and mean annual temperature of 20° C. Dominant soil in the study watershed is the Cuthbert series (fine, mixed, semiactive, thermic Typic Hapludults) (Table 2.1). Uplands soils are generally Cuthbert (fine sandy loam) and riparian soils are Rentzel (loamy fine sand). Other soil series found in the study watershed are Lilbert, Tenaha, and Bowie, all fine sandy loam soils. Vegetation in the study watershed consists predominantly of loblolly pine plantations (*Pinus taeda* L.). The underlying formations in the watershed are dominated by sandstone and shale (Soil Survey, USDA, 2004).

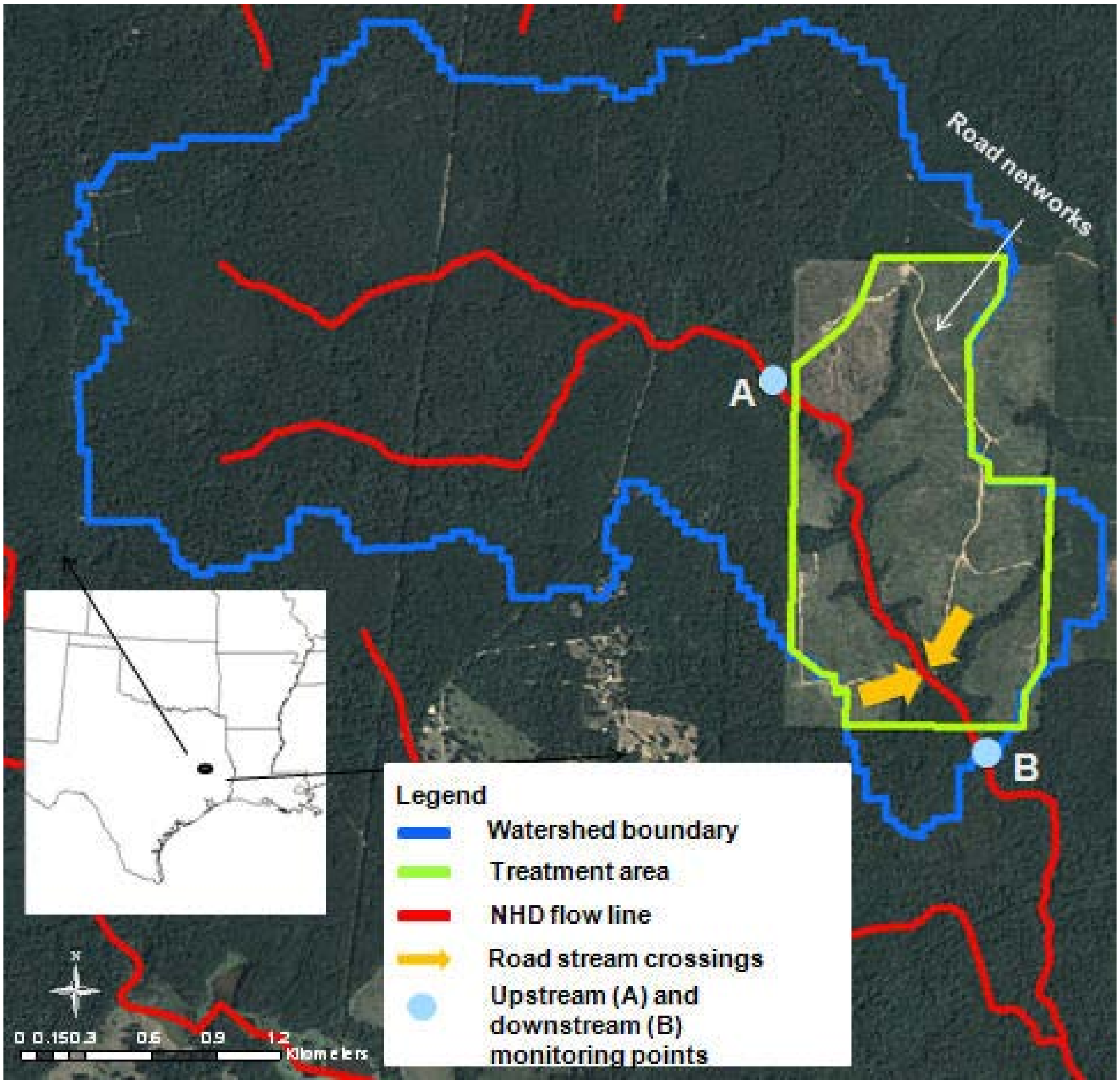

Figure 2.1 Aerial photograph of the Johnson Creek watershed (4.41 km^2), Houston County, Texas showing watershed boundary, post-harvest treatment area, location of road stream crossings, NHD flowline and upstream (A) and downstream (B) monitoring points.

Table 2.1 Soil series, soil types, and percent area of each soil series in the study watershed.

Soil Series	Soil Type	Percent Area
Cuthbert	Fine Sandy Loam	51
Bowie	Fine Sandy Loam	10
Rentzel	Loamy Fine Sand	14
Lilbert	Loamy Fine Sand	13
Tenaha	Loamy Fine Sand	11

Source : Natural Resources Conservation Service, USDA

Rainfall and runoff in the study watershed was monitored from November 2003 until September 2007 to evaluate the effectiveness of Texas Forestry Best Management Practices (BMPs) including SMZs, broad-based dips, and culverts to protect water quality. This was done to test the hypothesis that forestry operations, using properly applied BMPs, would not have a significant impact on water quality. Project sites were divided into two sections. The reference (point A) was located upstream of the treatment area and the test (point B) was located downstream of the treatment area.

Prior to harvesting operations, a culvert (length = 30 feet, diameter = 24 inch) was installed at the road stream crossing (Refer Figure 2.1 for location). Approximate date of culvert installation was 1 January, 2005. Harvesting began on 8 December, 2004 and was delayed approximately for a month due to wet weather. After harvesting was complete, the culvert was removed on 17 August, 2005. The road stream crossings were completely restored on 11 November, 2005 by seeding of road bed.

Test sections were established at an upstream (Point A), reference point and a downstream (Point B) watershed outlet point relative to the harvested treatment area. The clearcut treatment area of 1.14 km^2 comprised approximately 25% of the total 4.41 km^2 watershed area (Figure 2.1). Rainfall, runoff volume, and total suspended solids (TSS) data was collected for one year prior to treatment and for three years after the clearcut treatment both upstream and downstream of the treatment area (points A and B, respectively, Figure 2.1). Total nitrogen (TN) and total phosphorus (TP) were also monitored upstream and downstream of the treatment area. Only observed streamflow and TSS data were used in the present study. Harvests were conducted in accordance with Texas state recommended BMP guidelines (Texas Commission on Enviromental Quality, 2003) for commercial clearcut timber harvest, site preparation, and machine replanting of loblolly pine. Streamside management zones (SMZs) of 22.9 meters wide were retained along all streams during harvest. Road networks were constructed to provide access to the treatment areas harvest operations. During the post-harvest period, broad-based dips were installed after every 91 meters to divert the sediment laden runoff from roads into the vegetation.

2.2 DATA COLLECTION, MANIPULATION AND PREPARATION

A standard National Weather Service tipping bucket rain gauge was installed at the center of the treatment area. Precipitation was recorded with an Onset (Bourne, MA)

HOBO® event data loggers (Figure 2.2). Precipitation depth was measured to the nearest 0.254 mm for every storm flow event. Flow-weighted composite stormwater samples were also collected from the stream adjacent to the treatment area. An ISCO (Lincoln, NE) 4230 bubbler flowmeter was used to measure stage (flow depth) at stream monitoring points at continuous 15 minute intervals. A stage-discharge relationship was established during the study by estimating flow rate (discharge) with a Marsh-McBirney flowmeter at recorded stage events. Upon detecting a 0.9 meter rise in stream level, the bubbler flowmeter kept inside a metal box activated an ISCO 3700 water sampler (Figure 2.3). When the water sampler was enabled, samples were automatically collected upto 24 1000 ml plastic bottles. Sampling methods were in accordance with the protocols established by the Texas Commission on Environmental Quality (TCEQ, 2003). Flow-weighted composite samples retrieved from the sampler were manually flow weighted and placed in pre-preserved labeled sample bottles and placed on ice until delivered to the laboratory for analysis of TSS, TP, and TN concentration.

Figure 2.2 Rain gauge installed within the harvested treatment area. (Source: Texas Forest Service)

Figure 2.3 Stream monitoring station with ISCO 3700 water sampler and data logger inside raised metal box. (Source: Texas Forest Service)

Stormwater runoff samples were typically collected once every two weeks and more frequently after selected rainfall events. During the entire 4-year study period that included pre- and post-harvest operations, samples from 16 and 39 storm flow events, respectively, were collected at the upstream monitoring site (Point A). At the downstream monitoring site (Point B), samples from 16 and 39 pre- and post-harvest storm flow events, respectively, were collected. The intensity and duration of each rainfall event was determined using recorded tipping bucket data. The discharge hydrograph for resulting storm flow was graphed using ISCO Flowlink ® 5 software. Runoff ratios were determined for each rainfall-runoff event to check that runoff did not exceed approximately 50% of rainfall. Whenever this occurred, an error was indicated and the manual hydrograph delineation was adjusted.

During the study period, storm flow samples were collected after several storm flow events or sometimes frequently after a single storm flow events. After examining all rainfall and stormflow hydrograph data, only those storms from which the sampler detected and collected samples from single storm flow events were selected to compare measured data with WEPP model simulation results. Single events those from Point B only were selected because of inconsistency between Point A and Point B monitoring results. Comparative analysis of matching storm flow data from upstream (Point A) and downstream (Point B) monitoring points indicated lower storm flows at Point B compared Point A for all pre- and post-harvest storms indicating either flow data error or transmission loss within the stream channel. As a result, calculated sediment loads indicated that approximately 27% of pre-harvest and post-harvest storm flows at Point B had less sediment loads than the upstream monitoring Point B.

As a result, 13 and 20 storms were selected to represent pre-harvest conditions, respectively, downstream of the treatment area. Stormflow volume for each storm was calculated using a start and end time determined by visual inspection of the manually delineated discharge hydrograph. Sediment loading (kg ha^{-1}) for each storm flow event was computed using the composite sample concentration (TSS) multiplied by storm flow and divided by the area of the watershed.

Upstream and downstream sediment load comparisons as well as photographic observation (Figure 2.4) indicates that channel scouring and sediment deposition were occurring within the stream.

Figure 2.4 Channel scour on the bank of second-order stream (C3) during the pre-harvest period, September 9, 2004. (Source: Texas Forest Service)

The main focus of the Texas Forest Service study was to evaluate the effectiveness of streamside management zones along streams after harvesting. Consequently, above and below sample points were intended to provide a direct comparison of sediment calculation both before and after harvest. Simulations with the WEPP model used only the downstream monitoring data as a means to calibrate the entire watershed that included both harvested and non-harvested areas. The WEPP model was calibrated for pre- harvest conditions after processing all non-excluded observed storm flow and sediment data at the downstream monitoring point (Point B). Validation of the WEPP model was attempted using post-harvest conditions. Figure 2.5 shows the occurrence for pre- and post-harvest storm events selected for calibration and validation.

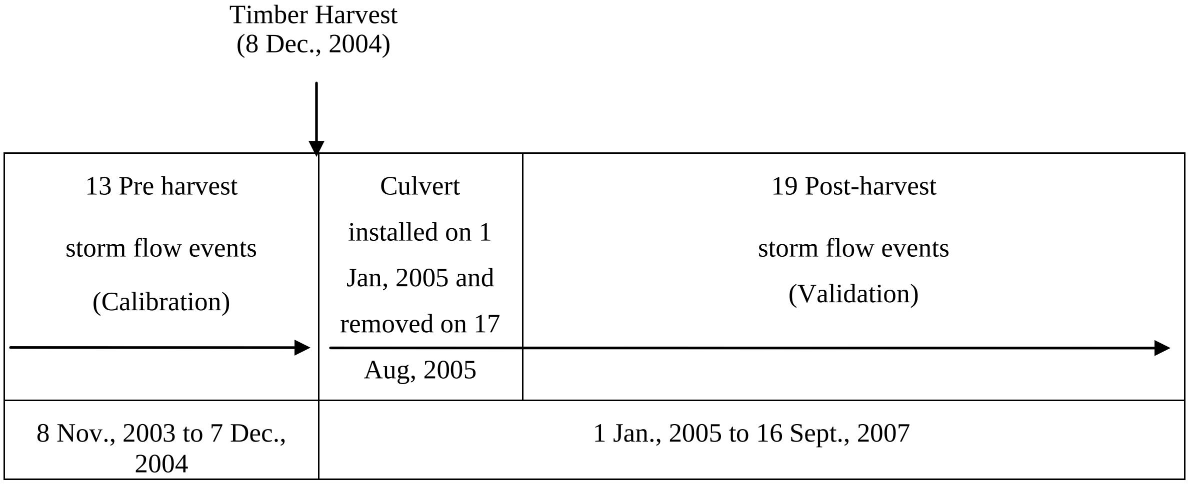

Figure 2.5 Timeline for pre- and post-harvest storms used for runoff and sediment yield calibration and validation at the watershed outlet.

2.3 SIMULATION METHODOLOGY

2.3.1 MODEL DESCRIPTION

The WEPP model evaluated in this study is a process-based, continuous simulation erosion prediction model built as an operating platform that incorporates multiple WEPP hillslopes. WEPP hillslope is based on the fundamentals of infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics. The WEPP hillslope model has the capability to estimate spatial and temporal distribution of soil loss for an entire profile (WEPP documentation, 1995).

Major data inputs to WEPP hillslope are a climate file, a slope file, a soil file, and a management file. The climate file can be built using two options; climate generator (CLIGEN) or breakpoint climate data generator (BPCDG). The CLIGEN program provides for selection of archived climate data from over 1,000 weather stations in the United States. The CLIGEN climate file provides several important precipitation variables including rainfall depth, duration, ratio of peak intensity to average rainfall intensity, and time to peak intensity. Other weather variables provided include daily maximum and minimum temperature, daily wind speed and wind direction, dew point temperature, and solar radiation (Laflen et al., 1994). In the BPCDG format, the user can manually specify the start and end time of rainfall, as well as the depth and intensity. The advantage of BPCDG over CLIGEN is that the user can input up to 50 breakpoint precipitation events in one day. The soil and management files can be built either in the WEPP hillslope interface, by text editor, or by direct import from WEPP archives. WEPP hillslope and watershed output in terms of runoff and sediment yield can be reported on a storm-by-storm, monthly, or average annual basis (Laflen et al., 1994).

The hillslope component of WEPP simulates the following processes: surface hydrology and hydraulics, subsurface hydrology, vegetation growth and residue decomposition, and sediment detachment and transport. The surface hydrology component in WEPP uses climate and management practices information to maintain a daily soil water balance. The sequences of calculations used for surface hydrology are infiltration, rainfall excess, depression storage, and peak discharge. Rainfall excess calculated in minute time step, represents the difference between rainfall rate and infiltration rate computed using the modified Green Ampt Mein-Larson equation (Mein and Larson, 1973; Chu, 1978). Overland flow routing and peak discharge estimation is performed using the kinematic wave equations when the model is run as a continuous simulation.

The subsurface hydrology routine computes lateral flows using Darcy's law. For forest applications, the layering of porous soil and low-permeability bedrock together with the effect of lateral tree roots leads to an anisotrophic system where subsurface lateral flow is greater than vertical flow (Bear, 1972; Brooks et al., 2004). Subsurface lateral flow from a hillslope is subsequently added directly to channel flow under two conditions; 1) when surface runoff and subsurface lateral flow occur simultaneously and 2) when only subsurface lateral flow occurs. In either case, it is assumed that subsurface lateral flow does not contribute sediment to the stream channels.

In WEPP, plant growth is simulated as a function of temperature, solar radiation, and soil water content. The soil-water balance is updated as a function of precipitation, infiltration, runoff, soil evaporation, plant transpiration, and subsurface runoff (Figure 2.6). The model maintains a continuous daily water balance using the following equation:

$$\theta = \theta_{\mathbf{in}} + \mathbf{P} - \mathbf{I} - \mathbf{D_s} - \mathbf{R} - \mathbf{R_s} - \mathbf{T_p} - \mathbf{E_s} - \mathbf{D} \qquad (8)$$

where

θ = the soil water content in the root zone in any given day,

θ_{in} = the initial soil water in the root zone, m

P = the cumulative precipitation, m

I = the cumulative interception loss, m

D_s = cumulative depression storage, m

R = the cumulative amount of surface runoff, m

E_si= the cumulative soil evaporation, m

T_p is the cumulative amount of evapotranspiration, m

D = the cumulative amount of percolation loss below the root zone, m

and R_s = subsurface lateral flow, m

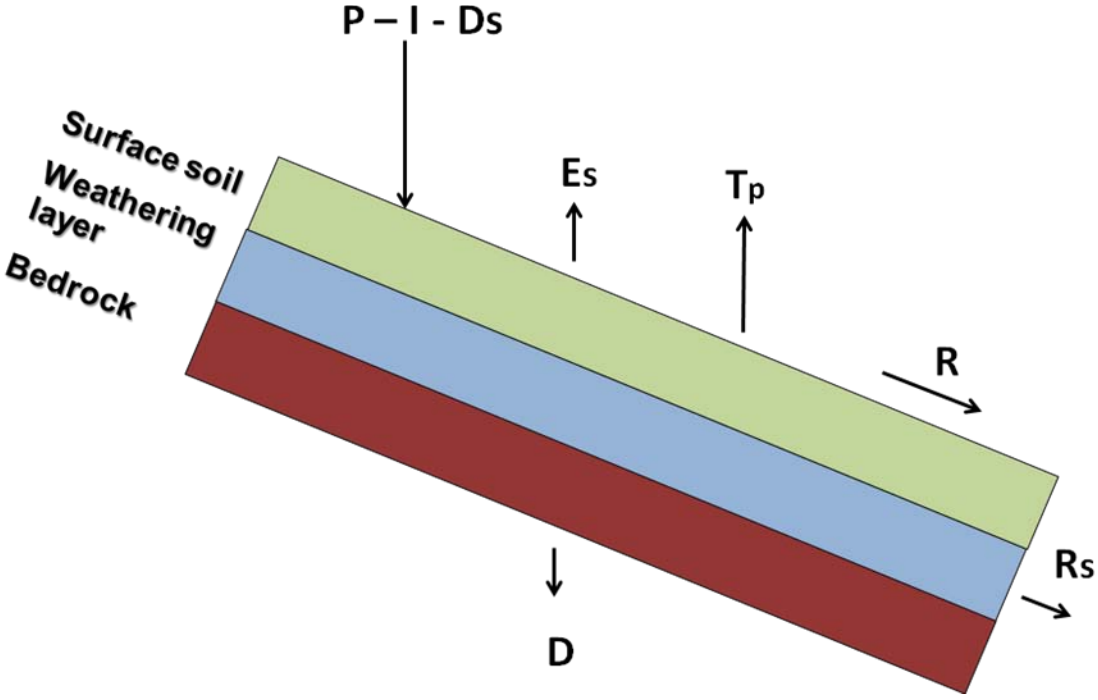

Figure 2.6 Hydrologic processes modeled by WEPP on a forest hillslope. (Adapted from Dun et al., 2008)

Interactions of vegetative and surface cover with runoff determine soil erosion and deposition across the hillslope. According to Laflen (1994) the status of plants and residue cover is vital to accurately estimate soil detachment and transport. The status of below and above-ground biomass must be accurately estimated to evaluate the effect of various management alternatives on soil erosion.

Soil erosion is represented in two ways by WEPP in an overland flow profile; 1) detachment of soil particles by raindrop impact and sheet flow on interrill areas and 2) soil particle detachment, transport, and deposition by concentrated flow in rill areas. Rill erosion is modeled as a function of flow capacity to detach and transport soil, versus the existing sediment load in the flow stream. To describe the movement of sediment in a rill the erosion component of WEPP uses a steady state sediment continuity equation (WEPP documentation, 1995) of the form:

$$\mathbf{dG}/\mathbf{dx} = \mathbf{D_f} + \mathbf{D_i} \qquad (9)$$

where:

x = distance downslope, m

G = sediment load, kg s^{-1} m^{-1}

D_f = rill erosion rate, kg s^{-1} m^{-2}

D_i = interrill sediment delivery to the rill, kg s^{-1} m^{-2}

The observed inter-rill erodibility (K_i) values were calculated using the formula (Elliot et al., 1989):

$$D_i = K_i I^2 S_f \qquad (10)$$

where:

D_i = interrill erosion rate, kg m^{-2} s^{-1}

K_i = interrill erodibility, kg s m^{-4}

I = rainfall intensity, m s^{-1}

S_f = slope factor (dimensionless = $1.05 – 0.85 \exp^{(-0.85 \sin[\theta])}$ where theta is expressed in degrees).

Soil detachment in rills occurs when the hydraulic shear stress exceeds the critical shear stress of the soil and when sediment load is less than sediment transport capacity. For the case of rill detachment, the equation is of the form:

$$\mathbf{D_f = D_c \left(1 - \frac{G}{T_c}\right)} \qquad (10)$$

where:

D_c = detachment capacity by rill flow, kg s^{-1} m^{-2}

T_c = sediment transport capacity in the rill, kg s^{-1} m^{-1}

When the hydraulic shear stress of rill flow exceeds the critical shear stress of the soil, detachment capacity, D_c is computed as follows:

$$\mathbf{D_c = K_r\ (\tau_f - \tau_c)} \qquad (11)$$

where:

K_r = rill erodibility parameter, s m^{-1}

τ_f = flow shear stress acting on the soil particles, Pa

τ_c = ctitical shear stress of the soil, Pa

Deposition occurs when the sediment load, G, is greater than the sediment transport capacity, T_c. For the case of deposition, the equation is as follows:

$$\mathbf{D_f = \frac{\beta\ V_f}{q}\ (T_c - G)} \qquad (12)$$

where:

V_f = effective fall velocity for the sediment, m s^{-1}

q = flow discharge per unit width, m^2 s^{-2}

β = a raindrop-induced turbulence coefficient.

The sediment transport capacity at the end of the slope is calculated using the modified Yalin equation (1963) (WEPP Documentation, 1995). The transport capacity

(T_c) is a function of flow shear stress and is calculated using a simplified transport equation of the form

$$\mathbf{T_C = k_t \, \tau_f^{3/2}} \tag{13}$$

where:

τ_f = hydraulic shear acting on the soil, Pa

k_t = a transport coefficient, $m^{0.5}$ s^{2} $kg^{-0.5}$

For watershed application, the sediment yield from an entire field can be estimated. The WEPP watershed model allows linkage of hillslopes with channels and impoundments. The channel component includes treatment of channel hydrology and erosion. The channel erosion component of the WEPP watershed model is similar to the simulation of rill erosion on the hillslopes. Channel hydrology routines compute infiltration, evaporation, soil water percolation, canopy rainfall interception, and surface depression storage similar to hillslope hydrology routines. The watershed model component assumes that hillslope erosion is either from a hillslope through overland sheet flow or from channels as a result of concentrated flow. Two methods are provided to estimate peak flow at a channel outlet, 1) the Rational equation similar to EPIC, and 2) the empirical equations in CREAMS model (WEPP documentation, 1995). The peak discharge at the channel outlet in CREAMS model is calculated using the equation

$$\mathbf{q_{po} = (7.171\,e^{-04})\,A_w{}^{0}.7\ S^{0}.159\ v^{0.71764\,(A_w\,0.0166)} lw^{-0.187}} \tag{14}$$

where:

q_{po} = the peak discharge at the channel outlet, m^3 s^{-1}

v = the average runoff depth at the channel outlet, in

lw = the watershed length to width ratio, unitless

A_w = the watershed area contributing to the channel, m^2

The CREAMS method to estimate peak flow was statistically derived using data from large watersheds usually greater than 70 hectares (WEPP documentation, 1995). Consequently, the CREAMS method for peak flow estimation was used in this study.

2.3.2 CREATION OF CLIMATE DATA

The breakpoint climate data generator, BPCDG (Gete et al., 2009) creates climate data from user observed weather data sets. BPCDG requires four input files. The first file requires precipitation information such as date, start and end of rainfall, rainfall depth, and intensity. The second file contains daily minimum and maximum temperature, and wind velocity and direction at 8 and 18 hours. The third file contains solar radiation (monthly or annual), dew point temperature (monthly or annual), and conversion tables for wind velocity and direction. The fourth file contains descriptive information such as station name, location, elevation, and years of record. Breakpoint rainfall data in this study was recorded from an on-site tipping bucket rain gauge. Maximum and minimum temperatures were obtained from the National Climatic Data Center (NCDC) for Houston County. Synthetic daily dew point temperature, solar radiation, and wind speed and direction data were generated on a daily basis using CLIGEN weather data generator from 2004 to 2007 (Flanagan, 2001). An example of a BPCDG file created for the simulation is presented as Appendix B.

2.3.3 SOIL INPUT FILES

The WEPP hillslope model contains archives for four textural classes of forest soils including sandy loam, loam, silt loam, and clay loam. These pre-programmed layers are used to identify each soil into one of the four textural classes. Texture classes are subsequently used by WEPP to estimate other important soil parameters including effective hydraulic conductivity, inter-rill erodibility, rill erodibility, and critical shear. Only four textural classes are available for forest soils because there are not enough data from forested areas to justify a more detailed classification (Elliot et al., 2000).

Because dominant soils series in the study watershed was Cuthbert (Soil Survey, USDA, 2004), each hillslope's soil properties were represented using a Cuthbert soil. The first step in developing the WEPP model was building the base soil files. Rather than relying completely on the default soil properties calculated from soil texture in WEPP, default soil files were revised using literature values and soil survey data (USDA, 2004). For example, the soil texture composition of the Cuthbert soil in terms of percent sand, silt, and clay was obtained from literature (Saleh et al., 2004). Effective hydraulic conductivity values and layer depth were taken from USDA County soil survey information. Default values for WEPP forest sandy loam soils were used for organic matter content, cation exchange capacity and percent rock. Because WEPP also allows the input of two critical hydrologic variables, anisotrophy (dominance of horizontal flow versus vertical flow) and saturated hydraulic conductivity of the restrictive layer (K_{sat}), these parameters were used to calibrate the hydrologic model. The restrictive layer in the study watershed beneath the Cuthbert series is sandstone (Soil Survey, USDA 2004) with a hydraulic conductivity varies from 108 x 10^{-5} to 21.6 mm hr^{-1} (Domenico and Schwartz, 1998). Example of soil file used for simulation is shown in Appendix C.

2.3.4 CHANNEL INPUT FILES

Channel parameters vary from watershed to watershed and from channel to channel within a watershed (Liu et al., 1997). WEPP default values for channel management were used for parameters such as depth to non erodible layer in mid channel, depth to non erodible layer on channel sides, Manning roughness coefficient for bare soil in the channel, and total Manning roughness coefficient including vegetation. A channel erodibility factor was used to calibrate sediment yield from the channel. For the channel soil input file, WEPP forest sandy loam default values were used.

2.3.5 MANAGEMENT INPUT FILES

Field studies have shown that the amount of surface cover has a dominant role in controlling runoff and erosion (Dissmeyer and Foster, 1981; Robichaud and Brown, 2002). WEPP model predicts surface cover every day after accounting for biomass accumulation from senescence (leaf fall) and loss through decomposition. Vegetative and surface cover is important in the determination of runoff and subsequent estimation of soil detachment and transport. Reported percent ground cover for the pre- and post-harvest conditions in this study was estimated using the step-point transect method (Evans and Love, 1957) on similarly harvested sites. Estimated percent ground cover before and after harvest is shown in Table 2.2. To estimate ground cover for the study watershed, similar harvested sites were selected based on their 1) geographic proximity to the original study watershed, 2) similarity in soil type (sandy loam) to the original site, and 3) age of the harvest corresponding to pre-harvest, harvest, first-year post-harvest, second year post-harvest, and third year post-harvest conditions. Total reported ground cover during the first-year after harvest (Table 2.2) decreased likely due to random sampling error since it would be expected to increase during the first year post-harvest period.

For an undisturbed forest, the default file in WEPP (Forest Perennial management file) assumes 100 percent inter-rill cover and 90 percent initial canopy cover. An example of the Forest Perennial file used to simulate undisturbed forest cover conditions is presented in Appendix D. Comparison of predicted inter-rill cover and measured ground cover for undisturbed forest are shown in Appendix G. For the treatment area in this study, a perennial forest growth routine was activated to represent regeneration of forest cover after harvest (Table 2.2). For the clearcut harvested area, the default Shrub Perennial management file was used for cover calibration after revising initial canopy cover to an assumed 10 percent (based on aerial photograpy). The parameters used to calibrate interrill cover for the undisturbed forest and the clearcut harvested area were biomass energy ratio, decomposition rate, and biomass remaining after senescence. These parameters were adjusted to obtain cover values increasing from 80% at harvest and increasing annually until 99% cover is achieved within 3 years. Estimated versus simulated forest growth is shown in Appendix H. The management file used for a road stream crossing during the period when the culvert was installed was a Forest Insloped Road – Unrutted. A Grass management file was used after the culvert was removed to represent the actual post-harvest road BMP conditions for the simulation. For SMZs, Forest Perennial management file was used similar to that used for undisturbed forest.

Table 2.2 Estimated ground cover for pre- and post-harvest conditions at study site using step transect method (Evans and Love, 1957).

Simulation Period	Ground Cover
Pre-harvest	100
At harvest	80
1st year post-harvest	73
2st year post-harvest	83
3st year post-harvest	99

2.3.6 TOPOGRAPHIC DATA AND WATERSHED DELINEATION

The watershed structure and slope files for the WEPP watershed model were generated from GeoWEPP, the geospatial interface for WEPP. For the study watershed, a 30 m DEM was downloaded from the National Map (USGS, 2002). GeoWEPP uses topographic analysis software, Topographic Parameterization (TOPAZ, Garbrecht and Martz, 1999) to divide watersheds into hillslopes and create the slope files required to run WEPP. Example of slope file used is shown in Appendix D. Input parameters required for TOPAZ includes the minimum source channel length (MSCL) and critical source area (CSA). The values for MSCL and CSA were adjusted until the derived channel network visually matched the observed channel network on the topographic map of the study watershed. For this research, the critical source area was fixed at 10 hectares and the minimum source channel length was fixed at 100 meters. The GeoWEPP delineated channels on the topographic map along with National Hydrography Datasets (NHD) lines are presented in Figure 2.7. The WEPP watershed interface, opened through GeoWEPP, discretized the watershed into 52 hillslopes and 21 channels to simulate pre-harvest conditions. GeoWEPP delineated subwatersheds and channels for pre-harvest conditions are presented in Figure 2.8. For each first-order stream, three hillslopes (left, right, and top) drain into a channel. Two hillslopes (left and right) drain into the second-order stream channel at the bottom of the watershed. For post-harvest conditions, 22.86 meters of SMZ were left along the streams within the treatment area. The clearcut treatment area (Figure 2.9) within each subwatershed was calculated and was represented as unique overland flow elements. Each hillslope profile was independently edited within the WEPP watershed interface. Insloped roads with channel connecting to a culvert were simulated from 1 Jan, 2005 until 17 August, 2005 at the road stream crossing to divert water from the roads to the upstream of the culvert. The remaining years of post-harvest simulations were conducted with grasses roads at the stream crossings without the culvert. Watershed structure file for pre-harvest, post-harvest with culvert and unpaved roads, and post-harvest without culvert and roads with grass management is presented in Appendix F.

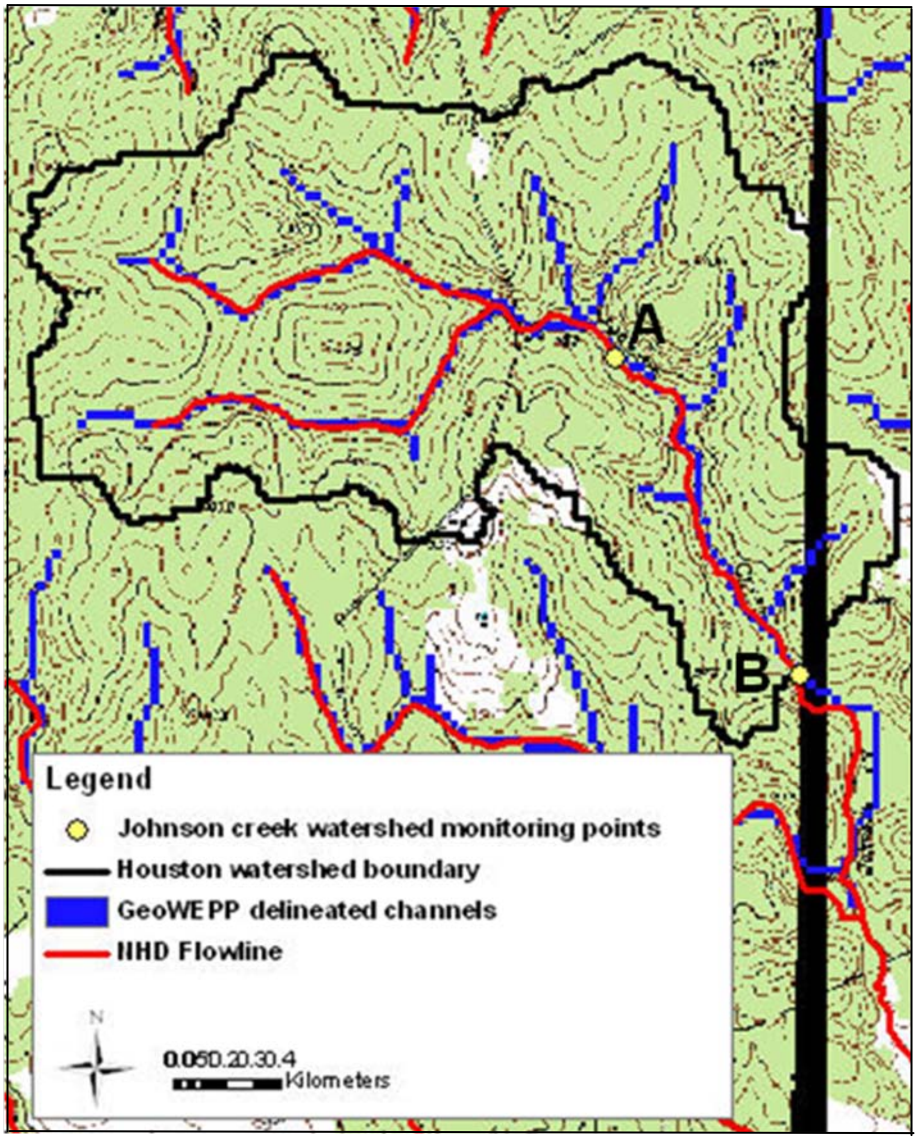

Figure 2.7 Topographic map of study watershed indicates GeoWEPP delineated watershed boundary and channels matching National Hydrography Dataset (NHD) flowline with upstream (A) and downstream (B) monitoring points.

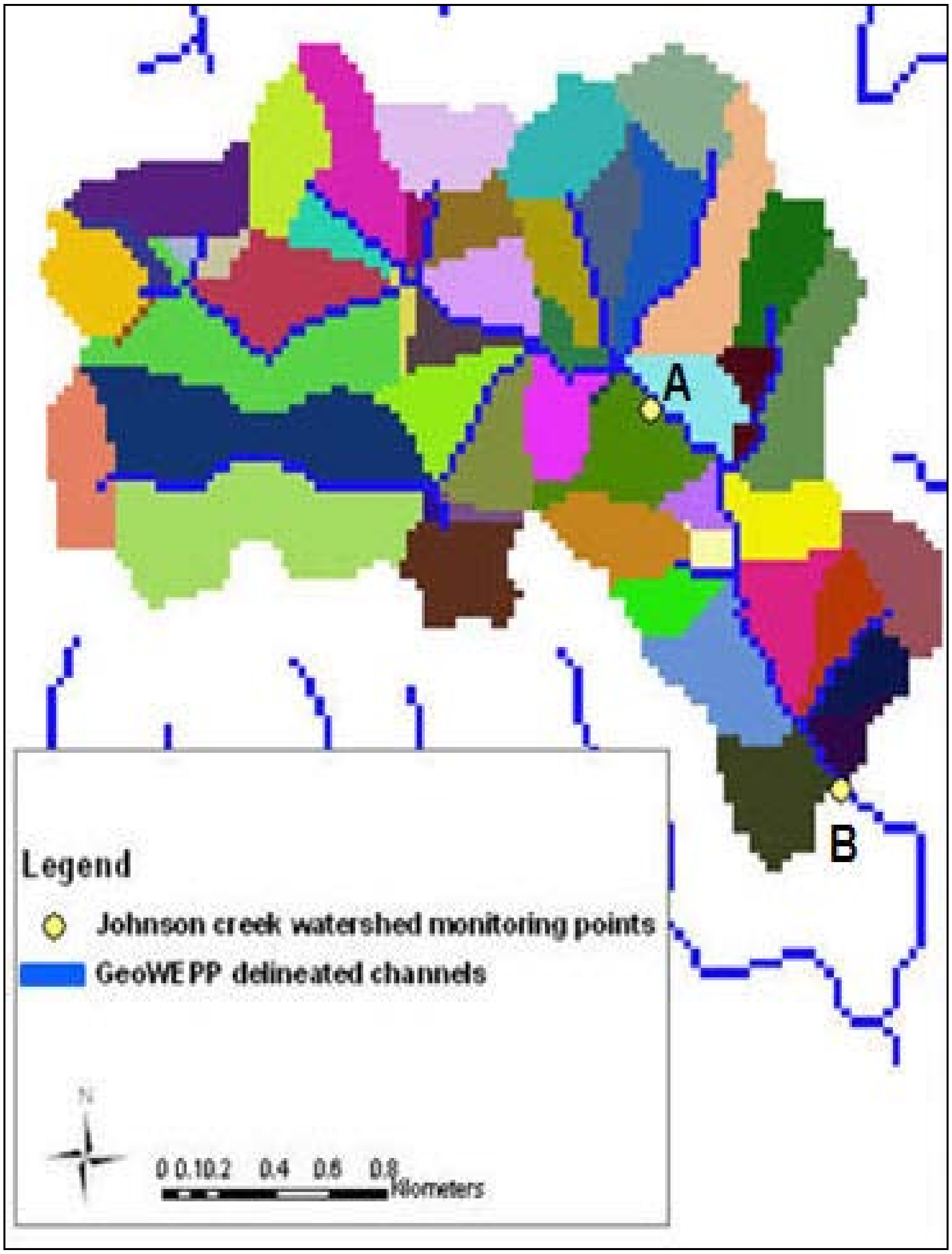

Figure 2.8 Study watershed showing 52 GeoWEPP delineated hillslopes and 21 channels with upstream (A) and downstream (B) monitoring points to simulate pre-harvest conditions.

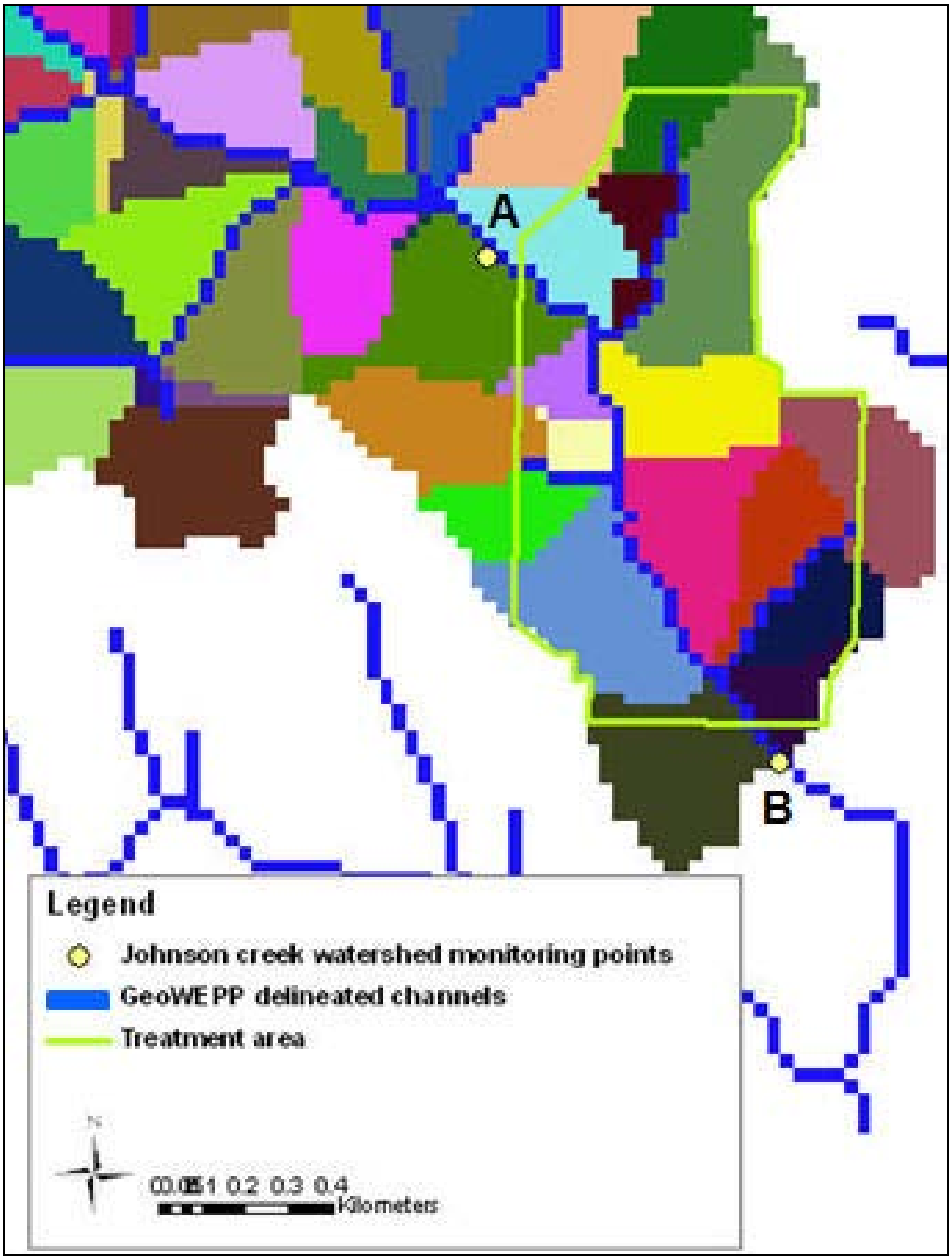

Figure 2.9 Study watershed shows treatment area within the watershed with upstream (A) and downstream (B) monitoring points simulating post-harvest conditions.

2.4 CALIBRATION AND VALIDATION

Model calibration is the process of estimating model parameters by comparing model predictions for a given set of assumed conditions with observed data for the same conditions (Moriasi, 2007). Model validation is the process of demonstrating that the model is capable of making sufficiently accurate simulations. For this study, continuous simulations were performed with the WEPP watershed interface for a four year period from 8 November 2003 to 16 September, 2007. The first year was used as a calibration period, with the remaining three years used for validation. The calibration of pre-harvest conditions at the watershed outlet was conducted using 52 hillslopes and 21 channels. The validation was conducted as two separate simulations. For the first eight months, with 54 hillslopes and 24 channels with roads and a culvert were included at the road stream crossing. The remaining years of validation were conducted using 54 hillslopes and 22 channels without culvert to represent the actual conditions at the site.

WEPP simulated runoff and sediment yield at the watershed outlet was calibrated using observed 13 selected storm runoff events in 2004 for pre-harvest conditions and was validated using 19 observed storm runoff events from 2005 to 2007. A serious limitation of the simulation is that the WEPP model predicts runoff and sediment for the storm events at the watershed outlet and does not simulate baseflow. Hence, WHAT baseflow separator program (Lim et., 2005) was used to separate total observed streamflow at the watershed outlet into direct runoff and baseflow components. WEPP runoff values were subsequently calibrated and validated using estimates of direct runoff from the WHAT baseflow program. For the study watershed, direct runoff determined from WHAT baseflow separator represents subsurface lateral flow (quick flow). WEPP sediment loads (kg/ha) were calibrated and validated with sediment estimated from WHAT baseflow separated runoff volume with sediment rating curves derived from observed data. Physically-based sediment rating curves were developed separately for pre- and post-harvest periods using observed total stream flow and observed total sediment. A sediment rating curve is a power function relationship between measured runoff (mm) and measured sediment yield (kg/ha). The following relationship derived by Walling (1974, 1978) was used to estimate sediment from direct runoff by putting direct runoff values for comparison with WEPP sediment yields in kg/ha:

$$\mathbf{SY} = \alpha\, \mathbf{Q}^{\beta} \tag{2.2.8}$$

where:

SY is sediment yield, kg/ha

Q is runoff, mm

α and β are constants

To calibrate predicted runoff and sediment with observed pre-harvest data the following information was used. Because observed overland flow in the study watershed was rare (personnel communication, Hughes Simpson), the effective hydraulic conductivity was fixed to limit overland flow from hillslopes. Hence, observed runoff at the watershed outlet was mainly by contribution of subsurface lateral flow from hillslopes. As a consequence, WEPP simulated runoff was calibrated by varying subsurface soil values for anisotrophy ratio and saturated hydraulic conductivity of bedrock. Since observed overland flow was negligible, most of the sediment yield at the watershed outlet is presumed to have come from the channel, possibly from channel scouring (personnel communication, Hughes Simpson, Texas Forest Service). Figure 2.4 shows photographic evidence indicating channel scouring on the bank of the second-order stream before harvest. The channel erodibility factor in WEPP is determined similar to hillslope rill erodibility. However, the channel erosion routines do not adjust channel erodibility as a function of climate, management, or other environmental factors as is done with rill erosion (WEPP User Manual, 1995). Particularly when hillslope sediment inputs are low and scour takes place within the channel, it is recommended to adjust the channel erodibility factor for channel erodibility (Baffaut et al., 1997). Hence, the sediment yield for pre-harvest conditions was calibrated by adjusting this critical channel erodibility factor. A summary of model parameters used for pre-harvest model calibration are shown in Table 2.3. Calibration was conducted by adjusting model parameters until model evaluation statistics for both runoff and sediment were satisfactory or better based on Moriasi et al. (2007) for all evaluation statistics ($NSE > 0.50$, $RSR < 0.70$, PBIAS for runoff $\leq \pm 25$, PBIAS for sediment $\leq \pm 55$) as discussed in the following section. Calibration was considered successful when the maximum Nash-Sutcliffe efficiency value was achieved. The validation was completed for post-harvest conditions using all calibrated pre-harvest input parameters with additional WEPP default road soil parameters (Table 2.4) for the roads at the stream crossing (Figure 2.10) for the remaining three years following the calibration period. In addition, a culvert section was modeled to simulate the constructed road crossing in place from 1 Jan, 2005 to 17 Aug, 2005.

Table 2.3 WEPP hillslope and channel soil parameters used for the calibration of pre- harvest runoff and sediment yield at the watershed outlet for 2004.

Hillslope and channel soil parameters	Value
Effective hydraulic conductivity (mm hr^{-1})	60*
Inter-rill erodibility (kg s m^{-4})	400,000*
Rill erodibility (s m^{-1})	0.0005*
Critical hydraulic shear stress (Pa)	2*
Anisotrophy ratio	8
K_{sat} (mm hr^{-1})	0.01
Channel erodibility factor (s m^{-1})	0.00002

***** WEPP default hillslope and channel soil parameter values used for pre-harvest conditions.

Table 2.4 Default WEPP road soil parameter values used for insloped roads at the stream crossings for post-harvest from 2005 to 2007.

Road soil parameters	Value
Effective hydraulic conductivity (mm hr^{-1})	3.8*
Inter-rill erodibility (kg s m^{-4})	2,000,000*
Rill erodibility (s m^{-1})	0.0004*
Critical hydraulic shear stress (Pa)	0.04*

***** WEPP default road soil parameter values used for pre-harvest conditions.

Figure 2.10 Road stream crossing constructed after harvest on 8 Dec, 2004. Refer Figure 2.1 for location. (Source: Texas Forest Service)

2.5 EVALUATION OF MODEL PERFORMANCE

In the present study, continuous simulation with WEPP model was performed for both pre- and post-harvest conditions. The model was calibrated for runoff and sediment yield using field measured data at the downstream monitoring location by adjusting surface and subsurface soil input parameters, as discussed in section 2.4. To evaluate model performance, quantitative statistical analysis methods including standard regression, dimensionless (NSE) and error index (RSR and PBIAS) were adopted based on the recommendations of the ASCE Task Committee (1993).

WEPP simulated runoff and sediment yield for all pre- and post-harvest storm runoff events were compared to measured data using mean, standard deviation (SD), coefficient of variation (CV), correlation coefficient (R) coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), RMSE-Observations standard deviation Ratio (RSR), and percent bias (PBIAS). Separate statistical analyses were conducted for the whole watershed with and without culvert for post-harvest runoff events to determine if the culvert incorporation improved the overall accuracy of the watershed model. Standard regression provided the best-fit regression line between simulated and measured data. Modeled results are in perfect agreement with observed data with a slope of one, y-intercept of zero, and R^2 of 1.0. NSE, a dimensionless model evaluation statistic is a goodness-of-fit criterion. A value of one indicates a perfect match between simulated and observed data whereas a value of zero indicates that model results are no better than the mean observed value and a value less than zero indicates that using the mean observed value is better than using predicted values. Correlation coefficient (R) indicates the strength of relationship between observed and simulated values. $R>0$ indicates positive linear relationship between simulated and observed values and $R<0$ indicates a negative linear relationship between them while $R=0$ indicates no linear relationship between them. RSR is an error index model evaluation method that standardizes the root mean square error (RMSE) of simulated and observed values divided by the observed standard deviation. RSR determines how close model predicted values are compared to observed values. RSR values of zero indicate model simulations are perfect. A large positive RSR value indicates large error between simulated and observed values.

PBIAS is an error index model evaluation method that indicates model accuracy in terms of over-estimation or under-estimation. Positive values signify model underestimation whereas negative values indicate over-estimation.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 PRE-HARVEST CALIBRATION

Runoff calibration

In the calibration period, 13 selected storm events out of total 16 available events were simulated for pre-harvest conditions using WEPP watershed model. The model was calibrated for runoff using WHAT baseflow separated runoff (surface and subsurface runoff). Simulated sediment yield was calibrated by comparison against estimated sediment from WHAT separated runoff derived from pre-harvest sediment rating curves. Results of pre-harvest WHAT estimated runoff and WEPP simulated runoff are shown in Figure 3.1. The scatterplot between WEPP simulated runoff and WHAT estimated runoff along with 1:1 line is presented in Figure 3.2.

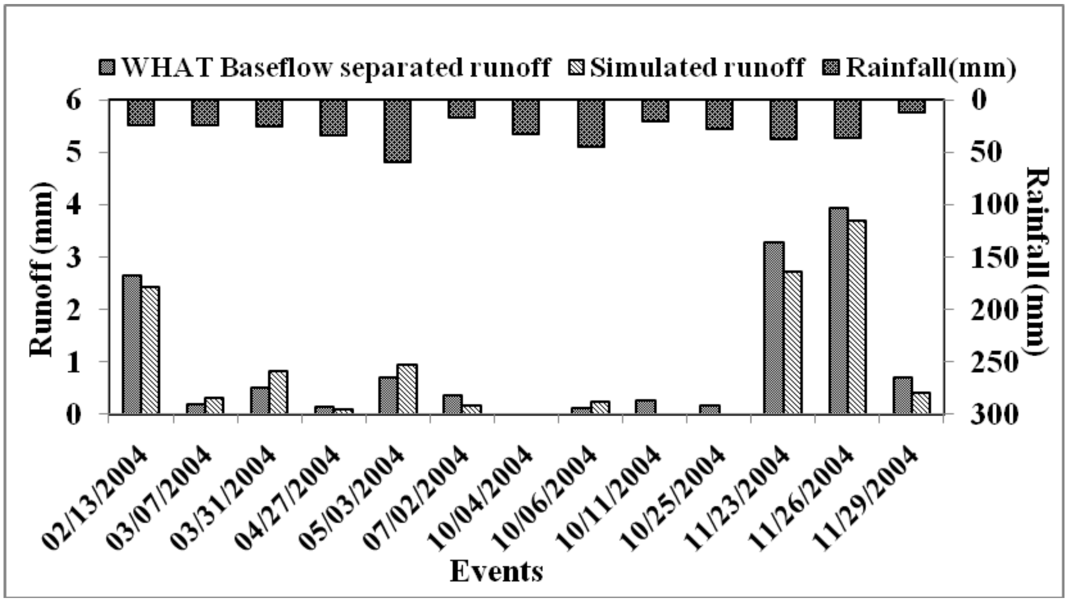

Figure 3.1 WHAT baseflow separated runoff and WEPP simulated runoff for pre-harvest conditions.

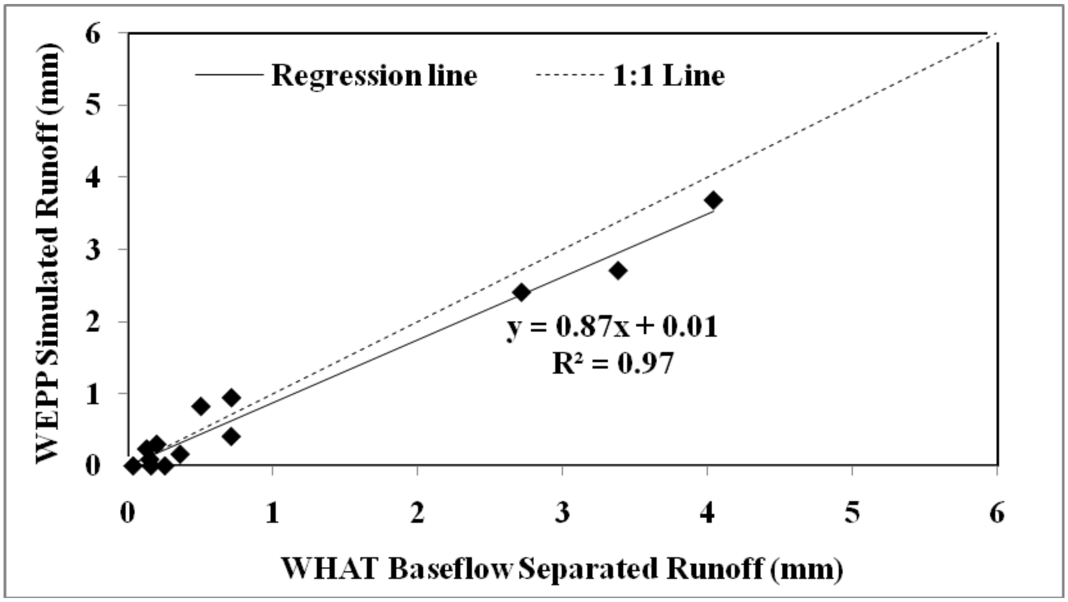

Figure 3.2 WEPP simulated runoff versus WHAT baseflow separated runoff for pre-harvest conditions.

It can be observed from Figure 3.1 that simulated runoff values are in general agreement with medium and high values of WHAT estimated runoff values. However, the model did not predict runoff in three low values of WHAT estimated runoff. WEPP simulated runoff and WHAT estimated runoff is compared along a 1:1 line in Figure 3.2. Figure 3.2 indicates that the WEPP simulated runoff values are uniformly distributed around the 1:1 line for low values of WHAT estimated runoff values. For higher values of WHAT estimated runoff, the WEPP simulated values are below the 1:1 line, indicating that the model under-predicted the high values of WHAT estimated runoff. High value of coefficient of determination ($R^2 = 0.97$) with a positive slope indicates a strong, positive linear relationship between WHAT estimated runoff and WEPP simulated runoff values.

Comparative statistical analysis of WHAT estimated runoff and WEPP simulated runoff is presented in Table 3.1. Mean of WEPP simulated runoff (0.91 ± 1.23 mm) of all simulated storm events is 12 percent lower than mean of WHAT estimated runoff (1.03 ±1.39 mm). A high value of Nash-Sutcliffe efficiency (NSE = 0.95) indicates very good performance of the flow calibrated component of the model. RSR value of 0.22 indicates that the under-prediction or over-prediction limits for WEPP simulated runoff is ±22% of WHAT estimated runoff. A positive value of percent bias (PBIAS = 11.67%) confirms the slight underprediction of pre-harvest runoff, which is also identified by a regression slope less than 1.0 (m = 0.87, Figure 3.2).

Table 3.1 Statistical comparison of WHAT estimated runoff and WEPP simulated runoff during pre-harvest calibration.

Statistical Parameters	Runoff (mm)	
	WHAT estimated	WEPP simulated
Mean	1.03	0.91
SD	1.39	1.23
CV(%)	135	135
R^2	0.97	
NSE	0.95	
RSR	0.22	
PBIAS (%)	11.67	

Sediment calibration

The WEPP simulated sediment and sediment estimated from WHAT estimated runoff is graphically shown in Figure 3.3 and the scatterplot between WEPP simulated sediment and sediment estimated from WHAT estimated runoff along the 1:1 line is graphically shown in Figure 3.4. A sediment rating curve (Appendix E) was developed between total observed sediment and total observed stream flow. High value of coefficient of determination (R^2 = 0.81) between total observed sediment and streamflow indicates a reasonable fit of observed data with the power function equation, $y = 0.66\ x^{1.40}$, where y = total observed sediment, x = total observed streamflow. This power function relationship was used to provide comparative sediment yield data using WHAT estimated runoff from all 13 pre-harvest storm events.

Figures 3.3 and 3.4 show comparasion of WEPP simulated and estimated sediment from runoff for the 13 selected pre-harvest storm events. It can be seen from Figure 3.3 that WEPP simulated sediment values are in relatively close agreement with estimated sediment from runoff except in three events (10/4/2004, 10/11/2004, and 10/25/2004), where the model failed to predict any sediment. A high coefficient of determination (R^2 = 0.90) between simulated and estimated sediment from runoff indicates a strong linear relationship at a slope less than 1.0 indicating under-prediction of sediment by the model. The scatter plot comparing WEPP simulated versus estimated sediment from runoff (Figure 3.4) confirms under-prediction of sediment yield for the three highest sediment yielding events (02/13/2004, 11/23/2004, and 11/26/2004). Sediment yields for several lower yielding events (03/07/2004, 03/31/2004, 05/03/2004, 10/06/2004) were over-predicted by the WEPP model.

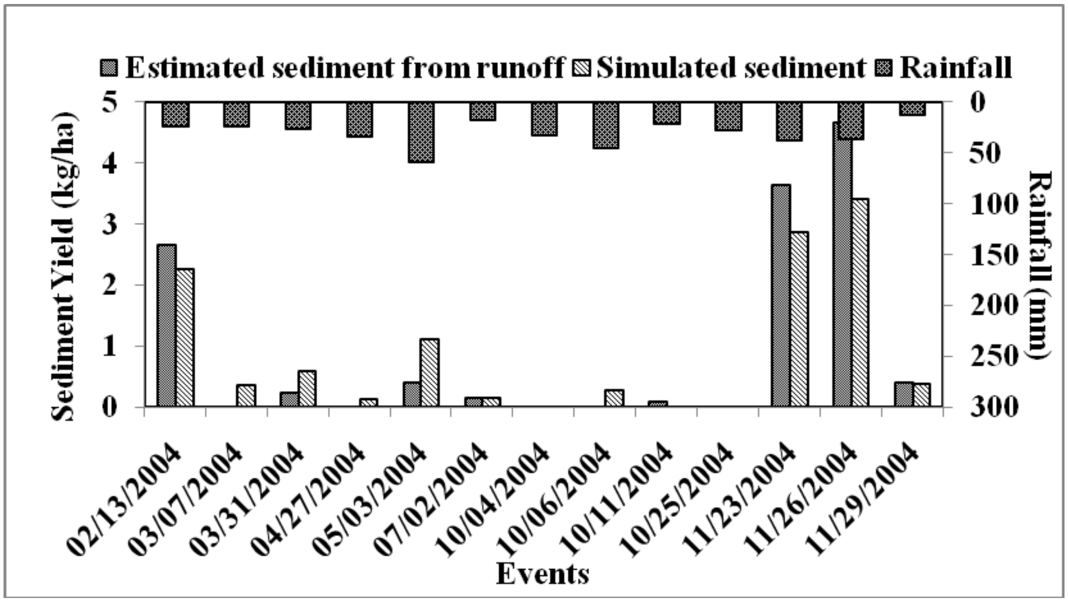

Figure 3.3 Estimated sediment from runoff and WEPP simulated sediment yield for pre-harvest conditions.

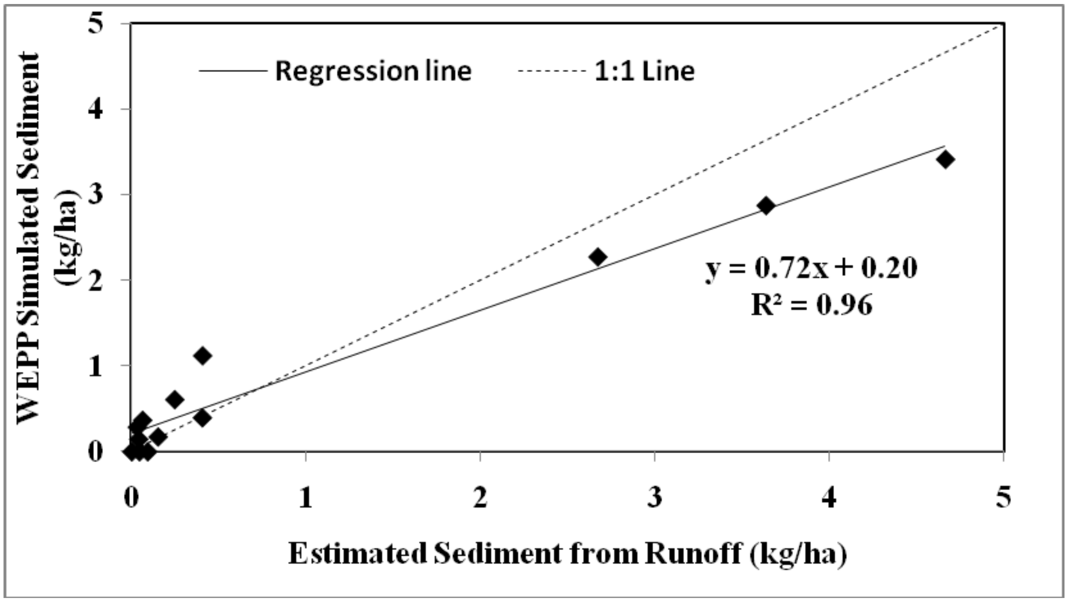

Figure 3.4 WEPP simulated runoff versus estimated sediment from runoff for pre-harvest.

Statistical comparisons between WEPP simulated and estimated sediment from runoff are shown in Table 3.2. Mean WEPP predicted sediment (0.90 ± 1.18 kg/ha) was 6 percent lower than mean of estimated sediment from runoff (0.96 ± 1.59 kg/ha) for all pre-harvest storm events. A high value of NSE (0.90) indicates very good performance of the sediment calibration. A RSR value of 0.32 indicates that WEPP simulated sediment values were ± 32% of the estimated sediment from runoff which again indicates satisfactory performance of the model. A low PBIAS value of 7% indicates slight underprediction of pre-harvest sediment yield values, as does a regression slope (m = 0.72, Figure 3.4) less than 1.0.

Table 3.2 Statistical comparison of sediment estimated from runoff and WEPP simulated sediment for pre-harvest conditions during calibration.

Statistical Parameters	Sediment (kg/ha)	
	Estimated from runoff using sediment rating curve	WEPP simulated
Mean	0.96	0.90
SD	1.59	1.18
CV(%)	166	131
R^2	0.96	
NSE	0.90	
RSR	0.32	
PBIAS (%)	7.00	

Overall, model evaluation statistics (R^2, NSE, RSR, and PBIAS) shown in Table 3.1 and 3.2 for both runoff and sediment were in the range of satisfactory to very good according to model performance rating guidelines provided by Moriasi et al. (2007) for model evaluation. Model sediment yield results were also consistent with previous studies conducted by Liu et al. (1997), Tiwari et al. (2000), and Pandey et al. (2008) using WEPP model that have shown over-estimation of sediment on low runoff events and under-estimation of sediment on high runoff events. Over-estimation of sediment on low runoff events and under-estimation of sediment on high runoff events is inherent to all soil erosion models as reported by Ghidey et al., (1995), Kramer and Alberts (1995), and Nearing (1998).

3.2 POST-HARVEST VALIDATION

Runoff validation

Validation of the calibrated WEPP model for Johnson Creek watershed was conducted for post-harvest conditions from 2005 to 2007. A culvert and unpaved road was simulated at a single road stream crossings from 1 Jan, 2005 to 17 Aug, 2005 to match actual field. The remaining years of observed data were used to validate the watershed model without the culvert and with grass covered roads since the roads were restored with the seeding operation after 17 Aug, 2005. Calibrated model parameters were applied to the validation data sets to see how well the calibrated model predicted post-harvest runoff and sediment yield. In the validation period, 19 selected storm events out of total 39 storms events were simulated for post-harvest conditions. WHAT baseflow separated runoff was used for model validation of runoff. WEPP simulated sediment yield was validated using estimated sediment from runoff at the watershed outlet. For post-harvest conditions, WHAT estimated runoff and WEPP simulated runoff is graphically shown in Figure 3.5. Figure 3.6 shows the scatterplot between WEPP simulated runoff and WHAT estimated runoff along with 1:1 line.

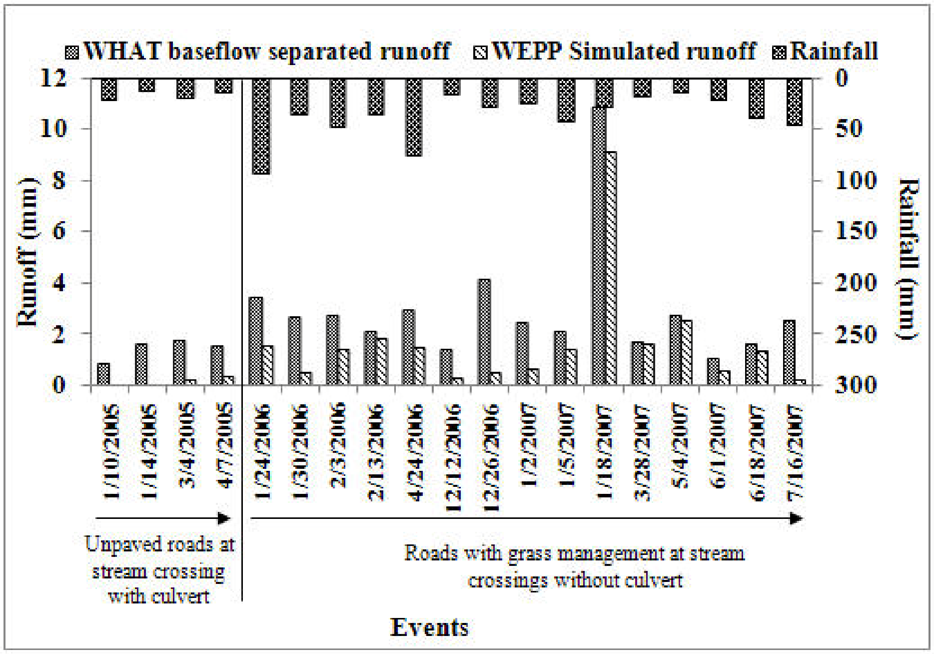

Figure 3.5 WHAT baseflow separated runoff and WEPP simulated runoff for post-harvest conditions.

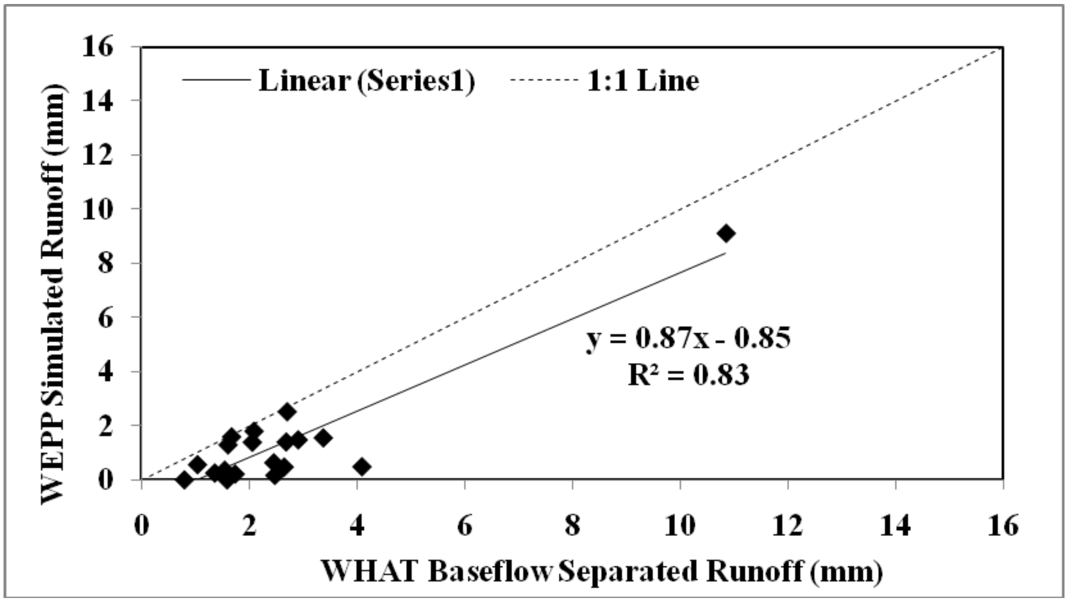

Figure 3.6 WEPP simulated runoff versus WHAT baseflow separated runoff for post-harvest conditions.

It can be observed from Figure 3.6 that the model predicted runoff in all the events except the two storms (1/10/2005 and 1/14/2005) that occurred immediately after the harvest during the period of installed culvert. The scatter plot (Figure 3.6) between WEPP simulated runoff and WHAT estimated runoff shows under-prediction of simulated runoff. The correlation coefficient (R = 0.91) indicates a strong, positive relationship between WEPP simulated runoff and WHAT estimated runoff. However, the slope (m = 0.87) of regression line confirms that simulated runoff is under-predicted in spite of the linear relationship that exists ($R^2 = 0.83$).

Mean values of WEPP simulated runoff (1.34 ± 2.02 mm) for all the post-harvest events were forty-nine percent lower than estimated direct runoff (2.62 ± 2.15 mm) (Table 3.3). The NSE value of 0.46 indicates unsatisfactory model performance. The RSR value of 74 is greater than 70, also signifing unsatisfactory performance by the model. The high value of PBIAS (48.72%) confirms that WEPP simulated runoff were highly under-predicted (Table 3.3).

Table 3.3 Statistical comparison of WHAT estimated runoff and WEPP simulated runoff for post-harvest conditions during validation.

Statistical Parameters	Runoff (mm)	
	WHAT estimated	WEPP simulated
Mean	2.62	1.34
SD	2.15	2.02
CV(%)	82	150
R^2	0.83	
NSE	0.46	
RSR	0.74	
PBIAS (%)	48.72	

Sediment validation

The WEPP simulated sediment and sediment estimated from runoff is graphically shown in Figure 3.7 and the scatterplot between simulated sediment and estimated sediment from runoff along the 1:1 line is graphically shown in Figure 3.8. To provide sediment yield data for comparison, a sediment rating curve was developed for post-harvest conditions using total observed sediment and streamflow data (Appendix G). The coefficient of determination ($R^2 = 0.27$) indicates a poor relationship between observed sediment and streamflow data with the fitted power equation $y = 0.23\ x^{1.27}$, where y = observed sediment and, x = observed streamflow. The derived power function was used to estimate the sediment from WHAT baseflow separated runoff to compare with WEPP simulated sediment values.

Figure 3.7 shows the comparison between sediment estimated from runoff and WEPP simulated sediment for all 19 post-harvest events. The model did not predict sediment for three events (1/10/2005, 1/14/2005, and 3/4/2005) immediately after the harvest during the period of installed culvert. It can be observed from the Figure 3.7 that WEPP simulated sediment yield was generally over-predicted in most but not all storm flows. Figure 3.8 shows the scatter plot between WEPP simulated sediment and sediment estimated from runoff. The high correlation coefficient (R = 0.91) between WEPP simulated sediment and sediment estimated from runoff indicates a positive linear relationship and the slope of regression line greater than one (m = 1.54, R^2 = 0.91) indicates that the WEPP model generally over-predicted sediment yield. Table 3.4 confirms above findings using additional statistical comparison of sediment estimated from runoff and WEPP simulated sediment for post-harvest conditions. Mean values of estimated sediment from runoff (0.85 ± 0.99 kg/ha) of all 19 storms is 36 percent lower than WEPP simulated sediment (1.16 ± 1.68 kg/ha). NSE value of 0.11 and RSR value of 0.94 indicates unsatisfactory model performance. However, a PBIAS value of -37% indicates satisfactory performance of the sediment portion of the model with regard to over-prediction. The generally poor results during validation period could be due to uncalibrated road soil parameters, lack of measured stage-discharge information for the culvert and the uncertainties in the measured data during the post-harvest simulation period where the observed streamflow and sediment yield data had several contradictory data pairs that are not realistic.

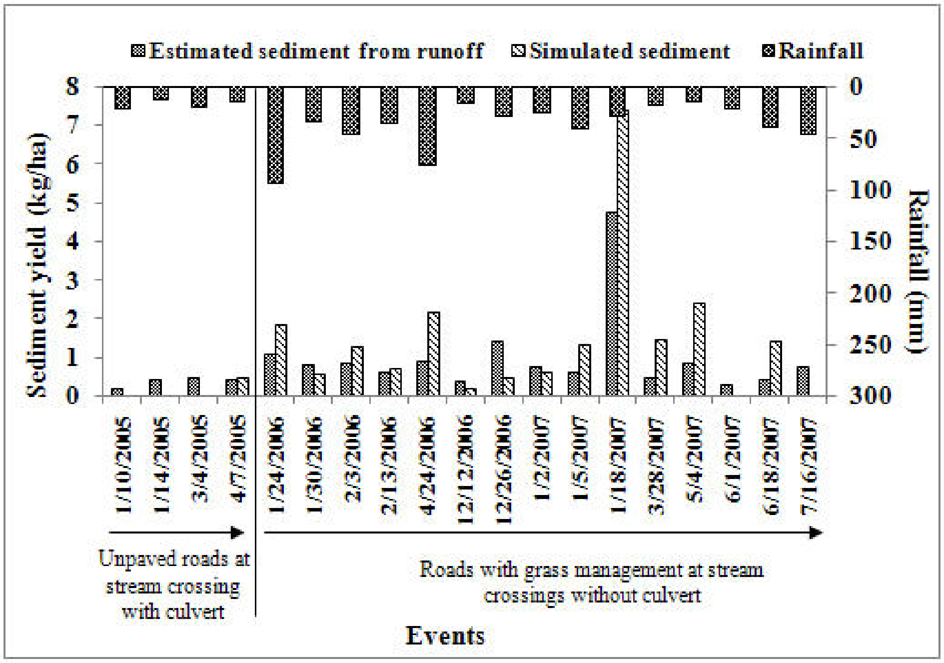

Figure 3.7 Estimated sediment from runoff and WEPP simulated sediment for post-harvest conditions.

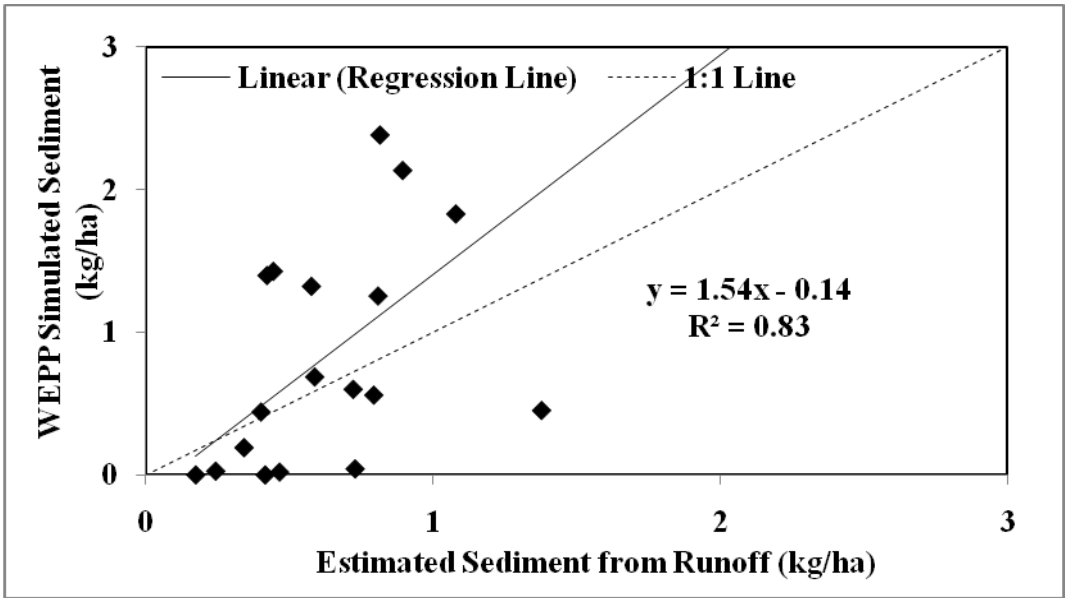

Figure 3.8 WEPP simulated sediment versus estimated sediment from runoff for post-harvest.

Table 3.4 Statistical comparison of sediment estimated from runoff and WEPP simulated sediment for post-harvest conditions during validation.

Statistical Parameters	Sediment (kg/ha)	
	Estimated from runoff using sediment rating curve	WEPP simulated
Mean	0.85	1.16
SD	0.99	1.68
CV(%)	117	144
R^2	0.83	
NSE	0.11	
RSR	0.94	
PBIAS (%)	-37.00	

In summary, an attempt was made to validate the calibrated watershed model for post-harvest conditions. Overall, model validation for runoff and sediment was unsatisfactory. The following reasons could explain the unsatisfactory results obtain during validation; 1) inconsistent observed post-harvest data which is indicated by the poorly fit sediment rating curve developed between post-harvest observed streamflow and sediment yield (Appendix J). 2) the limitation of WEPP model for use on watersheds that have perennial streams, since several in-stream erosion processes such as flood flow routing are not simulated by WEPP model, 3) post-harvest conditions included simulation of roads and a culvert at the stream crossings. Unfortunately, all structural data required for proper simulation of the in-stream culvert was not collected. Consequently, accurate stage and discharge data upstream and downstream of the culvert was not available and cross-sectional dimensions had to be estimated from a site photograph (Figure 2.10). Further, default road soil parameters were used due to unavailability of actual soil parameters. Therefore, separate statistical analysis were conducted between WHAT estimated runoff and WEPP simulated runoff, and sediment estimated from runoff and WEPP simulated sediment with the culvert (Appendix L) for the year 2005 and without the culvert (Appendix M) from 2006 to 2007 to separately evaluate the performance of the model validation with the installed culvert duration and after the culvert was removed.

The statistical comparison with 4 storm events during the validation period with culvert and unpaved roads for runoff and sediment presented in Appendix L indicated poor performance of the model predictions. Low R^2 values for runoff (R^2 = 0.27) and sediment ($R^2 = 0.07$) indicates poor linear relationship between WHAT estimated runoff and WEPP simulated runoff, and sediment estimated from runoff and WEPP simulated sediment. The mean values of WHAT estimated and WEPP simulated runoff were 1.43 ± 0.42 and 0.14 ± 0.18 mm, respectively and mean values of estimated sediment from runoff and WEPP simulated sediment were 0.37 ± 0.13 and 0.12 ± 0.22 kg/ha, respectively. Negative values of NSE for runoff (-12.12) and for sediment (-7.03) also confirms the poor performance by the model. High PBIAS values for runoff (89.91%) and sediment (69%) indicates that WEPP under-predicted runoff and sediment yield compared to measured data. Analysis of runoff and sediment from road hillslopes was also conducted. Mean values of WEPP predicted runoff and sediment from unpaved road hillslopes from 4 storms during the validation period with culvert were 0.00035 mm and 277.78 kg/ha, respectively (Appendix N). The high WEPP-predicted sediment from road hillslopes compared to mean WEPP simulated sediment (0.12 ± 0.22 kg/ha) at the watershed outlet suggests that sediment deposition was occurring within the channel. Poor validation during culvert operation could also be due to the improper stage-discharge data required for the simulation of culvert and uncalibrated road soil parameters.

Similarly, the statistical comparison with 15 storm events during the validation period without culvert and roads with grass management for runoff and sediment presented in Appendix M again indicated unsatisfactory performance of the model predictions during validation of post-harvest. The R^2 value for runoff ($R^2 = 0.82$) and sediment ($R^2 = 0.82$) indicates linear relationship between WHAT estimated runoff and

WEPP simulated runoff, and sediment estimated from runoff and WEPP simulated sediment. The mean values of WHAT estimated and WEPP simulated runoff were 2.94 ± 2.32 and 1.67 ± 2.17 mm, respectively and mean values of estimated sediment from runoff and WEPP simulated sediment were 0.97 ± 1.08 and 1.44 ± 1.79 kg/ha, respectively. NSE value runoff (0.49) and sediment (0.07) indicates unsatisfactory performance by the model during the validation period without the culvert. Positive PBIAS value for runoff (43.40%) indicates that WEPP under-predicted runoff and negative PBIAS value for sediment indicates that WEPP over-predicted sediment compared to measured data. Mean values of WEPP predicted runoff and sediment from road hillslopes with grass management of 15 storms during the validation period without culvert were 0.00270 mm and 1003.21 kg/ha (Appendix O). High mean value of WEPP predictions of sediment from road hillslopes compared to the mean value of WEPP simulated sediment (1.44 ± 1.79 kg/ha) of 15 storms at the watershed outlet again indicates that sediment deposition was taking place within the channel. Unsatisfactory validation without culvert could be due uncalibrated road soil parameters and insufficient road surface conditions.

Overall, model evaluation statistics (R^2, NSE, RSR, and PBIAS) for both combined and separate validation with culvert and unpaved roads and without culvert and roads with grass management indicated unsatisfactory validation according to model performance rating guidelines provided by Moriasi et al. (2007) for model evaluation. Generally, model sediment yield results showed over-prediction of sediment due to uncalibrated road soil parameters that indicated sediment deposition was occurring within the channel. Model validation results can likely be improved by adopting a scientific approach as described by Klemes (1994). Further investigations such as proper data collection for culvert, measured road soil parameters, evidence of sediment deposition within the streams as well as incorporation of baseflow component and in-stream channel processes for perennial streams in WEPP model can improve model results.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The present study was carried out to evaluate the process based, distributed parameter WEPP watershed model for the estimation of runoff and sediment yield from a managed 4.41 km^2 forested watershed with perennial and ephemeral streams in East Texas. The effects of silvicultural management practices on stream runoff and sediment loading at the watershed outlet were examined using observed data from 2004 to 2007. Continuous stormflow simulations were conducted in an attempt to calibrate and subsequently validate the WEPP model for pre- and post-harvest conditions, respectively, using observed runoff and sediment yield data. Calibration was conducted using 13 selected stormflow events; and the validation process was attempted using 19 selected post-harvest stormflow events. A methodology was developed to remove estimated baseflow observed streamflow to compare WEPP simulated runoff and sediment values with observed data. For both pre- and post-harvest conditions, WEPP simulated runoff values were compared with WHAT baseflow separated runoff whereas WEPP simulated sediment values were compared with sediment estimated from the same WHAT baseflow separated runoff with actual sediment rating curves. Statistical analyses including correlation coefficient (R), coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE) - observation standard deviation ratio (RSR), percent bias (PBIAS), as well as mean, standard deviation, and coefficient of variation were used to evaluate both calibration and validation steps.

During pre-harvest calibration, selected model parameters were adjusted from default values based on available literature and reported observations. Effective hydraulic conductivity, anisotrophy ratio and saturated hydraulic conductivity of bedrock were the parameters used to calibrate runoff (mm). Sediment load (kg/ha) was calibrated with only one parameter, channel erodibility factor (s/m). R and NSE values for pre-harvest runoff were 0.98 and 0.95, respectively, indicating positive correlation and good model prediction of runoff. Corresponding sediment yield R and NSE values were 0.98 and 0.90, respectively, indicating similar positive model calibration. The RSR values for calibrated runoff and sediment were 0.22 and 0.32, respectively, indicating that simulated values were ±22% and ±32% of corresponding observed values. PBIAS values for calibrated runoff (11.67%) and sediment (7.00%) indicated generally under-predicted WEPP simulated results. In addition, it was noted that WEPP simulated sediment values were generally over-predicted for smaller runoff events and under-predicted for higher runoff events, similar to results reported by others. Overall, WEPP model calibration performance was considered “very good” for runoff prediction and “satisfactory” to “very good” for sediment prediction.

Subsequent validation of the calibrated watershed model for post-harvest conditions included the addition of a temporary culvert and road management files with default road soil parameters matched to the dominant soil series in the watershed. For the clearcut harvest area, rill and inter-rill cover was calibrated according to WEPP model guidelines, with initial ground cover increasing each year after harvest from an initial cover of 80%. Separate simulations were conducted with and without the temporary culvert at the road stream crossing to evaluate model response to a major stream obstruction. Results indicated that R and NSE values for post-harvest runoff were 0.91 and 0.46, respectively, whereas sediment yield R and NSE values were 0.91 and 0.11, respectively. RSR values were 0.74 and 0.94 runoff and sediment, respectively. PBIAS value for runoff (48.72%) confirmed that WEPP under-predicted runoff during validation while over-predicting sediment yield (PBIAS = -37%). Model performance was judged to be "unsatisfactory" for both runoff and sediment yield in spite of the high positive linear correlation achieved between observed and WEPP simulated values. Separate statistical analysis for WEPP simulated runoff and sediment without the culvert did not indicate significant improvements in runoff and sediment prediction performance. In spite of a well-calibrated model for pre-harvest, model validation was unsatisfactory based on observed post-harvest conditions. Model validation may have been more successful had more precise data for culvert and road soil parameters been available. WEPP model performance for 1st and 2nd order streams can almost certainly be improved by incorporating a baseflow component and in-stream channel erosion processes into the model, including the use of deep percolation data from each hillslope output.

4.2 LIMITATION OF RESULTS

Though our study provides results which can be used to better understand the hydrology and erosion processes of the study forested watershed, there are several limitations of results presented. Incorporation of these limitations in future work may improve the quality of predicted results in this watershed model in particular and in the evaluation of forest management practices at the watershed scale in general. Some of these limitations are as follows:

1) Although the WEPP model has been applied in this study to a large watershed, it is not currently designed for the application of 1st and 2nd order watershed streams since WEPP hydrology routines are not currently capable of simulating baseflow. This is the major limitation in this study. To overcome this limitation in our research, baseflow in observed flow data was manually removed using the WHAT baseflow separator program to provide a comparative analysis with WEPP hydrologic output. Similarly, WEPP is designed to predict sediment from storms on ephemeral streams only, so does not incorporate sediment that may occur as a result of stream baseflow. To overcome this limitation in this study, sediment from runoff only was estimated from actual stream sediment rating curve and WHAT baseflow separated runoff. Consequently, calibration and validation results depend heavily on the accuracy of the baseflow separation.

2) GeoWEPP interface was used to delineate individual sub-watersheds as single hillslopes of unique cover, slope, and soil. However, on a large watershed such as our study watershed having multiple soils, the WEPP model is not currently able to represent each existing soil due to limited capability for rectangular hillslope divisions. In our

research, the dominant Cuthbert soil series was therefore used to represent soils for each of the hillslopes.

3) For the study watershed, channel scouring was indicated by observation to be the main source of sediment at the watershed outlet. Although WEPP includes a channel erosion routine, WEPP does not adjust channel erodibility as a function of climate, management, or other environmental factors as is done with rill erosion. Therefore, the channel erodibility parameter required a single adjusted value to account for this significant contribution of total soil loss in this watershed. Since the channel erodibility parameter was the only parameter adjusted for the calibration of sediment yield, little flexibility with regard to sediment yield validation in perennial streams is provided.

4) Measured road soil parameters and stage-discharge data upstream and downstream of culvert and road surface conditions could have improved validation. It is acknowledged that during this research, default road soil parameters and estimated culvert information were used during the validation period and may not have accurately simulated actual road and road stream crossing conditions.

4.3 SUGGESTIONS FOR FUTURE RESEARCH

The WEPP model was successfully calibrated for the prediction of runoff and sediment at a watershed outlet for pre-harvest conditions on a 4.41 km^2 forested watershed. The calibrated model results indicated reasonable predictions of runoff and sediment. However, validation with the calibrated model for post-harvest conditions did not provide satisfactory runoff or sediment predictions. The following recommendations for future research are provided to guide future research aimed to improve the applicability of the WEPP model for watersheds having both perennial and ephemeral streams:

1) Due to lack of field data for simulation of post-harvest conditions for the study watershed and the added complexities of road and stream crossings, calibration and validation with WEPP model should be attempted using a portion of existing post-harvest runoff and sediment yield data to further evaluate the model capabilities. This exercise is needed to learn more about the capabilities of the model under harvesting conditions in a perennial stream. Since the purpose of model validation is to provide confidence in use of the model for evaluation of environmental impacts from silvicultural management practices, our recommendation is to independently calibrate and validate the model for post-harvest conditions.

2) Additional sediment and runoff calibration should be done with an alternate set of baseflow separated runoff, to verify that the physically based baseflow estimate used in this analysis were appropriate.

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APPENDICES

APPENDIX A

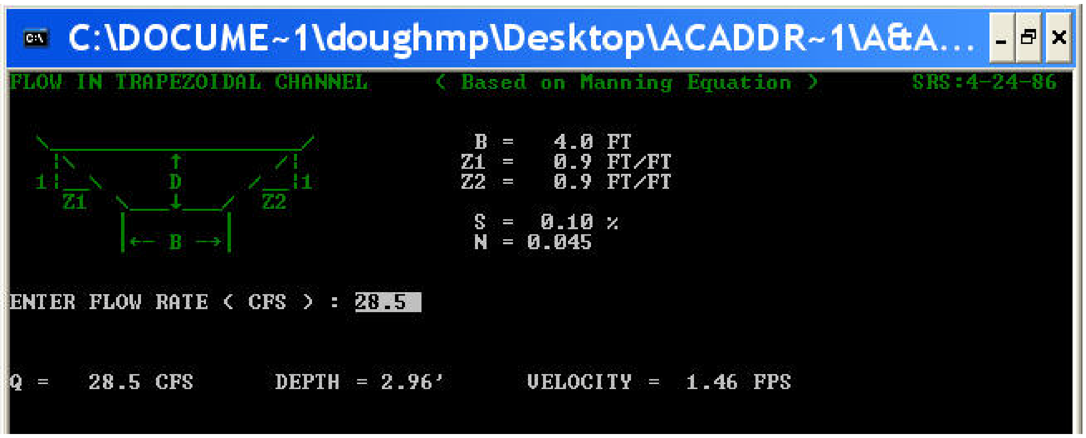
CULVERT CALCULATIONS FOR OVERTOPPING

Figure 1. Road stream crossing constructed after harvest.

Assumed design parameters:
Q_{DESIGN} = 28.46 cfs
Elevation invert in = 100.00 ft; Design top of roadway = 106.00 ft

Culvert specifications (refer Figure 1):
Culvert size = 24”; Culvert length = 30 ft; Slope = 0.001 ft/ft
Manning n = 0.014 (steel, concrete); n = 0.023 (corrugated metal)
HW/D = 2 or 3, based on 28.5cfs and 24” culvert, using either concrete or C.M. pipe culverts with inlet control nomograph (Bureau of Public Roads, Revised May 1964)

Calculation of downstream tailwater depth (refer Figures 1 and 2):
Base = 4 ft; Z = 0.883 ft/ft; S = 0.001 ft/ft
Manning n = 0.045 (rough stream channel)
Q = 28.5 cfs
Depth of water in channel = 2.96 ft (i.e., assumed tailwater)



```
FLOW IN TRAPEZOIDAL CHANNEL      < Based on Manning Equation >       SRS:4-24-86

                                          B =    4.0 FT
                                         Z1 =    0.9 FT/FT
                                         Z2 =    0.9 FT/FT

                                          S =   0.10 %
                                          N =  0.045

ENTER FLOW RATE < CFS > : 28.5


Q =   28.5 CFS      DEPTH = 2.96'      VELOCITY =  1.46 FPS
```

Figure 2. Downstream tailwater depth estimation.

Structure	Size D (in)	Inv.In (ft)	Inv.Out (ft)	Length L (ft)	Slope S (ft/ft)	Total Flow Q_{10} (cfs)	N	Flow per Barrel Q/N	n	Inlet Control			Outlet Control									Inlet / Outlet Control	Controlling HW Elev.	V_{out} (fps)
										HW/D	HWi (ft)	Elhi (ft)	TW (ft)	d_c (ft)	$(d_c+D)/2$	h_o (ft)	ke	H (ft)	HWo (ft)	Elho (ft)				
										1	2	3	4	5		6	7	8	9	10	11	12	13
example	**30**	**1901.30**	**1891.90**	**103.0**	0.0913	**23.8**	**1**	23.8	**0.013**	**1.10**	2.75	1904.05	2	1.73	2.12	2.12	0.5	0.89	-6.39	1894.91	Inlet	1904.05	**19.49**
Conc. culvert	**24**	**100.00**	**99.97**	**30.0**	0.0010	**28.5**	**1**	28.5	**0.014**	**2.00**	4.00	104.00	2.46	1.90	1.95	2.46	0.9	2.97	5.40	105.40	Outlet	105.40	**flow > pipe capacity**
C.M. culvert	**24**	**100.00**	**99.97**	**30.0**	0.0010	**28.5**	**1**	28.5	**0.023**	**3.00**	6.00	106.00	2.46	1.90	1.95	2.46	0.9	3.90	6.33	106.33	Outlet	106.33	**flow > pipe capacity**

Notes:

1 headwater/culvert height: from nomographs, Bureau of Public Roads - Headwater depth fo concrete or C.M. pipe culverts with inlet control Revised May 1964.
2 required headwater from the invert of control section to the energy grade line: Diam. x col.1
3 design headwater elevation: col.2 + highest invert
4 tailwater depth above the outlet invert: assumed 0.8 x Diam. or Manning analysis of downstream channel (less 0.5 ft drop below culvert outlet)
5 critical depth: Excel Macro (can be checked with critical depth nomograph (Jan. 1964). Note: critical depth can not be greater than D.
6 depth from culvert outlet invert to the hydraulic grade line: greater of TW and (dc+D)/2
7 entrance loss coefficient: from Table 12, VDOT Drainage Manual (ke=0.5 for end section conforming to fill slope)
8 losses through culvert barrel: Excel Macro (can be checked with nomograph, Figure III-20, VDOT Drainage Manual.
9 HWo: H + Ho - (length x slope) can be used to check col. 10 by manually adding HWo to Inv. In to get Elho
10 required outlet control headwater elevation: invert out + H + ho
11 higher of inlet or outlet HW elevation is designated as controlling HW elevation
12 if outlet control HW elevation exceeds design HW elevation (col.3), a new culvert configuration must be selected
13 outlet velocity: from Open Channel program where outlet velocity is based on normal depth & velocity of 10-yr. storm in culvert barrel (velocity at normal depth is assumed to be outlet velocity)

NOTE: USE CAPS FOR OPEN CHANNEL PROGRAM
ENTER SLOPE AS PERCENT.

APPENDIX B

EXAMPLE OF BREAKPOINT CLIMATE FILE

```
0
1   1   0
Station: Houston/Texas

Latitude Longitude Elevation (m) Obs. Years    Beginning year  Years
simulated
   29.65  -95.20            15             5          2003         5

Observed monthly ave max temperature (C)

16.55 16.86 22.74 26.09 29.81 33.07 33.99 35.97 33.34 29.31 23.89 16.28

Observed monthly ave min temperature (C)

4.70 5.15   10.65 12.92 17.78 21.49 23.04 23.08 19.33 15.98 11.46 2.7

Observed monthly ave solar radiation (Langleys)

289.7 329.5 392.5 448.3 553.2 586.9 598.7 545.9 464.9 392.4 295.5 260.6

Observed monthly ave rainfall (mm)

115.3  85.2  63.6  49.2  65.9  69.9  80.7  58.5  34.4  90.2  82.7  25.3

   day mon year nbrkpt tmax  tmin    rad   w-vel  w-dir   dew

                (mm)    (C)   (C) (ly/day) m/sec    deg    (C)

    8  11  2003  12    31.90   21.60 359.0    1.50  292.5   5.7

07.75     0.000

07.76     0.300

08.00     0.300

08.01     0.600

08.75     0.600

08.90     0.900

09.25     0.900

09.38     1.200

16.50     1.200

16.53     1.500
```

```
17.00     1.500

17.13     1.800

    9  11  2003   0    26.20   11.60 165.0    1.50   45.0   6.2

   10  11  2003   0    26.90   19.90 214.0    1.50  135.0  16.4

   11  11  2003   0    21.60    7.50 317.0    1.50  292.5  11.0

   12  11  2003   0    28.70   14.90 252.0    1.50  157.5   6.9

   13  11  2003   0    29.60   20.80 284.0    1.50  315.0  15.2

   14  11  2003   0    27.20   18.80 192.0    1.50  135.0   9.0

   15  11  2003  24    21.40   11.70 393.0    3.00  292.5  13.9

13.50     0.000

13.53     0.300

14.50     0.300

14.73     0.600

14.75     0.600

14.95     1.100

20.50     1.100

20.63     1.400

21.25     1.400

21.48     2.400

21.50     2.400

21.53     3.200

22.00     3.200

22.11     3.500
```

APPENDIX C

EXAMPLE OF WEPP SOIL FILE

```
2006.2

comments: soil file

1 1

'Forest sandy loam_AS_HWS' 'sandy loam' 4 0.300000 0.500000

400000.000000 0.000500 2.000000 60.000000

   203 81.8 8.5 4.900 15.0 25.0

   737 33.5 47.5 0.670 23.8 3.4

   864 48.0 35.0 0.220 17.5 4.6

   1524 48.8 32.5 0.070 16.3 5.3

1 8.000000 0.01
```

APPENDIX D

EXAMPLE OF WEPP FOREST MANAGEMENT FILE

```
98.4
#
#
#
#

1 # number of OFE's
2 # (total) years in simulation

#######################
# Plant Section       #
#######################

1  # Number of plant scenarios


For_5352
use with WSU senescence modification in WEPP code
(null)
W. Elliot 01/07
1  #landuse
WeppWillSet
14.00000 3.00000 15.00000 2.00000 5.00000 5.00000 0.00000 20.00000
0.50000 0.25000
0.50000 0.80000 0.90000 0.99000 17.00000 0.00000 0.42000 6.00000
2  # mfo - <non fragile>
0.00600 0.00600 20.00000 0.10000 2.00000 2.00000 0.33000 0.50000 90
40.00000
-40.00000 6.00000 0.00000

#######################
# Operation Section   #
#######################

0  # Number of operation scenarios




###############################
# Initial Conditions Section  #
###############################

1  # Number of initial scenarios


For_5688
Initial conditions for forest
With WSU WEPP Senescence change
W. Elliot  01/07
1  #landuse
1.10000 0.90000 1000 1000 0.00000 1.00000
1 # iresd  <For_5352>
2 # mang perennial
```

```
999.99799 0.10000 1.00000 0.10000 0.00000
1  # rtyp - temporary
0.00000 0.00000 0.10000 0.20000 0.00000
0.50003 0.50003




############################
# Surface Effects Section  #
############################

0  # Number of Surface Effects Scenarios



#######################
# Contouring Section  #
#######################

0  # Number of contour scenarios


#######################
# Drainage Section    #
#######################

0  # Number of drainage scenarios


#######################
# Yearly Section      #
#######################

1  # looper; number of Yearly Scenarios
#
# Yearly scenario 1 of 1
#
Year 1



1  # landuse <cropland>
1  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
2 # management <perennial>
   250 # senescence date
   0 # perennial plant date --- 0 /0
   0 # perennial stop growth date --- 0/0
   0.0000  # row width
   3  # neither cut or grazed
```

```
#######################
# Management Section  #
#######################

Manage
description 1
description 2
description 3
1   # number of OFE's
    1   # initial condition index
2  # rotation repeats
1  # years in rotation

#
# Rotation 1: year 1 to 1
#

   1  #  <plants/yr 1> - OFE: 1>
      1     # year index

#
# Rotation 2: year 2 to 2
#

   1  #  <plants/yr 1> - OFE: 1>
      1     # year index
```

APPENDIX E

EXAMPLE OF A SLOPE FILE

```
97.5

#

# from slope

#

#

1

219.826 519.411

5 147.281998

0.000000, 0.040000 0.250000, 0.125000 0.500000, 0.088000 0.750000,
0.103000 1.000000, 0.111000
```

APPENDIX F

WATERSHED STRUCTURE FILE FOR PRE-HARVEST, POST-HARVEST WITH CULVERT AND UNPAVED ROADS AT THE STREAM CROSSINGS, AND POST-HARVEST WITH CULVERT AND ROADS AT STREAM CROSSINGS WITH GRASS MANAGEMENT

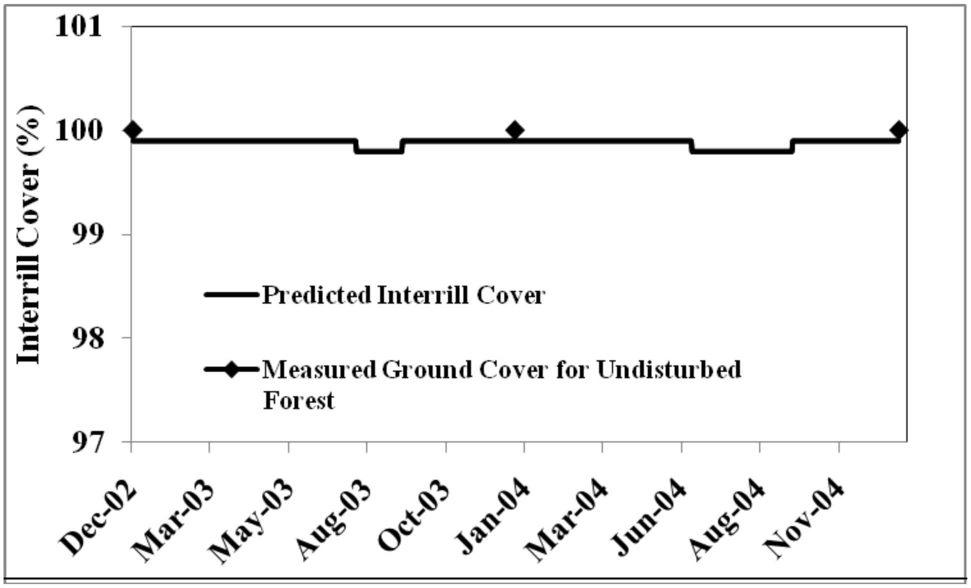
```
WATERSHED STRUCTURE INPUT FILE (Pre-harvest)
------------------------------

Hillslope Elements: 1 -  52

                            (CONTRIBUTING ELEMENTS MATRIX)
                       HILLSLOPE          CHANNEL        IMPOUNDMENT
ELEM.    ELEMENT
 #     FED    NUM    L     R     T     L     R     T     L     R     T
---    ---    ---   ---   ---   ---   ---   ---   ---   ---   ---   ---

  53   CHANNEL   1   H52   H51   H50
  54   CHANNEL   2   H48   H49   H47
  55   CHANNEL   3   H45   H46   H44
  56   CHANNEL   4   H42   H43   H41
  57   CHANNEL   5   H39   H40   H38
  58   CHANNEL   6   H35   H37   H36
  59   CHANNEL   7   H33   H34   H32
  60   CHANNEL   8   H29   H31   H30
  61   CHANNEL   9   H27   H28         C7    C8
  62   CHANNEL  10   H26   H25         C6    C9
  63   CHANNEL  11   H23   H24         C5    C10
  64   CHANNEL  12   H21   H22   H20
  65   CHANNEL  13   H17   H18   H19
  66   CHANNEL  14   H15   H16         C12   C13
  67   CHANNEL  15   H13   H14         C11   C14
  68   CHANNEL  16         H12         C4    C15
  69   CHANNEL  17   H10   H11         C3    C16
  70   CHANNEL  18   H9    H8          C2    C17
  71   CHANNEL  19   H6    H7    H5
  72   CHANNEL  20   H3    H4          C18   C19
  73   CHANNEL  21   H1    H2          C1    C20
```

```
WATERSHED STRUCTURE INPUT FILE (Post-harvest with culvert and unpaved
roads at the road stream crossings)
------------------------------

Hillslope Elements: 1 -  54

                            (CONTRIBUTING ELEMENTS MATRIX)
                       HILLSLOPE          CHANNEL        IMPOUNDMENT
ELEM.    ELEMENT
 #     FED    NUM    L     R     T     L     R     T     L     R     T
---    ---    ---   ---   ---   ---   ---   ---   ---   ---   ---   ---

  55   CHANNEL   1   H48
  56   CHANNEL   2   H46   H47   H45
  57   CHANNEL   3   H43   H44   H42
  58   CHANNEL   4   H40   H41   H39
  59   CHANNEL   5   H37   H38   H36
  60   CHANNEL   6   H33   H35   H34
  61   CHANNEL   7   H31   H32   H30
  62   CHANNEL   8   H27   H29   H28
  63   CHANNEL   9   H25   H26         C7    C8
  64   CHANNEL  10   H24   H23         C6    C9
  65   CHANNEL  11   H21   H22         C5    C10
  66   CHANNEL  12   H19   H20   H18
  67   CHANNEL  13   H15   H16   H17
  68   CHANNEL  14   H13   H14         C12   C13
  69   CHANNEL  15   H11   H12         C11   C14
  70   CHANNEL  16         H10         C4    C15
  71   CHANNEL  17   H8    H9          C3    C16
  72   CHANNEL  18   H7    H6          C2    C17
  73   CHANNEL  19   H4    H5    H3
  74   CHANNEL  20   H1    H2          C18   C19
  75   CHANNEL  21         H49
  76   IMPOUND   1                     C1    C21   C20
  77   CHANNEL  22                                                   C1
  78   CHANNEL  23   H51   H52   H50
  79   CHANNEL  24   H53   H54               C23   C22
```

```
WATERSHED STRUCTURE INPUT FILE (post-harvest without culvert and roads
with grass management at the road stream crossings)
------------------------------

Hillslope Elements: 1 -  54

                            (CONTRIBUTING ELEMENTS MATRIX)
                       HILLSLOPE          CHANNEL        IMPOUNDMENT
ELEM.    ELEMENT
 #     FED    NUM    L     R     T     L     R     T     L     R     T
---    ---    ---   ---   ---   ---   ---   ---   ---   ---   ---   ---


  55   CHANNEL   1   H46   H47   H45
  56   CHANNEL   2   H43   H44   H42
  57   CHANNEL   3   H40   H41   H39
  58   CHANNEL   4   H37   H38   H36
  59   CHANNEL   5   H33   H35   H34
  60   CHANNEL   6   H31   H32   H30
  61   CHANNEL   7   H27   H29   H28
  62   CHANNEL   8   H25   H26         C6    C7
  63   CHANNEL   9   H24   H23         C5    C8
  64   CHANNEL  10   H21   H22         C4    C9
  65   CHANNEL  11   H19   H20   H18
  66   CHANNEL  12   H15   H16   H17
  67   CHANNEL  13   H13   H14         C11   C12
  68   CHANNEL  14   H11   H12         C10   C13
  69   CHANNEL  15         H10         C3    C14
  70   CHANNEL  16   H8    H9          C2    C15
  71   CHANNEL  17   H7    H6          C1    C16
  72   CHANNEL  18   H4    H5    H3
  73   CHANNEL  19   H1    H2          C17   C18
  74   CHANNEL  20   H54   H48                     C19
  75   CHANNEL  21   H50   H51   H49
  76   CHANNEL  22   H52   H53               C21   C20
```

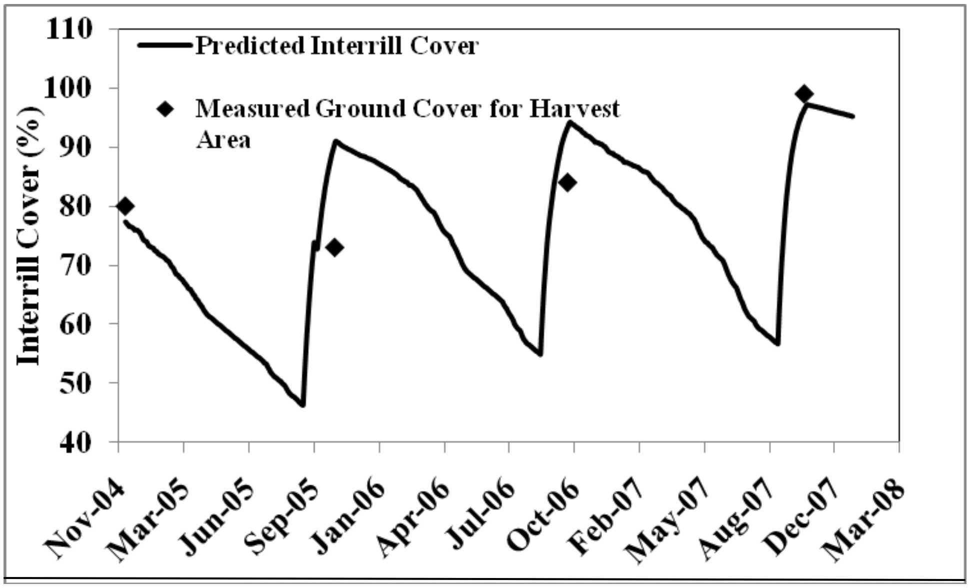
APPENDIX G

COMPARISON OF WEPP CALIBRATED INTERRILL COVER AND MEASURED GROUND COVER FOR PRE-HARVEST UNDISTURBED FOREST FROM 2003 TO 2004


101
100
99
98
97
Interrill Cover (%)
Predicted Interrill Cover
Measured Ground Cover for Undisturbed Forest
Dec-02
Mar-03
May-03
Aug-03
Oct-03
Jan-04
Mar-04
Jun-04
Aug-04
Nov-04

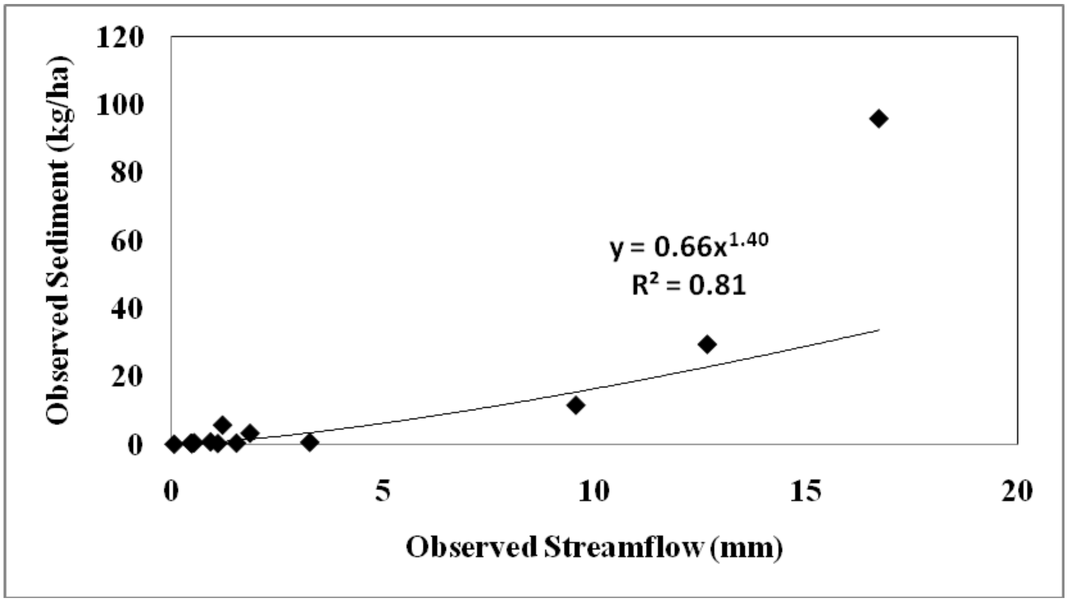
APPENDIX H

COMPARISON OF WEPP CALIBRATED INTERRILL COVER AND MEASURED GROUND COVER FOR POST-HARVEST SHOWING SENESCENCE AND FOREST REGENERATION FROM 2005 TO 2007


110
100
90
80
70
60
50
40
Interrill Cover (%)
Predicted Interrill Cover
Measured Ground Cover for Harvest Area
Nov-04
Mar-05
Jun-05
Sep-05
Jan-06
Apr-06
Jul-06
Oct-06
Feb-07
May-07
Aug-07
Dec-07
Mar-08

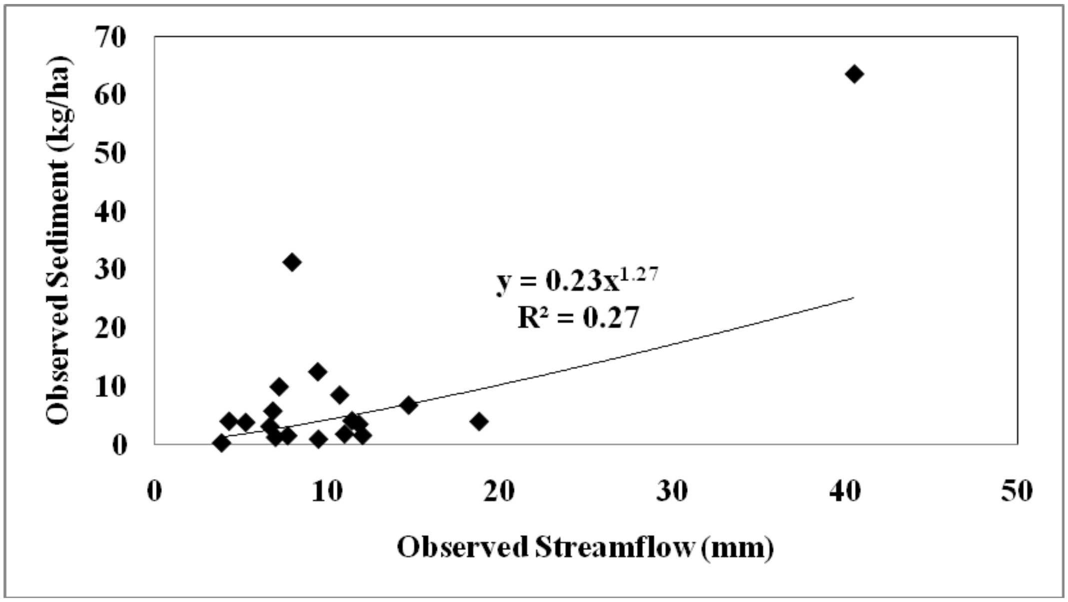
APPENDIX I

SEDIMENT RATING CURVE FOR PRE-HARVEST CONDITIONS SHOWING POWER FUNCTION RELATIONSHIP BETWEEN OBSERVED SEDIMENT YIELD AND OBSERVED STREAMFLOW


Observed Sediment (kg/ha)
120
100
80
60
40
20
0
0
5
10
15
20
Observed Streamflow (mm)
y = 0.66x^1.40
R² = 0.81

APPENDIX J

SEDIMENT RATING CURVE FOR POST-HARVEST CONDITIONS SHOWING POWER FUNCTION RELATIONSHIP BETWEEN OBSERVED SEDIMENT YIELD AND OBSERVED STREAMFLOW


70
60
50
40
30
20
10
0
Observed Sediment (kg/ha)
y = 0.23x^1.27
R² = 0.27
0
10
20
30
40
50
Observed Streamflow (mm)

APPENDIX K

EXAMPLE OF WATERSHED OUTPUT FILE

```
WATERSHED OUTPUT: DISCHARGE FROM WATERSHED OUTLET
(Results listed for Runoff Volume > 0.005m^3)

Day          Precip.    Runoff      Peak       Sediment
   Month     Depth      Volume      Runoff     Yield
       Year  (mm)       (m^3)       (m^3/s)    (kg)
-------------------------------------------------------

   16    1     2  34.1       232.50      0.04036          4.7

   17    1     2  26.3      2090.13      0.31118        742.5

   18    1     2   4.6      2316.06      0.33851        951.9

   19    1     2   0.0      1737.28      0.25944        704.5

   20    1     2   0.0       999.89      0.15563        399.4

   21    1     2   0.0       362.72      0.06157          8.4

   22    1     2   0.0       363.52      0.06226          8.6

   24    1     2  75.0     16821.88      2.11948       6188.2

   25    1     2   0.0     11764.70      1.52252       4191.3

   26    1     2   0.0      9421.89      1.23976       3451.7

   27    1     2   0.0      8674.37      1.14849       3205.8

   28    1     2   0.0      8463.79      1.12267       3133.0

   29    1     2   9.8      8527.48      1.13048       3233.2

   30    1     2   0.0      8023.80      1.06857       2994.0

   31    1     2   0.0      5992.51      0.81569       2311.3

    1    2     2   7.6      4782.80      0.66211       1941.5

    2    2     2   0.0      3433.97      0.48732       1367.4

    3    2     2   0.0      2224.53      0.32612        890.9

    4    2     2   7.3      1752.02      0.26148        774.3

    5    2     2   9.9      2255.33      0.33029       1005.1

    6    2     2   0.0      1763.01      0.26300        694.6
```

APPENDIX L

STATISTICAL COMPARISON OF WHAT ESTIMATED RUNOFF AND WEPP SIMULATED RUNOFF AND SEDIMENT ESTIMATED FROM RUNOFF AND WEPP SIMULATED SEDIMENT FOR POST-HARVEST CONDITIONS DURING VALIDATION WITH CULVERT

Statistical parameters	**Unpaved roads at stream crossing with culvert (2005)**			
	Runoff (mm)		**Sediment (kg/ha)**	
	Estimated runoff from WHAT baseflow separator	**WEPP simulated**	**Estimated from runoff using sediment rating curve**	**WEPP simulated**
Mean	1.43	0.14	0.37	0.12
SD	0.42	0.18	0.13	0.22
CV(%)	30	123	36	189
n	4		4	
R^2	0.27		0.05	
NSE	-12.12		-7.03	
RSR	3.62		2.83	
PBIAS (%)	89.91		69	

n = number of storms

APPENDIX M

STATISTICAL COMPARISON OF WHAT ESTIMATED RUNOFF AND WEPP SIMULATED RUNOFF AND SEDIMENT ESTIMATED FROM RUNOFF AND WEPP SIMULATED SEDIMENT FOR POST-HARVEST CONDITIONS DURING VALIDATION WITHOUT CULVERT

Statistical parameters	Roads with grass management at stream crossing without culvert (2006-07)			
	Runoff (mm)		Sediment (kg/ha)	
	Estimated runoff from WHAT baseflow separator	WEPP simulated	Estimated from runoff using sediment rating curve	WEPP simulated
Mean	2.94	1.67	0.97	1.44
SD	2.32	2.17	1.08	1.79
CV(%)	79	130	111	124
n	15		15	
R^2	0.82		0.82	
NSE	0.49		0.07	
RSR	0.71		0.97	
PBIAS (%)	43.40		-48	

n = number of storms

APPENDIX N

WEPP SIMULATED RUNOFF AND SEDIMENT FROM UNPAVED ROAD HILLSLOPES FOR POST-HARVEST CONDITIONS DURING VALIDATION WITH CULVERT

Events date	Rainfall (mm)	Unpaved roads at stream crossing (2005)	
		Runoff (mm)	Sediment (kg/ha)
1/10/2005	22.30	0.00000	0.00
1/14/2005	13.90	0.00052	444.44
3/4/2005	19.90	0.00000	0.00
4/7/2005	14.20	0.00086	666.67
	Mean	0.00035	277.78

APPENDIX O

WEPP SIMULATED RUNOFF SEDIMENT FROM ROAD HILLSLOPES WITH GRASS MANAGEMENT FOR POST-HARVEST CONDITIONS DURING VALIDATION WITHOUT CULVERT

Events date	Rainfall (mm)	Roads with grass management at stream crossing (2006-07)	
		Runoff (mm)	Sediment (kg/ha)
1/24/2006	93.60	0.00077	2537.18
1/30/2006	35.20	0.00060	349.96
2/3/2006	47.50	0.00061	1049.87
2/13/2006	35.70	0.00048	524.93
4/24/2006	76.60	0.01153	2887.14
12/12/2006	16.20	0.00031	87.49
12/26/2006	29.10	0.00000	0.00
1/2/2007	26.20	0.00056	349.96
1/5/2007	42.20	0.00047	1049.87
1/18/2007	29.50	0.00247	87.49
3/28/2007	18.00	0.00055	174.98
5/4/2007	15.20	0.00651	1487.31
6/1/2007	22.40	0.00024	612.42
6/18/2007	39.20	0.01272	3237.10
7/16/2007	46.50	0.00268	612.42
	Mean	0.00270	1003.21