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APPLYING ONLINE WEPP TO ASSESS FOREST WATERSHED HYDROLOGY

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Applying Online WEPP to Assess Forest Watershed Hydrology

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Abstract

The U.S. Army Corps of Engineers (USACE) and the Great Lakes Commission are developing technologies and predictive tools to aid in watershed management with an ultimate goal of improving and preserving the water quality in the Great Lakes Basin. A new version of the online Water Erosion Prediction Project (WEPP) GIS interface has been developed to assist in evaluating sediment sources associated with forests and forest management within the Basin.

The online WEPP GIS interface uses the OpenLayers and MapServer GIS software with base image data from Google. WEPP inputs for watershed applications, including digital elevation data (USGS 30-m National Elevation Data), land cover maps (USGS land cover), and soil maps (NRCS SSURGO soils), are automatically retrieved from web servers. DEM data are used to generate WEPP watershed structure and topographical inputs for each watershed element. Landuse and management files in the WEPP database are linked to polygons in the land cover map, and WEPP soil input files are generated on the server for the area of interest by querying the NRCS soil database. For areas where NRCS SSURGO data are not available, soil files in the WEPP database are linked to the polygons of the land cover map. Surface cover and soil properties of the WEPP management file and soil file can be customized to represent site-specific conditions, and functions to substitute the default inputs with user-specified landuse or soil files for a sub-catchment are provided. Daily climate inputs are generated from the long-term climate parameters of the nearest weather station using CLIGEN. Monthly climate parameters can be adjusted by using the gridded data of PRISM to account for locations distant from CLIGEN stations.

No instrumented forested watersheds with long-term observation data within the Great Lakes Basin were available for testing the online WEPP GIS interface. However, within the Fernow Experimental Forest, West Virginia, there are seven watersheds with more than 50 years of observed climate and streamflow data available online. Among them, WS1 and WS4 have been completely covered with mature forest for the last two decades and were therefore selected for applying the online WEPP GIS interface.

The most recent 20 years (1987–2007) of available observation data for WS1 and WS4 were acquired and used for WEPP simulation. The Penman-Monteith method in the WEPP model was used for ET simulation and a crop coefficient for growth season in the FAO Penman-Monteith equation was set to 0.71 to reproduce the 640 mm of the average annual ET observed at the Fernow Experimental Forest. A site-specific WEPP soil file was created by combining the automatically generated WEPP soil file from SSURGO database with the soil file for mature forest in the WEPP database and adding a restrictive layer to represent the bedrock beneath the soil profile. The saturated hydraulic conductivity of the restrictive layer was fitted through desktop WEPP-simulation using observed precipitation and air temperature as climate inputs to reproduce observed average annual runoff.

Online WEPP simulations were carried out and the model performance was examined by comparing simulated and observed streamflow data and sediment yield derived from the observed stream water chemistry data. The online WEPP model reasonably simulated average annual runoff and the annual maximum runoff series for both watersheds. Sediment yield was slightly under-predicted for annual average and slightly over-predicted for the annual maximum series. In addition, the simulation results adequately reflected the differences between WS1 and WS4 in their hydrological characteristics. Future studies assessing the performance of the online WEPP GIS interface in simulating different hydrologic, landuse, and management conditions are needed.

KEYWORDS. Forest watershed, Water erosion, Hydrologic modeling, Online WEPP GIS interface.

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INTRODUCTION

The U.S. Army Corps of Engineers (USACE) and the Great Lakes Commission are developing technologies and predictive tools to aid in watershed management with an ultimate goal of improving and preserving the water quality in the Great Lakes Basin. An online tool, the online Water Erosion Prediction Project (WEPP) GIS interface, has been developed to assist in evaluating sediment sources associated with forests and forest management within the basin (Frankenberger et al., 2011).

The online GIS WEPP interface uses the OpenLayers and MapServer GIS software with base image data from Google (Frankenberger et al., 2011). WEPP inputs for watershed applications including digital elevation model (DEM) data (USGS 30-m National Elevation Data), land cover map (USGS land cover), and soil maps (NRCS SSURGO soils), are automatically retrieved from web servers. DEM data are used for generating WEPP watershed structure and topographic inputs for each watershed element. Landuse and management files in the WEPP database are linked to polygons in the land cover map, and WEPP soil input files are generated on the server for the area of interest by querying the NRCS soil database. For areas where NRCS SSURGO data are not available, the land cover information can be used to estimate soil characteristics and default soil files in the WEPP database are linked to the polygons of the land cover map. Surface cover and soil properties of the WEPP management and soil files can be further modified to represent site-specific conditions, and functions to substitute the default with user-specified landuse or soil files for a sub-catchment are provided. Daily climate inputs are generated from the long-term climate statistical parameters of the nearest weather station using CLIGEN. Monthly climate parameters can be adjusted by using the gridded data of PRISM to account for locations distant from CLIGEN stations (Frankenberger et al., 2011).

The objective of this study was to examine model performance of the new online WEPP GIS interface by applying it to forested watersheds in the vicinity of the Great Lakes Basin. Since there were no instrumented forested watersheds with long-term observation data available within the basin suitable for the study, two monitored watersheds at the Fernow Experimental Forest in West Virginia, were chosen for WEPP applications. Simulated runoff and erosion from the online WEPP model were compared with the observations at the study watersheds.

FERNOW EXPERIMENTAL FOREST

The Fernow Experimental Forest is located in Tucker County, West Virginia, approximately 1.3 km south of Parsons (Fig. 1a), in the Allegheny Mountain section of the Appalachian Plateau (USDA, 2011a). The forest is comprised of unglaciated, humid-mountainous topography sculpted by a series of hillslope and fluvial processes (Taylor and Kite, 1997). Bedrock is weathered and fractured sedimentary strata of interbedded sandstone and shale or interbedded marine limestones and calcareous shales with low dip angle (approximately 5–10° to the southeast) on broad, open folds (Taylor and Kite, 1997). Soils, originated from the bedrock, are mainly loam and silt loam soils with an average depth of about 1 meter (USDA, 2011a).

At the Fernow Experimental Forest, mean annual precipitation is 1,470 mm, distributed evenly throughout the year (USDA, 2011a). About 12% of the annual precipitation falls in the form of snow. Winter snow fall can be heavy, though the snowpack is intermittent (USDA, 2011a). Land cover of the region is characterized by a mixed hardwood forest (USDA, 2011a) with an annual average evapotranspiration (ET) of 640 mm (Adams et al., 1994; Wilson et al., 2001).

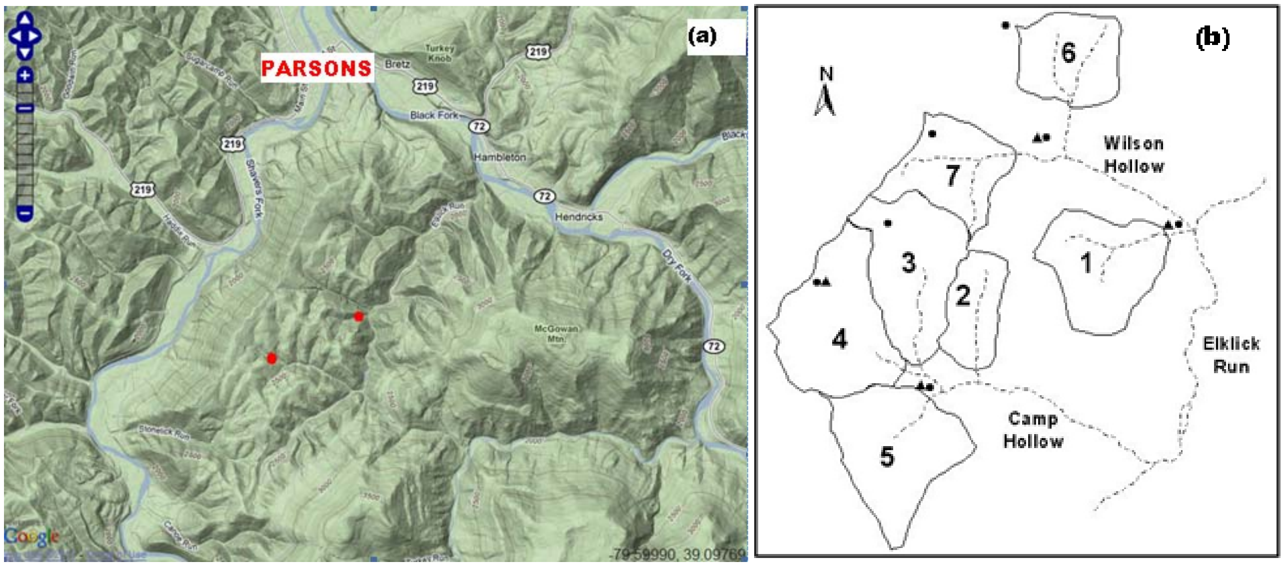

Figure 1. (a) Outlets (red dots) of gauged watersheds #1 (WS1) and #4 (WS4) in the Fernow Experimental Forest. (b) Monitored watersheds in the Fernow Experimental Forest. The triangles and circles are recording and standard rain gauges, respectively (Courtesy of USDA, 2011b).

Watershed research at the Fernow Experimental Forest has been carried out for decades. In Elklick Run watershed, seven sub-watersheds under different forest managements (Fig. 1b) have been gauged with 120-degree V-notch weirs instrumented with Belfort FW-1 water level recorders since 1951 (USDA, 2011b). Daily streamflows during 1951–2007 are calculated from the observed water levels using an empirical equation calibrated to each installation and available online (USDA, 2011b). Meanwhile, precipitation is observed using a network (Fig. 1b) of four recording rain gauges (Belfort 780 series) and seven standard rain gauges (8-inch, Belfort model 5-400); the Thiessen polygon method is applied to calculate the online daily precipitation data of each watershed (USDA, 2011b). Air temperature data are collected at the weather station at the mouth of Watershed #5 (Fig. 1b) and are available online (USDA, 2011b). Stream water chemistry during 1980–2007, including concentrations of Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Cl^{-}, NO_3^{-}, and SO_4^{2-}, are also available (USDA, 2011b).

Watershed #1 (WS1) and #4 (WS4) are small watersheds with collection areas of 30 ha and 34 ha, respectively. There has been no tree cutting for WS1 since a clearcut with 74% basal area removal during 1957–1958, and for WS4 since the last known harvesting during 1905–1910. Streamflow measurements for these two watersheds have been continuous since gage installation in 1951 (USDA, 2011b). Both WS1 and WS4 have been completely covered with mature forest for the last two decades; they were therefore chosen for WEPP applications.

Though WS1 and WS4 are close to each other, they are slightly different in hydrological conditions. Soils are mainly Calvin channery silt loam in WS1, and are Calvin channery silt loam, Dekalb channery loam, and Ernest cobbly silt loam for WS4 (NRCS, 2011). The underlying bedrocks are weathered and fractured shale for both watersheds (USGS, 2011). For the last 20 water years (Oct–Sep) of the observation data, mean annual precipitation of WS1 (1,517 mm) was greater than that of WS4 (1,440 mm). Runoff from WS1 (610 mm) was less than that from WS4 (659 mm). Sediment yield derived from stream water chemistry data for WS1 (278 kg ha^{-1} yr^{-1}) was greater than that for WS4 (165 kg ha^{-1} yr^{-1}). In this study, the responses of the online WEPP model to these varying hydrological conditions were examined.

WEPP SIMULATIONS AND MODEL PERFORMANCE EVALUATIONS

WEPP Simulations

The online WEPP GIS interface was applied to WS1 and WS4 for 20-yr (1987–2007) watershed simulations. Default WEPP landuse and management files (mature-forest files for the forested areas) of the online WEPP model were used with no change. The soil input files generated by the online WEPP interface from SSURGO soil data were modified to reflect the site-specific conditions. Daily climate inputs were generated using CLIGEN, a stochastic climate generator, based on long-term climate statistics embedded in the online WEPP interface. The historical climate statistics from the nearest NOAA weather station (Rowlesburg 1, WV, COOP ID: 467785, 20 mi. north of the watersheds) in the WEPP database were chosen and were further adjusted using the gridded data of PRISM to account for the differences between the watersheds and the NOAA weather station.

Deep percolation, governed by the saturated hydraulic conductivity (K_{sat}) of the restrictive bedrock layer, is crucial in adequately simulating water flow of the soil profile. To properly simulate deep percolation and to reproduce the observed annual average streamflows, separate WEPP simulations were carried out to calibrate the K_{sat} of the restrictive layer using the desktop WEPP model interface and climate files containing field-observed air temperatures, available for the study region, and precipitation data, available for each watershed (USDA, 2011b), with the remaining climate inputs (e.g., wind velocity and direction, and solar radiation) generated using CLIGEN based on the climate statistics of the Rowlesburg 1 NOAA station.

Penman Equation vs. FAO Penman-Monteith Method for Simulating ET

WEPP includes both the Penman (1963) equation and the FAO Penman-Monteith method (Allen et al., 1998) for estimating ET (Flanagan and Nearing, 1995; Dun et al., 2003). Annual average ET estimated using the Penman equation was about 1,000 mm for WS1 and WS4, a value that is much greater than the observed (640 mm) on the hardwood forests of the region. The FAO Penman-Monteith Method (Wu and Dun, 2006) was therefore chosen for ET estimation in the WEPP simulations of this study. To reproduce the observed average annual ET, the crop coefficient for middle growth season in the FAO Penman-Monteith equation (Allen et al., 1998) was set to 0.71.

Developing Site-specific Soil Inputs

The soil inputs were generated by combining the SSURGO soil texture profile with the hydraulic and erosion parameters in the forest loam soil file in the WEPP database. The soil file was further adjusted by adding to it parameters describing a restrictive layer at the bottom of the soil profile to represent the bedrock underneath. Functions for combining soil files and further modifying a soil file are provided in the online WEPP GIS interface.

Table 1 shows the WEPP soil inputs for the predominant soil (Calvin channery silt loam) of the simulated watersheds. In WEPP, baseline effective hydraulic conductivity (K_b) of a cropland surface soil layer is calculated using a pedotransfer function (eq. 1; Flanagan and Nearing, 1995).

$$\begin{aligned} K_{sat} &= -0.265 + 0.0086 \times SAND^{1.8} + 11.46 \times CEC^{-0.75} \qquad CLAY \le 40 \\ K_{sat} &= 0.0066 \times e^{(244/CLAY)} \qquad CLAY > 40 \end{aligned} \tag{1}$$

where *SAND* and *CLAY* are the percents of sand and clay, and *CEC* (meq/100g) is the cation exchange capacity of the soil. The estimated K_b of the Calvin channery silt loam is approximately 4 mm hr^{-1}. The field-measured saturated hydraulic conductivity (K_{sat}) for the soil was 50–150 mm hr^{-1} (NRCS, 2011). An anisotropy ratio of 25 was therefore used to appropriately simulate subsurface lateral flow, a dominant water flow process of the region. The K_{sat} of the restrictive layers of the two watersheds were best-fitted to reproduce the observed runoff.

Model Performance Evaluation

The soil files with the fitted K_{sat} of the restrictive layers were used to run the online WEPP model. Simulated runoff and sediment yield using observed precipitation and air temperatures were compared with observed runoff and sediment yield derived from the observed stream water chemistry data. Runoff and sediment yield for the events with return periods (eq. 2) of 2, 5, and 10 years in the simulated series from both WEPP runs were compared with those of the observed values.

$$T = (N + 1)/m \qquad (2)$$

where T is the return period, N is the number of simulation years, and m is the rank of the annual maximum events in descending order.

Patric (1976) found that the particulate part of the eroded material was about equal to the dissolved matter in carefully managed forestland. In our study, dissolved matter was calculated from the observed stream chemistry data by assuming that the only unmeasured ion of the dissolved matter was HCO_3^-. Sediment yield was estimated by doubling the estimated dissolved matter. This assumption may lead to an over estimation of sediment at low stream flows, and an under estimation at high flows.

Table 1. Major WEPP soil input parameters for Calvin channery silt loam.

Surface soil parameters		Effective hydraulic conductivity mm hr^{-1}	Interrill erodibility kg s m^{-4}	Rill erodibility s m^{-1}	Critical shear stress Pa
		35	1e+5	1e−5	1
Soil texture profile					
Depth mm	Sand %	Clay %	Organic matter %	CEC Meq/100g soil	Rock fragments %
130	29.1	17.5	6.6	14	10
790	22.4	22.5	0.26	16	12
1190	22.4	22.5	0.18	13	13
Other parameters		Anisotropy ratio		Restrictive layer K_{sat} mm hr^{-1}	
				Watershed #1	Watershed #4
		25		0.036	0.008

RESULTS AND DISCUSSION

With the calibrated K_{sat} for the restrictive layers, the desktop WEPP model simulations using observed climate data could reproduce the average annual runoff values and the seasonal trends of daily runoff for both watersheds (Table 2). However, the simulated timing of the large events did not always coincide with the observed. The Nash-Sutcliffe model efficiency coefficients (Nash and Sutcliffe, 1970) for daily runoff were −0.08 and 0.06 for WS1 and WS4, respectively. Paired t-tests for each year indicated that simulated annual runoff was not significantly different from the observed at $\alpha = 0.01$ for both watersheds. The average P-value was 0.61 for WS1 with the smallest value of 0.08 for the year 1991, and was 0.53 for WS4 with the smallest value of 0.02 for 2002. The Nash-Sutcliffe model efficiency coefficients for annual runoff were 0.95 and 0.93 for WS1 and WS4, respectively.

The observed sediment yields from these two undisturbed forest watersheds were low, and the simulated values were slightly lower than the observed for both watersheds (Table 2). The WEPP model adequately simulated lower annual sediment yield coming from larger annual runoff from WS4 than from WS1 throughout the 20-yr simulation period and as observed.

Average annual precipitation, runoff, and sediment yield simulated with the online WEPP GIS interface were 1,499 mm, 588 mm, and 0.17 T ha^{-1} for WS1, and 1,478 mm, 697 mm, and 0.14 T ha^{-1} for WS4. Compared with the observations, average annual precipitation generated from the online WEPP model was slightly lower for WS1 and slightly higher for WS4. Consequently, average annual runoff simulated was slightly smaller for WS1 and slightly larger for WS4. As a result, average annual sediment yield simulated for WS4 from the online WEPP model was larger than simulated using the observed precipitation and air temperature. The simulated annual sediment yields were smaller than observed for both watersheds. The online WEPP model results reflected the observed differences in the hydrological conditions between WS1 and WS4. WS1 had slightly greater precipitation, smaller runoff, and larger sediment yield than WS4.

Table 3 shows the frequency analysis on the extreme events of annual maximum series. The observed values for WS1 and WS4 were similar in precipitation and runoff. The estimated sediment yield for WS1 was larger than for WS4. Runoff and sediment yield values of the annual maximum simulated using observed precipitation and air temperatures were larger than those of the observations. Annual precipitation maximums generated with the online WEPP model were slightly larger than observed, and annual maximums of runoff and sediment yield simulated using the online WEPP model were larger than simulated using observed precipitation and air temperatures. WS1 and WS4 had similar annual maximums of simulated precipitation and runoff. Simulated sediment yield values of the extreme events for WS1 and WS4 were also similar except for the 5-yr return period when observed climate data were used for WEPP simulation. The simulated sediment yields, however, were greater than the observed, and we attribute this to over prediction of channel erosion, which accounted for more than 90 percent of the delivered sediment. For forested watersheds, both observed and simulated erosion rates were low. The relative variability with such data sets is typically high, making comparisons of erosion rates near zero difficult (Nearing, 2000).

Table 2. Observed and WEPP-simulated annual runoff and sediment yield using observed precipitation and air temperature data.

Water year	Watershed #1					Watershed #4				
	Observed			WEPP-simulated		Observed			WEPP-simulated	
	Precip. mm	Runoff mm	Sed. yield T ha^{-1}	Runoff mm	Sed. yield T ha^{-1}	Precip. mm	Runoff mm	Sed. yield T ha^{-1}	Runoff mm	Sed. yield T ha^{-1}
1987–1988	1324	460	0.22	428	0.18	1257	480	0.12	467	0.19
1988–1989	1701	726	0.25	731	0.29	1646	809	0.20	846	0.33
1989–1990	1548	632	0.36	582	0.16	1484	670	0.18	692	0.13
1990–1991	1377	574	0.35	508	0.14	1314	600	0.16	583	0.12
1991–1992	1376	466	0.31	452	0.09	1266	489	0.13	501	0.04
1992–1993	1352	467	0.24	451	0.14	1306	506	0.13	483	0.06
1993–1994	1943	966	0.40	991	0.37	1894	1038	0.25	1135	0.24
1994–1995	1181	381	0.16	327	0.06	1131	413	0.10	383	0.06
1995–1996	2082	970	0.46	1018	0.41	2023	1069	0.28	1128	0.38
1996–1997	1610	659	0.30	636	0.16	1520	714	0.17	728	0.12
1997–1998	1604	723	0.29	708	0.17	1562	803	0.19	864	0.12
1998–1999	1156	411	0.20	372	0.08	1074	434	0.11	363	0.03
1999–2000	1441	464	0.19	490	0.14	1393	504	0.13	519	0.07
2000–2001	1430	584	0.28	526	0.17	1349	645	0.16	570	0.11
2001–2002	1334	444	0.19	439	0.11	1229	502	0.13	426	0.05
2002–2003	1636	709	0.29	737	0.17	1557	797	0.20	784	0.09
2003–2004	1820	844	0.35	885	0.21	1699	907	0.22	964	0.15
2004–2005	1319	527	0.22	476	0.03	1187	584	0.15	510	0.01
2005–2006	1630	644	0.25	655	0.20	1533	625	0.15	666	0.15
2006–2007	1474	560	0.23	567	0.09	1383	594	0.14	605	0.03
Average	1517	610	0.28	599	0.17	1440	659	0.17	661	0.12

Table 3. Frequency analysis of the observed and simulated runoff and sediment yield. Note that the means and standard deviations in the table are for the annual maximum series.

		Observed			WEPP-Simulated using observed climate data		Simulated using online WEPP GIS interface		
		Precip. mm	Runoff mm	Sed. Yield T ha^{-1}	Runoff mm	Sed. Yield T ha^{-1}	Precip. mm	Runoff mm	Sed. Yield T ha^{-1}
Watershed #1									
Return period yr	10	88.4	52.7	0.0078	52.8	0.084	103.4	54.0	0.12
	5	80.5	37.4	0.0075	51.3	0.072	76.6	49.5	0.066
	2	63.5	24.1	0.0041	33.6	0.033	60.7	37.7	0.042
Mean		64.0	28.5	0.0048	34.6	0.043	65.8	37.6	0.048
Standard deviation		16.4	13.9	0.0026	12.9	0.027	22.7	14.7	0.034
Watershed #4									
Return period yr	10	90.2	55.4	0.0050	56.4	0.084	103.1	57.7	0.11
	5	73.7	36.5	0.0046	46.6	0.054	76.4	52.0	0.079
	2	65.0	24.9	0.0026	34.5	0.034	60.5	41.0	0.036
Mean		62.6	28.1	0.0030	34.8	0.035	65.5	42.3	0.044
Standard deviation		16.8	14.9	0.0012	13.2	0.026	22.8	16.0	0.034

SUMMARY

Two watersheds (WS1 and WS4) with long-term monitored records of streamflow and water chemistry at the Fernow Experimental Forest near Parsons, West Virginia, were selected for testing the online WEPP GIS interface. Both watersheds have been covered with mature forest for the last two decades and are located in proximity to each other with slightly different hydrological conditions. WS1 produced smaller average annual runoff with larger mean annual precipitation and greater sediment yield with smaller runoff than WS4. Observed precipitation and air temperature data were used in calibrating K_{sat} of the restrictive bedrock layer to adequately reproduce the observed surface runoff.

Online WEPP simulations were carried out using soil inputs adapted from the SSURGO database to site-specific conditions. The performance of the online WEPP was examined by comparing the simulated and observed streamflow and sediment yield estimated from the observed stream water chemistry data. The online WEPP model reasonably simulated average annual runoff and the annual maximum runoff series for both watersheds. Sediment yields were slightly under-predicted for annual average and slightly over-predicted for the annual maximum series. The under prediction of sediment for smaller events is likely due to the assumption that sediment delivery was approximately double the dissolved matter in the stream water. The over prediction for large events may be due to an over prediction of channel erosion by WEPP, suggesting that channel bed erodibility properties may need to be adjusted. The simulation results properly reflected the differences between WS1 and WA4 in their hydrological conditions. Future studies examining the performance of the online WEPP interface under different hydrologic, landuse, and management conditions are needed.

SPECIAL NOTES

Part of the data in this publication was obtained by scientists at the Timber and Watershed Laboratory and Fernow Experimental Forest; this publication has not been reviewed by those scientists. The Fernow Experimental Forest is operated and maintained by the Northeastern Research Station, Forest Service, U.S. Department of Agriculture, Newtown Square, Pennsylvania.

References

1. Adams, M. B., J. N. Kochenderfer, F. Wood, T. R. Wood, and P. Edwards. 1994. Forty years of hydrometerological data from the Fernow Experimental Forest, West Virginia. USDA, Forest Service, Northeastern Forest Experiment Station, Gen. Tech. Rep. NE-184.
2. Allen, R. G., L. S. Pereira, D. Reas, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirement. *FAO Irrig. Drain. Pap. No.56*. Rome: UN FAO. 300 p.
3. Dun, S., J. Q. Wu, and W. J. Elliot. 2003. Modification of the evapotranspiration routines in the WEPP (Water Erosion Prediction Project) model. ASAE Ann. Meet., Las Vegas, NV, Jul 2003.
4. Flanagan, D. C., and M. A. Nearing. eds. 1995. USDA—Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation. National Soil Erosion Research Laboratory Rep. 10. West Lafayette, Ind.: USDA-ARS NSERL.
5. Frankenberger J. R., S. Dun, D. C. Flanagan, J. Q. Wu, and W. J. Elliot. 2011. Development of a GIS interface for WEPP model application to Great Lakes forested watersheds. In *Proc. Intl. Symp. on Erosion and Landscape Evolution*, Paper 11139. St. Joseph, Mich.: ASABE.
6. Nash, J. E. and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models part I — A discussion of principles. *J. Hydrol.*10: 282–290.
7. Nearing, M. A. 2000. Evaluating soil erosion models using measured plot data: Accounting for variability in the data. *Earth Surf. Process. Landforms* 25: 1035–1043.
8. NRCS. 2011. Soil Survey Geographic (SSURGO) Database. Washington, D.C.: USDA, Natural Resources Conservation Service. Available at: soils.usda.gov/survey/geography/ssurgo/. Accessed 4 May 2011.
9. Patric, J. H. 1976. Soil erosion in the eastern forest. *J. Forest.* 74: 671–677
10. Penman, H. L. 1963. Vegetation and Hydrology. *Tech. Com. No. 53*. Harpenden, England: Commonwealth Bureau of Soils. 125 pp.
11. Taylor, S. B., and J. S. Kite. 1997. Final Report on Surficial and Bedrock Geology Project, Fernow Experimental Forest. Parsons, West Virginia: USDA, Forest Service, Fernow Experimental Forest. 40 p.
12. USDA. 2011a. Fernow Experimental Forest. Newtown Square, Pennsylvania: USDA, Forest Service, Northeastern Research Station. Available at: nrs.fs.fed.us/ef/locations/wv/fernow/. Accessed 23 April 2011.
13. USDA. 2011b. Fernow Experimental Forest Data Page. Newtown Square, Pennsylvania: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. Available at: www.fs.fed.us/ne/parsons/webdata/index.htm. Accessed 23 April 2011.
14. USGS. 2011. West Virginia Geologic Map Data. Washington, D.C.: USDOI, U.S. Geological Survey. Available at: tin.er.usgs.gov/geology/state/state.php?state=WV. Accessed 23 April 2011.
15. Wilson, K. B., P. J. Hanson, P. J. Mulholland, D. D. Baldocchi, and S. D. Wullschleger. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agr. Forest Meteorol.* 106(2): 153–168
16. Wu, J. Q., and S. Dun. 2006. Incorporating the Penman-Monteith ET Method in WEPP. Final Rep. to USDA, Forest Service, Rocky Mtn. Res. Stn.