

MODIFYING WEPP TO IMPROVE STREAMFLOW SIMULATION IN A PACIFIC NORTHWEST WATERSHED



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ABSTRACT. *The assessment of water yield from hillslopes into streams is critical in managing water supply and aquatic habitat. Streamflow is typically composed of surface runoff, subsurface lateral flow, and groundwater baseflow; baseflow sustains the stream during the dry season. The Water Erosion Prediction Project (WEPP) model simulates surface runoff, subsurface lateral flow, soil water, and deep percolation. However, to adequately simulate hydrologic conditions with significant quantities of groundwater flow into streams, a baseflow component for WEPP is needed. The objectives of this study were (1) to simulate streamflow in the Priest River Experimental Forest in the U.S. Pacific Northwest using the WEPP model and a baseflow routine, and (2) to compare the performance of the WEPP model with and without including the baseflow using observed streamflow data. The baseflow was determined using a linear reservoir model. The WEPP-simulated and observed streamflows were in reasonable agreement when baseflow was considered, with an overall Nash-Sutcliffe efficiency (NSE) of 0.67 and deviation of runoff volume (D_v) of 7%. In contrast, the WEPP simulations without including baseflow resulted in an overall NSE of 0.57 and D_v of 47%. On average, the simulated baseflow accounted for 43% of the streamflow and 12% of precipitation annually. Integration of WEPP with a baseflow routine improved the model's applicability to watersheds where groundwater contributes to streamflow.*

Keywords. *Baseflow, Deep seepage, Forest watershed, Hydrologic modeling, Subsurface lateral flow, Surface runoff, WEPP.*

The assessment of water yield from hillslopes into streams is critical in managing water supply and aquatic habitat. A streamflow hydrograph is affected by several runoff processes, including surface runoff, subsurface lateral flow, and baseflow. Surface runoff typically contributes most to the rising limb and the peak, subsurface lateral flow dominates the falling limb, and, baseflow, generated from the water stored in shallow unconfined aquifers, sustains the stream during the

non-rainy season.

In mountainous forest regions, flows into streams typically originate as subsurface lateral flow and groundwater baseflow (Bachmair and Weiler, 2011). Quantification of baseflow from lands with different topography, soil characteristics, geology, vegetation, and climate is beneficial in managing water resources. Many studies have been conducted to determine discharge from shallow groundwater reservoirs, and to estimate baseflow necessary to maintain water quality and quantity during low-flow seasons (Wittenberg and Sivapalan, 1999; Wittenberg, 2003; Katsuyama and Ohte, 2005; Fiori et al., 2007).

The Water Erosion Prediction Project (WEPP) is a physically based, continuous-simulation, distributed-parameter model (Flanagan and Nearing, 1995). It is based on the fundamentals of hydrology, hydraulics, plant science, and erosion mechanics (Nearing et al., 1989). WEPP was intended for cropland and rangeland applications where the hydrology is dominated by surface runoff and ephemeral streamflow (Flanagan and Livingston, 1995), and it is not suitable for watersheds with substantial baseflow. Recent improvements to WEPP included (1) a Penman-Monteith method for reference and actual evapotranspiration (ET) developed by Allen et al. (1998) (Wu and Dun, 2004), (2) improved subroutines for snow accumulation with snow-rain partition determined from dewpoint temperature following Link and Marks

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(1999) and for snowmelt based on the U.S. Army Corps of Engineers generalized snowmelt equation (Flanagan and Nearing, 1995), (3) an improved subroutine for frost simulation based on energy balance (Dun et al., 2010), and (4) enhanced algorithms for deep percolation and subsurface lateral flow, allowing for saturation-excess runoff (Dun et al., 2009). These improvements have increased the applicability of the WEPP model to forest watersheds. However, the model remains inadequate for applications where baseflow is important (Dun et al., 2009), and the need for incorporating a groundwater baseflow component into WEPP has been submitted in several studies (Zhang et al., 2009; Brooks et al., 2010). Zhang et al. (2009) simulated streamflow from a forested watershed in the headwater of Paradise Creek in northern Idaho using WEPP. They suggested that the model underpredicted the streamflow because of the absence of the baseflow. Brooks et al. (2010) applied the WEPP model to several watersheds in the Lake Tahoe basin and estimated the baseflow from WEPP-simulated daily deep percolation using a linear reservoir model.

Numerous studies have been carried out to investigate the behavior of the baseflow contribution to streams (Weisman, 1977; Nathan and McMahon, 1990; Moore, 1997; Wittenberg, 1999). Dooge (1960) developed a method to estimate baseflow using a linear reservoir model when recharge into a shallow unconfined aquifer is known. The method is based on the assumption that the outflow from the groundwater reservoir is directly proportional to groundwater storage. The linearity between storage and outflow has been reported in a number of field studies (Langbein, 1938; Snyder, 1939; Knisel, 1963; Toebees and Strang, 1964; Brutsaert and Nieber, 1977; Nathan and McMahon, 1990; Brandes et al., 2005), and the linear groundwater reservoir is widely recognized as a good approximation for most practical situations (Zecharias and Brutsaert, 1988; Vogel and Kroll, 1992; Chapman, 1999). More recent studies also show that the linear reservoir approach adequately represents baseflow recession (Fenicia et al., 2006; Brutsaert, 2008; van Dijk, 2010; Krakauer and Temimi, 2011).

The objectives of this study were (1) to simulate streamflow in the Priest River Experimental Forest in the U.S. Pacific Northwest using the WEPP model and a baseflow routine, and (2) to compare the performance of the WEPP model with and without including the baseflow using observed streamflow data.

METHOD

COMBINING A BASEFLOW ROUTINE WITH WEPP

WEPP conceptualizes watersheds as hillslopes and channel networks (Baffaut et al., 1997). For watershed applications, the model links all hillslopes to channels and impoundments. Water balance and erosion are first computed for each hillslope. Surface runoff and subsurface lateral flow from hillslopes are combined as discharge to the channels and are routed to the watershed outlet. WEPP outputs water balance for each hillslope and channel

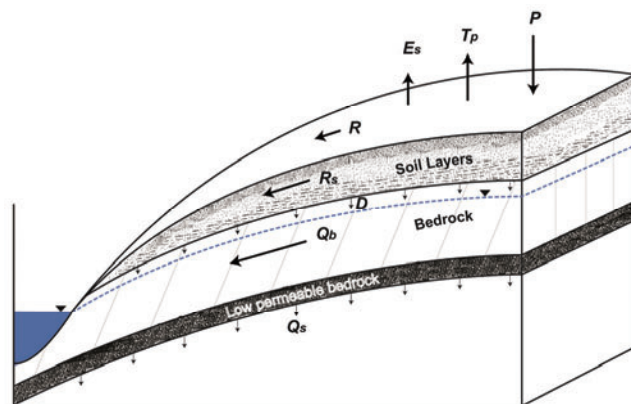


Figure 1. Hydrologic processes included in WEPP and groundwater flow: P = precipitation, E_s = soil evaporation, T_p = plant transpiration, R = surface runoff, R_s = subsurface lateral flow, D = deep percolation, Q_b = baseflow, and Q_s = deep seepage.

segment, surface runoff, deep percolation, ET, subsurface lateral flow, and total soil water on a daily basis. Deep percolation in the current WEPP (v2010.1) is the amount of the water that drains out of the simulated soil profile, i.e., the model domain.

In this study, we adopted the linear reservoir model in estimating the groundwater baseflow. The WEPP-simulated daily deep percolation values from each hillslope were summed and added to the fluctuating groundwater reservoir (fig. 1). Baseflow and deep seepage from the groundwater reservoir and the reservoir storage were calculated using an auxiliary program following equations 1 through 3:

$$Q_{bi} = k_b \cdot S_i \quad (1)$$

$$Q_{si} = k_s \cdot S_i \quad (2)$$

$$S_{i+1} = S_i + (D_i - Q_{bi} - Q_{si}) \quad (3)$$

where D_i , Q_{bi} , Q_{si} , and S_i are, respectively, the deep percolation from the soil profile, baseflow, deep seepage out of the reservoir, and reservoir storage on day i (all in mm), and k_b and k_s are baseflow and deep seepage coefficients, respectively.

Groundwater contribution to streams depends on the depth of the water table and hydraulic conductivity of the aquifer. Typically, the topography governs the flow of water in the unconfined aquifer toward the adjacent stream, and the hydraulic conductivity of the confining bed controls deep seepage into the underlying aquifer (Graham et al., 2010; Uchida et al., 2003; Katsuyama and Ohte, 2005). In combining the baseflow component with WEPP, we assumed that the baseflow is primarily dependent on the groundwater storage and independent of other flow components, including surface runoff and subsurface lateral flow.

MODEL APPLICATION

Study Site

The forested watershed (5.52 ha) selected for this study is located in the Priest River Experimental Forest in northern Idaho (48.35°N, -116.78°W) (fig. 2). Elevation

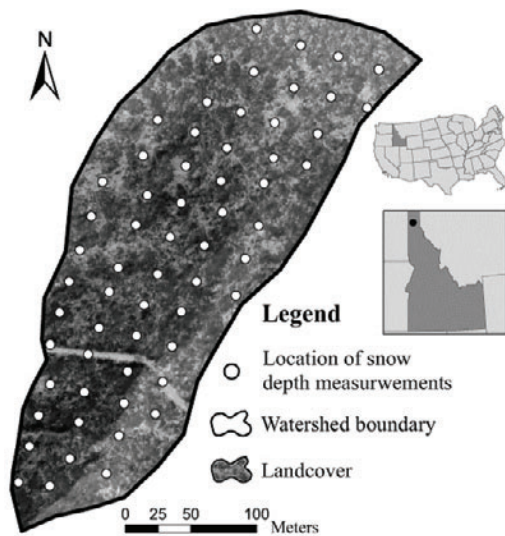


Figure 2. Study watershed in the Priest River Experimental Forest.

ranges from 689 to 1456 m above sea level, with an average slope gradient of 29%. Long-term (1900-2011) mean annual precipitation in the area is 789 mm, with 30% of precipitation as snow. Mean daily maximum and minimum temperatures are 15°C and 0°C, respectively. The dominant soil in the study watershed is the Vay silt loam (medial over loamy-skeletal, amorphic over isotic Vitric Haplocryands). Vegetation in the region consists primarily of Western larch (*Larix occidentalis*), Douglas fir (*Pseudotsuga menziesii*), and Western white pine (*Pinus monticola*). The underlying geologic formation of the watershed is metamorphic rocks of gneiss and schists (USDA, 2010). No treatment or harvesting was implemented to the study watershed during the past 50 years. In the summer of 2004, a 30 cm (1 ft) H-flume was installed at the watershed outlet. Water levels in the flume were recorded at 30 min intervals using an MTS Temposonics sensor from January 2005 to December 2009. A rating curve for the stage-discharge relationships was used to determine the discharge during 2005-2009. The observed discharges were summed over the day and divided by the area of the watershed to obtain daily runoff in millimeters. Snow depth was measured biweekly from February, when the snowfall was at its peak, to the complete melt during 2006-2009 using a 1 m marked iron rod at 30 m intervals (fig. 2).

WEPP Setup and Inputs

GeoWEPP, a geospatial interface of WEPP (Renschler, 2003), was used to delineate the watershed for WEPP simulations from a 10 m DEM. The minimum source channel length and critical source area were 100 m and 3 ha, respectively, which yielded a channel network that best matched that observed on the topographic map of the study watershed (fig. 3). The watershed was discretized into one channel and three hillslopes (fig. 3, table 1).

The climatic inputs included observed daily precipitation and maximum and minimum temperatures for 2005-2009, acquired from a NOAA weather station (NCDC, 2010) located within the Priest River Experimental

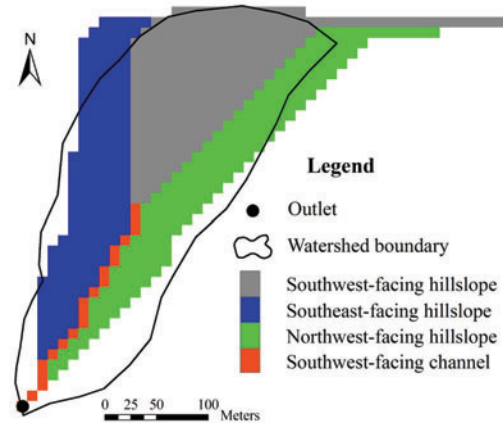


Figure 3. GeoWEPP-delineated watershed. Solid line shows the watershed boundary, and black dot indicates the watershed outlet.

Table 1. Priest River watershed configuration for WEPP simulation.

	Southwest-Facing Hillslope	Southeast-Facing Hillslope	Northwest-Facing Hillslope	Southwest-Facing Channel
Length (m)	253	66	67	250
Width (m)	86	250	250	1
Average slope (m m ⁻¹)	0.24	0.19	0.43	0.42
Aspect (°)	210	120	300	210
Area (m ²)	21,700	16,500	16,800	250

Station (fig. 4) 3.3 km southwest of the study site at an elevation of 739 m. CLIGEN (Nicks et al., 1995), WEPP's auxiliary stochastic climate generator, was used to fill in the missing 0.38% of precipitation data and to generate the remaining climatic inputs (solar radiation, dewpoint temperature, wind velocity, and wind direction) based on monthly statistics of the long-term historical weather data from the NOAA Sandpoint Experiment Station, located 16.8 km southeast of the study site.

Major soil inputs for the channel and hillslopes are presented in tables 2 and 3. Soil textural and hydraulic properties for each of the four soil layers were obtained from the STATSGO database (USDA, 2010). Soil organic matter content for the top two layers of the hillslopes was taken from Page-Dumroese and Jurgensen (2006), and a lower value was used for the channel. WEPP default values for forest silt loam were used for soil albedo, initial saturation, and erodibility parameters, i.e., rill erodibility, interrill erodibility, and critical shear (table 3).

For the hillslopes, the management inputs, including the sensitive parameters of initial ground and canopy cover and days of senescence, were the default values for perennial forests in the WEPP database (table 3). A leaf area index (LAI) of 6 was used, following Pocewicz et al. (2003). For the channel, the default values for an earth channel under fallow management were used.

WEPP Simulation Scenarios

Two sets of continuous WEPP simulations (with a daily time step) were carried out for the observation period 2005-2009: without baseflow (scenario 1) and with baseflow (scenario 2). Under scenario 2, we calibrated the model using observed daily streamflow for 2005-2006 and

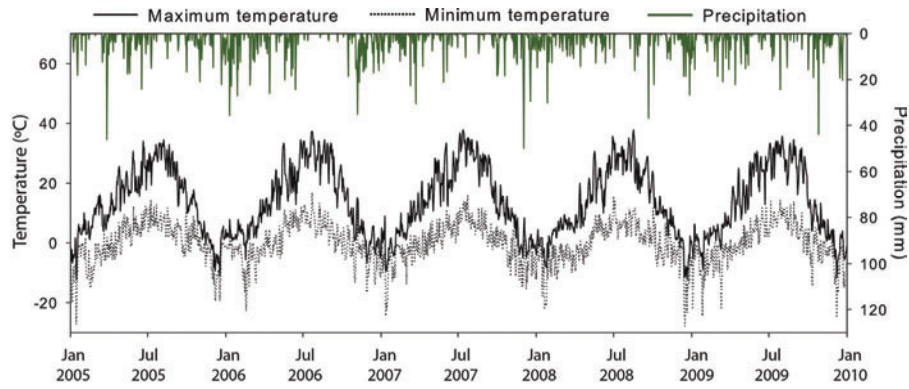


Figure 4. Observed daily precipitation and maximum and minimum temperature, Priest River Experimental Forest, Idaho.

Table 2. Soil textural inputs for different layers.

Layer	Depth (mm)	Sand (%)	Clay (%)	Organic Matter (%)	CEC (meq per 100 g)	Rock (%)
1	152.4	36.3	6.0	7.0	15.0	15.0
2	254.0	52.7	6.0	5.0	4.2	20.0
3	228.6	64.7	6.0	2.0	4.2	50.4
4	432.0	72.4	3.5	1.0	2.5	61.0

Table 3. Default and calibrated parameter values for soil surface, erodibility, and management conditions.^[a]

Parameters	Default Value
Albedo	0.23
Initial saturation level (%)	50
Effective hydraulic conductivity (mm h ⁻¹)	50.4
Rill erodibility (kg s m ⁻⁴)	1.0 × 10 ⁻⁶
Interrill erodibility (s m ⁻¹)	4.0 × 10 ⁻⁴
Critical shear (Pa)	1.5
Anisotropy ratio	25 (15)
Saturated hydraulic conductivity of restrictive layer (mm h ⁻¹)	0.036
Leaf Area Index	6
Mid-season crop coefficient	0.95 (0.75)
Readily available water	0.75
Initial groundcover (%)	100
Initial canopy cover (%)	90
Day of senescence	250

^[a] Values in parenthesis are calibrated parameters.

evaluated the model performance using the remaining streamflow data for 2007-2009. The same WEPP inputs were used for both simulation scenarios.

WEPP Calibration

The FAO Penman-Monteith method (Allen et al., 1998) was used to estimate actual ET from the reference ET. Actual ET was obtained by adjusting for (1) the existing vegetation by changing the mid-season crop coefficient (K_{cb}) and (2) the environmental conditions by changing the coefficient of readily available water (RAW). Conifers, the dominant species at the study watershed, are sensitive to vapor pressure deficit, and unlike other vegetation, they close their stomata when the humidity falls, even if the soils are wet (John Marshall, University of Idaho, personal communication). Similarly, Allen et al. (1998) reported that conifers exhibit substantial stomata control, and K_{cb} can be below 0.95, a representative value for well-watered conditions. In our study, the default value of 0.75 was used for RAW, and K_{cb} was calibrated to 0.75 for the simulated actual ET to agree with the literature value for typical Pacific Northwest forest watersheds (Zhang et al., 2009).

Two critical parameters in WEPP for subsurface lateral flow, important in mountainous regions, are the anisotropy ratio of the hydraulic conductivity of the soil profile and the saturated hydraulic conductivity (K_{sat}) of the restrictive layer underlying the soil profile. The median K_{sat} value (0.036 mm h⁻¹) for typical metamorphic rocks (Tsihrintzis and Jain, 2010) was used, and the anisotropy ratio was calibrated through sensitivity analysis.

In the baseflow routine, the initial groundwater storage, baseflow, and deep seepage coefficients were determined with the least-squares estimation (LSE) method based on observed streamflow. The LSE minimizes the sum of squared difference between the observed and simulated streamflow.

Model Performance Evaluation

Comparisons were made of (1) simulated and observed hydrographs, and (2) snow depths simulated by WEPP, field-measured (average of 61 points across watershed), and acquired from the NCDC (2010). Statistical indices, including the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) and deviation of runoff volume (D_v ; Gupta et al., 1999), were obtained, and together they were used to rate the general model performance following Moriasi et al. (2007).

NSE is a goodness-of-fit criterion demonstrating the agreement between the simulated and observed values, with a value of 1 indicating a perfect match and values between zero and one indicating an acceptable level of model performance. It is computed as:

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_{obs,i} - Y_{sim,i})^2}{\sum_{i=1}^n (Y_{obs,i} - Y_{mean})^2} \quad (4)$$

where $Y_{obs,i}$ and $Y_{sim,i}$ are the i th observed and simulated values, respectively, Y_{mean} is the mean of observed data, and n is the total number of observations.

The percent deviation of runoff volume (D_v) is an error indicator for model accuracy in terms of over- or underestimation of simulated results (Gupta et al., 1999), with positive values indicating underestimation and negative values indicating overestimation. D_v is given by (ASCE, 1993):

$$D_v = \left[\frac{\sum_{i=1}^n (Y_{obs,i} - Y_{sim,i}) \times 100}{\sum_{i=1}^n Y_{obs,i}} \right] \quad (5)$$

RESULTS AND DISCUSSION

CALIBRATED ANISOTROPY RATIO AND BASEFLOW PARAMETERS

WEPP-simulated subsurface lateral flow was sensitive to the anisotropy ratio (fig. 5), and a value of 15 yielded the optimum agreement overall between simulated and observed streamflow, with NSE and D_v values of 0.67 and 7%, respectively (fig. 5). The low and high values of the anisotropy ratio (1, 5, 20, and 25) resulted in negative deep seepage coefficients, indicating insufficient storage in the groundwater reservoir for baseflow and an upward recharge from the deeper aquifer. However, such a recharge process is unlikely, as our study watershed is situated in a

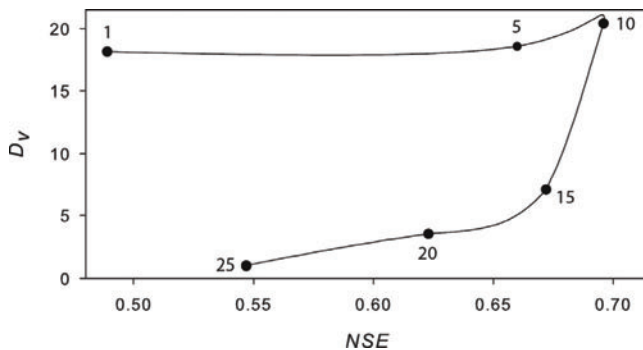


Figure 5. NSE and D_v values for different anisotropy ratios under scenario 2 with baseflow included.

headwater area where confined flow conditions are uncommon (Fetter, 1994). The LSE estimates of the initial groundwater reservoir storage and the baseflow and deep seepage coefficients were 60 mm, 0.0156 d^{-1} , and 0.00026 d^{-1} , respectively.

STREAMFLOW

WEPP-simulated and observed daily streamflow for 2005-2009 for scenarios 1 and 2 are shown in figure 6. In general, spring snowmelt controls the hydrograph. Low flows were observed during the winter months, and high peaks were observed in the months of April and May.

In scenario 1, WEPP-simulated streamflow was entirely from the subsurface lateral flow (fig. 6a). Simulated recessions on the falling limbs of the hydrograph were steeper than observed. No streamflow was simulated for late June until the next March, inconsistent with the field-observed streamflow for the period as sustained by the baseflow. In contrast, the scenario 2 simulation (fig. 6b) reproduced the observed recessions on the falling limbs. The simulated streamflow was generated as a combination of subsurface lateral flow and baseflow. The estimated average residence times of baseflow and deep seepage, i.e., the reciprocals of the coefficients, were 64 days and 3300 days, respectively, which are within the upper ranges reported by Brandes et al. (2005). The slow release from the groundwater reservoir is reflective of the relatively low hydraulic conductivity of the metamorphic bedrock at the study watershed.

For both simulations, WEPP underpredicted the runoff peaks for 2005, 2008, and 2009 and overpredicted the peaks for 2006 and 2007. A possible reason may be that the snow accumulation and timing of snowmelt were not properly simulated by WEPP (fig. 7) because stochastically generated, instead of field-observed, solar radiation, dewpoint temperature, and wind velocity were used. Dun et

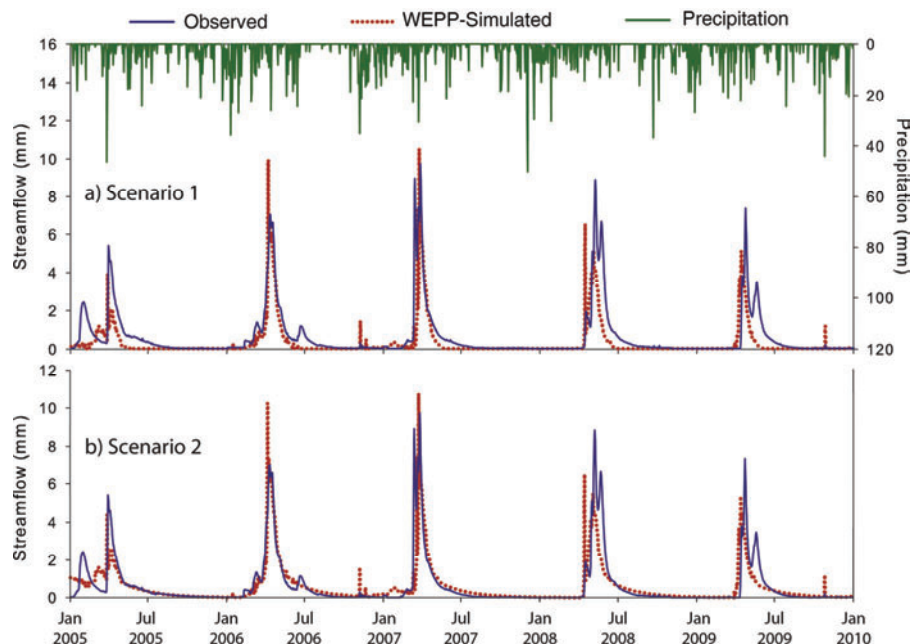


Figure 6. Comparison of WEPP-simulated and observed daily streamflows for scenario 1 (without baseflow) and scenario 2 (with baseflow).

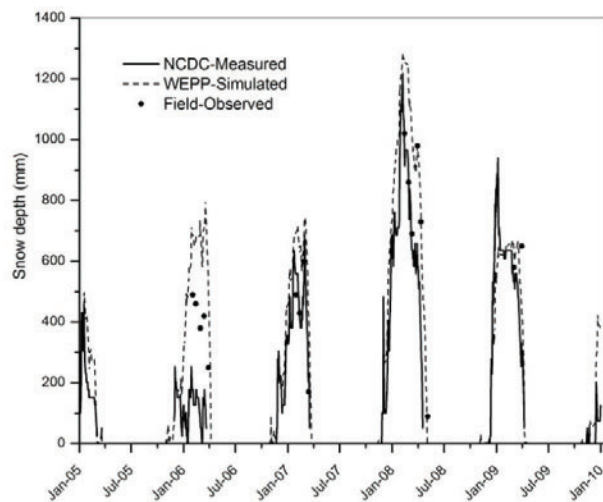


Figure 7. Comparison of WEPP-simulated, NCDC, and field-observed snow depths for 2005-2009.

al. (2010) noted similar results of lack of agreement between simulated and observed time and magnitude of runoff peaks during snowmelt seasons for an intermittent stream in central Idaho.

WATER BALANCE

Major water balance components for the two scenarios are shown in table 4. The mean annual precipitation from 2005 to 2009 was 794 mm, and no surface runoff was simulated. Surface runoff is rare in forests due to the presence of a thick duff layer and the highly permeable soils, which increase the surface retention and roughness and the infiltration capacity (Elliot et al., 2000). Runoff at the watershed outlet primarily originates from subsurface lateral flow and baseflow.

The simulated annual ET from the watershed varied from 483 to 608 mm for the simulated years and accounted for 70% of annual precipitation, which agrees with literature

values for other Pacific Northwest forest watersheds (e.g., Zhang et al., 2009). Low hydraulic conductivity of the bedrock restricts the downward movement of water from the soil profile, thereby helping retain the soil water content above the soil-bedrock interface and allowing more water for plant use, as shown in our study. The simulated deep percolation from the soil profile, occurring mainly during the snowmelt season, accounted for 10% of annual precipitation. Simulated soil water storage varies from year to year, with a maximum increase of 65 mm in 2006 and a maximum decrease of 54 mm in 2007. The net decrease of 5 mm (0.6% of average precipitation) over the five-year simulation period, however, is insignificant. The simulated subsurface lateral flow ranged from 98 to 203 mm and was the second largest component of the water balance, after ET, and accounted for 18% of precipitation. Previous studies indicated that highly porous soils and lateral tree roots in combination with a low-permeability layer underneath could lead to dominant lateral flows under anisotropic conditions (Brooks et al., 2004; Dun et al., 2009; Bachmair and Weiler, 2011).

Under scenario 2, simulated baseflow to the stream and deep seepage from the groundwater reservoir accounted for 12% and 0.2% of annual precipitation, respectively. The baseflow index (BFI) ranged from 37% to 63% over the five years, with an average of 43%, suggesting the important contributions of both subsurface lateral flow and baseflow to streamflow at the study watershed (table 4). The simulated average annual streamflow for scenarios 1 and 2 were 123 and 214 mm, respectively, with the former being much less than, and the latter compatible with, the observed 231 mm (table 5). A similar water movement mechanism, in which the recharge from the soil profile into the bedrock travels laterally and discharges into the stream system, was also observed by Anderson et al. (1997), Asano et al. (2002), Montgomery and Dietrich (2002), and Fiori et al. (2007).

Table 4. Simulated annual water balance of the study watershed.^[a]

Year	<i>P</i> (mm)	<i>R</i> (mm)	<i>R_s</i> (mm)	ET (mm)	<i>D</i> (mm)	<i>SW</i> (mm)	Scenario 2		
							<i>Q_b</i> (mm)	<i>Q_s</i> (mm)	BFI (%)
2005	744	0	98	589	68	-46	125	2	63
2006	957	0	203	535	109	65	101	2	37
2007	769	0	173	483	90	-54	94	2	39
2008	768	0	144	608	80	-20	78	1	38
2009	729	0	106	557	60	29	59	1	39
Average	794	0 (0)	145 (18)	554 (70)	81 (10)	-5 (-0.6)	91 (11.5)	2 (0.2)	43

^[a] *P* = precipitation, *R* = surface runoff, *R_s* = subsurface lateral flow, ET = evapotranspiration, *D* = deep percolation from soil profile, *SW* = yearly change in soil water calculated as the last day's value minus the first day's, *Q_b* = baseflow, *Q_s* = deep seepage from groundwater reservoir, and BFI = baseflow index (percent baseflow of streamflow). Values in parentheses are the percentage of precipitation of each water balance component.

Table 5. Simulated vs. observed annual streamflow, Nash-Sutcliffe efficiency (NSE), and deviation of runoff volume (*D_v*).^[a]

Year	Observed Streamflow (mm)	Scenario 1			Scenario 2		
		Simulated Streamflow (mm)	NSE	<i>D_v</i> (%)	Simulated Streamflow (mm)	NSE	<i>D_v</i> (%)
2005	209	75	0.263	64.2	200	0.531	4.2
2006	264	174	0.874	34.1	275	0.898	-4.0
2007	248	149	0.605	39.8	243	0.630	1.9
2008	257	127	0.535	50.7	205	0.665	20.3
2009	176	91	0.360	48.5	150	0.534	15.2
Average	231 (29)	123 (16)	0.570	46.7	214 (27)	0.672	7.1

^[a] Values in parentheses are the percentage of precipitation of the streamflow.

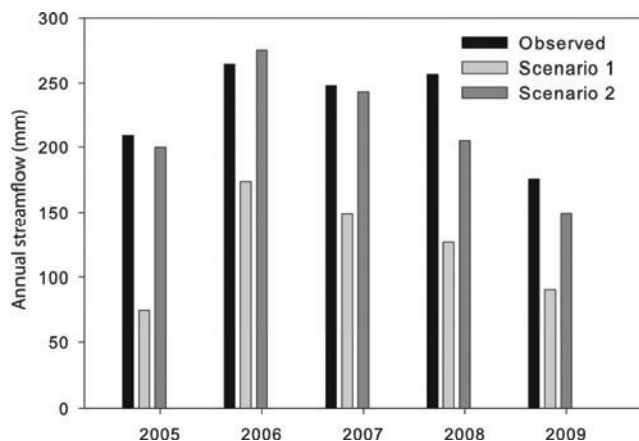


Figure 8. Comparison of observed and WEPP-simulated annual streamflow (scenario 1 = without baseflow and scenario 2 = with baseflow).

STATISTICAL ANALYSIS

On average, the NSE for streamflow was 0.570 for scenario 1 and 0.672 for scenario 2. For each simulation year, the NSE was higher for scenario 2 than for scenario 1, particularly for the two dry years of 2005 and 2009 (table 5), demonstrating improvements in WEPP streamflow simulation when baseflow was included. Moriasi et al. (2007) proposed 0.65 to 0.75 as the range of NSE as a criterion for “good performance” for hydrologic models with a monthly time step.

Similarly, the D_v for streamflow also indicated an improvement in WEPP simulation by including baseflow. The average D_v was 47% for scenario 1 (table 5), a considerable underestimate of streamflow and representing “unsatisfactory” model performance following Moriasi et al. (2007), and 7% for scenario 2, suggesting “very good” model performance. The underprediction in scenario 1 was particularly serious for 2005, 2008, and 2009 (table 5, fig. 8).

SUMMARY AND CONCLUSIONS

The WEPP model and a baseflow routine based on a linear groundwater reservoir model were used to simulate streamflow from a watershed in the headwaters of the Priest River Experimental Forest in the U.S. Pacific Northwest. WEPP simulations were carried out with and without the baseflow included. The model performance was evaluated using observed streamflow data for 2005–2009.

WEPP reproduced the peaks of the streamflow when only the subsurface lateral flow was included but not the baseflow. However, the simulated recessions on the falling limbs of the hydrograph were steeper than observed. In addition, flows during the dry seasons of late June until the next March were not simulated, leading to a considerable underestimate of the flows in these months, as reflected in a high D_v value.

The least-squares estimates of the baseflow and deep seepage coefficients for the study watershed were 0.0156 d^{-1} and 0.00026 d^{-1} , respectively. With these baseflow parameters, the simulated baseflow was 12% of the annual precipitation, accounting for 43% of the simulated stream-

flow on average. An overall NSE of 0.672 and D_v of 7% demonstrated the adequacy of including groundwater baseflow in the streamflow for the study watershed. Linking the WEPP model with a baseflow routine improved the model’s applicability to watersheds where the contribution of baseflow to streamflow is substantial. This approach should be further examined with future applications to watersheds under different climatic and geological conditions.

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REFERENCES

- Allen, R. G., L. S. Pereira, D. Reas, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirement. Irrigation and Drainage Paper 56. Rome, Italy: United Nations FAO.
- Anderson, S. P., W. E. Dietrich, D. R. Montgomery, R. Torres, M. E. Conrad, and K. Loague. 1997. Subsurface flow paths in a steep, unchanneled catchment. *Water Resour. Res.* 33(12): 2637–2653.
- Asano, Y., T. Uchida, and N. Ohte. 2002. Residence times and flow paths of water in steep unchanneled catchments, Tanakami, Japan. *J. Hydrol.* 261(1–4): 173–192.
- ASCE. 1993. Criteria for evaluation of watershed models. *J. Irrig. Drain. Eng.* 119(3): 429–442.
- Bachmair, S., and M. Weiler. 2011. New dimensions of hillslope hydrology. In *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*, 455–481. D. F. Levia, D. Carlyle-Moses, and T. Tanaka, eds. Ecological Studies Series No. 216. Heidelberg, Germany: Springer-Verlag.
- Baffaut, C., M. A. Nearing, J. C. Ascough II, and B. Y. Liu. 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watersheds. *Trans. ASAE* 40(4): 935–943.
- Brandes, D., J. G. Hoffmann, and J. T. Mangarillo. 2005. Baseflow recession rates, low flows, and hydrologic features of small watersheds in Pennsylvania, USA. *J. American Water Resour. Assoc.* 41(5): 1177–1186.
- Brooks, E. S., J. Boll, and P. D. McDaniel. 2004. A hillslope-scale experiment to measure the lateral saturated hydraulic conductivity. *Water Resour. Res.* 40(4): W04208, doi: 10.1029/2003WR002858.
- Brooks, E. S., W. J. Elliot, J. Boll, and J. Q. Wu. 2010. Final report: Assessing the sources and transport of fine sediment in response to management practices in the Tahoe basin using the WEPP model. Berkeley, Cal.: U.S. Forest Service, Pacific Southwest Research Station. Available at: www.fs.fed.us/psw/partnerships/tahoescience/documents/final_rpts/P005FinalReportJan2011.pdf. Accessed 15 February 2012.
- Brutsaert, W. 2008. Long-term groundwater storage trends estimated from streamflow records: Climate perspective. *Water Resour. Res.* 44(2): W02409, doi: 10.1029/2007WR006518.
- Brutsaert, W., and J. L. Nieber. 1977. Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resour. Res.* 13(3): 637–643.
- Chapman, T. 1999. A comparison of algorithms for streamflow recession and baseflow separation. *Hydrol. Proc.* 13(5): 701–714.

- Dooge, J. C. I. 1960. The routing of groundwater recharge through typical elements of linear storage. Commission of Subterranean Waters, General Assembly of Helsinki. *Intl. Assoc. Sci. Hydrol. Pub.* 52: 286-300.
- Dun, S., J. Q. Wu, W. J. Elliot, P. R. Robichaud, D. C. Flanagan, J. R. Frankenberger, R. E. Brown, and A. C. Xu. 2009. Adapting the Water Erosion Prediction Project (WEPP) model for forest applications. *J. Hydrol.* 366(1-4): 46-54.
- Dun, S., J. Q. Wu, D. K. McCool, J. R. Frankenberger, and D. C. Flanagan. 2010. Improving frost-simulation subroutines of the Water Erosion Prediction Project (WEPP) model. *Trans. ASABE* 53(5): 1399-1411.
- Elliot, W. J., D. E. Hall, and D. L. Scheele. 2000. Disturbed WEPP (draft 02/2000) WEPP interface for disturbed forest and range runoff, erosion and sediment delivery. Moscow, Idaho: U.S. Forest Service, Moscow Forestry Sciences Laboratory. Available at: <http://forest.moscowfs.wsu.edu/fswepp/docs/distweppdoc.html>. Accessed 22 November 2011.
- Fenicia, F., H. H. G. Savenije, P. Matgen, and L. Pfister. 2006. Is the groundwater reservoir linear? Learning from data in hydrological modeling. *Hydrol. Earth Syst. Sci.* 10(1): 139-150.
- Fetter, C. W. 1994. *Applied Hydrogeology*. 3rd ed. Upper Saddle River, N.J.: Prentice-Hall.
- Fiori, A., M. Romanelli, D. J. Cavalli, and D. Russo. 2007. Numerical experiments of streamflow generation in steep catchments. *J. Hydrol.* 339(3-4): 183-192.
- Flanagan, D. C., and S. J. Livingston. 1995. WEPP user summary. NSERL Report No. 11. W. Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.
- Flanagan, D. C., and M. A. Nearing. 1995. USDA Water Erosion Prediction Project: Hillslope profile and watershed model documentation. NSERL Report No. 10. W. Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.
- Graham, C. B., W. V. Verseveld, H. R. Barnard, and J. J. McDonnell. 2010. Estimating the deep seepage component of the hillslope and catchment water balance within a measurement uncertainty framework. *Hydrol. Proc.* 24(25): 3631-3647.
- Gupta, H. V., S. Sorooshian, and P. O. Yapo. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *J. Hydrol. Eng.* 4(2): 135-143.
- Katsuyama, M., and N. Ohte. 2005. Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment. *Water Resour. Res.* 41(1): W01010, doi: 10.1029/2004WR003275.
- Knisel, W. G. 1963. Baseflow recession analysis for comparison of drainage basins and geology. *J. Geophys. Res.* 68(12): 3649-3653.
- Krakauer, N. Y., and M. Temimi. 2011. Stream recession curves and storage variability in small watersheds. *Hydrol. Earth Syst. Sci.* 15(7): 2377-2389.
- Langbein, W. B. 1938. Some channel storage studies and their application to the determination of infiltration. *Eos Trans. AGU* 19(1): 435-447.
- Link, T. E., and D. Marks. 1999. Point simulation of seasonal snow cover dynamics beneath boreal forest canopies. *J. Geophys. Res.* 104(D22): 27841-27857.
- Montgomery, D. R., and W. E. Dietrich. 2002. Runoff generation in a steep, soil-mantled landscape. *Water Resour. Res.* 38(9): 1168, doi: 10.1029/2001WR000822.
- Moore, R. D. 1997. Storage-outflow modelling of streamflow recessions, with application to a shallow-soil forested catchment. *J. Hydrol.* 198(1-4): 260-270.
- Moriassi, N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50(3): 885-900.
- Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principals. *J. Hydrol.* 10(3): 282-290.
- Nathan, R. J., and T. A. McMahon. 1990. Evaluation of automated techniques for baseflow and recession analysis. *Water Resour. Res.* 26(7): 1465-1473.
- NCDC. 2010. Online station locator. Asheville, N.C.: National Climatic Data Center. Available at: <http://lwf.ncdc.noaa.gov/oa/climate/stationlocator.html>. Accessed 20 December 2010.
- Nearing, M. A., G. R. Foster, L. J. Lane, and S. C. Finkner. 1989. A process-based soil erosion model for USDA Water Erosion Prediction Project technology. *Trans. ASAE* 32(5): 1587-1593.
- Nicks, A. D., L. J. Lane, and G. A. Gander. 1995. Weather generator. In *USDA Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation*. D. C. Flanagan and M. A. Nearing, eds. NSERL Report No. 10. W. Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.
- Page-Dumroese, D. S., and M. F. Jurgensen. 2006. Soil carbon and nitrogen pools in mid- to late-successional forest stands of the northwestern United States: Potential impact of fire. *Canadian J. Forest Res.* 36(9): 2270-2284.
- Pocewicz, A. L., P. Gessler, and A. P. Robinson. 2003. The relationship between effective plant area index and Landsat spectral response across elevation, solar insolation, and spatial scales in a northern Idaho forest. *Canadian J. Forest Res.* 34(2): 465-480.
- Renschler, C. S. 2003. Designing geo-spatial interfaces to scale process models: The GeoWEPP approach. *Hydrol. Proc.* 17(5): 1005-1017.
- Snyder, F. F. 1939. A concept of runoff phenomena. *Eos Trans. AGU* 20: 725-738.
- Toebes, C., and D. D. Strang. 1964. On recession curves: 1. Recession equations. *J. Hydrol.* 3: 2-5.
- Tsihrintzis, G., and L. C. Jain. 2010. *Multimedia Services in Intelligent Environments: Software Development and Solutions*. 1st ed. Heidelberg, Germany: Springer.
- Uchida, T., Y. Asano, N. Ohte, and T. Mizuyama. 2003. Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope. *Water Resour. Res.* 39(1): 1018, doi: 10.1029/2002WR001298.
- USDA. 2010. The U.S. General Soil Map (STATSGO2). Washington, D.C.: USDA Natural Resources and Conservation Service. Available at: <http://soildatamart.nrcs.usda.gov>. Accessed 6 December 2010.
- van Dijk, A. I. J. M. 2010. Climate and terrain factors explaining streamflow response and recession in Australian catchments. *Hydrol. Earth Syst. Sci.* 14(1): 159-169.
- Vogel, R. M., and C. N. Kroll. 1992. Regional geohydrologic-geomorphic relationships for the estimation of low flow statistics. *Water Resour. Res.* 28(9): 2451-2458.
- Weisman, R. N. 1977. The effects of evapotranspiration on streamflow recession. *Hydrol. Sci. Bull.* 22(3): 371-377.
- Wittenberg, H. 1999. Baseflow recession and recharge as nonlinear storage processes. *Hydrol. Proc.* 13(5): 715-726.
- Wittenberg, H. 2003. Effects of season and man-made changes on baseflow and flow recession: Case studies. *Hydrol. Proc.* 17(11): 2113-2123.
- Wittenberg, H., and M. Sivapalan. 1999. Watershed groundwater balance estimation using streamflow recession analysis and baseflow separation. *J. Hydrol.* 219(1-2): 20-33.
- Wu, J. Q., and S. Dun. 2004. Developing a forest subwatershed template for the WEPP model: Part I. Incorporation of the

- Penman-Monteith ET method into the WEPP model. Agreement No. 01-JV-11222065-261. Report submitted to U.S. Forest Service, Rocky Mountain Research Station.
- Zecharias, Y. B., and W. Brutsaert. 1988. Recession characteristics of groundwater outflow and baseflow from mountainous watersheds. *Water Resour. Res.* 24(10): 1651-1658.
- Zhang, J. X., J. Q. Wu, K. Chang, W. J. Elliot, and S. Dun. 2009. Effects of DEM source and resolution on WEPP hydrologic and erosion simulation: A case study of two forest watersheds in northern Idaho. *Trans ASABE* 52(2): 447-457.