

APPLICATION OF THE WATER EROSION PREDICTION PROJECT (WEPP) MODEL TO SIMULATE STREAMFLOW IN A PNW FOREST WATERSHED

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ABSTRACT

Assessment of water yields from watersheds into streams and rivers is critical to managing water supply and supporting aquatic life. Surface runoff typically contributes the most to peak discharge of a hydrograph while subsurface flow dominates the falling limb of hydrograph and baseflow contributes to streamflow from shallow unconfined aquifers primarily during the non-rainy season. The Water Erosion Prediction Project (WEPP) model is a physically-based, distributed-parameter, continuous-simulation model. Recent improvements to WEPP include enhanced computation of evapotranspiration (ET) by incorporating the Penman-Monteith method into the model, and improved calculation of subsurface lateral flow by properly setting a restrictive layer and soil anisotropic ratios. These modifications have substantially improved the performance of the WEPP model for forested watersheds. In order to further enhance the model applicability, a baseflow component needs to be incorporated to adequately represent hydrologic conditions where significant quantities of ground water flow to streams.

The specific objectives of this study were to incorporate a baseflow component into the WEPP model based on a linear reservoir model and to evaluate the performance of the improved WEPP model by applying it to a representative PNW forest watershed. The study watershed selected is located in the Priest River Experimental Forest in northern Idaho State (48.35°N, -116.78°W). WEPP discretizes a watershed into hillslopes, hydraulic structures, and channel networks. Currently, WEPP simulates daily water balance with the following components: surface runoff, subsurface lateral flow, ET, soil water, and percolation. For the baseflow component, percolation was added to the ground-water reservoir from which ground-water baseflow and deep leakage are derived following a linear reservoir model that assumes outflow from a reservoir is a linear fraction of the ground-water storage in an unconfined aquifer.

In general, WEPP predicted streamflow with reasonable accuracy. Nash-Sutcliffe efficiency (*NSE*) values ranged from 0.50 to 0.89 for the simulation period of 2005 till 2009, with an overall value of 0.67, indicating satisfactory performance of the model. An overall deviation of the runoff volume (D_v) of 9% indicates that simulated streamflow is under-predicted compared to the observed. The model under-predicted hydrograph peaks for 2005, 2008, and 2009, and over-predicted peaks for 2006 and 2007. The calibrated baseflow and deep seepage coefficients are 0.0232 d^{-1} and 0.0057 d^{-1} , respectively. The mean annual simulated baseflow contribution is 59% of total simulated streamflow. Results from this study suggest that incorporation of a linear ground-water reservoir model into WEPP allows the model to be applicable to watersheds with significant amounts of baseflow.

KEYWORDS. Forest watershed, Surface runoff, Subsurface lateral flow, Baseflow, Hydrologic modeling, WEPP.

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INTRODUCTION

Water yield assessment from watersheds into the streams or rivers is critical to managing water supply demands and supporting aquatic life. Streamflow hydrographs can be separated into three parts to represent three individual contributions to streamflow. Surface runoff typically contributes most to peak discharge of a hydrograph; subsurface lateral flow dominates the falling limb of a hydrograph; and, baseflow, generated from water stored in shallow unconfined aquifers, sustains the stream during the non-rainy season. Numerous studies have been conducted to relate recharge to, and discharge from, shallow ground-water reservoirs, and to estimate flows necessary to maintain water quality and quantity during low-flow seasons (Wittenberg and Sivapalan, 1999). Quantification of baseflow from lands with different topography, soil characteristics, geology, vegetation, and climate is beneficial in the monitoring and management of water resources.

The Water Erosion Prediction Project (WEPP) model is a physically-based, continuous-simulation, distributed-parameter model (Flanagan and Nearing, 1995) based on the fundamentals of hydrology, hydraulics, plant science, and erosion mechanics (Nearing et al., 1989). WEPP was intended for crop- and rangeland applications where the hydrology is dominated by Hortonian overland flow, which limits its application largely to watersheds with ephemeral streams (Flanagan and Livingston, 1995) and excludes its use for watersheds subject to saturation-excess runoff. Recent improvements to WEPP include enhanced computation of evapotranspiration (ET) by incorporating the Penman-Monteith method into the model as well as improved calculations of percolation and subsurface lateral flow by properly setting a restrictive layer and soil anisotropic ratios. These additions have significantly improved the performance of the WEPP model (Dun et al., 2009). However, Dun et al. (2009) and Wang et al. (2010) emphasize the need to incorporate a ground-water baseflow component to adequately represent streamflow in watersheds where considerable amounts of ground water discharge to the stream. The objective of this research is to improve WEPP v2010.1 to make it applicable for watersheds with substantial amounts of baseflow. Specific objectives were to develop a baseflow subroutine for WEPP using a linear reservoir model; and to evaluate the performance of the improved WEPP model by applying it to a representative forest watershed in the PNW where there is a substantial amount of baseflow.

METHOD

Incorporating a baseflow component into WEPP

The WEPP model is a process-based, continuous-simulation, distributed-parameter model for hydrology and water erosion (Flanagan and Nearing, 1995). WEPP is based on the fundamentals of hydrology, plant science, hydraulics, and erosion mechanics (Nearing et al., 1989). The major advantage of the WEPP model is its ability to estimate spatial and temporal distribution of soil loss or deposition. 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, and surface runoff and subsurface lateral flow generated from all hillslopes are combined and routed through the channels to the watershed outlet. WEPP creates water balance file for each hillslope and channel component. Surface runoff, subsurface lateral flow, ET, total soil water, and percolation are calculated on a daily basis. Percolation in the current WEPP version is considered out of the model domain.

To compute watershed baseflow, daily percolation values from each hillslope were summed and added to the fluctuating ground-water reservoir. A linear reservoir model that assumes outflow from the ground-water reservoir is a linear fraction of the storage in the unconfined aquifer was used to compute baseflow and deep leakage from the entire watershed following Equations 1 and 2 (Figure 1). Calculated baseflow was added to surface runoff and subsurface lateral flow to obtain streamflow.

$$Q_b = k_b \cdot S \quad (1)$$

$$Q_l = k_l \cdot S \quad (2)$$

where Q_b is baseflow (mm); Q_l is deep leakage (mm); k_b and k_l are baseflow and deep leakage coefficients, respectively; S is the amount of water in the ground-water reservoir (mm).

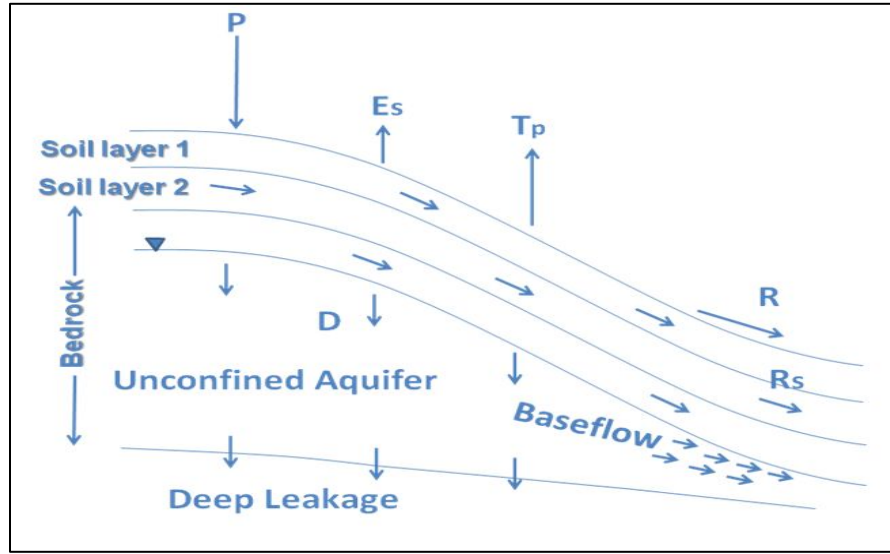


Figure 1. Baseflow incorporation in WEPP. Hydrologic processes are: P, precipitation; Es, Soil evaporation; Tp, Plant transpiration; R, Surface runoff; Rs, Subsurface lateral flow, and D, deep percolation through the bottom profile (adapted from Dun et al., 2009).

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) (Figure 2). Elevation ranges 689–1456 m above sea level with an average slope gradient of 29%. Mean annual precipitation in the area is 794 mm with 30% of precipitation as snow. Mean maximum and minimum temperatures are 14°C and 0°C, respectively. Vay (*medial over loamy-skeletal, amorphous over isotic Vitric Haplocryands*) is the dominant soil series in the study watershed with a silt loam texture. Vegetation cover in the region consists predominantly of Douglas fir (*Larix occidentalis-Pseudotsuga menziesii*) and Western white pine (*Pinus monticola*). The underlying geologic formation of the watershed is gneiss. The study watershed experienced no treatment or harvesting during the past 50 years. In the summer of 2004, a flume was installed at the watershed outlet and discharge was measured during January 2005 to December 2010. Instrument malfunction, especially during winter months, was identified and flow data for those periods were adjusted accordingly.

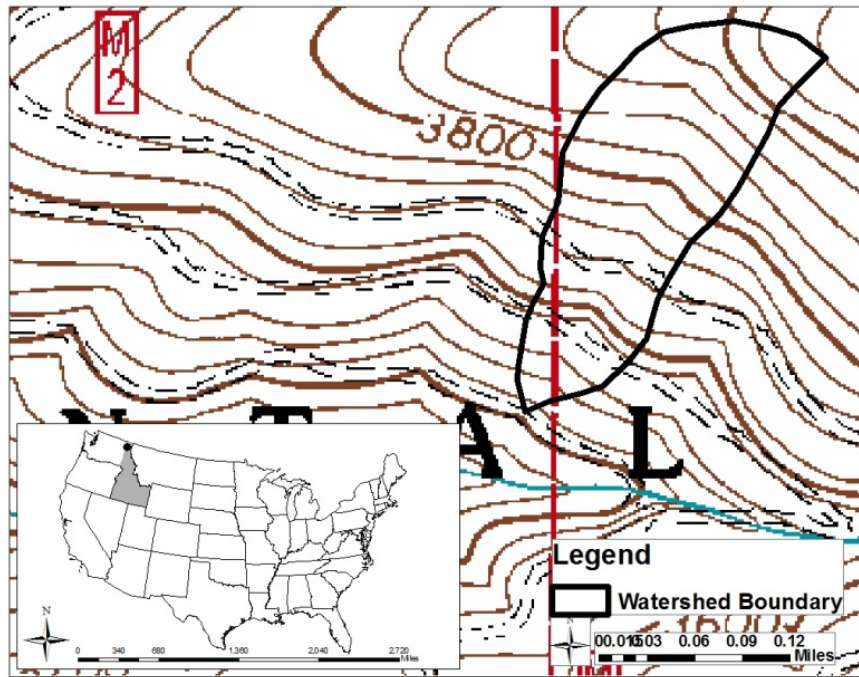


Figure 2. Location of study site in Priest River Experimentation Forest, Idaho.

WEPP inputs

The climate file for the study site was created for 2005–2009 using WEPP’s auxiliary stochastic climate generator, CLIGEN (Nicks et al., 1995). CLIGEN requires daily observed precipitation, and maximum and minimum temperatures (Figure 3), acquired from the National Climatic Data Center (NCDC) for the Priest River Experiment Station. Missing data were filled and additional climate parameters were generated simultaneously on a daily basis using CLIGEN based on monthly statistics of 82 years of historical weather data from the Sandpoint weather station, 16.8 km SE of the study site.

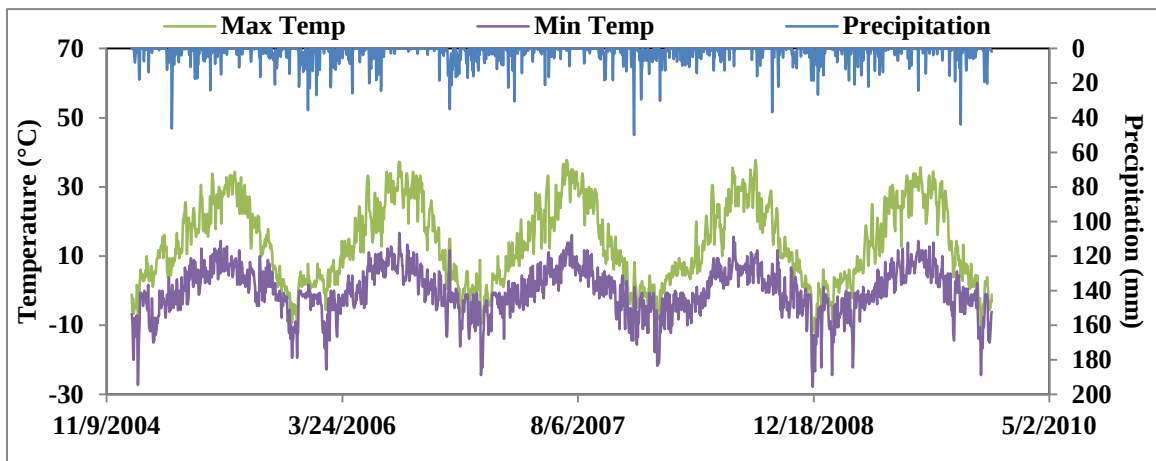


Figure 3. Daily observed precipitation, maximum and minimum temperature acquired from the National Climatic Data Center (NCDC) for Priest River Experimental Forest, Idaho, 2005 to 2009.

Soil inputs for WEPP simulations consist of a combination of STATSGO soil data, parameters from the WEPP soil database, and literature values. Soil textural inputs for different layers are summarized in Table 1. Effective hydraulic conductivity for the surface soil was taken from STATSGO soil data. The

saturated hydraulic conductivity of the restrictive layer at the bottom of the soil profile was estimated to be 0.1 mm hr^{-1} , based on literature values (Tsihrintzis and Jain, 2010). An anisotropy ratio of 15 was used to represent the relative predominance of lateral versus vertical flow. A summary of the soil hydraulic and erodibility parameters is presented in Table 2.

Table 1. Soil textural inputs for different layers.

Layer	Depth (mm)	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	CEC (meq/100g)	Rock (%)
1	152.4	36.3	57.7	6.0	7.0	15.0	15.0
2	254.0	52.7	41.3	6.0	5.0	4.2	20.0
3	228.6	64.7	29.3	6.0	2.0	4.2	50.4
4	432.0	72.4	24.1	3.5	1.0	2.5	61.0

Table 2. Major soil inputs for WEPP application for Priest River watershed.

Parameters	Values
Albedo	0.3
Initial soil saturation (%)	50
Baseline inter-rill erodibility (kg s m^{-4})	1.0×10^6
Baseline rill erodibility (s m^{-1})	4.0×10^{-4}
Baseline critical shear (Pa)	1.5
Effective hydraulic conductivity of surface soil (mm hr^{-1})	50.4
Saturated hydraulic conductivity of restrictive layer (mm hr^{-1})	0.1
Soil anisotrophy ratio	15

The default perennial forest management file in the WEPP database was adapted for the entire watershed. A leaf area index (LAI) of 6 was used to describe the forest ET characteristics following Pcewicz (2003). Default values were used for other parameters, including initial ground cover, initial canopy cover, and days of senescence.

GeoWEPP, a geospatial interface of WEPP, was used to delineate the watershed for WEPP simulations using a 10-m DEM. GeoWEPP discretized the study watershed into one channel section (south-west facing) and three sub-catchments (south-west, south-east, and north-west facing) draining into the channel from top, left, and right. Length, width, slope, and aspect for each hillslope were derived by GeoWEPP and used for WEPP simulations (Table 3).

Table 3. Configuration of Priest River watershed for WEPP simulations.

Hillslope	South-west facing hillslope	South-east facing hillslope	North-west facing hillslope	South-west facing channel
Length, m	253	66	67	250
Width, m	86	250	250	1
Avg. slope, m m^{-1}	0.245	0.186	0.433	0.424
Aspect, degree	210	120	300	210
Area, m^2	21,700	16,500	16,800	250

WEPP simulations and model performance evaluation

Continuous simulations with the WEPP model v2010.1 were performed in two stages. The model was calibrated for years 2005 and 2006 using measured streamflow data and the following input parameters were adjusted: saturated hydraulic conductivity of restrictive layer and soil anisotrophy ratio. Baseflow and deep leakage coefficients were determined using the least-squares estimation method. Estimated baseflow and deep leakage coefficients were 0.0232 d^{-1} and 0.0057 d^{-1} , respectively. Once the model was calibrated, the same parametric values were used for verification for years 2007, 2008, and 2009. Water balance was obtained for each of the following components: surface runoff, subsurface lateral flow, baseflow, deep leakage, soil water content, and ET.

To evaluate model performance, WEPP-simulated streamflow was compared with measured streamflow using quantitative statistical tools including Nash-Sutcliffe efficiency (NSE , Nash and Sutcliffe, 1970) and deviation of runoff volume (D_v). These statistics were calculated separately for calibration and verification periods based on the recommendations of the ASCE Task Committee (1993).

NSE is a goodness-of-fit criterion computed as:

$$NSE = 1 - \left[\sum_{i=1}^n (Y_{obs, i} - Y_{sim, i})^2 / \sum_{i=1}^n (Y_{obs, i} - Y_{mean})^2 \right] \quad (3)$$

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.

D_v is an error index model evaluation method that indicates model accuracy in terms of over- or under-estimation of simulated results. The equation used for computing D_v is:

$$D_v = \left[\sum_{i=1}^n (Y_{obs, i} - Y_{sim, i}) * (100) / \sum_{i=1}^n (Y_{obs, i}) \right] \quad (4)$$

where D_v = deviation of runoff volume, expressed as a percent.

RESULTS AND DISCUSSION

Major water balance components for the study watershed are shown in Table 4. Discharge at the watershed outlet was a result of subsurface lateral flow and baseflow, with no surface runoff simulated for the forest conditions at the study watershed. For the five-year period, simulated subsurface lateral flow, baseflow, and deep leakage accounted for 13%, 15% and 4% of annual precipitation, respectively. Change in soil water storage averaged 5 mm for the entire five years. The fraction of streamflow that was from baseflow ranged from 0.55 to 0.70, with an annual average of 59%. Annual ET from the watershed varied from 419 mm to 533 mm for the simulated years and accounted for 61% of annual precipitation on average, agreeable with literature values (Finklin, 1983).

Table 4. Simulated annual water balance of Priest River watershed.

Year	P (mm)	R (mm)	R _s (mm)	ET (mm)	SW (mm)	Q _b (mm)	Q _l (mm)	BFI (%)
2005	744	0	71	518	42	120	30	70
2006	957	0	150	475	-56	150	38	55
2007	769	0	126	419	46	133	34	56
2008	768	0	102	533	19	123	31	58
2009	729	0	81	490	-26	88	22	57
Avg.	794	0 (0)	106 (13)	487 (61)	5 (0.6)	123 (15)	31 (4)	59

P = precipitation, R = surface runoff, R_s = subsurface lateral flow, ET = evapotranspiration, SW = change in soil water, Q_b = baseflow, Q_l = deep leakage, BFI = baseflow index. Percent values of each averaged water balance component are shown in parentheses.

Figure 4 shows the daily comparison of observed and simulated streamflow for all the five years. Precipitation in the study area was in the form of snow during the winter period starting in October and lasting until March. Runoff peaks were observed mainly in the month of April and May, which were the results of spring snowmelt. WEPP under-predicted runoff peaks for 2005, 2007, and 2008 and over-predicted peaks for 2007. A possible reason could be that snow accumulation and the timing of snowmelt were not properly simulated by the WEPP model. Dun et al. (2009) noted similar results on a seasonal stream in central Idaho, with certain disagreements between simulated and observed time and magnitude of peak runoff during snowmelt seasons.

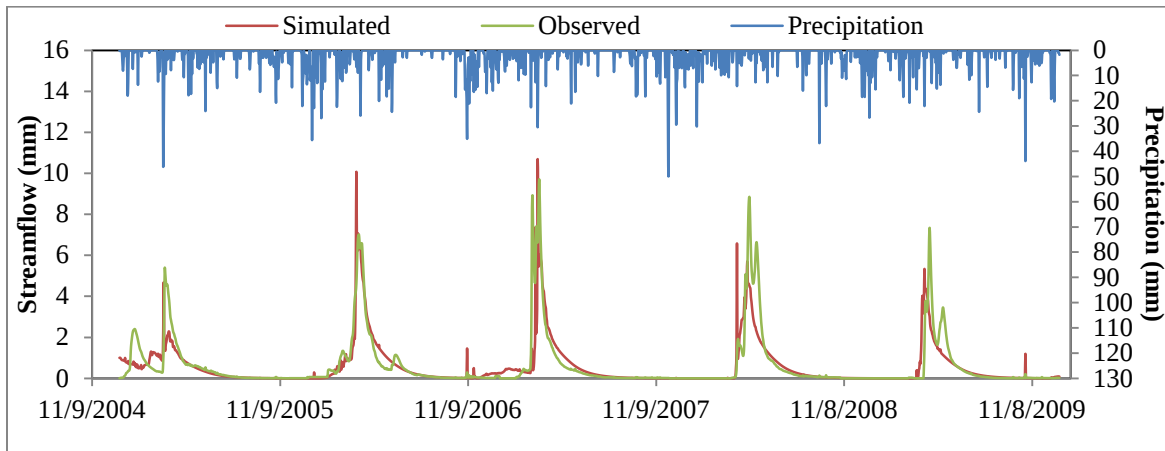


Figure 4. Daily comparison of observed vs WEPP-simulated streamflow for Priest River watershed.

Comparisons of annual observed and simulated watershed discharge and the results of statistical analyses to evaluate model performance are shown in Table 5. Simulated streamflow for the simulation period totaled 1051 mm compared to the observed total of 1154 mm. *NSE* values ranged from 0.50 to 0.89, with an overall *NSE* of 0.67, indicating satisfactory performance of the model. Similar *NSE* values were reported by Dun et al. (2009) on a small forest watershed in central Idaho with a seasonal flow. D_v values varied from -4% to 18% for the simulation period in this study. WEPP under-predicted streamflow for years 2005, 2007, 2008, and 2009, and over-predicted streamflow for year 2006. Overall, WEPP under-predicted streamflow by 9%.

Table 5. Comparison between observed- and WEPP-simulated streamflow and Nash-Sutcliffe efficiency (*NSE*) and deviation of runoff volumes (D_v).

Year	Observed streamflow (mm)	Simulated streamflow (mm)	<i>NSE</i>	D_v (%)
2005	209	171	0.50	18
2006	264	275	0.89	-4
2007	248	238	0.62	4
2008	257	210	0.70	18
2009	176	156	0.55	11
Overall	1154	1051	0.67	9

CONCLUSIONS

This study aimed at developing a baseflow component for WEPP v2010.1 to enhance the model's applicability to watersheds where contribution of baseflow to streamflow is substantial. Five-year simulations (2005–2009) were conducted for a small forested watershed in the PNW with perennial flow to assess the performance of WEPP. Daily percolation that was considered out of the system in the current version of WEPP was added to ground-water storage. A linear ground-water reservoir model was used to extract the baseflow as well as deep leakage. The first two years of simulated results were used to fit baseflow with observed streamflow using the least square estimation technique and to obtain the coefficients of the linear reservoir. The fitted baseflow and deep leakage coefficients were then used in the simulation of the remaining three years to assess model performance.

The calibrated baseflow and deep leakage coefficients were 0.0232 d^{-1} and 0.0057 d^{-1} , respectively. The mean annual baseflow accounted for 59% of simulated streamflow. An overall (2005–2009) *NSE* of 0.67 indicates that WEPP adequately simulated streamflow for the study watershed. The overall D_v of 9% suggests a slight under-prediction of streamflow by the WEPP model. Results from this study suggest that incorporation of a linear ground-water reservoir model into WEPP makes it applicable to

watersheds with considerable baseflow. The baseflow component can be further refined with future WEPP applications to various other watersheds with varying climatic and geological settings. In a snow-hydrology-dominated watershed as ours, improving the simulation of snow accumulation and melt would likely improve the modeling of the spring hydrographs.

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