Journal of Hydrology 610 (2022) 127776

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

WEPPcloud: An online watershed-scale hydrologic modeling tool. Part II. Model performance assessment and applications to forest management and wildfires

Mariana Dobre [a,*], Anurag Srivastava [a], Roger Lew [b], Chinmay Deval [a], Erin S. Brooks [a], William J. Elliot [a], Peter R. Robichaud [c]

[a] *Department of Soil and Water Systems, University of Idaho, Moscow, ID 83844-2060, USA*
[b] *Virtual Technology and Design, University of Idaho, Moscow, ID 83844-2481, USA*
[c] *USDA Forest Service, Rocky Mountain Research Station, 1221 South Main, Moscow, ID 83843, USA*

ARTICLE INFO

This manuscript was handled by N. Basu, Editor-in-Chief

Keywords:
Decision-support tools
WEPPcloud
Gauged-ungauged watersheds
Soil erosion
Forest management
Phosphorous
Sediment yield

ABSTRACT

Suspended sediment and nutrients following forest management activities or wildfires are transported to streams and lakes via surface runoff and are a major threat to water quality. Land and water managers resort to hydrologic models to test hypotheses that can help them make informed decisions to minimize disturbances and protect water resources. We present applications of an online interface, WEPPcloud, for the Water Erosion Prediction Project (WEPP) model as a pre- and post-disturbance management tool to model various gauged and ungauged forested watersheds throughout the western U.S. We compare simulated streamflow, sediment, and phosphorus to observations at USGS gauging stations and assess the accuracy of the online interface with minimal or no calibration. Specifically, we present modeling results from 28 relatively undisturbed forested watersheds in the states of California, Nevada, Oregon, Washington, and Idaho. Across all watersheds, the *NSEs* based on the daily streamflow values, were in the range of 0.43 to 0.64 indicating satisfactory agreement between modeled and observed values. Similarly, annual average *NSE* for sediment yield was 0.61, while for phosphorus it was 0.75, 0.71, and 0.66, for total, particulate, and soluble reactive phosphorus, respectively. Additionally, we demonstrate the utility of the WEPPcloud interface as a tool to compare model results for ungauged watersheds from various disturbed conditions including prescribed fire, thinning, and wildfire to undisturbed model results to better understand the effects of forest management and wildfires on water quality and quantity.

1. Introduction

Consequences of fire suppression and climate change on wildfire risks and forest health have been extensively researched in recent years, and there is a consensus among scientists and managers that fuel treatments, specifically mechanical thinning and prescribed fire, are necessary to restore forest structure and to decrease wildfire risks (Collins et al., 2017; Graham et al., 2010; Higuera and Abatzoglou, 2021; Kolden, 2019; Krofcheck et al., 2018; Miller et al., 2005; Miller et al., 2010; Weisberg, 2004). Most forest disturbances will result in partial or total removal of the over- and under-story vegetation and decrease soil ground cover, which in turn will decrease snow interception, forest evapotranspiration, and soil hydraulic conductivity, and increase soil erodibility, among many other effects on soil properties (Elliot, 2013; Srivastava et al, 2018). These changes will cause an increase in streamflow peaks (Neary et al., 2003; Niemeyer et al., 2020) and soil erosion (Elliot, 2013; Srivastava et al, 2018) especially in the first year following disturbance and will return to pre-disturbance conditions as the vegetation recovers, usually within five years following the disturbance (Elliot, 2013; Robichaud et al., 2007). Land and water managers are now faced with complex management decisions compounded by increased pressure on natural resources due to population growth, wildfires, and climate change.

Decision-support tools are software or information systems

* Corresponding author.
E-mail addresses: mdobre@uidaho.edu (M. Dobre), srivanu@uidaho.edu (A. Srivastava), rogerlew@uidaho.edu (R. Lew), chinmaydeval@uidaho.edu (C. Deval), ebrooks@uidaho.edu (E.S. Brooks), welliot@uidaho.edu (W.J. Elliot), peter.robichaud@usda.gov (P.R. Robichaud).

https://doi.org/10.1016/j.jhydrol.2022.127776

Available online 30 March 2022

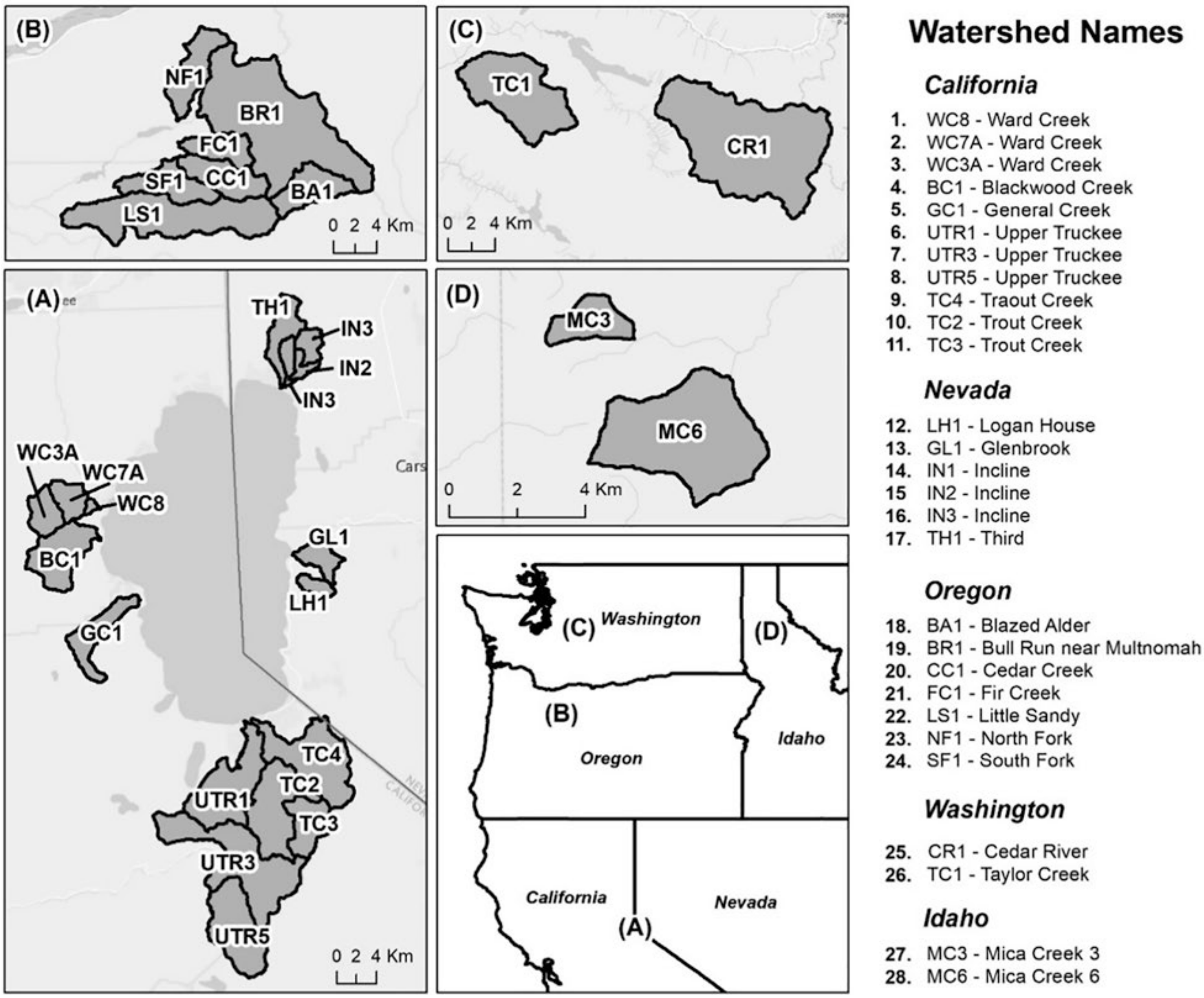

Fig. 1. Location of the gauged study watersheds in the western U.S.

developed to aid managers in the decision process. This is accomplished by including the best available scientific knowledge into tools that are accessible, easy to use, and that require minimal training to support management decisions. The WEPPcloud interface (Lew et al. 2022) is such a decision-support tool developed to facilitate hydrologic model runs with the Water Erosion Prediction Project (WEPP) watershed model (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995, Flanagan et al., 2007; Flanagan et al., 2012) and to help land managers assess the effects of forest management treatments and wildfire on runoff, sediment, and phosphorus yield at hillslope and watershed scale.

The WEPP model is a process-based hydrology and erosion model based on the fundamentals of infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan and Nearing, 1995). A detailed description of the modeled processes is provided in Flanagan and Nearing (1995) as well as in other papers describing recent improvements to the model, specifically for forested applications (Dun et al., 2009; Srivastava et al., 2013, 2017, 2018, 2020; Brooks et al., 2016; Miller et al., 2011; Miller et al., 2019; Elliot, 2013, Elliot et al. 2015). A summary of these processes as well as more detailed information on the WEPPcloud interface can be found in Lew et al. (2022), Part I of this two-part manuscript.

The WEPPcloud interface has two major advantages compared to the WEPP model, besides the online applicability and the easiness of the model runs. First, WEPPcloud includes a baseflow component similar to Srivastava et al., (2013, 2017, 2018, 2020), which is a major hydrologic process important in modeling larger watersheds. And second, WEPPcloud incorporates simplistic algorithms that allow users to simulate pollutant (e.g. phosphorus) transport based on known concentrations of the respective pollutant in surface runoff, lateral flow, baseflow, and attached to sediment (Lew et al., 2022). Forests are considered sinks for nutrients, rather than sources, and therefore are not impacted by the major fertilizer management as with agricultural soils (Piatek and Allen, 2001; Miller et al., 2005). However, wildfire disturbances and management activities such as timber harvest, site preparation, road construction, and maintenance, have the potential to increase nutrient concentration in streams through increased runoff and soil erosion (Deval et al., 2021; Gravelle et al., 2009; Ice and Binkley, 2003). Streamflow from undisturbed watersheds with old forest cover can generate large nutrient concentrations (Binkley, 2001). Therefore, incorporating capabilities to simulate water quality pollutants into decision-support tools is critical for forest management.

WEPPcloud automatically builds input files for the WEPP model, based on publicly available national databases. Model outputs are generated in both tabular and GIS formats that are easy to interpret by users. The WEPP model requires four main input files for each hillslope and channel: topography, soil, management, and weather. Topography or slope structure is extracted from a 10- or 30-m DEM using the TOPAZ (Topographic Parameterization Program, Garbrecht and Martz, 1997) model. The TOPAZ model is also used to delineate a watershed in hillslopes and channels based on a Critical Source Area (CSA) and a Minimal Channel Length (MCL) selected by the user. Soil files are created by automatically extracting the necessary soil properties from the high-

Table 1
List of gauged study watersheds, simulation dates, areas, elevations, and precipitation. Full USGS station codes and names, the corresponding WEPPcloud interface model run names, and web addresses for the model runs are provided in the supplementary material (Table S1 in supplementary material).

No.	Name	Abbreviated Name	USGS station	Simulation date range YYYY/MM/DD		Watershed area	Min. elevation	Max. elevation	Mean Annual Precipitation
				Start	End	(ha)	(m)	(m)	(mm)
	California								
1	Ward Creek	WC8[§]	10336676	1990/01/01	2014/09/30	2310	1920	2700	1406
2	Ward Creek	WC7A[§]	10336675	1991/10/01	2001/09/30	2170	1967	2700	1414
3	Ward Creek	WC3A[§]	10336674	1991/10/01	2011/11/01	1160	2021	2700	1496
4	Blackwood Creek	BC1	10336660	1990/01/01	2014/09/30	2670	1904	2676	1476
5	General Creek	GC1	10336645	1990/01/01	2014/09/30	1820	1913	2640	1271
6	Upper Truckee River	UTR1[§]	10336610	1990/01/01	2014/09/30	13320	1899	3052	1025
7	Upper Truckee River	UTR3[§]	103366092	1990/06/01	2012/09/30	9380	1926	3050	1117
8	Upper Truckee River	UTR5[§]	10336580	1990/05/12	2011/10/11	3410	1981	3050	1218
9	Trout Creek	TC4[§]	10336780	1990/01/01	2014/09/30	9870	1899	3306	905
10	Trout Creek	TC2[§]	10336775	1990/06/01	2012/09/30	5560	1914	3259	880
11	Trout Creek	TC3[§]	10336770	1990/05/22	2011/03/31	1780	2124	3259	900
	Nevada								
12	Logan House Creek	LH1	10336740	1990/01/01	2011/10/12	500	2030	2688	657
13	Glenbrook Creek	GL1	10336730	1990/01/01	2012/09/30	990	1903	2689	616
14	Incline Creek	IN1[§]	10336700	1990/01/01	2014/09/30	1580	1904	2807	928
15	Incline Creek	IN2[§]	103366995	1990/01/01	2004/09/30	1070	1942	2807	999
16	Incline Creek	IN3[§]	103366993	1990/05/01	2011/03/31	690	2114	2807	1061
17	Third Creek	TH1	10336698	1990/01/01	2014/09/30	1470	1900	3135	1081
	Oregon								
18	Blazed Alder	BA1[§]	14138800	1980/01/01	2018/12/31	1800	791	1345	3076
19	Bull Run River	BR1[§]	14138850	1980/01/01	2018/12/31	11880	326	1441	3358
20	Cedar Creek	CC1[§]	14139700	1980/01/01	2003/09/29	1930	605	1287	3583
21	Fir Creek	FC1	14138870	1980/01/01	2018/12/31	1300	455	1285	2939
22	Little Sandy River	LS1	14141500	1980/01/01	2018/12/31	5740	224	1290	2861
23	North Fork	NF1	14138900	1980/01/01	2018/12/31	2000	323	1222	4057
24	South Fork	SF1[§]	14139800	1980/01/01	2018/12/31	3840	297	1287	3441
	Washington								
25	Cedar River	CR1	12115000	1980/01/01	2018/12/31	9760	484	1658	2585
26	Taylor Creek	TC1	12117000	1980/01/01	2018/12/31	4260	290	1249	2891
	Idaho								
27	Mica Creek	MC3	-	1990/01/01	2007/12/31	230	1179	1612	1411
28	Mica Creek	MC6	-	1990/01/01	2007/12/31	1130	1034	1563	1403

See Fig. 1 for watershed location and Table S1 in the supplementary material for full watershed names.
[§] Denotes nested watersheds.

resolution SSURGO (SSS-NRCS, Reybold and TeSelle, 1989) database, with the additional ability to extract soil properties from the coarser-resolution State Soil Geographic (STATSGO) (Schwartz and Alexander, 1995) databases for regions where SSURGO data are missing. Pre-built management files for various current land use (e.g. forest, shrub, rangeland, etc.) are assigned to each hillslope based on the 2016 USGS National Land Cover Database (NLCD) (Dewitz, 2019). Proposed land managements can be selected by the user from a dropdown list of predefined management files (e.g. forest thinned, low severity fire, prescribed fire, etc.). Lastly, daily weather files can be created from various climate options, including a stochastically generated weather file using the CLImate GENerator (CLIGEN) weather generator model (Nicks et al., 1995; Srivastava et al., 2019), interpolated historical weather from grid-based Daymet (Thornton et al., 2016), or gridMET (Abatzoglou, 2013) databases, and future climate scenarios downscaled from Coupled Model Intercomparison Project General Circulation Model 5 (CMIP5 GCM) models (Abatzoglou and Brown, 2012). A single storm event can also be specified by the user.

In the 1990s and early 2000s, a significant effort was invested by the USDA Forest Service Rocky Mountain Research Station (RMRS) to determine soil hydraulic conductivity and rill and interrill erodibility values for both undisturbed and disturbed forested conditions (Elliot and Hall, 1997; Elliot, 2004; Elliot and Robichaud, 2010; Moffet et al., 2007; Robichaud et al., 2007, Robichaud et al., 2010; 2016a, Robichaud et al., 2016b; Wagenbrenner et al., 2010). These studies found that the land cover had more influence on soil erodibility properties than texture. Management-specific soil properties measured in those studies, and in other more recent studies (Elliot et al., 2013, Robichaud et al., 2016a) also found that soil depth was another important property. The results of the RMRS studies relating erodibility to land cover and four soil textural categories have been merged with the NRCS SSURGO and STATSGO (Reybold and TeSelle, 1989) databases to generate WEPP input files with RMRS erodibility values and NRCS soil profile properties (Lew et al. 2022). This merged database is part of the WEPPcloud interface and is the basis for evaluating the impacts of wildfire and forest management activities on soil erosion. The database can be easily modified, should new data become available or expanded to include results from future studies.

In this paper, we assess the ability of the WEPPcloud interface to adequately represent the hydrologic response to management in forested ecosystems across the western U.S. and summarize the strengths and challenges of the use of WEPPcloud to guide land and water management decisions in data-poor environments. Specifically, we demonstrate model performance when applied to simulate surface runoff, sediment, and phosphorus yield under current conditions in selected case-study watersheds with no or minimal calibration and discuss sensitive calibrating parameters when applied to various geographic regions in the western U.S. We focus on phosphorus as a pollutant in this manuscript as it is a nutrient found in streams in both adsorbed and dissolved form and, therefore is well suited to demonstrate the pollutant loading capabilities with WEPPcloud, but also because it is a nutrient of interest for managers for our test watersheds and there were long-term USGS data available for model parameterization and assessment.

We demonstrate that when key topographic, weather, soils, and vegetative properties are well represented, the WEPP model can be successfully used in management applications, especially when a quick assessment of a study area is desired. We also demonstrate how the interface can be further parameterized for pre- and post-wildfire management scenarios testing in ungauged watersheds. We will not discuss specific model results from the management scenarios testing here, rather we will describe the methodology for running such simulations with the WEPPcloud interface. Lastly, we discuss the current limitations of the WEPPcloud interface and the challenges in applying process-based models for directing management applications. The paper is presented in two parts: Part I: Model description (Lew et al., 2022), and Part II: Model performance assessment and applications to forest management and wildfires (*this paper*).

2. Material and methods

2.1. Study sites

For this study, we selected 28 forested watersheds in the western U.S. (Fig. 1; Table 1) representing a wide range of physiographic conditions. These watersheds are involved in unique ongoing land and water management decision-making where stakeholders are interested in the potential benefits of applying geospatial hydrologic modeling to assess the impacts of alternative forest management or natural disturbance on water quantity and quality. The modeling included comparing the effects of proposed forest treatments and wildfires on sediment and phosphorus yield (Lake Tahoe basin, California/Nevada), understanding the risks associated with wildfires to drinking water supply watersheds (Bull Run Watershed, Oregon; Cedar River and Taylor Creek, Washington), and evaluating the effects of forest treatments such as thinning, clear-cutting, and broadcast burning on water quantity and quality (Mica Creek Experimental Watershed, MCEW, Idaho).

Lake Tahoe is an alpine lake situated in the Sierra Nevada mountain range and is known for its lake clarity (Fig. 1A). The basin is comprised of 63 watersheds that drain directly into the lake and two-thirds of these watersheds are located in California while the rest are in Nevada. Climate is wet in the winters and dry in the summers with mean annual precipitations of 1400 mm yr^{-1} in the west- and 670 mm yr^{-1} near the lake in the east side of the basin (Coats et al., 2016) (Table 1). Most of the precipitation falls as snow between November and April. The basin is moderately-to-densely vegetated, consisting of mixed coniferous forests that are actively managed through thinning and prescribed fire operations. Soils are derived from volcanic parent material in the northern and northwestern part of the basin, and granitic parent material in the rest of the basin.

The Bull Run Watershed is located on the western side of the Cascade mountain range and since 1895 has been the primary water supply watershed for the city of Portland, Oregon (Fig. 1B). The mean annual air temperature in Bull Run is 10 °C (USDA-FS (U.S. Department of Agriculture, Forest Service), 1997) and the overall climate is maritime with wet cold winters and dry cool summers. The annual average precipitation is 3500 mm and approximately 70% of the annual precipitation occurs between November and April (PWB (Portland Water Bureau), 2003) (Table 1). Most of the precipitation in the catchment falls as rain (PWB (Portland Water Bureau), 2003). The vegetation is comprised of densely mixed coniferous forests that have been under strict protection since 1996. The soils are derived from Columbia River basalt and andesite mixed with volcanic ash and are predominantly deep and well-drained gravelly loam and silty loam (Snyder and Brownwell, 1996). Burns et al. (2015) found that 21% and 15% of the watershed is highly susceptible to shallow and deep landslides, respectively.

The upper Cedar River and Taylor Creek are located in the Cascade Mountain range and are two of the three municipal water-supply watersheds for the city of Seattle, Washington (Fig. 1C). The climate in these two watersheds is wet and mild with annual average precipitation of more than 2500 mm, most of the precipitation occurring from November to April (Srivastava et al., 2017) (Table 1). Soils in Cedar River are loamy sand and gravely sandy loam (Srivastava et al., 2017) and the vegetation is comprised of old-growth and second-growth coniferous forest.

The MCEW is located in northern Idaho in the Northern Rockies and is part of a long-term paired and nested catchment study designed by the Potlach-Deltic Corporation, Lewiston, Idaho to assess the direct and cumulative impacts of forest management practices on water quantity and quality (Deval et al., 2021, Hubbart et al., 2007, Karwan et al., 2007, Srivastava et al., 2020) (Fig. 1D). For our study, we selected two watersheds from the MCEW study that were assigned as undisturbed reference watersheds from 1990−2007, namely, WS3 and WS6. The annual average temperature at MCEW is 5 °C and the annual average precipitation is 450 mm yr^{-1}, with more than 70% of all precipitation falling as snow from November to May (Table 1). Vegetation is comprised of a naturally regenerated second-growth mixed coniferous forest of approximately 90–100 years old. Soils are predominantly deep silt loam weathered from schist, gneiss, granitic, and quartzite bedrock.

2.2. Model setup

We used the WEPPcloud interface to automatically delineate watersheds, prepare the input data, and run the WEPP model. All watersheds were discretized into hillslopes and channels internally with the TOPAZ model using a 30-m USGS National Elevation Dataset (NED), except for the smaller MCEW watersheds, where a 10-m resolution was used. WEPPcloud is designed to access (via Python modules that reside on the interface) locally stored databases or to access freely available national databases to create all input files required by WEPP, including the topography, soils, management, and weather files at the centroid of each hillslope and channel. Since our goal was to run the model with minimal calibration, it was imperative that the input data and local hydrologic conditions were well represented. Therefore, where available, we supplemented the WEPPcloud interface database with additional information from other databases or previous hydrologic studies.

Soil input files were assigned to each hillslope from the 1:12000 scale SSURGO database, except for the Bull Run Watershed, where SSURGO soils were missing in the lower half of the watershed. The missing soils were assigned based on a local soil survey map developed by the Forest Service as presented in the 1997 Bull Run Watershed Analysis (BRWA; USDA-FS (U.S. Department of Agriculture, Forest Service), 1997). The BRWA database includes similar soil mapping units as SSURGO and provides fundamental information on soil texture and basic topographic attributes; however, it does not include all soil parameters required by WEPP. We assigned the remaining soil attributes by matching similar SSURGO and BRWA map units based on similarities in soil name, texture, and slope and then uploaded the newly created map into the WEPPcloud interface.

The management parameter files were assigned to each hillslope by the WEPPcloud interface based on the default 2016 National Land Cover Database (NLCD) categories (e.g. forest, shrubs, grass, etc.). For the Bull Run Watershed, we replaced the default NLCD map with a map provided by the Portland Water Bureau, which was generated from LANDSAT based on the Gradient Nearest Neighbor (GNN) method (Ohmann and Gregory, 2002). A WEPPcloud-equivalent NLCD management parameter file was assigned to each GNN map class.

WEPP weather files were created automatically from two available options on the WEPPcloud interface. For watersheds in the Lake Tahoe basin, we used the Daymet option while for all other watersheds we selected the gridMET option with PRISM revisions. The Daymet option is at 1 km spatial resolution and generated weather files based on daily precipitation, and minimum and maximum temperature for each hillslope based on a cubic interpolation at the centroid of the hillslopes. The gridMET with PRISM revision option generated a weather file based on daily precipitation, minimum and maximum temperature, wind speed and direction for the centroid of the watershed. The gridMET dataset has a course 4 km grid while PRISM has a higher resolution of 800 m. The PRISM revisions option in WEPPcloud is used to distribute daily precipitation, and minimum and maximum temperature with elevation similar to Brooks et al. (2016). All other weather data required by the model, including precipitation characteristics (duration of storm, time-to-peak intensity, and peak intensity), dew point temperature, solar radiation, wind speed and direction were stochastically generated within WEPPcloud with CLIGEN v5.3.2 (Nicks et al., 1995; Srivastava et al., 2019; Frankenberger, 2021) from the nearest NCDC long-term historic weather data. The weather files were built for the time period that matched the streamflow and water quality data available at the outlet of the modeled watersheds (Table 1).

2.3. Model calibration and performance assessment

The minimal calibration that was conducted on these watersheds followed a simple manual stepwise calibration process (Boyle et al., 2000). This is consistent with the approach in Brooks et al. (2016) and will be a typical approach adopted by most users of the WEPPcloud tool. It is possible to fully calibrate the key model parameters using Parameter Estimation (PEST) (Doherty, 2005) after downloading WEPPcloud projects to a desktop computer. However, we did not adopt this approach in this study as it was not an appropriate assessment of the predictive capabilities of the model and may not necessarily provide increased understanding based on equifinality issues (Beven, 2001). Moreover, most land and water managers will have limited skills and time to perform advanced model calibrations. Therefore, the goal of the model calibration was to identify the most sensitive calibrating parameters that would produce acceptable results in all modeled watersheds.

To calibrate the model, we ran the WEPPcloud interface with default parameters and downloaded all the model runs (including all the input and output data) with the wepppy-win-bootstrap (Lew, 2021). This is a freely available Python package developed to allow advanced users to download, modify, and run WEPPcloud projects locally on Windows computers. We first calibrated daily streamflow and total water yield as described below and then calibrated key parameters related to sediment and phosphorus yield. Model performance was assessed for each watershed simulation by utilizing a variety of publicly available USGS data sources: daily streamflow data measured at USGS gauging stations, daily streamflow data recorded with flumes, flow-weighted annual loads of sediment and phosphorus processed in previous studies, and flow-weighted monthly concentrations of phosphorus. Model performance efficiency was assessed using several goodness-of-fit statistics: the Nash-Sutcliffe Efficiency (*NSE*; Nash and Sutcliffe, 1970), the Kling-Gupta efficiency (*KGE*; Gupta et al., 2009), and percent bias (*PBias* (%); Yapo et al., 1996). These indices were calculated with the '*hydroGOF*' R package (Zambrano-Bigiarini, 2020).

2.3.1. Streamflow and water yield

Streamflow calibration was performed using only the linear baseflow recession coefficient (k_b), the saturated hydraulic conductivity of the underlying geology (K_{sub}), and the rain/snow temperature threshold ($T_{rain/snow}$). The k_b coefficient represents the fixed proportion of the total water stored in a dynamic groundwater reservoir that provides baseflow to the stream on any given day and typically varies between 0.01 d^{-1} and 0.1 d^{-1} (Beck et al., 2013; Sánchez-Murillo et al., 2014). Brooks et al. (2016) determined that the observed streamflow recessions on the western side of Lake Tahoe could be represented by a linear reservoir coefficient k_b of 0.04 d^{-1}. However, due to a complex hydrogeology of the east side of the Lake Tahoe basin, attributed to large geologic faults and high permeability rates (Nolan and Hill, 1991), the authors proposed that additional deep seepage losses of groundwater were occurring and suggested that the rate of groundwater loss from the reservoir could be quantified by calibrating a second deep seepage reservoir coefficient (k_s) for groundwater lost from the system. For our simulations, we assigned a default k_b value of 0.04 d^{-1} to all modeled watersheds, except to the watersheds from the MCEW, where we assigned a value of 0.02 d^{-1} based on Srivastava et al. (2020), and to those from the east side of Lake Tahoe basin, where we followed the Brooks et al. (2016) approach.

The K_{sub} values for the subsurface geology in the Lake Tahoe basin were based on default WEPPcloud values, and for the soils in the MCEW, they were set to 0.02 mm h^{-1}, based on Srivastava et al. (2020). For watersheds in the Bull Run Watershed, we manually calibrated K_{sub} based on a combination of the bedrock geology, specifically the distribution of the rhododendron layer (Trimble, 1963), and a map of shallow landslide susceptibility (Burns et al., 2015) of three classes (low, medium, and high) based on the assumption that regions most highly susceptible to landslides would have poorer subsurface drainage into the underlying bedrock.

The $T_{rain/snow}$ is the threshold temperature at which WEPP partitions precipitation between rain and snow (Srivastava et al., 2017). The default value in WEPP is 0 °C, and no calibration of this parameter was necessary for the watersheds in Lake Tahoe (California and Nevada), which we simulated with weather files based on the Daymet climate database. In contrast, the $T_{rain/snow}$ was calibrated to − 2 °C for watersheds in Oregon, Washington, and Idaho, where the gridMET climate database was used.

Daily streamflow observations were measured at USGS gauging stations at all watersheds, except at two watersheds in the MCEW, where they were recorded with large H-flumes. More information on the equipment used to collect the MCEW data can be found in Hubbart et al. (2007), Karwan et al. (2007), and Srivastava et al. (2020). For the streamflow model performance assessment, we used a maximum of 25 years (1990–2014) of observed daily streamflow data in the watersheds from the Lake Tahoe basin, 39 years (1980–2018) of observed daily streamflow data measured at seven stream gauges in the Bull Run, and at the Cedar River and Taylor Creek watersheds, and 18 years (1990–2007) of observed daily streamflow data measured with flumes at the two undisturbed watersheds from the MCEW (Table 1).

2.3.2. Sediment yield

The WEPP model can simulate soil erosion from hillslopes and channels, soil deposition within the hillslope and channel profile, and sediment yield at the watershed outlet. The most important calibrating variables for simulating soil erosion are effective hydraulic conductivity, rill and interrill erodibilities, hillslope critical shear, percent ground cover, and channel bed critical shear stress (τ_c) (Nearing et al., 1990). For hillslopes, these parameters were set by default in the WEPPcloud interface based on previous field observations in forest soils of various textures (Lew et al., 2022). Similarly, for channel erosion, Srivastava et al. (2020) demonstrated good agreement between observed and model simulations in the MCEW by varying only the channel τ_c. The authors found a direct relationship between WEPP-calibrated τ_c and the median particle size (D_{50}) and suggested that pebble count data can be used to parametrize the channel τ_c in forested watersheds. For the watersheds in the MCEW, we used τ_c values recommended by Srivastava et al. (2020). In the Lake Tahoe watersheds, pebble count data were available at few locations, which were provided by the land managers from the Lake Tahoe basin. We calculated the D_{50} from the observed pebble count data and identified the channel bed critical shear stress-equivalent following Berenbrock and Tranmer (2008).

Observations of event-based suspended sediment concentrations (SSC) were available at the USGS gauging stations for all watersheds in the Lake Tahoe basin and the two flumes in MCEW. Additionally, for watersheds in the Lake Tahoe basin, we also had available flow-weighted annual loads of SSC estimated in a previous study in the basin by Coats et al. (2016). The authors estimated and compared annual loads from several regression equations after correcting the sources of bias in the USGS water quality database.

2.3.3. Phosphorus yield

Simulated phosphorus yield in WEPPcloud is based on simple static phosphorus concentrations in each of the three components of the

Table 2
Goodness-of-fit statistics for observed and simulated streamflow simulations. D = daily, M = monthly, A = annually (Water Year) statistics.

No.	Name	Abbreviated Name	Begin	End	NSE			KGE			PBias (%)		
					D	M	A	D	M	A	D	M	A
	California												
1	Ward Creek	WC8	1/1/1990	9/30/2014	0.59	0.69	0.94	0.60	0.72	0.84	4.5	4.8	4.5
2	Ward Creek	WC7A	10/1/1991	9/30/2001	0.59	0.71	0.98	0.62	0.77	0.92	0.3	0.4	0.3
3	Ward Creek	WC3A	10/1/1991	11/1/2011	0.61	0.71	0.96	0.65	0.73	0.94	0.3	0.5	0.3
4	Blackwood Creek	BC1	1/1/1990	9/30/2014	0.59	0.66	0.94	0.61	0.69	0.85	0.1	0.3	0.1
5	General Creek	GC1	1/1/1990	9/30/2014	0.54	0.61	0.90	0.66	0.71	0.89	10.7	11	10.7
6	Upper Truckee River	UTR1	1/1/1990	9/30/2014	0.53	0.63	0.91	0.73	0.78	0.86	12.8	13.1	12.8
7	Upper Truckee River	UTR3	6/1/1990	9/30/2012	0.56	0.66	0.96	0.77	0.82	0.9	6.3	6.4	6.3
8	Upper Truckee River	UTR5	5/12/1990	10/11/2011	0.59	0.73	0.93	0.78	0.83	0.84	−7.7	−7.8	−7.7
9	Trout Creek	TC4	1/1/1990	9/30/2014	0.64	0.69	0.86	0.75	0.77	0.74	−9.9	−9.8	−9.9
10	Trout Creek	TC2	6/1/1990	9/30/2012	0.54	0.60	0.92	0.77	0.79	0.84	−6.8	−6.8	−6.8
11	Trout Creek	TC3	5/22/1990	3/31/2011	0.48	0.53	0.87	0.67	0.69	0.76	0.3	0.3	0.3
	Nevada												
12	Logan House Creek	LH1	1/1/1990	10/12/2011	−0.09	0.49	0.77	0.39	0.48	0.62	−3.2	−3.1	−3.2
13	Glenbrook Creek	GL1	1/1/1990	9/30/2012	0.53	0.66	0.87	0.56	0.60	0.77	2.8	2.8	2.8
14	Incline Creek	IN1	1/1/1990	9/30/2014	0.44	0.57	0.72	0.56	0.56	0.60	−3.2	−3.2	−3.2
15	Incline Creek	IN2	1/1/1990	9/30/2004	0.48	0.65	0.81	0.62	0.61	0.70	−2.2	−2.2	−2.2
16	Incline Creek	IN3	5/1/1990	3/31/2011	0.48	0.71	0.80	0.69	0.66	0.68	−1.5	−1.4	−1.5
17	Third Creek	TH1	1/1/1990	9/30/2014	0.60	0.82	0.86	0.76	0.89	0.87	0	−0.1	0
	Oregon												
18	Blazed Alder	BA1	1/1/1980	12/31/2018	0.54	0.69	0.87	0.62	0.81	0.93	−1.8	−1.8	−1.8
19	Bull Run River	BR1	1/1/1980	12/31/2018	0.57	0.81	0.86	0.79	0.89	0.84	2.4	2.4	2.4
20	Cedar Creek	CC1	1/1/1980	9/29/2003	0.57	0.82	0.84	0.78	0.88	0.76	3.5	3.4	3.5
21	Fir Creek	FC1	1/1/1980	12/31/2018	0.58	0.74	0.86	0.71	0.86	0.90	−3.2	−3.2	−3.2
22	Little Sandy River	LS1	1/1/1980	12/31/2018	0.57	0.73	0.80	0.67	0.84	0.90	−7.3	−7.2	−7.3
23	North Fork	NF1	1/1/1980	12/31/2018	0.48	0.75	0.85	0.74	0.87	0.88	2.2	2.3	2.2
24	South Fork	SF1	1/1/1980	12/31/2018	0.57	0.76	0.83	0.76	0.88	0.91	2.2	2.2	2.2
	Washington												
25	Cedar River	CR1	1/1/1980	12/31/2018	0.53	0.71	0.90	0.74	0.85	0.95	−4.4	−4.4	−4.4
26	Taylor Creek	TC1	1/1/1980	12/31/2018	0.43	0.80	0.78	0.69	0.87	0.89	9	9	9
	Idaho												
27	Mica Creek	MC3	4/5/1991	9/30/2013	0.58	0.77	0.90	0.79	0.86	0.92	4.3	4.4	4.3
28	Mica Creek	MC6	9/12/1991	9/30/2013	0.53	0.68	0.72	0.70	0.78	0.73	−5.9	−5.9	−5.9
		Mean[§]			**0.55**	**0.70**	**0.87**	**0.70**	**0.78**	**0.84**	**0.29**	**0.35**	**0.29**

See Fig. 1 for watershed location and Table S1 in the supplementary material for full watershed names.
[§]Mean values calculated without LH1 watershed.

streamflow hydrograph (surface runoff, subsurface lateral flow, and baseflow), and particulate phosphorus concentration on the delivered sediment. Due to data limitations at most other watersheds, these static concentrations were calculated only for the Lake Tahoe watersheds based on long term observed streamflow (*USGS code: 00060—Discharge, ft^3 s^{-1}*) and event-based Total Phosphorus (TP) concentrations (*USGS code: 00665—Phosphorus, water, unfiltered, mg l^{-1}P*), Soluble Reactive Phosphorus (SRP; *USGS code: 00671—Orthophosphate, water, filtered, mg l^{-1}P*), SSC (*USGS code: 80154—Suspended sediment concentration, mg l^{-1}*), and streamflow (*USGS code: 00061—Discharge, instantaneous, ft^3 s^{-1}*) measured at the USGS stream gauging stations and bias-corrected by Coats et al., 2016. Particulate phosphorus (PP; mg L^{-1}) is not typically measured at the USGS stream gauging stations and was calculated by subtracting SRP from TP. Since these observations were event-based, we calculated the flow-adjusted daily concentrations with the LOAD ESTimator (LOADEST; Runkel et al., 2004) model, which is a USGS model used to derive relationships between event-based streamflow and suspended sediment concentrations based on eleven pre-defined regression equations. For each watershed, we ran the LOADEST model with an automated regression model selection.

On 1 January 1997 and 31 December 2005, a few watersheds on the western side of the Lake Tahoe experienced significant rain-on-snow events that caused record peak streamflow events. For example, Blackwood Creek, USGS code 10336660, recorded 83 m^3 s^{-1} (247 mm) in 1997 and 64 m^3 s^{-1} (191 mm) in 2005 peak streamflow. Therefore, when using the entire data record generated bias model results, we ran seasonally piecewise LOADEST models for all years except for WY 1997 and WY 2006, and then separately for years WY 1997 and WY 2006. Gao et al. (2018) found that the seasonally piecewise method performed better than the year-round method in estimating monthly nitrogen loads.

Static phosphorus concentrations needed as input to the WEPPcloud interface were further calculated from the flow-weighted concentrations for each watershed. We assumed the phosphorus concentrations in the surface runoff are typical of the streamflow SRP concentrations (mg L^{-1}) during spring snowmelt (months April and May) and that the phosphorus concentrations in the baseflow are typical of the streamflow SRP concentrations (mg L^{-1}) in the fall (September and October). For the phosphorus concentrations in lateral flow, we averaged the SRP streamflow concentrations (mg L^{-1}) for the remaining months. We calculated the particulate phosphorus concentrations adsorbed to sediments with equation (1).

$$pSediment = \left(\frac{TP - SRP}{SSC}\right)10^6 \tag{1}$$

where *pSediment* (PP) is the particulate phosphorus concentration (mg kg^{-1}), calculated for May, which is the month with the highest runoff and SSC. We used the phosphorus concentrations determined from the observed data as initial input to the model and further calibrated these values to match simulated values with observed annual average flow-adjusted loads of TP, SRP, and PP.

2.4. Model parameterization for management scenario testing

To demonstrate WEPPcloud’s ability to assess the impact of various management and wildfire scenarios, we selected as a case study the Lake Tahoe basin, where land managers are considering increasing the use of forest thinning and prescribed fires to reduce wildfire risks. Specifically,

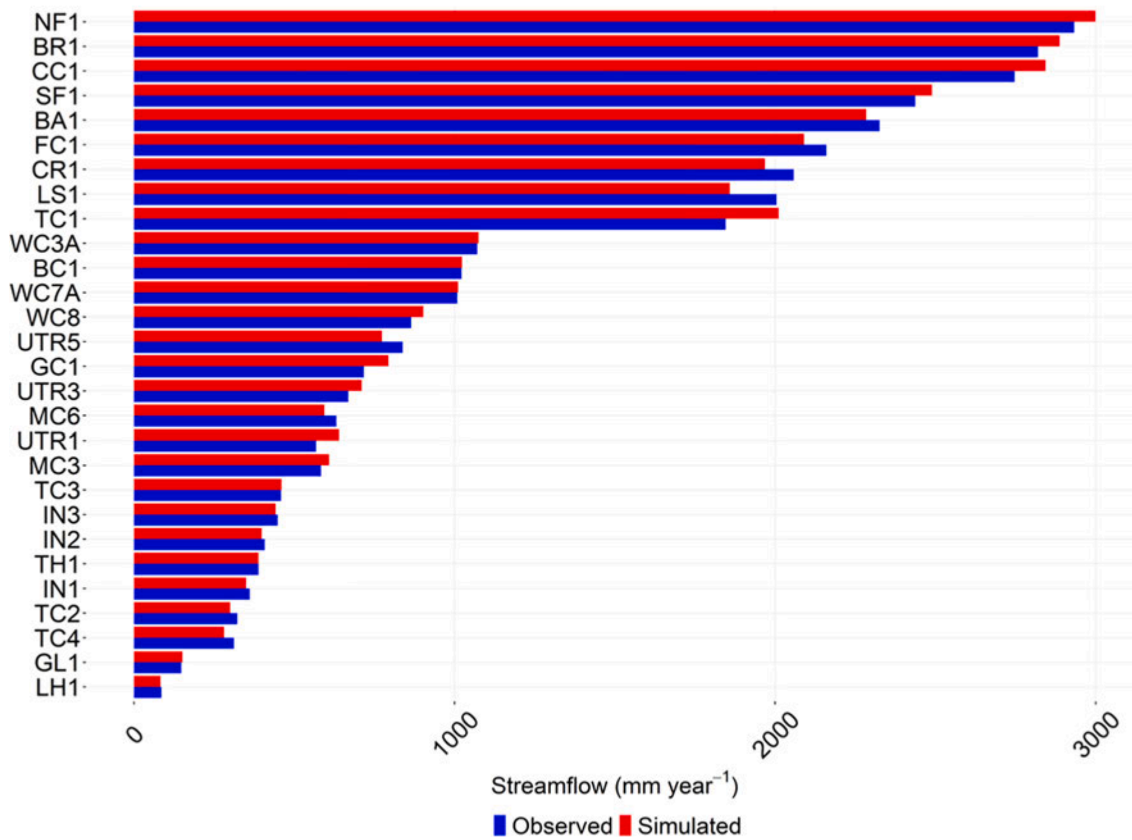

Fig. 2. Comparison of observed and simulated average annual water yield for the study watersheds.

managers were interested in exploring the benefits of expanding fuel management into remote forested areas and estimating the tradeoffs in long-term sediment yield between fuel management and wildfire. For this analysis, we modeled upland erosion for 11 management scenarios, or conditions, including current conditions/'do nothing', three thinning scenarios (with 96, 92, and 85% ground cover post-thinning), one prescribed fire scenario, and erosion following three different wildfire severity (low, moderate, and high) scenarios. The management parameters used to simulate these treatments are provided in Table S2 (in supplementary material). Thinning was only allowed on forested hillslopes, while prescribed fires or wildfires were also allowed to occur on areas covered by shrubs.

The Lake Tahoe basin is comprised of 63 watersheds that drain directly into the lake, but only 17 watersheds have water quality observations for calibration. The k_b and k_s, channel τ_c, and phosphorus concentrations in surface runoff, subsurface lateral flow, baseflow, and sediment for the calibrated watershed runs were distributed to uncalibrated watersheds across the basin based on the watershed's similarities, parent material, and proximity.

All simulations were performed using Python batch processing scripts that generate WEPPcloud compatible projects and results were further compiled in tabular data files and GIS data files. In the current version of the WEPPcloud interface, users can perform similar scenario testing for only individual watersheds, however, future interface developments will allow select users to perform similar batch hydrologic modeling for multiple watersheds and scenarios at the same time.

3. Results and discussion

3.1. Model performance assessment

3.1.1. Streamflow and water yield assessment

The WEPP model (via the WEPPcloud interface) was applied to several western U.S. watersheds of varying sizes with a wide variety of climatic and physiographic settings exhibiting distinct runoff regimes. The overall goodness-of-fit statistics for the WEPP-simulated and observed daily streamflow comparisons for the watersheds indicate reasonable results (Table 2). Across the watersheds, *NSEs* based on daily streamflow values were in the range of 0.43 to 0.64 indicating satisfactory agreement between modeled and observed values (Table 2). The only exception was the Logan House Creek watershed (LH1), located on the eastern side of the Lake Tahoe basin, with an *NSE* of − 0.09 signifying poor model performance. Brooks et al. (2016) reported similar results for the LH1 watershed, which the authors attributed to water loss through fractures in the bedrock. The WEPP model was not able to simulate this complex hydrogeology without additional calibration. Positive *KGE* values in the range of 0.39 to 0.79 (Table 2) suggest reasonable model performance when considering mean flow as a *KGE* estimation criterion. *Pbias* within ± 13% across all watersheds indicated slight over- and under-prediction of streamflow (Table 2).

The WEPP model captured runoff regimes across all watersheds reasonably well, and the simulated annual trends of water yield were similar to the trends of observed yield (Figs. 2 and 3, and Figs. S4 and S5 in supplementary material). Compared to daily streamflow, monthly and annual goodness-of-fit statistics showed improved model performance for all watersheds (Table 2).

While the streamflow and water yield assessment provided good evidence that the WEPPcloud interface can accurately represent the hydrology of distinct geographic regions, many water resources management issues require an understanding of a watershed's streamflow regime and the impacts of forest management on peak flows (e.g. for protecting culverts and roads). Daily peak flows were overestimated in most watersheds, except in the watersheds from the western side of Lake Tahoe (Figs. S1–S3 in supplementary material). Using a similar modeling approach as automated on the WEPPcloud interface, Brooks et al. (2016) and Srivastava et al. (2017, 2020) reported that the

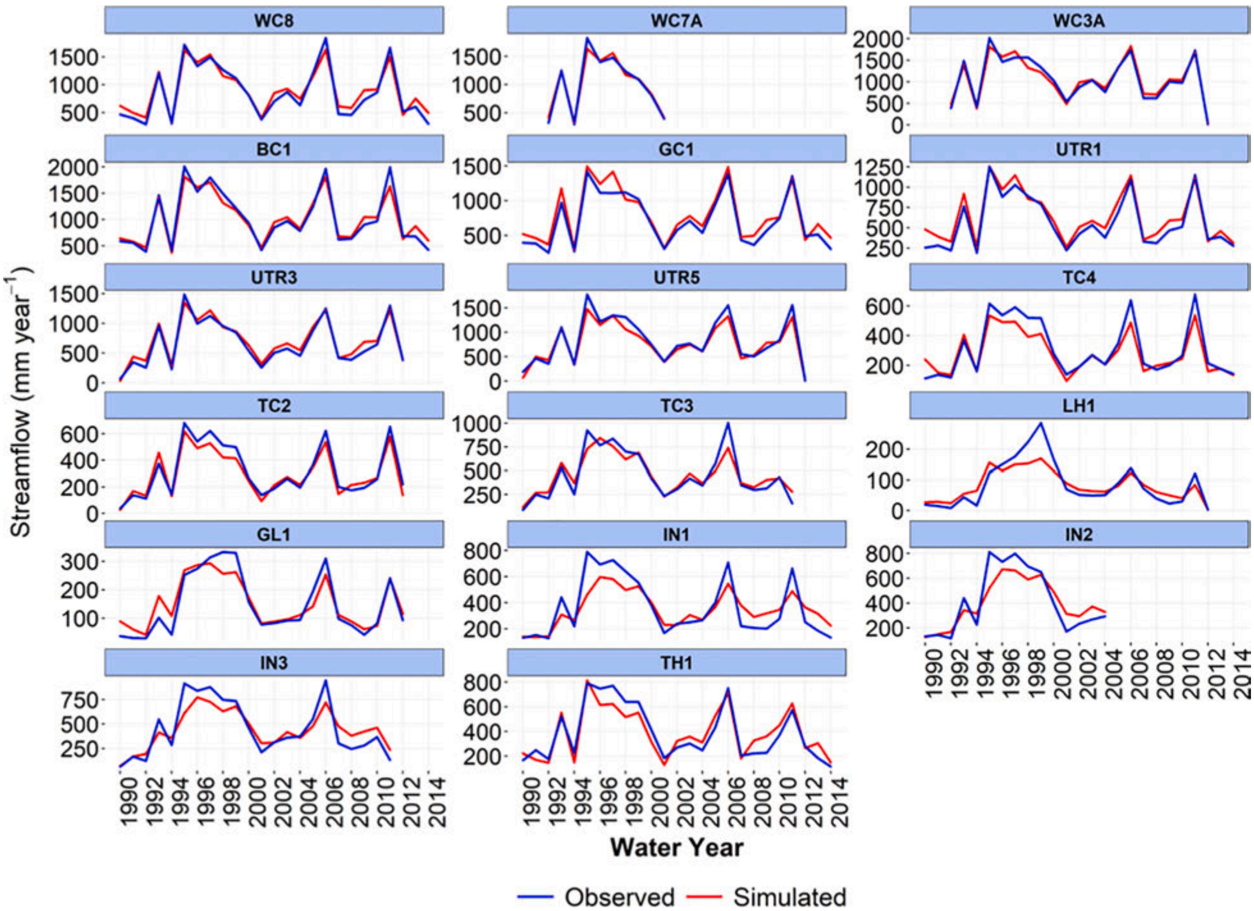

Fig. 3. Comparison of simulated and observed annual streamflow for the Lake Tahoe Basin watersheds California/Nevada. Additional graphs for the other watersheds are presented in Figs. S4 and S5 in the supplementary material.

discrepancies between the modeled and observed peak hydrograph could be arising from inaccuracies in WEPP's snow accumulation and melt processes. Currently, WEPP partitions precipitation into rain and snow using a single threshold approach (USACE U.S. Army Corps of Engineers, 1956). Research on snow hydrology suggests a double threshold approach in partitioning precipitation is more appropriate to better represent snow accumulation and melt processes (Dai, 2008).

Another potential source of daily peak flow overestimation may be that within the WEPP code, there is a flag that sets the infiltration rate to zero for the day if the soil is saturated at the end of the previous day's water balance. This suggests that if there are several rainy days in succession, the runoff of the second or third wet day could be overestimated due to saturation excess runoff. Miller et al. (2011) found that the flag for the infiltration rate in the WEPP code resulted in overestimation of runoff and erosion from only the wettest climates in the Pacific NW, but did not appear to affect results elsewhere in the western U.S. Nevertheless, uncalibrated model results in this study suggest that the WEPPcloud interface can satisfactorily represent the hydrology of distinct geographic regions and that water resources managers could apply the interface to ungauged watersheds for forest management decisions. Future efforts to improve hydrologic simulations with the WEPPcloud interface are underway to improve the snow hydrology routines in WEPP.

A linear groundwater reservoir with a default k_b of 0.04 d^{-1} was appropriate to model low summer streamflow in most watersheds of this study, except in the drier watersheds on the east side of Lake Tahoe basin and in the watersheds at MCEW. For the eastern side of the Lake Tahoe basin, the initial model results showed overestimations in water yield. Similar results were reported by Brooks et al. (2016) in Logan House (LH1) and Glenbrook Creek (GC1) watersheds located on the eastern portion of the Lake Tahoe basin. In their study, the authors used a secondary reservoir to simulate water yield by allowing groundwater loss through hydrogeological fractures and, therefore, bypassing the USGS stream gauge. In this study, the addition of a second aquifer reservoir in nine watersheds located in the NE, E, and SE of the Lake Tahoe basin improved water yield simulations, supporting the hypothesis that these watersheds could be characterized by complex hydrogeology (Hyne et al., 1972). For MCEW watersheds, a single linear reservoir with a default value of 0.02 d^{-1}, as suggested by Srivastava et al. (2020), was appropriate to simulate streamflow. Calibrated k_b and k_s for all watersheds are shown in Table 3. Sánchez-Murillo et al. (2015) demonstrated that in the Inland Pacific Northwest, the baseflow recession coefficients depend on several climatic and terrain attributes, including the geologic substrate. Results and recommendations from Sánchez-Murillo et al. (2015) work will be incorporated in future versions of the WEPPcloud interface to further reduce the data parameterization required from users.

For watersheds in the Bull Run catchment, we manually calibrated the saturated hydraulic conductivity of the restrictive bedrock (K_{sub}) based on maps of the rhododendron geologic layer (Trimble, 1963) and landslide susceptibility (Burns et al., 2015) of three classes (low, medium, and high). Specifically, we assumed the K_{sub} was highest (0.5 mm h^{-1}) where landslide susceptibility was the lowest, and low (0.005 mm h^{-1}) where landslide susceptibility was the highest. For the moderate landslide susceptibility, we assigned a middle value of 0.05 mm h^{-1}. Since the rhododendron layer in these watersheds is associated with landslides and bank erosion (Rinella, 1987; Peterson et al., 1995), we assigned it the lowest K_{sub} value (0.0001 mm h^{-1}). The K_{sub} for the soils

Table 3
Calibrated parameter values for baseflow and deep seepage coefficients, channel critical shear stress, and phosphorus concentrations in surface runoff, subsurface lateral flow, baseflow, and sediment.

No.	Name	Abbreviated Name	Baseflow coefficient (d^{-1})	Deep seepage Coefficient (d^{-1})	τ_c (Nm^{-2})	P_{runoff} (mg L^{-1})	$P_{lateral}$ (mg L^{-1})	$P_{baseflow}$ (mg L^{-1})	$P_{sediment}$ (mg L^{-1})
	California								
1	Ward Creek	WC8	0.04	0	30	0.004	0.005	0.006	1300
2	Ward Creek	WC7A	0.04	0	30	0.005	0.006	0.007	1100
3	Ward Creek	WC3A	0.04	0	30	0.003	0.004	0.005	900
4	Blackwood Creek	BC1	0.04	0	10	0.003	0.004	0.005	1100
5	General Creek	GC1	0.04	0	45	0.002	0.003	0.004	1300
6	Upper Truckee River	UTR1	0.04	0	15	0.004	0.005	0.006	1200
7	Upper Truckee River	UTR3	0.04	0	70	0.003	0.004	0.005	1300
8	Upper Truckee River	UTR5	0.04	0	180	0.007	0.008	0.009	1300
9	Trout Creek	TC4	0.01	0.0062	45	0.008	0.009	0.010	1800
10	Trout Creek	TC2	0.0168	0.0105	45	0.008	0.009	0.010	1700
11	Trout Creek	TC3	0.01	0.0010	75	0.007	0.008	0.009	1500
	Nevada								
12	Logan House Creek	LH1	0.0005	0.0009	40	0.001	0.002	0.003	2500
13	Glenbrook Creek	GL1	0.0018	0.0016	35	0.015	0.016	0.017	3500
14	Incline Creek	IN1	0.0019	0.0010	35	0.011	0.012	0.013	1500
15	Incline Creek	IN2	0.0017	0.0006	40	0.011	0.012	0.013	1300
16	Incline Creek	IN3	0.0022	0.0009	45	0.010	0.011	0.012	1300
17	Third Creek	TH1	0.0130	0.0134	25	0.008	0.009	0.010	700
	Oregon								
18	Blazed Alder	BA1	0.04	0	50	-	-	-	-
19	Bull Run River	BR1	0.04	0	200	-	-	-	-
20	Cedar Creek	CC1	0.04	0	150	-	-	-	-
21	Fir Creek	FC1	0.04	0	150	-	-	-	-
22	Little Sandy River	LS1	0.04	0	110	-	-	-	-
23	North Fork	NF1	0.04	0	140	-	-	-	-
24	South Fork	SF1	0.04	0	160	-	-	-	-
	Washington								
25	Cedar River	CR1	0.04	0	-	-	-	-	-
26	Taylor Creek	TC1	0.04	0	-	-	-	-	-
	Idaho								
27	Mica Creek	MC3	0.02	0	50	-	-	-	-
28	Mica Creek	MC6	0.02	0	37	-	-	-	-

See Fig. 1 for watershed location and Table S1 in supplementary material for full watershed names.

in Cedar River and Taylor Creek watersheds were calibrated to 0.05 mm h^{-1} and 0.15 mm h^{-1}, respectively, while for the two watersheds in MCEW we used a value of 0.02 mm h^{-1} as suggested by Srivastava et al. (2020). For all the watersheds in the Lake Tahoe basin, we used K_{sub} values of the restrictive layer as reported in the SSURGO database.

$T_{rain/snow}$ threshold was calibrated in the model to − 2 °C for watersheds where the gridMET climate database was used. The gridMET product utilizes the North American Land Data Assimilation System Phase 2 (NLDAS-2, Mitchell et al., 2004) for temporal daily data and the Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly et al., 2008) for spatial interpolation at 4-km resolution. The Daymet product uses the Global Historical Climatology Network (GHCN) for temporal daily data and is spatially interpolated at 1-km resolution. Our results suggest that the use of different climate products of varying spatial resolution in conjunction with WEPP could potentially influence snow accumulation/melt processes and thereby, hydrologic modeling. A detailed investigation of the impact of using different climate products with WEPP is recommended to guide users in selecting appropriate climate products for hydrologic simulations.

3.1.2. Sediment load

Overall, we were able to estimate the magnitudes of annual average sediment load in watersheds from both the Lake Tahoe basin and MCEW (Fig. 4, Table 4). Observed annual average sediment loads in the Lake Tahoe basin generally varied between the west- and the east-side, and from watershed to watershed. Eastern watersheds generated considerably less sediment compared to watersheds from the western side of the basin. Observed annual average sediment loads ranged from 5 Mg yr^{-1} at Logan House Creek (LH1) to 2852 Mg yr^{-1} from Blackwood Creek (BC1). This difference is mainly due to differences in area and precipitation since the LH1 watershed received less than half of the precipitation recorded in the BC1 (657 mm yr^{-1} precipitation in LH1 compared to 1476 mm yr^{-1} recorded in BC1; Table 1). Other watershed characteristics such as watershed soils, geology, and vegetation, likely contributed to the difference in sediment loads between the two watersheds, albeit to a lesser extent.

Model results showed an underestimation of annual sediment loads at three watersheds on the western side of the Lake Tahoe basin, namely at Blackwood Creek (BC1), Ward Creek (WC8), and General Creek (GC1) (Figs. 4 and 5). The main reason for this underestimation was the observed sediment delivery associated with a few high peak flow events from 1 and 2 January 1997 (WY 1997) and on 31 December 2005 (WY 2006), which were not captured by the model. These high peak flow rates were caused by rain-on-snow events that are often observed in the mid-winter in Pacific Northwest (Marks et al., 2001) and in watersheds in the Sierra Nevada mountains (Kattelmann, 1997; McCabe et al., 2007). In the Lake Tahoe basin, the 1997 event was considered a 100-year flood event (Tetra Tech, 2007), which caused peak suspended sediment loads with return periods ranging from 40 to 60 years only in streams from the western side of the Lake Tahoe basin (Simon et al., 2004). Brooks et al. (2016) demonstrated that the WEPP model can accurately simulate the 1997 high peak flow in the Upper Truckee River (UTR5) when scaling the weather data across the watershed based on data from a lower elevation SNOTEL station, which recorded a slightly different rain distribution for the day. Since most of the sediment is delivered during these high peak flow events, an accurate representation of weather data is essential to model such events.

Another potential source of underestimation of sediment load by WEPP may be sediment delivery from landslides, as the WEPP model does not consider mass wasting sources of sediment. There is some evidence of mass wasting, particularly in the steeper upland portions of the Blackwood Creek (BC1) watershed (Gavigan, 2007). Additional

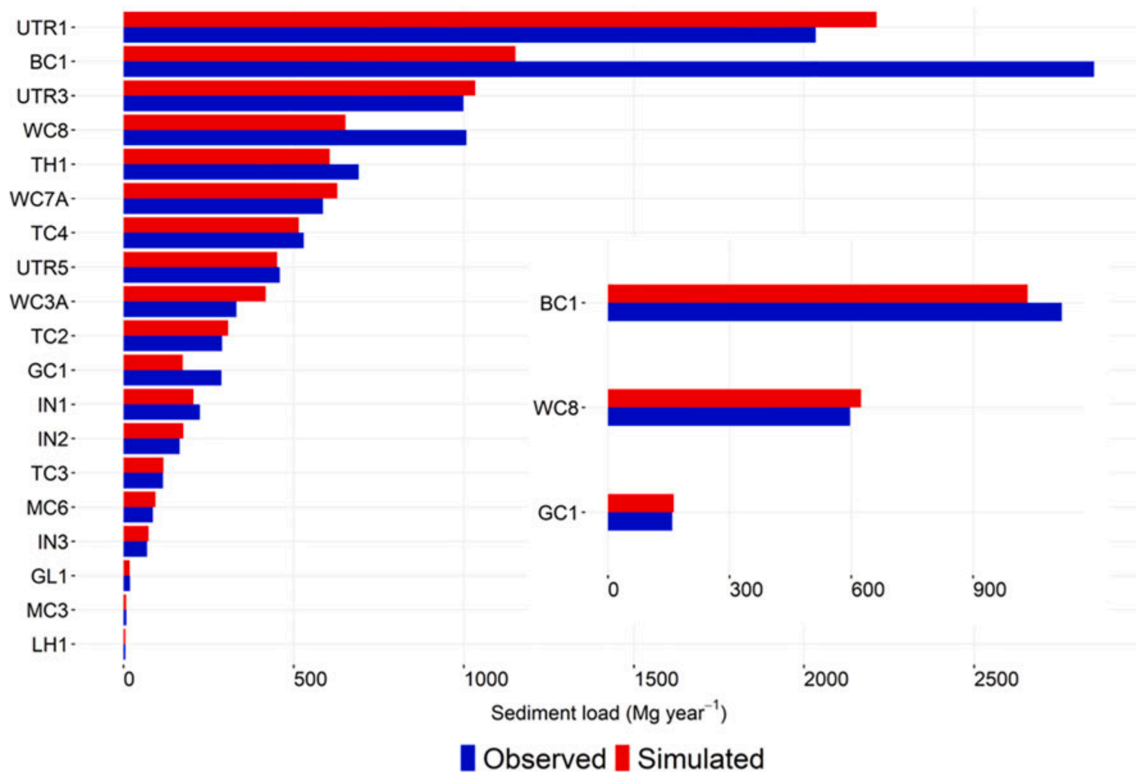

Fig. 4. Comparison of WEPP-simulated and observed average annual sediment load for the Lake Tahoe basin and MCEW watersheds. WEPP underestimated sediment loads in the three watersheds (WC8, BC1, and GC1) that were affected by the rain-on-snow events in WY 1997 and 2006. The inset figure shows WEPP-simulated and observed sediment load after excluding these two years.

sediment during peak flows may also be from channel erosion processes not fully addressed by the WEPP model, like side sloughing during channel drawdown following flood flows that would have saturated the stream banks (Simon et al. 2009).

The goodness-of-fit statistics based on annual sediment loads for all simulated years show that WEPP predictions were in reasonable agreement with observed data except for WC8, BC1, and GC1 watersheds (Table 4). Results for the three watersheds improved substantially when the water years with high peak flow events (1997 and 2006) were omitted from the analysis. For example, *NSE*, *KGE*, and *Pbias* for watershed BC1 improved from 0.05 to 0.63, −0.15 to 0.48, and −60% to −7%, respectively.

We manually calibrated the τ_c in the Lake Tahoe watersheds to match the simulated to observed annual sediment loads at the watershed outlets, assuming minimal upland erosion. These values ranged from 10 N m^{-2} in the Blackwood Creek watershed to 180 N m^{-2} in the headwaters of the Upper Truckee River (UTR5) watershed (Table 3). Lower values of the τ_c are associated with smaller D_{50} particle size (Srivastava et al., 2020), and therefore higher soil erodibility for channel beds. Conversely, higher values of τ_c are associated with larger D_{50} particle sizes and result in lower erodibility values. Indeed, the Blackwood Creek watershed is known in the Lake Tahoe basin as the top contributor of sediment yield to the lake and has been the subject of several channel restoration efforts (Norman et al., 2014; Oehrli, 2013). The headwater portion of the Upper Truckee River watershed is characterized by rock outcrops of low infiltration rates and erodibilities (Brooks et al., 2016), which can be an explanation for the higher τ_c calibrated by the model. Median pebble count data (D_{50}) was available for two of the modeled watersheds in the Lake Tahoe basin and τ_c equivalents for these two watersheds approximately matched the calibrated values $\tau_{c\text{-calibrated}}$: Blackwood Creek, mainstream, $D_{50} = 42$, $\tau_c = 26$, $\tau_{c\text{-calibrated}} = 10$; Ward Creek, $D_{50} = 68$ $\tau_c = 54$, $\tau_{c\text{-calibrated}} = 30$.

3.1.3. Phosphorus yield

The magnitudes of all three phosphorus constituents simulated by the WEPP model were in close agreement with the observed across all watersheds (Fig. 6a and 6b, and Fig. S7 in the supplementary material). The goodness-of-fit statistics based on annual values for watersheds in Lake Tahoe were very good for all three phosphorus constituents (Table 5): TP (*NSE* = 0.75, *KGE* = 0.71, *PBias* = −0.5%), PP (*NSE* = 0.71, *KGE* = 0.70, *PBias* = −1.3%), and SRP (*NSE* = 0.66, *KGE* = 0.66, *PBias* = −4.6%) (Table 5). The simulated annual loads of TP, PP, and SRP followed the trends of observed load (Figs. 7, and S8 and S9 in supplementary material), which is expected since PP is the major form of phosphorus transport in streams from Lake Tahoe (Hatch et al., 2001). Therefore, similar to the sediment load, the TP and PP load for the three watersheds (WC8, BC1, and GC1) that experienced the rain-on-snow events in WY 1997 and 2006 were also underestimated (Fig. 6a). Simulated annual SRP load was better captured by the model, except in Logan House (LH1) where the model underestimated the observed loads (*PBias* = −95%; Table 5). However, it is worth noting that the difference between the observed and simulated phosphorus load for this watershed is insignificant (1.5 kg yr^{-1}).

The simplistic coefficient-based phosphorus algorithms implemented in the WEPPcloud interface were sufficient to capture the general trends of annual phosphorus loads associated with surface runoff, subsurface lateral flow, baseflow, and sediment in our study watersheds (Figs. 6 and 7). Most process-based phosphorus models use complex processes involving mineralization, decomposition, and immobilization pools and their interaction among them for phosphorus transport computations. Hydrologic simulations with such algorithms may improve the spatial and temporal estimates of phosphorus for watershed simulation studies. A version of the WEPP model with a water quality module is under development (personal communication, D.C. Flanagan) and would likely be available for the evaluation of nutrient transport in forest settings in a future version of WEPPcloud.

Table 4
Goodness-of-fit statistics for the WEPP-simulated and observed annual sediment load. Italicized rows denote watersheds where statistics were recalculated after eliminating sediment load in 1997 and/or 2006 water years that experienced high peak flow events and extreme soil erosion.

No.	Name	Abbreviated Name	nPairs	NSE	KGE	PBias (%)
	California					
1	Ward Creek	WC8	25	0.16	0.03	–35.3
1	Ward Creek	WC8[†]	25	0.62	0.48	4.6
2	Ward Creek	WC7A	10	0.78	0.70	7.2
3	Ward Creek	WC3A	20	0.67	0.60	26
4	Blackwood Creek	BC1	25	0.05	–0.15	–59.6
4	Blackwood Creek	BC1[††]	25	0.63	0.48	-7.2
5	General Creek	GC1	25	0.15	0.03	–39.4
5	General Creek	GC1[††]	25	0.58	0.49	1.9
6	Upper Truckee River	UTR1	25	0.82	0.88	8.8
7	Upper Truckee River	UTR3	21	0.60	0.56	3.5
8	Upper Truckee River	UTR5	21	0.80	0.70	–1.7
9	Trout Creek	TC4	25	0.47	0.38	–2.8
10	Trout Creek	TC2	21	0.41	0.32	6.1
11	Trout Creek	TC3	20	0.65	0.53	0.9
	Nevada					
12	Logan House Creek	LH1	22	0.73	0.74	–2.2
13	Glenbrook Creek	GL1	22	0.79	0.81	–6.6
14	Incline Creek	IN1	25	0.43	0.36	–8.3
15	Incline Creek	IN2	14	0.36	0.39	6.4
16	Incline Creek	IN3	20	0.51	0.45	7.2
17	Third Creek	TH1	25	0.12	0.02	–12.4
	Idaho					
27	Mica Creek	MC3	16	0.78	0.6	–5
28	Mica Creek	MC6	16	0.89	0.86	8.7
		Mean[§]		**0.61**	**0.54**	**1.85**

[†] Calculations without WY 1997.
[††] Calculations without WY 1997 and 2006.
[§] Mean values calculated without WY 1997 and WY 2006 for WC8, BC1, and GC1.
See Fig. 1 for watershed location and Table S1 in supplementary material for full watershed names.

In watersheds from the Lake Tahoe basin, P concentration values in surface runoff inferred from the observed data varied between 0.0028 mg L^{-1} in General Creek (GC1) to 0.013 mg L^{-1} in Glenbrook Creek (GL1). The lateral flow and baseflow P concentrations were higher than those in the runoff and ranged between 0.026 mg L^{-1} in Logan House (LH1) to 0.0153 mg L^{-1} in Glenbrook Creek (GL1) for lateral flow, and from 0.0024 mg L^{-1} in Logan House (LH1) to 0.0228 mg L^{-1} in Glenbrook Creek (GL1) for baseflow, respectively. In general, these values were lower in watersheds located on the western side and higher in those from the eastern side of the Lake Tahoe basin. The observed P concentrations in the sediments varied between 840 mg kg^{-1} in Third Creek (TH1) to 4397 mg kg^{-1} in Glenbrook Creek (GL1). Similarly, as with the streamflow P concentrations, sediment P concentrations varied among watersheds, with lower values in watersheds on the northern, western, and southern sides of the basin and higher values in watersheds from the eastern side of the basin (Table 6).

The significant difference in P concentration in runoff and sediment between watersheds on the west- and east sides of Lake Tahoe, respectively, is likely due to differences in the parent material. Specifically, watersheds located on the NW and W of Lake Tahoe are mainly underlying volcanic soils with poorly crystalline iron and aluminum oxides that retain P and limit the P movement in water (Heron et al., 2021). Watersheds on the eastern side of the Lake Tahoe basin, however, are developed mainly on granitic parent material with greater potential for P mobilization to streamflow (Heron et al., 2021).

We found a strong linear relationship (R^2 = 0.93) between the P runoff concentrations values determined from the observed data and the calibrated values in watersheds from Lake Tahoe (Fig. 8). Similarly, the P concentration values in the sediment determined from observed data were linearly related to the calibrated values (R^2 = 0.75). The dissolved P concentrations in lateral flow and baseflow, however, were only linearly related to the calibrated values from WEPP for watersheds with a second aquifer reservoir (R^2 = 0.94 for lateral flow; R^2 = 0.86 for baseflow) and not for watersheds with a single reservoir (R^2 = 0.05 for lateral flow; R^2 = 0.08 for baseflow). The poor agreement between observed and calibrated P concentrations for both lateral flow and baseflow for the watersheds with a single reservoir is a surprising result. We were expecting this mismatch for watersheds that were calibrated with a second aquifer as those watersheds are believed to have complex hydrogeology and lose water either to a second reservoir through fractures or to areas outside of the basin (Brooks et al., 2016), and therefore the observed P concentrations at the watershed outlets would be smaller. Further investigation is required to understand how the complex groundwater system is contributing to inconsistencies in the analysis of P concentrations. In all stream locations across the Lake Tahoe, the observed dissolved P concentrations were very low (<0.020 mg L^{-1}) and even using a single constant dissolved P concentration in runoff, lateral flow, and baseflow, produced similar annual P loading results at watersheds with both single and double aquifers (data not shown).

3.2. Management scenario testing

The model calibration for 17 watersheds in the Lake Tahoe basin allowed us to identify the minimum number of critical calibrating parameters in the model to confidently simulate streamflow, and sediment and phosphorus yield. Model results suggested that most of the calibrated parameters are fairly consistent across each ecosystem where a calibrated value in one watershed is also reasonable for a neighboring watershed in the same ecosystem. For example, eight watersheds in the western side of the basin were calibrated with a single linear reservoir aquifer and a baseflow recession coefficient of 0.04 day^{-1}. Conversely, all watersheds located NE, E, and SE were calibrated with a second linear reservoir and various deep seepage coefficients. These similarities among watersheds allowed us to apply the calibrated values to model the rest of the ungauged watersheds within the basin. Regional differences were also observed for the channel critical shear and phosphorus concentrations, which were similarly distributed across the basin. The supplementary material contains maps of the groundwater baseflow and seepage coefficients, critical shear, and phosphorus concentrations for all watersheds in the basin (Figs. S10, S11, S12).

WEPPcloud simulated output can be downloaded as tables and GIS shapefiles and managers can use this information to compare runoff, sediment yield, and phosphorus yields from individual hillslopes and watersheds (https://wepp.cloud/weppcloud/lt/). For example, maps of sediment yield output suggest that under undisturbed conditions there are erosion hot spots within several watersheds in the basin (e.g. Blackwood Creek, Ward Creek, the upland portion of the Upper Truckee River, and Third Creek) and that sediment yield from these areas tends to increase with disturbance severity (Fig. 9). Another observation with great implications for management is that for the eastern watersheds, the model simulated minimal to no erosion even after a wildfire (<1 kg ha^{-1}). Two of the eastern watersheds have been identified in previous research studies as sinks, rather than sources, of sediments mainly due to their small size and low precipitation and runoff rates (Simon et al., 2004). This finding could be useful for managers that are seeking to prioritize areas for treatment in the basin.

Previous research in the basin suggested that high peak flows associated with rain-on-snow events (e.g., year 1997) can flush stored sediment from the stream channels and reduce the sediment load in the following years (Simon et al., 2004). Since forest disturbances have the potential to increase peak flows (Grant et al., 2008), we could expect rill and interrill erodibilities and the channel critical shear to change immediately post-disturbance. However, without clear guidelines from the available literature, we were unable to parameterize the WEPPcloud interface to reflect these complex changes within the channel streambed post-disturbance.

Similarly, forest treatments and wildfire have the potential to

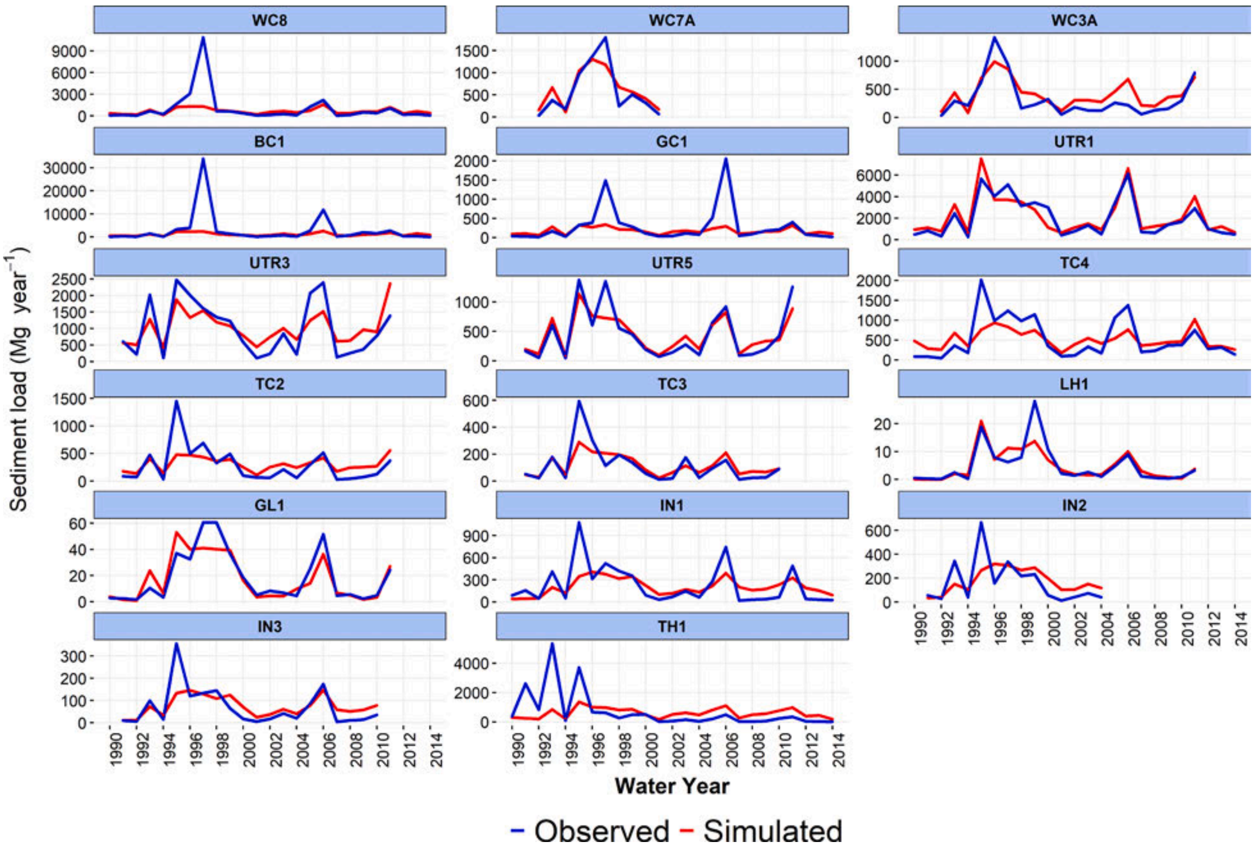

Fig. 5. Comparison of WEPP-simulated and observed annual sediment load for the Lake Tahoe basin watersheds. A similar graph for the MCEW watersheds is presented in Fig. S6 in the supplementary material.

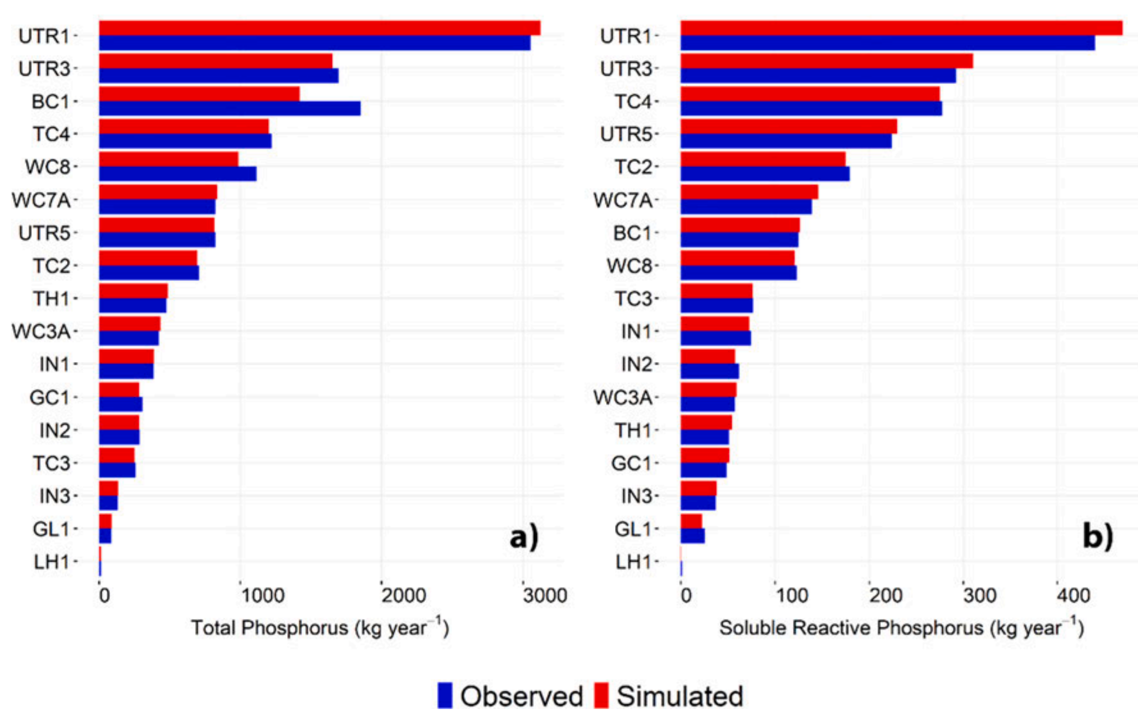

Fig. 6. Comparison of WEPP-simulated and observed average annual TP (a) and SRP (b) loads for watersheds from the Lake Tahoe basin. A similar figure for PP loads is presented in Fig. S7 in the supplementary material.

Table 5
Goodness-of-fit statistics for the average annual phosphorus load for the three constituents (TP = Total Phosphorus, PP = Particulate Phosphorus, and SRP = Soluble Reactive Phosphorus) for the Lake Tahoe basin watersheds. Italicized rows denote watersheds where statistics were recalculated after eliminating phosphorus load in 1997 and/or 2006 water years that experienced high peak flow events and extreme soil erosion.

No.	Name	Abbreviated Name		TP			PP			SRP		
			nPairs	NSE	KGE	Pbias (%)	NSE	KGE	Pbias (%)	NSE	KGE	Pbias (%)
	California											
1	Ward Creek	WC8	25	0.56	0.43	−11.5	0.53	0.41	−12.7	0.83	0.70	−2.2
1	Ward Creek	WC8†	25	0.79	0.65	2.5	0.77	0.71	2.6	0.83	0.71	0.6
2	Ward Creek	WC7A	20	0.94	0.96	1.6	0.93	0.96	0.8	0.94	0.91	5
3	Ward Creek	WC3A	10	0.75	0.82	2.8	0.75	0.83	2.3	0.64	0.66	3.9
4	Blackwood Creek	BC1	25	0.39	0.28	−23.3	0.37	0.25	−25.2	0.69	0.67	1.2
4	Blackwood Creek	BC1††	25	0.70	0.63	0.4	0.69	0.62	0.3	0.69	0.62	0.5
5	General Creek	GC1	25	0.64	0.53	−8	0.57	0.46	−11	0.75	0.84	6.2
5	General Creek	GC1††	25	0.79	0.74	4.1	0.75	0.82	3.3	0.74	0.82	6.1
6	Upper Truckee River	UTR1	25	0.81	0.85	2.3	0.75	0.78	1.5	0.8	0.68	6.6
7	Upper Truckee River	UTR3	21	0.83	0.71	−2.4	0.79	0.70	−4.3	0.77	0.69	6.3
8	Upper Truckee River	UTR5	21	0.86	0.83	−0.7	0.76	0.77	−2	0.94	0.89	2.5
9	Trout Creek	TC4	25	0.80	0.65	−1.6	0.75	0.61	−1.8	0.87	0.76	−0.9
10	Trout Creek	TC2	21	0.70	0.55	−1.6	0.59	0.47	−1.5	0.9	0.79	−2.4
11	Trout Creek	TC3	20	0.84	0.83	−3.3	0.81	0.81	−4.6	0.89	0.83	−0.8
	Nevada											
12	Logan House Creek	LH1	22	0.63	0.68	−21.9	0.53	0.64	−28.6	−1.17	-0.39	−94.6
13	Glenbrook Creek	GL1	22	0.83	0.91	3	0.75	0.81	2.3	0.77	0.79	−10.9
14	Incline Creek	IN1	25	0.65	0.58	1.2	0.64	0.58	2.1	0.64	0.49	−2.3
15	Incline Creek	IN2	14	0.59	0.59	−0.8	0.56	0.59	0.9	0.66	0.54	−6.2
16	Incline Creek	IN3	20	0.82	0.79	3	0.80	0.82	2.4	0.56	0.65	2.5
17	Third Creek	TH1	25	0.41	0.36	2.7	0.37	0.33	1.9	0.75	0.83	5.7
		Mean§		**0.75**	**0.71**	**−0.51**	**0.71**	**0.70**	**−1.32**	**0.66**	**0.66**	**−4.61**

†Calculations without WY 1997.
††Calculations without WY 1997 and 2006.
§Mean values calculated without WY 1997 and WY 2006 for WC8, BC1, and GC1.
See Fig. 1 for watershed location and Table S1 in the supplementary material for full watershed names.

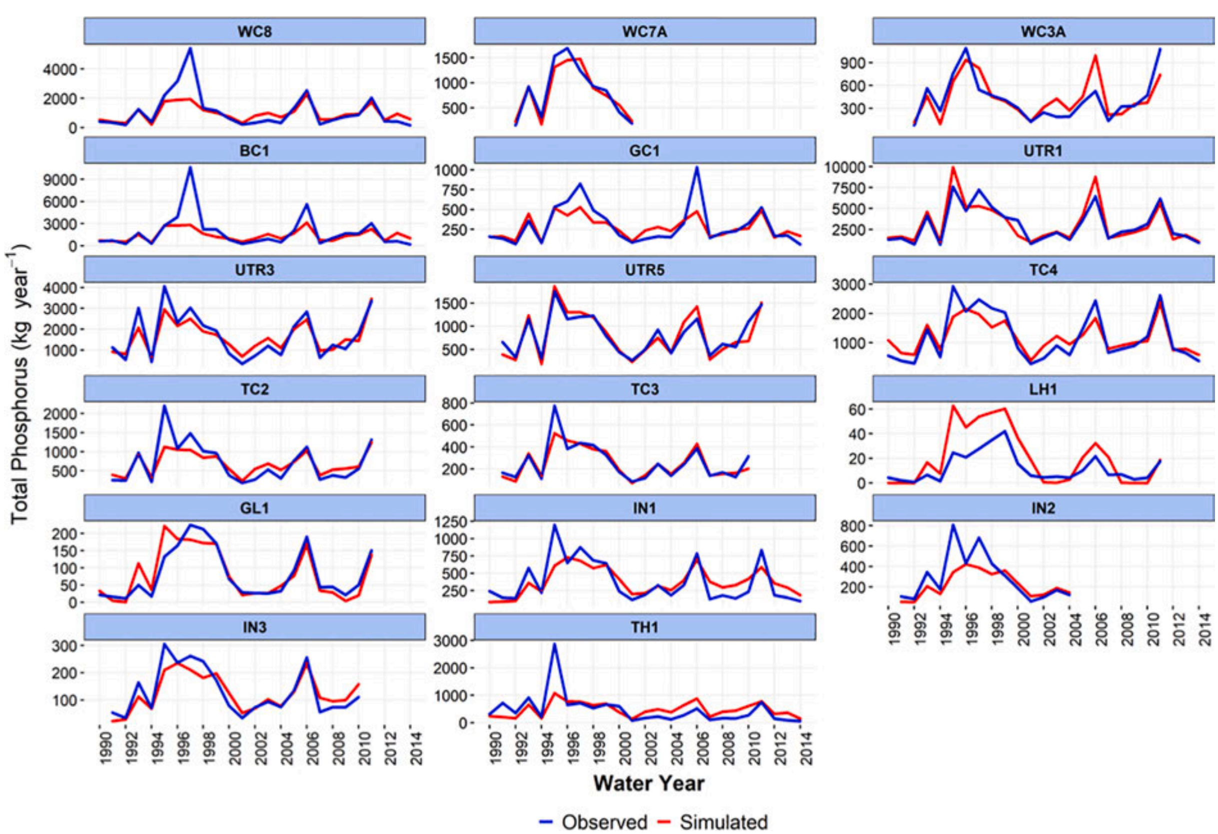

Fig. 7. Comparison of WEPP-simulated and observed annual TP loads for the Lake Tahoe basin watersheds. Similar figures for SRP and PP are presented in Figs. S8 and S9 in the supplementary material.

Table 6
Observed (Obs.) and calibrated (Calib.) phosphorus concentrations. Observed values are inferred from the flow-weighted phosphorus and sediment concentrations calculated with the LOADEST model.

No.	Name	Abbreviated Name	Single/ Doubleaquifer reservoir	Obs. in runoff (mg L^{-1})	Calib. in runoff (mg L^{-1})	Obs. in lateral flow (mg L^{-1})	Calib. in lateral flow (mg L^{-1})	Obs. in baseflow (mg L^{-1})	Calib. in baseflow (mg L^{-1})	Obs. in sediment (mg kg^{-1})	Calib. in sediment (mg kg^{-1})
	California										
1	Ward Creek	WC8	Single	0.0059	0.004	0.009	0.005	0.0125	0.006	2059	1300
2	Ward Creek	WC7A	Single	0.0053	0.005	0.009	0.006	0.0147	0.007	1188	1100
3	Ward Creek	WC3A	Single	0.0034	0.003	0.004	0.004	0.0045	0.005	1600	900
4	Blackwood Creek	BC1	Single	0.0040	0.003	0.007	0.004	0.0116	0.005	1166	1100
5	General Creek	GC1	Single	0.0028	0.002	0.009	0.003	0.0187	0.004	1303	1300
6	Upper Truckee River	UTR1	Single	0.0049	0.004	0.006	0.005	0.0070	0.006	1362	1200
7	Upper Truckee River	UTR3	Single	0.0034	0.003	0.004	0.004	0.0050	0.005	1896	1300
8	Upper Truckee River	UTR5	Single	0.0052	0.007	0.010	0.008	0.0209	0.009	2466	1300
9	Trout Creek	TC4	Double	0.0073	0.008	0.008	0.009	0.0094	0.01	2966	1800
10	Trout Creek	TC2	Double	0.0080	0.008	0.009	0.009	0.0099	0.01	1789	1700
11	Trout Creek	TC3	Double	0.0077	0.007	0.009	0.008	0.0104	0.009	2545	1500
	Nevada										
12	Logan House Creek	LH1	Double	0.0037	0.002	0.003	0.003	0.0024	0.004	3875	2300
13	Glenbrook Creek	GL1	Double	0.0130	0.015	0.015	0.016	0.0228	0.017	4397	3500
14	Incline Creek	IN1	Double	0.0109	0.011	0.012	0.012	0.0141	0.013	1727	1500
15	Incline Creek	IN2	Double	0.0123	0.011	0.012	0.012	0.0120	0.013	1248	1300
16	Incline Creek	IN3	Double	0.0104	0.01	0.011	0.011	0.0127	0.012	2280	1300
17	Third Creek	TH1	Double	0.0080	0.008	0.011	0.009	0.0138	0.01	840	700
		Mean	**Single**	**0.004**	**0.004**	**0.007**	**0.005**	**0.012**	**0.006**	**1630**	**1188**
		Mean	**Double**	**0.009**	**0.009**	**0.010**	**0.010**	**0.012**	**0.011**	**2407**	**1733**

Observed in runoff: Average SRP concentrations for April and May.
Observed in lateral flow: Average SRP concentrations of all months, except April, May, September, and October.
Observed in baseflow: Average SRP concentrations for September and October.
Observed in sediment: Average (TP-SRP) x 106 /SSC for May.
See Fig. 1 for watershed location and Table S1 in the supplementary material for full watershed names.

increase P concentrations in forested ecosystems mainly through increases in soil erosion and increased availability of ash that has an elevated P concentration (Santín et al., 2018). However, studies have found little effects from thinning (Deval et al., 2021) or from a combination of thinning and prescribed fires on P delivery (Kaye et al., 2005; Martin and Harr, 1989). Since forest wildfires, especially those that result in high soil burn severity, affect soil properties, there is more evidence that P concentrations post-wildfire increase (Lane et al., 2008; Murphy et al., 2006; Santín et al., 2018; Smith et al., 2011). However, because this information is limited in the research literature, we did not attempt to include in the model any temporal changes in phosphorus concentrations with treatment. Moreover, even if such changes were implemented, we lacked post-disturbance phosphorus observations at the modeled watersheds to validate model results.

3.3. Advantages and limitations

The WEPPcloud interface overcomes several challenges that users faced in the past when applying the WEPP model to forested watersheds. Major advantages and limitations of the WEPPcloud interface for forest applications are presented in Table 7.

4. Summary and conclusion

For many years, the application of complex hydrologic models for land management was limited to trained hydrologists and modelers with extensive knowledge of computer programming and data manipulation. Transferability of knowledge from the modeler to the manager was slow and oftentimes hindered by managers' limited accessibility to the actual model for further scenario testing or model parameterization with additional observed data. Increased accessibility to national databases via web applications is now facilitating the development of online decision-support tools, such as WEPPcloud, that provide managers with more flexibility in modeling and interpreting results to better understand watershed processes and to evaluate the effects of forest management actions on water resources.

In the current study, we demonstrated that the WEPPcloud interface can successfully simulate general trends in streamflow, sediment, and phosphorus in watersheds with different physiographic settings with minimal calibration. Additionally, we demonstrated the applicability of the interface to various forest fuel treatments and wildfire scenarios, which can provide land and water resources managers with site-specific information of the spot areas in their watersheds to control soil erosion and phosphorus transport with forest management practices. The minimal calibration performed in this study involved manual alterations of calibrating parameters that are not easily found in national databases (i.e., k_b, K_{sub}, τ_c, P concentrations). However, previous research, and the current study, demonstrate that at least some of these parameters could be inferred from geology (k_b) or could be determined from observed data at nearby watersheds (k_b, τ_c, P concentrations). Future applications of

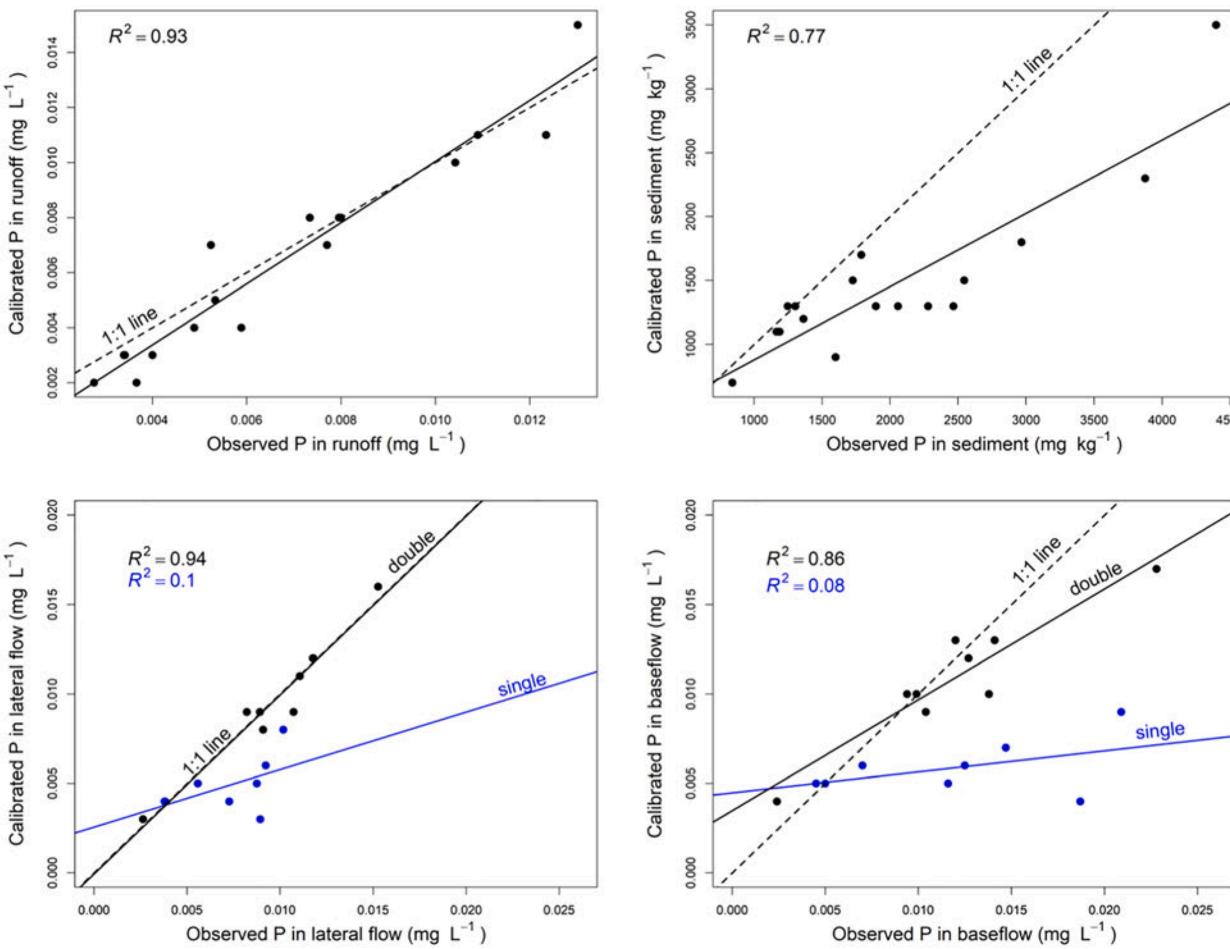

Fig. 8. Comparison between observed and calibrated P concentrations in runoff, lateral flow, baseflow, and sediment for watersheds in the Lake Tahoe Basin calibrated with a single aquifer (blue line) and double aquifer (black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

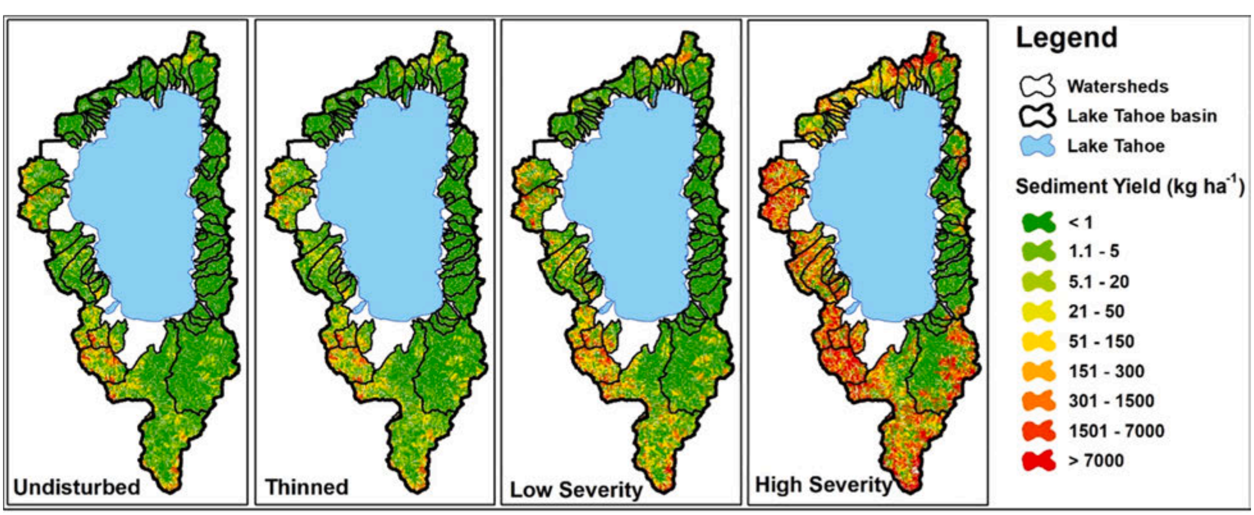

Fig. 9. Annual average sediment delivery rate for four scenarios: undisturbed, thinned, uniform low severity fire, and uniform high severity fire at the Lake Tahoe basin watersheds. Similar maps can be created from the model results for other hydrologic components (e.g. runoff, lateral flow, baseflow) or scenarios (e.g. uniform prescribed fire, uniform moderate severity fire, based on future climate scenarios, etc.).

the interface to watersheds located in different ecoregions of U.S. will help with the identification of regional calibrating parameters that could improve model simulations. There is also a need to improve the WEPP model hydrologic routines to improve peak flow estimation in wet climates.

Perhaps the most obvious limitation to any hydrologic model is an accurate representation of the weather patterns or climatic conditions, specifically precipitation, and minimum and maximum temperature.

Table 7
Advantages and limitations of the WEPPcloud interface for forest applications.

Advantages	
Pre-processed input	Accesses and extracts data from inherent digital elevation model, soil, and landcover spatial data maps, and converts the data into WEPP-ready input formats. WEPP weather files can be created from various gridded climate products (e.g., Daymet, gridMET, CLIGEN with/without PRISM adjustments) from 1980 until present for the continental U.S. Observed gridMET weather data can be accessed within 48 h of the present day.
Post-processed output	Provides results in tabular and spatial formats that can help users better visualize WEPP outputs and rapidly evaluate the forest management on water quality.
Efficient	Watershed delineation and hydrologic simulations can be conducted anywhere in the continental U.S., Australia, and Europe within minutes.
Software	Does not require any GIS environment or specialized software skills other than an internet connection and a web browser.
Memory	Housed on a large cloud server with enough memory storage to satisfy multiple watershed analyses simultaneously.
Local database	Can be parameterized with future data or algorithms to improve model simulations.
Flexible	Allows advanced WEPP users to download model run input files for further parametrization. With this option, users can couple WEPP with any parameter optimization tool (e.g. PEST) for validation studies.
Limitations	
Vegetation regeneration	Currently, model simulations on WEPPcloud are performed with management parameters that represent static vegetation growth. This management setup is appropriate for probabilistic simulations largely used for forest management decision-making for the first year after disturbance. Future version of the WEPP model codes will include dynamic forest regeneration following clear-cut, thinning, and wildfires, similar to the approach demonstrated by Srivastava et al. (2020).
Static parameters	Current model parameters such as the effective hydraulic conductivity, rill and interrill erodibility, channel critical shear stress, percent ground cover and canopy cover, and phosphorus input concentrations do not change with time. Future research into how these parameters change with time and treatment could be incorporated into the model.
User inputs	The WEPPcloud interface only allows users to modify critical parameters (e.g. rain-snow threshold, saturated conductivity of the restrictive layer, channel bed critical shear stress etc.) based on previous research studies (Brooks et al., 2016; Srivastava et al., 2020). The WEPPcloud interface also restricts user's ability to upload their own created input file due to compatibility issues.
Roads	Forest roads are major contributors to sediment yield in forests. Cao et al. (2021) demonstrated that roads could alter flow paths and reroute water and sediment through ditches directly into streams, affecting and sediment delivery. Delineation and simulation of road segments alongside simulation of hillslopes and channels on the WEPPcloud interface would provide managers with cumulative effects of forest treatments on hydrology and soil erosion.
Multiple overland flow elements (OFEs)	Although the WEPP model itself could handle multiple OFEs, the current WEPPcloud interface cannot create input files needed for such simulations. Boll et al. (2015) showed that WEPP can better predict the spatial and temporal location of subsurface lateral flow, saturation excess runoff, and infiltration down the hillslope profile when multiple OFEs are used for simulations. Moreover, the incorporation of multiple OFEs would enhance the model applications to watersheds with the simulation of streamside management zones.

Despite performing simulations with the best available spatially distributed climate datasets, our results show that we are still not able to accurately capture extreme peak flow events, which are needed in many management applications. However, increased access to remotely-sensed data and the tendency to improve the spatial resolution of such observations such as radar, should provide evidence that we are getting closer to providing accurate hydrologic simulations in ungauged basins in near real-time.

Although there will most certainly be needs and opportunities in the future to reduce uncertainty in geospatial model predictions, the technology incorporated within WEPPcloud provides managers with a comprehensive physically-based hydrologic tool developed based on the most accurate readily available geospatial and climatic data. WEPPcloud results provide managers with long-term historic or future hillslope and watershed-specific simulated streamflow, sediment, and nutrient outputs in the manner of minutes. With a large forestry and wildfire management database parameterized with the latest region-specific scientifically-defensible experimental studies and a user-friendly interface capable of storing multiple scenario runs, WEPPcloud has great potential to be a useful decision-support tool for many forestry management applications.

CRediT authorship contribution statement

Mariana Dobre: Conceptualization, Methodology, Data curation, Formal analysis, Funding acquisition, Visualization, Writing – original draft. **Anurag Srivastava:** Conceptualization, Methodology, Formal analysis, Software, Writing – review & editing. **Roger Lew:** Conceptualization, Methodology, Software, Writing – review & editing. **Chinmay Deval:** Data curation, Visualization, Writing – review & editing. **Erin S. Brooks:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **William J. Elliot:** Conceptualization, Methodology, Resources, Investigation, Funding acquisition, Writing – review & editing. **Peter R. Robichaud:** Conceptualization, Resources, Investigation, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported with partial funds from the following sources: USDA AFRI-NIFA program, grant 2016-67020-25320/project accession 1009827, NSF award DMS-1520873, USDA Forest Service Rocky Mountain Research Station, Lake Tahoe Basin Management Unit, and Pacific Southwest Research Station, and Portland Water Bureau. We thank the Potlach Deltic Corporation for providing the observed streamflow and sediment data, the Portland Water Bureau for providing additional soil, landcover, and previous hydrologic studies on the Bull Run Watershed, and the Forest Service Pacific Southwest Research Station for providing pebble count observations from streams in Lake Tahoe. We are also grateful to the USDA Agricultural Research Service, National Soil Erosion Laboratory for ongoing support in the development of the WEPPcloud interface. The findings and conclusions in this article are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy.

Data sharing

All hydrologic simulations performed in this study and the model results are made available through the WEPPcloud online interface at https://wepp.cloud/weppcloud/joh/.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.127776.

References

Abatzoglou, J.T., Brown, T.J., 2012. A comparison of statistical downscaling methods suited for wildfire applications. Int. J. Climatol. 32 (5), 772–780. https://doi.org/10.1002/joc.2312.

Abatzoglou, J.T., 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol. 33 (1), 121–131. https://doi.org/10.1002/joc.3413.

Beck, H.E., van Dijk, A.I.J.M., Miralles, D.G., de Jeu, R.A.M., Bruijnzeel, L.A., McVicar, T.R., Schellekens, J., 2013. Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. Water Resour. Res. 49 (12), 7843–7863. https://doi.org/10.1002/2013WR013918.

Berenbrock, C., Tranmer, W.A., 2008. Simulation of flow, sediment transport, and sediment mobility of the lower Coeur d'Alene river. USGS Scientific Investigation Report, Idaho, p. 43. https://doi.org/10.3133/sir20085093.

Beven, K.J., 2001. Rainfall-Runoff Modelling: The Primer. Wiley, Chichester, UK.

Binkley, D., 2001. Patterns and processes of variation in nitrogen and phosphorus concentrations in forested streams. Tech. Bull. Natl. Counc. Air Stream Improv. 836, 143.

Boll, J., Brooks, E.S., Crabtree, B., Dun, S., Steenhuis, T.S., 2015. Variable source area hydrology modeling with the Water Erosion Prediction Project model. JAWRA 51, 330–342. https://doi.org/10.1111/1752-1688.12294.

Boyle, D.P., Gupta, H.V., Sorooshian, S., 2000. Toward improved calibration of hydrologic models: Combining the strengths of manual and automatic methods. Water Resour. Res. 36, 3663–3674. https://doi.org/10.1029/2000WR900207.

Brooks, E.S., Dobre, M., Elliot, W.J., Wu, J.Q., Boll, J., 2016. Watershed-scale evaluation of the Water Erosion Prediction Project (WEPP) model in the Lake Tahoe basin. J. Hydrol. 533, 389–402. https://doi.org/10.1016/j.jhydrol.2015.12.004.

Burns, W.J., Mickelson, K.A., Jones, C.B., Tilman, M.A., Coe, D.E., 2015. Bull Run Watershed. Surficial and bedrock engineering geology, landslide inventory and susceptibility, and surface hydrography of the Bull Run Watershed, Clackamas and Multnomah Counties, Oregon. Special paper 46. Oregon Department of Geology and Mineral Industries.

Cao, L., Elliot, W.J., Long, J.W., 2021. Spatial simulation of forest road effects on soil erosion after fire. Hydrol. Process. 35 (6), e14139 https://doi.org/10.1002/hyp.14139.

Coats, R., Lewis, J., Alvarez, N., Arneson, P., 2016. Temporal and spatial trends in nutrient and sediment loading to Lake Tahoe, California-Nevada, USA. J. Am. Water Resour. Assoc. 52, 1347–1365. https://doi.org/10.1111/1752-1688.12461.

Collins, B.M., Fry, D.L., Lydersen, J.M., Everett, R., Stephens, S.L., 2017. Impacts of different land management histories on forest change. Ecol. Appl. 27, 2475–2486. https://doi.org/10.1002/eap.1622.

Dai, A., 2008. Temperature and pressure dependence of the rain-snow phase transition over land and ocean. Geophys. Res. Lett. 35, L12802 https://doi.org/10.1029/2008GL033295.

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., Pasteris, P.A., 2008. Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. Int. J. Climatol. 28, 2031–2064. https://doi.org/10.1002/joc.1688.

Deval, C., Brooks, E.S., Gravelle, J.A., Link, T.E., Dobre, M., Elliot, W.J., 2021. Long-term response in nutrient load from commercial forest management operations in a mountainous watershed. For. Ecol. Manage. 494, 119312 https://doi.org/10.1016/j.foreco.2021.119312.

Dewitz, J., 2019. National Land Cover Database (NLCD). In: 2016 Products: U.S. Geological Survey data release. https://doi.org/10.5066/P96HHBIE.

Doherty, J., 2005. PEST model independent parameter estimation user manual. 5th ed. Retrieved from: http://www.pesthomepage.org/Downloads.php.

Dun, S., Wu, J.Q., Elliot, W.J., Robichaud, P.R., Flanagan, D.C., Frankenberger, J.R., Brown, R.E., Xu, A.C., 2009. Adapting the Water Erosion Prediction Project (WEPP) model for forest applications. J. Hydrol. 366 (1–4), 46–54. https://doi.org/10.1016/j.jhydrol.2008.12.019.

Elliot, W.J., Brooks, E., Traeumer, D., Dobre, M., 2015. Extending WEPP technology to predict fine sediment and phosphorus delivery from forested hillslopes, Presented at the SEDHYD 2015 Interagency Conference. 19–23 April 2015, Reno, NV, 12 pp. https://www.fs.usda.gov/treesearch/pubs/49573.

Elliot, W.J., Hall, D.E., 1997. Water Erosion Prediction Project (WEPP) Forest Applications. General Technical Report INT-GTR-365. Ogden, UT: U.S. Dept. of Agriculture Forest Service, Intermountain Research Station. 17 p. Retrieved from https://forest.moscowfsl.wsu.edu/engr/library/Elliot/Elliot1997f/1997f.pdf.

Elliot, W.J., 2004. WEPP Internet interfaces for forest erosion prediction. J. American Water Res. Assoc. 40 (2), 299–309.

Elliot, W.J., 2013. Erosion processes and prediction with WEPP technology in forests in the northwestern U.S. Trans. ASABE 56, 563–579.

Elliot, W.J., Robichaud, P.R., 2010. In: Handbook of Erosion Modelling. Wiley, pp. 313–323.

Flanagan, D.C., Livingston, S.J., 1995. WEPP User Summary. NSERL Report #11, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN.

Flanagan, D.C., Nearing, M.A., 1995. Water Erosion Prediction Project hillslope profile and watershed model documentation. NSERL Report #10, USDA-ARS National Soil Erosion. Research Laboratory, West Lafayette, IN.

Flanagan, D.C., Gilley, J.E., Franti, T.G., 2007. Water Erosion Prediction Project (WEPP): development history, model capabilities, and future enhancements. Trans. ASABE. 50 (5), 1603–1612. https://doi.org/10.13031/2013.23968.

Flanagan, D.C., Frankenberger, J.R., Ascough II, J.C., 2012. WEPP: Model use, calibration and validation. Trans. ASABE. 55 (4), 1463–1477. https://doi.org/10.13031/2013.42254.

Frankenberger, J., 2021. CLIGEN v.5.3.2. https://github.com/rogerlew/jimf-cligen532/tree/2021.06.04 doi: 10.5281/zenodo.4902238.

Gao, X., Chen, N., Yu, D., Wu, Y., Huang, B., 2018. Hydrological controls on nitrogen (ammonium versus nitrate) fluxes from river to coast in a subtropical region: Observation and modeling. J. Environ. Manage. 213, 382–391. https://doi.org/10.1016/j.jenvman.2018.02.051.

Garbrecht, J., Martz, L.W., 1997. TOPAZ: An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation, and subcatchment parameterization: Overview. ARS-NAWQL 95-1. USDA-ARS National Agricultural Water Quality Laboratory. Durant, OK.

Gavigan, T., 2007. Total maximum daily load for bedded sediment Blackwood Creek, Placer County. Final Staff Report. South Lake Tahoe, CA: California Regional Water Quality Control Board. https://www.waterboards.ca.gov/lahontan/water_issues/programs/tmdl/blackwood/docs/blackwood_tmdl_final.pdf.

Graham, R.T., Jain, T.B., Matthews, S., 2010. Fuel management in forests of the Inland West, Chapter 3. in: Elliot, W.J., Miller, I.S., Audin, L. (Eds.), Cumulative watershed effects of fuel management in the western United States. USDA Forest Service RMRS. Gen. Tech. Rep. RMRS-GTR-231. Fort Collins, OK. pp. 19−68.

Grant, G.E., Lewis, S.L., Swanson, F.J., Cissel, J.H., McDonnell, J.J., 2008. Effects of forest practices on peak flows and consequent channel response: A state-of-science report for Western Oregon and Washington. USDA, Pacific Northwest Research Station, General Technical Report PNW-GTR-760. Portland, OR.

Gravelle, J.A., Ice, G., Link, T.E., Cook, D.L., 2009. Nutrient concentration dynamics in an inland Pacific Northwest watershed before and after timber harvest. Forest Ecol. and Manag. 257, 1663–1675. https://doi.org/10.1016/j.foreco.2009.01.017.

Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. J. Hydrol. 377, 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003.

Hatch, L.K., Reuter, J.E., Goldman, C.R., 2001. Stream phosphorus transport in the Lake Tahoe basin, 1989–1996. Environ. Monit. Assess. 6 (9), 63–83. https://doi.org/10.1023/a:1010752628576.

Heron, T., Strawn, D.G., Dobre, M., Cade-Menun, B.J., Deval, C., Brooks, E.S., Piaskowski, J., Gasch, C., Crump, A., 2021. Soil phosphorus speciation and availability in meadows and forests in alpine lake watersheds with different parent material. Frontiers in Forests and Global Change. 3, 604200 https://doi.org/10.3389/ffgc.2020.604200.

Higuera, P.E., Abatzoglou, J.T., 2021. Record-setting climate enabled the extraordinary 2020 fire season in the western United States. Glob. Chang. Biol. 27, 1–2. https://doi.org/10.1111/gcb.15388.

Hubbart, J.A., Link, T.A., Gravelle, J.A., Elliot, W.J., 2007. Timber harvest impacts on water yield in the continental/maritime hydroclimatic region of the United States. For. Sci. 53, 169–180.

Hyne, J.N., Chelminxki, P., Court, J.E., Gorsline, D.S., Goldman, C.R., 1972. Quaternary history of Lake Tahoe. California-Nevada. GSA Bulletin 83 (5), 1435–1448. https://doi.org/10.1130/0016-7606(1972)83[1435:QHOLTC]2.0.CO;2.

Ice, G., Binkley, D., 2003. Forest streamwater concentrations of nitrogen and phosphorus: a comparison with EPA's proposed water quality criteria. J. For. 101 (1), 21–28.

Karwan, D.L., Gravelle, J.A., Hubbart, J.A., 2007. Effects of timber harvest on suspended sediment loads in Mica Creek. Idaho. For. Sci. 53 (2), 181–188.

Kattelmann, R., 1997. Flooding from rain-on-snow events in the Sierra Nevada. In: Leavesley, G.H., Lins, H.F., Nobilis, F., Randolph, S.P., Schneider, V.R., Van de Ven, F.H.M. (Eds.), Destructive Water: Water-Caused Natural Disasters, Their Abatement and Control. IAHS Publication 239, Wallingford, Oxfordshire, UK, pp. 59–65.

Kaye, J.P., Hart, S.C., Fulé, P.Z., Covington, W.W., Moore, M.M., Kaye, M.W., 2005. Initial carbon, nitrogen, and phosphorus fluxes following ponderosa pine restoration treatments. Ecol. Appl. 15, 1581–1593. https://doi.org/10.1890/04-0868.

Kolden, C.A., 2019. We're not doing enough prescribed fire in the western United States to mitigate wildfire risk. Fire 2, 1–10. https://doi.org/10.3390/fire2020030.

Krofcheck, D.J., Hurteau, M.D., Scheller, R.M., Loudermilk, E.L., 2018. Prioritizing forest fuels treatments based on the probability of high-severity fire restores adaptive capacity in Sierran forests. Glob. Chang. Biol. 24, 729–737. https://doi.org/10.1111/gcb.13913.

Lane, P.N.J., Sheridan, G.J., Noske, P.J., Sherwin, C.B., 2008. Phosphorus and nitrogen exports from SE Australian forests following wildfire. J. Hydrol. 361, 186–198. https://doi.org/10.1016/j.jhydrol.2008.07.041.

Lew, R., 2021. wepppy-win-bootstrap. https://github.com/rogerlew/wepppy-win-bootstrap doi:10.5281/zenodo.4902236.

Lew, R., Dobre, M., Srivastava, A., Brooks, E.S., Elliot, W.J., Robichuad, P.R., Flanagan, D.C., 2022. WEPPcloud: An online watershed-scale hydrologic modeling

tool. Part I. Model description. J. Hydol. 608, 15 pp. https://doi.org/10.1016/j.jhydrol.2022.127603.
Marks, D., Link, T., Winstral, A., Garen, D., 2001. Simulating snowmelt processes during rain-on-snow over a semi-arid mountain basin. Ann. Glaciol. 32, 195–202.
Martin, C.W., Harr, R.D., 1989. Logging of mature Douglas-fir in western Oregon has little effect on nutrient output budgets. Can. J. For. Res. 19, 35–43. https://doi.org/10.1139/x89-005.
McCabe, G.J., Clark, M.P., Hay, L.E., 2007. Rain-on-snow events in the western United States. Bull. Am. Meteorol. Soc. 88, 319–328. https://doi.org/10.1175/BAMS-88-3-319.
Miller, M.E., Billmire, M., Elliot, W., Robichaud, P., Miller, S., 2019. NASA RRED user manual for running QWEPP. Michigan Technological Research Institute, Ann Arbor, MI http://rred.mtri.org/baer/static/RRED_user_manual_for_QGIS.pdf.
Miller, M.E., MacDonald, L.H., Robichaud, P.R., Elliot, W.J., 2011. Predicting post-fire hillslope erosion in forest lands of the western United States. Intl. J. Wildland Fire, 20(8), 982–999.Miller, W.W., Johnson, D.W., Denton, C., Verburg, P.S.J., Dana, G.L., Walker, R.F., 2005. Inconspicuous nutrient laden surface runoff from mature forest Sierran watersheds. Water Air Soil Pollut. 163, 3–17.
Miller, W.W., Johnson, D.W., Karam, S.L., Walker, R.F., Weisberg, P.J., 2010. A synthesis of Sierran forest biomass management studies and potential effects on water quality. Forests 1, 131–153. https://doi.org/10.3390/f1030131.
Miller, W.W., Johnson, D.W., Denton, C., Verburg, P.S.J., Dana, G.L., Walker, R.F., 2005. Inconspicuous nutrient laden surface runoff from mature forest Sierran watersheds. Water. Air. Soil Pollut. 163, 3–17.
Mitchell, K.E., Lohmann, D., Houser, P.R., Wood, E.F., Schaake, J.C., Robock, A., Cosgrove, B.A., Sheffield, J., Duan, Q., Luo, L., Higgins, R.W., Pinker, R.T., Tarpley, J.D., Lettenmaier, D.P., Marshall, C.H., Entin, J.K., Pan, M., Shi, W., Koren, V., Bailey, A.A., 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. J. Geo. Res.: Atmos. 109(7), D07S90, 1–32. https://doi.org/10.1029/2003jd003823.
Moffet, C.A., Pierson, F.B., Robichaud, P.R., Spaeth, K.E., Hardegree, S.P., 2007. Modeling soil erosion on steep sagebrush rangeland before and after prescribed fire. Catena 71 (2), 218–228.
Murphy, J.D., Johnson, D.W., Miller, W.W., Walker, R.F., Carroll, E.F., Blank, R.R., 2006. Wildfire effects on soil nutrients and leaching in a Tahoe basin watershed. J. Environ. Qual. 35, 479–489. https://doi.org/10.2134/jeq2005.0144.
Nash, J., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. J. Hydrol. 10, 282–290.
Nearing, M.A., Deer-Ascough, L., Laflen, J.M., 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. Trans. ASAE 33 (3), 839–849.
Neary, D.G., Gottfried, G.J., Ffolliott, P.F., 2003. Post-wildfire watershed flood responses. In: Paper 1B7. Second International Fire Ecology and Fire Management Congress. Orlando, FL, pp. 16–20.
Nicks, A.D., Lane, L.J., Gander, G.A., 1995. Chapter 2. Weather generator. in: Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation, NSERL Report. In: Flanagan, D.C., Nearing, M.A. (Eds.), USDA Agricultural Research Service (ARS), No. 10. National Soil Erosion Research Laboratory, West Lafayette, IN.
Niemeyer, R.J., Bladon, K.D., Woodsmith, R.D., 2020. Long-term hydrologic recovery after wildfire and post-fire forest management in the interior Pacific Northwest. Hydrol. Process. 34, 1182–1197. https://doi.org/10.1002/hyp.13665.
Nolan, K.M., Hill, B.R., 1991. Suspended-sediment budgets for four drainage basins tributary to Lake Tahoe, California and Nevada, 1984–87. USGS Water-Resources Investig. Rep. 91–4054, 45.
Norman, S., Oehrli, C., Tolley, T., Brill, N., 2014. Blackwood Creek Reach 6 Restoration (Phase IIIA) Effectiveness Monitoring Results, UDSA Forest Service LTBMU.
Oehrli, C. Blackwood Creek Stream Channel Restoration Monitoring. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd498697.pdf.
Ohmann, J.L., Gregory, M.J., 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon. USA. Can. J. For. Res. 32, 725–741. https://doi.org/10.1139/X02-011.
Peterson, C.D., Hamilton, D.M., Burns, S., 1995. Historic sedimentation rates in Bull Run reservoir No. 1: Implications for pre- and post-logging sediment yields, and for catastrophic floods in the Bull Run Watershed, Oregon. Final Report submitted to City of Portland, Bureau of Water Works. Portland State University, Portland, OR.
Piatek, K.B., Allen, H.L., 2001. Are forest floors in mid-rotation stands of loblolly pin (*Pinus taeda*) a sink for nitrogen and phosphorus? Canadian J. of For. Res. July 2001. doi: 10.1139/x01-049.
PWB (Portland Water Bureau), 2003. Source Water Assessment Report. Bull Run Water Supply. City of Portland Water Bureau. Portland, OR.
Reybold, W.U., TeSelle, G.W., 1989. Soil geographic data bases. J. Soil Water Conserv. 44 (1), 28–29.
Rinella, F.A., 1987. Water quality variations in the Bull Run Watershed, Oregon, under 1978 to 1983 management conditions. USGS Water Resour. Invest. Report 87–4128, 61.
Robichaud, P.R., Elliot, W.J., Pierson, F.B., Hall, D.E., Moffet, C.A., 2007. Predicting post-fire erosion and mitigation effectiveness with a web-based probabilistic erosion model. Catena 71 (2), 229–241. https://doi.org/10.1016/j.catena.2007.03.003.
Robichaud, P.R., Wagenbrenner, J.W., Brown, R.E., 2010. Rill erosion in natural and disturbed forests: 1. Measurements. Water Resour. Res. 46, W10506. https://doi.org/10.1029/2009WR008314.
Robichaud, P.R., Elliot, W.J., Lewis, S.A., Miller, M.E., 2016a. Validation of a probabilistic post-fire erosion model. Int. J. Wildland Fire 2016 (25), 337–350. https://doi.org/10.1071/WF14171.
Robichaud, P.R., Wagenbrenner, J.W., Pierson, F.B., Spaeth, K.E., Ashmun, L.E., Moffet, C.A., 2016b. Infiltration and interrill erosion rates after a wildfire in western Montana, USA. Catena 142, 77–88. https://doi.org/10.1016/j.catena.2016.01.027.
Runkel, R., Crawford, C., Cohn, T.A., 2004. Load Estimator (LOADEST): A FORTRAN Program for estimating constituent loads in streams and rivers: USGS Techniques and Methods, 4-A5. p. 75. http://pubs.usgs.gov/ tm/2005/tm4A5/.
Sánchez-Murillo, R., Brooks, E.S., Elliot, W.J., Gazel, E., Boll, J., 2015. Baseflow recession analysis in the inland Pacific Northwest of the United States. Hydrogeol. J. 23, 287–303.
Santín, C., Otero, X.L., Doerr, S.H., Chafer, C.J., 2018. Impact of a moderate/high-severity prescribed eucalypt forest fire on soil phosphorous stocks and partitioning. Sci. Total Environ. 621, 1103–1114.
Schwartz, G.E., Alexander, R.B., 1995. State Soil Geographic (STATSGO) database for the Conterminous United States. USGS Open-File Report 95–449.
Simon, A., Langendoen, E., Bingner, R., Wells, R., Heins, A., Jokay, N., Jaramillo, I., 2004. Lake Tahoe Basin framework implementation study: sediment loadings and channel erosion. USDA-ARS National Sedimentation Laboratory Research. Report. No. 39, 377.
Simon, A., Pollen-Bankhead, N., Mahacek, V., Langendoen, E., 2009. Quantifying reductions of mass-failure frequency and sediment loadings from streambanks using toe protection and other means: Lake Tahoe, United States J. Am. Water Resour. As. 45 (1), 170-186. doi: 10.1111 / j.1752-1688.2008.00268.x.
Smith, H.G., Sheridan, G.J., Lane, P.N.J., Nyman, P., Haydon, S., 2011. Wildfire effects on water quality in forest catchments: A review with implications for water supply. J. Hydrol. 396, 170–192. https://doi.org/10.1016/j.jhydrol.2010.10.043.
Snyder, D.T., Brownwell, D.L., 1996. Hydrologic setting and preliminary estimates of hydrologic components for Bull Run Lake drainage basin. Multnomah and Clackamas counties, Oregon. USGS USGS Water Resour. Invest. Report 96–4064, 47.
Srivastava, A., Brooks, E.S., Dobre, M., Elliot, W.J., Link, T.E., 2020. Modeling forest management effects on water and sediment yield from nested, paired watersheds in the interior Pacific Northwest. USA using WEPP. Sci. Total Environ. 701, 134877.
Srivastava, A., Dobre, M., Wu, J.Q., Elliot, W.J., Bruner, E.A., Dun, S., Brooks, E.S., Miller, I.S., 2013. Modifying WEPP to improve streamflow simulation in a Pacific Northwest watershed. Trans. ASABE 56, 603–611. https://elibrary.asabe.org/abstract.asp?aid=42691.
Srivastava, A., Flanagan, D.C., Frankenberger, J.R., Engel, B.A., 2019. Updated climate database and impacts on WEPP model predictions. J. Soil Water Conserv. 74, 334–349. https://doi.org/10.2489/jswc.74.4.334.
Srivastava, A., Wu, J.Q., Elliot, W.J., Brooks, E.S., Flanagan, D.C., 2017. Modeling streamflow in a snow-dominated forest watershed using the water erosion prediction project (WEPP) model. Trans. ASABE 60, 1171–1187. doi:10.13031/trans.12035.
Srivastava, A., Wu, J.Q., Elliot, W.J., Brooks, E.S.,Flanagan, D.C., 2018. A simulation study to estimate effects of wildfire and forest management on hydrology and sediment in a forested watershed, Northwestern U.S. Trans. ASABE 61(5), 1579–1601. https://doi.org/10.13031/trans.12326.
Tetra Tech Inc, 2007. Watershed hydrologic modeling and sediment and nutrient loading estimation for the Lake Tahoe total maximum daily load. Final Modeling Report. Lahontan Reg, Water Quality Control Board, South Lake Tahoe, CA.
Trimble, D.E., 1963. Geology of Portland, Oregon and adjacent areas. Bulletin 1119, U.S. Geological Survey, Washington, DC, pp. 119.
Thornton, M.M., Thornton, P.E., Wei, Y., Mayer, B.W., Cook, R.B., Vose, R.S., 2016. Daymet: monthly climate summaries on a 1-km grid for North America, Version 3. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1345.
USACE (U.S. Army Corps of Engineers), 1956. Snow hydrology: Summary report of the snow investigations. North Pacific Division Portland, Oregon, pp. 141–189.
USDA-FS (U.S. Department of Agriculture, Forest Service), 1997. Bull Run watershed analysis. Mt, Hood National Forest, Sandy Oregon.
Wagenbrenner, J.W., Robichaud, P.R., Elliot, W.J., 2010. Rill erosion in natural and disturbed forests: 2. Modeling approaches. Water Resour. Res. 46, W10507. https://doi.org/10.1029/2009WR008315.
Weisberg, P.J., 2004. Importance of non-stand-replacing fire for development of forest structure in the Pacific Northwest. USA. For. Sci. 50, 245–258.
Yapo, P., Gupta, H.V., Sorooshian, S., 1996. Calibration of conceptual rainfall-runoff models: sensitivity to calibration data. J. Hydrol. 181, 23–48.
Zambrano-Bigiarini, M., 2020. hydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series. R package Version v0.4-0. doi: 10.5281/zenodo.839854. https://github.com/hzambran/hydroGOF.