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WEPPcloud: An online watershed-scale hydrologic modeling tool. Part I. Model description

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ABSTRACT

We developed a new online interface for the Water Erosion Prediction Project (WEPP) model (WEPPcloud) with a framework that allows the incorporation and development of several other models and applications to make hydrologic models more accessible to land managers and facilitate the decision-making process. All inputs to WEPP, such as topography, soils, land use, and weather, are automatically created from publicly available online international databases and converted into input formats readable by the model. The WEPPcloud interface can be applied to forested, cropland, and rangeland conditions, but it is specialized for undisturbed forest conditions, post-wildfire, and pre- and post-wildfire management scenarios such as forest thinning, prescribed fire, or post-wildfire mulching. Users only need a computer or device with a web browser and an internet connection to perform advanced hydrologic simulations. All the model runs are stored remotely on WEPPcloud, which can be accessed by the users at any given time. This modeling tool is presented in two parts: Part I: Model description and parameterization, and Part II: Model performance assessment and applications to forest management and wildfires.

1. Introduction

One of the critical ecosystem services provided by forests is clean water, which from undisturbed forests is of high quality. However, forest disturbances such as wildfire, timber harvest, and fuel reduction often result in increased upland and channel erosion, leading to a deterioration in water quality (Elliot, 2013). Climate change is also impacting forest hydrologic processes, and the impacts of climate change on water quality are not clearly understood. Warmer climates will likely result in increased fire frequency and associated erosion, frequent high-intensity rainfall events, and infrequent low-intensity snowmelt (Elliot et al., 2016a). Hydrologic models are commonly used to understand the impacts of forest disturbances and climate change on water quality (Borrelli, 2021; Elliot, 2013; Elliot et al., 2016b; Sidman et al., 2015). However, forest watershed managers often lack the skills or the time to apply complex models (Elliot, 2004; Robichaud and Ashmun, 2013).

The Water Erosion Prediction Project (WEPP) model is a process-based hydrology and erosion model used by many researchers and land managers to predict surface runoff and soil erosion from croplands, rangelands, and forests (Laflen et al., 1997). The WEPP model simulates surface hydrology and hydraulics, subsurface hydrology, vegetation growth, residue accumulation and decay, and sediment detachment and transport along each hillslope and channel segment using four major input files: climate, slope, soil, and vegetation. WEPP maintains a continuous daily water balance of surface runoff, subsurface lateral flow, soil evaporation, plant transpiration, residue evaporation, total soil–water, deep percolation, snow accumulation and melt, and frozen soils.

The WEPP model has been in use for several decades and there exists a plethora of publications describing the model development and applicability to a wide range of management conditions for both croplands and forests (Brooks et al., 2016; Covert et al., 2005; Dun et al., 2009; Elliot, 2013; Elliot et al., 2015; Flanagan and Livingston, 1995; Flanagan and Nearing, 1995; Laflen et al., 1997; Miller et al., 2011;

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Miller et al., 2019; Robichaud et al., 2007; Srivastava et al., 2013, 2017, 2018, 2020; Wang et al., 2010; Zhang et al., 2009). Detailed descriptions of each of the erosion processes simulated by WEPP are provided in Flanagan and Nearing (1995). Lastly, WEPP can simulate individual hillslope profiles, as well as small to large watersheds (Flanagan and Livingston, 1995).

Several interfaces have been developed for the WEPP hillslope version to address specific forest and rangeland disturbances. The most widely used WEPP interfaces for forestry applications are those developed by the USDA Forest Service, FSWEPP (Elliot, 2004, 2013; Elliot et al., 2015; Flanagan et al., 2013; Frankenberger et al., 2011; Robichaud et al., 2007). Managers currently apply these targeted interfaces to predict erosion and sediment delivery and make management decisions based on probability risk analysis. Specifically, WEPP:Road allows users to simulate roads and buffers, ERMiT (Erosion Risk Management Tool) to simulate post-wildfire erosion with and without erosion mitigation treatments in forest, rangeland, and chaparral landscapes, Disturbed WEPP to simulate disturbances in forestlands and rangelands, and WEPP:FuMe (Fuel Management Erosion Analysis) to simulate fuel management practices including thinning, prescribed burns with or without road networks (follow https://forest.moscowfsl.wsu.edu/fswepp). These interfaces are simplistic, requiring users to specify hillslope topography, and select the soil texture, land cover and climate from an abbreviated list of options. The soil and land cover databases for the FSWEPP interfaces are based on US field observations. Since their initial development, these hillslope tools have completed more than 1.3 million runs across the US, with additional runs from Europe, Australia, and anywhere else where users could describe the local climate.

Concomitantly with these efforts was the development of several interfaces for the WEPP model such as GeoWEPP (Geo-spatial interface for WEPP), QWEPP (QGIS Interface for WEPP), and WEPP Online GIS. GeoWEPP, is an ArcGIS-dependent tool designed to automatically discretize a watershed into multiple hillslopes and channel segments, and then assign a specific slope shape, soil, weather, and landcover/management file for each hillslope, as well as for the entire watershed (Renschler, 2003; Flanagan et al., 2013). QWEPP was developed to run on the open-source QGIS platform instead of ArcMap (Miller et al., 2019) and is customized to use landscape soil and cover layers from the Rapid Response Erosion Database (RRED; Miller et al., 2016). RRED provides WEPP-formatted soil files, in the WEPP 1997 format (version 97.3) merged with the SSURGO (Soil Survey Geographic Database) or STATSGO2 (State Soil Geographic Database) (Reybold and TeSelle, 1989) soil data and the USGS land cover layer or post-wildfire soil burn severity map. QWEPP can be applied to both burned and unburned conditions using WEPP-formatted soil and management files.

The WEPP Online GIS tool was developed at the USDA-ARS National Soil Erosion Research Laboratory (NSERL) as an online GIS application for running the WEPP Watershed model (Frankenberger et al., 2011). The application uses OpenLayers for mapping and Hypertext Preprocessor (PHP) for file management (https://milford.nserl.purdue.edu/ol/wepp/index.php). This interface accesses Google Maps for spatial orientation, the online NRCS SSURGO soils database (Reybold and TeSelle, 1989), and 2011 USGS National Land Cover Database (NLCD) Maps (Homer et al., 2015) to facilitate and automate WEPP model setups and runs. To predict runoff and erosion, users only need a computer or tablet connected to the internet. These tools were mainly developed for small agricultural field-sized watersheds and are currently running with a WEPP version that does not include baseflow, an important component of the streamflow hydrographs in larger forested watersheds (Elliot et al., 2016a).

Web-based applications are becoming increasingly common to support information, commerce, and services. This has also been the case for watershed managers with the development of the SSURGO soils database, and the USGS land cover and topographic databases providing spatial information for watershed modelers. Web-based models and hydrologic modeling tools are now available for users that have limited modeling capabilities and recently several tools have emerged for acquiring and sharing data (HydroShare/CUAHSI, https://www.hydroshare.org: WikiWatersheds, https://wikiwatershed.org; StreamStats, https://streamstats.usgs.gov/ss/) that help land managers delineate watersheds and gather useful information from freely available databases. Watershed managers are now familiar with accessing spatial data online that are readily available. Web-based tools have been developed that utilize machine-to-machine translation of data with limited human intervention, eliminating many of the difficulties involved in applying standalone GIS watershed tools. These developments motivated us to build an enhanced online interface to the WEPP Watershed model to support forest watershed management.

In this paper, we present a new online interface for the WEPP model (WEPPcloud) and a framework (*wepppy*) that allows the incorporation and the development of several other hydrologic models and applications. Our goal was to make complex models more accessible to land managers to facilitate the decision-making process. WEPPcloud is complementary to the previously described WEPP tools, but it incorporates additional data sources (e.g. gridded climate national databases such as PRISM (Parameter-elevation Regressions on Independent Slopes Model, Daly et al., 2000, 2008), Daymet (Daily Surface Weather and Climatological Summaries, Thornton et al., 2016), and GridMET (Gridded Surface Meteorological, Abatzoglou, 2011)), algorithms (e.g. baseflow, pollutant, ash transport, hourly seepage computations to improve lateral flow, and computations of frost) and ability to alter input files (e.g. post-disturbance ground cover, channel properties, and saturated hydraulic conductivity of the restricting layer), which make the model more applicable to larger forested watersheds (300–10,000 ha) and accessible to novice users. WEPP modeling can be complex; however, from our experience, reasonable results can be obtained using default parameters (Dobre et al., 2022b). Additionally, WEPPcloud also provides enough flexibility to refine models with further parameterization. WEPPcloud is open-source and has a full open-source modular software stack (watershed delineation and processing of climates, soils, and land covers are done independently of WEPPcloud), which can be coupled with other hydrologic models and decision-support tools such as the Rangeland Hydrology and Erosion Model (Nearing et al., 2011).

The WEPPcloud modeling tool is presented in two parts: Part I: WEPPcloud system description (this paper), and Part II: WEPPcloud and WEPP performance assessment and applications to forest managements and wildfires (Dobre et al., 2022b). Part I of this manuscript presents the model platform description, data inputs and outputs, and modeled processes, while Part II presents modeling results of streamflow, sediment and phosphorus yield from 28 relatively undisturbed gauged forested watersheds in the states of California, Nevada, Oregon, Washington, and Idaho. Additionally, Part II of this manuscript demonstrates the applicability of the WEPPcloud interface as a decision-support tool to evaluate the effects of forest management and wildfires on water quality and quantity from ungauged watersheds.

2. WEPPcloud development and structure

2.1. Platform description

WEPPcloud (https://wepp.cloud/) is a web application implemented in the Python programming language (https://python.org) that uses Flask (https://flask.palletsprojects.com) to provide a web interface and web API (Application Programming Interface) for hydrologic models. The WEPPcloud interface is powered by *wepppy*, which is an open-source (BSD-3 License) scientific Python module for WEPP modeling (Lew, 2021) implemented specifically to support WEPPcloud. Unlike all other existing WEPP interfaces (GeoWEPP, WEPP Online GIS, and QWEPP) *wepppy* does not rely on TOPWEPP, a C++ application responsible for preparing input files for WEPP from TOPAZ (Topographic Parameterization; Garbrecht and Martz, 1997) and mapping output files (Flanagan et al., 2013). This functionality has been supplanted by *wepppy*, which greatly enhances the flexibility and error handling of the platform. A common problem with TOPWEPP is segmentation faults when model inputs are not properly formatted. The object-oriented *wepppy* codebase improves code re-use resulting in a codebase less than 1/10 that of the previous online interfaces with a reliance on procedural PHP scripts. Because of the modular architecture, *wepppy* can be used for the online development of other hydrologic models that rely on freely available environmental data, as shown by the inclusion of the Rangeland Hydrology and Erosion Model (RHEM, Nearing et al., 2011; Table 1) in the suite of WEPPcloud tools. *Wepppy* can also support batch processing of watersheds with simple Python scripts. The *wepppy* sub-modules can be used independently of WEPPcloud to work with geospatial datasets, prepare and run hydrologic models, and aggregate and analyze model results.

The components of *wepppy* can be described as belonging to five functional categories as described below (Fig. 1).

2.1.1. WEPPcloud interface Frontend

The WEPPcloud interface is served by a Python Flask app and has views and controls defined using *jinja* templates (HTML with templating). The WEPPcloud Frontend also includes JavaScript controllers for communicating with the Flask App. The web clients make use of Bootstrap (https://getbootstrap.com) for formatting, Leaflet.js (https://leafletjs.com) for maps, jQuery (https://jquery.com) for asynchronous communication and dynamic views, and d3.js (https://d3js.org) for charts (Fig. 1).

A notable feature of the frontend is the ability to support both SI (International System of Units) and English units. In the *jinja* templates, the values are “unitized” by specifying the value and their units. When the page is rendered in the browser, the HTML contains the value in a variety of units (e.g. kg, lb, and grams) with all but one hidden from view. Users can change their unit preferences and the correct value and units are displayed.

2.1.2. WEPPcloud interface backend

WEPPcloud uses a PostgreSQL database to manage user accounts and permissions with the assistance of Flask-Security. Individual WEPPcloud projects, however, function independently from any centralized relational databases allowing them to be migrated by simply moving the files. In fact, all users can export their projects in their entirety to conduct further analyses or make modifications and rerun WEPP on their own machines. In the cloud, projects are stored in a file directory structure and users can browse the files from a web-based file explorer. The independence is made possible by taking a “*NoDb*” approach to the organization, storage, and manipulation of project parameters and data, and is a key component to the flexibility provided by *wepppy*. The *wepppy.nodb* classes serialize project metadata in JSON (JavaScript Object Notation). The JSON files reside in the project folder and can be rapidly deserialized into Python class instances. In layman’s terms this provides a Pythonic interface for creating and manipulating WEPPcloud projects in the form of the *wepppy.nodb* classes. From a programmatic perspective, a user can simply assign values to object attributes, (e.g. $topaz.mcl = 5$) and behind the scenes those assignments are made persistent by writing to the JSON serialized representations of the class objects. This process is made robust by locking the JSON files to prevent more than one instance from making simultaneous changes. In contrast, the PHP-based online interface for WEPP relies on sessions for tracking model parameters. These parameters must be manually passed from page to page and no longer exist after the session expires.

When users interact with the WEPPcloud web interface, jQuery sends asynchronous requests to a Python Flask Service. The Flask service utilizes the *wepppy.nodb* classes to acquire data, transform data, create inputs, run models, analyze model outputs, and provide reports. Even for non-programmatically inclined users, this approach provides tremendous flexibility. By clicking through a series of web-based

Table 1
A suite of interfaces published on the WEPPcloud website (https://wepp.cloud/).

Interface	Description
(Un)Disturbed	The primary interface developed for running hydrologic and erosion simulations for both undisturbed and post-fire conditions. Other interfaces are available for legacy purposes. The (Un)Disturbed interface uses the SSURGO/STATSGO2 soil databases to create the WEPP soil inputs, (Reybold and TeSelle, 1989), and 2016 NLCD (Jin et al., 2019) to identify the land use for unburned conditions. For post-fire conditions, a user can upload a Soil Burn Severity (SBS) map (see Fig. 2; Parsons et al., 2010) to specify the burn severity as unburned, low, medium, or high for each hillslope and augment the soil and management parameters (Fig. 3). The soil and management files can also be customized by assigning treatments (e.g. thinning, prescribed fire) to hillslopes. For all conditions, soil and management files are procedurally generated and parameterized based on soil texture, landuse, and burn severity or treatment. This allows specific hillslopes to be burned or treated based on landuse. The parameterization enables meaningful comparisons between unburned, burned, and treated conditions.
WEPPcloud-PEP	This interface was the first WEPPcloud prototype for postfire simulations and has been replaced by the Un(Disturbed) WEPPcloud interface. It is currently available for legacy runs.
WATAR (Wildfire Ash Transport And Risk estimation tool).	The WEPPcloud Wildfire Ash Transport and Risk (WATAR) tool is used to estimate the delivery of ash following wildfire. Ash can be high in nutrients and heavy metals, and thus is of special interest for managers of municipal watersheds (Neris et al., 2021). The WATAR model links ash delivery to surface runoff events and gives an estimate of the probability of delivering a given ash amount the first year following a wildfire. Ash availability declines during the year so that runoff events occurring shortly after a wildfire will deliver large amounts of ash, whereas events occurring after a wind event, or several months after the wildfire will deliver much less ash.
RHEM (Rangeland Hydrology and Erosion Model)	RHEM is an interface for the ARS Rangeland Hydrology and Erosion Model (Nearing et al., 2011) and allows users to simulate surface runoff and soil erosion from rangelands at hillslope scales in the US. Foliar and ground covers are estimated from NLCD Shrubland 2016 data (Rigge et al., 2019; Young, 2017), where available, and soil textures are determined from SURGO/STATSGO2.
EU (Un)Disturbed for watersheds in the European Union	Interface with European databases. The managements are assigned based on European Soil Data Centre (ESDAC) landuses (https://esdac.jrc.ec.europa.eu/resource-type/datasets; Panagos et al., 2012). Soil files are built from ESDAC and EU-SoilHydroGrids (https://esdac.jrc.ec.europa.eu/content/3d-soil-hydraulic-database-europe-1-km-and-250-m-resolution; Tóth et al., 2017). The climates utilize an international CLIGEN database based on GHCN data. (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn; Fullhart et al., 2021).
AU (Un)Disturbed for watersheds in Australia	Interface with Australian databases. Managements are assigned based on landuse of Australia 2010–11 (https://www.awe.gov.au/abares/aclump/land-use/land-use-of-australia-2010-11). Soil files are built from the Australian Soil Resources Information System (ASRIS) soil database (https://www.asris.csiro.au). AU

(*continued on next page*)

Table 1 (*continued*)

Interface	Description
	climate station statistics are selected based on NOAA – Global Historical Climatology Network (GHCN) data (GHCN) monthly precipitation and temperature (http://www.auscover.org.au/datasets/australian-gridded-climate-data/). The climates utilize an international CLIGEN database based on GHCN data (Fullhart et al., 2021).
Site-Specific Interfaces	Site-specific interfaces have been built for the Lake Tahoe Basin and the municipal watershed of Seattle, WA. The municipality databases are similar to the (Un)Disturbed database, but the Lake Tahoe interface has a customized soil database. These interfaces also include completed WEPP runs for sub-watersheds within the basin so a manager can compare and contrast or download files of management scenarios without needing to do the sequence of WEPP runs.

controls, users can obtain a stack of rasters and other files with terrain, topographic analyses, soils, landuse, and climate without having to perform any actual programming.

2.1.3. *Webservices*

WEPPcloud acquires many datasets on-the-fly as users build projects. However, some datasets are stored on WEPPcloud servers and made available via *webservices*. A service called *wmesque* provides several raster layers like the 2016 USGS NED (National Elevation Dataset) as well as a SSURGO MUKEY (Mapunit Key) raster layer for geolocating soil parameters. The service allows for easily obtaining georeferenced raster stacks for areas of interest. The *wmesque* service is public-facing allowing acquisition via other means like a reflective object-oriented programming curl, a web-browser, and R software.

WEPPcloud can access many climate datasets and utilizing these with a stochastic weather generator, CLIGEN (CLImate GENerator, Nicks et al., 1995), requires obtaining monthly normals for a set of locations. A *metquery* webservice provides monthly climate normals (daily maximum temperature, daily minimum temperature, precipitation) for several meteorological datasets.

Other webservices are implemented to allow the WEPPcloud Frontend to query elevation data (*elevationquery*) as well as to transform coordinates from UTM to WGS (*geo_transformer*). Lastly, webservices are implemented to build WEPP soil files using SSURGO/STATSGO2 datasets (*weppsoilbuilder*) and to build CLIGEN climate files (*cligen*).

2.1.4. *Data clients and data handlers (wepppy core modules)*

As anyone who has worked with GIS Datasets can attest, they can come in a variety of different formats with a plethora of different options with regards to data types, georeferencing, and units. The *wepppy* core modules provide Pythonic object-oriented classes for reading, writing, and manipulating data. The intent of these is to provide higher-level abstractions for working with the data and encapsulating the intricacies of dealing with different data formats, unit conversions, and geo-referencing. They are implemented such that they can be used independently of the *wepppy.nodb* classes.

2.1.5. *Model command line interface adapters*

We refer to WEPPcloud as an online "interface" for WEPP because it allows users to run the WEPP model and other models like TOPAZ (Topographic Parameterization Program), TauDEM (Terrain Analysis Using Digital Elevation Models), CLIGEN, and RHEM without having to install or type commands into a command prompt. The command-line interface (CLI) wrappers use Python's *subprocess.Popen* to run these command-line applications. The wrappers read the unix standard output (stdout) and error (stderr) data streams from the models to provide error tracing when the models crash. The previous WEPP interfaces do not have this ability, which makes troubleshooting much more difficult.

2.2. *Interfaces*

The WEPPcloud site is hosted on the Research Computing and Data Services servers at University of Idaho (https://hpc.uidaho.edu). WEPPcloud is available to users worldwide and supports locales in the US, Europe, and Australia. Users can create projects anonymously or create a WEPPcloud account and private projects. Users with accounts can be granted access to advanced "PowerUser" features or to find and collaborate on model runs with other users. By default, runs can be easily shared via the unique URL (Uniform Resource Locator or web address/link) that is assigned to each project.

Perhaps the most important feature of WEPPcloud is its ability to automate the acquisition and processing of data for running WEPP. All

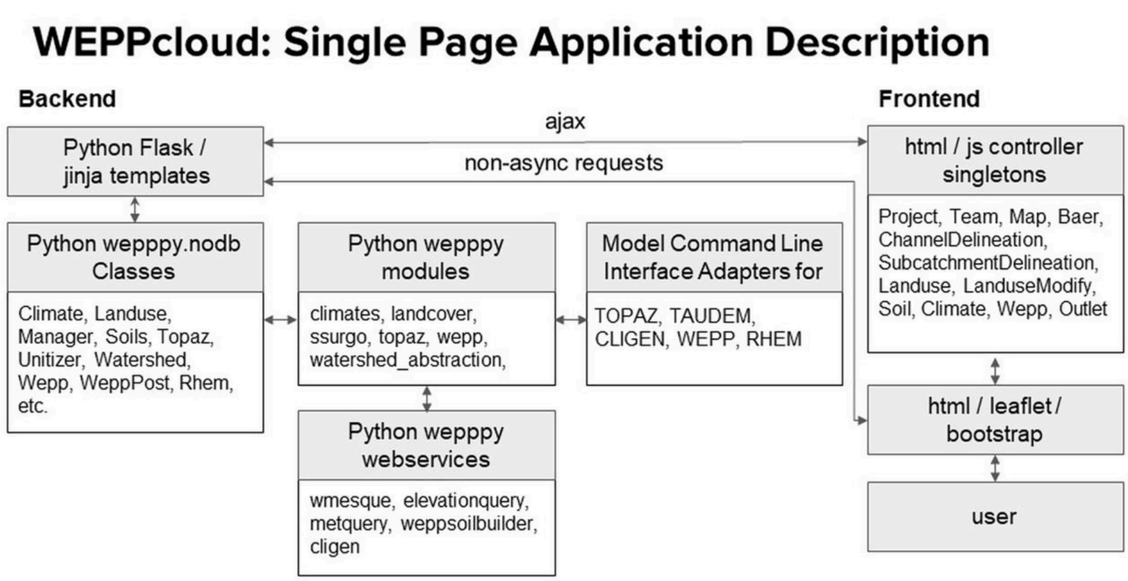


Fig. 1. Schematic representation of the organization of modules and classes within the *wepppy* Python package for the WEPPcloud application (capitalization of classes, modules, webservices, and singletons represents naming in the codebase to follow Python coding standards).

the data processing for the WEPP model is done within the WEPPcloud interface, to allow users to create and store WEPP model runs. With our primary (Un)Disturbed interface, users first select an area of interest or upload a soil burn severity (SBS) map, which will automatically zoom in to the area of interest. Then a channel network is built and displayed on the map. Users can then select an outlet location and *wepppy* automates the delineation of hillslopes by running Digital Elevation Models (10- or 30-m DEMs) through the TOPAZ or TauDEM tools to create a series of hillslopes and channels for the desired watershed based on the watershed outlet selected by the user.

Further, *wepppy* accesses online or uploaded landuse maps and online databases for soils and climates. Information from these databases is used to automatically create WEPP-specific input files by assigning respective soil, management, and climate files to each hillslope and channel segment. The CLIGEN model builds a daily stochastic climate from weather station statistics. *Wepppy* also identifies the land cover and soil layers, and then builds the WEPP management and soil files for each hillslope and channel segment. Users can then use the interfaces to run WEPP to simulate streamflow, peak runoff, soil erosion, and sediment and phosphorus delivery from hillslopes, channels, and watersheds for various management conditions (undisturbed/current conditions or disturbed for pre- and post-fire management operations).

To simulate post-wildfire conditions, users can upload a SBS map of four burn classes: unburned, low, moderate, and high severity. These maps are created by the US Forest Service—Geospatial Technology and Applications Center (GTAC) and Burned Area Emergency Response (BAER) Imagery Support. Initially, GTAC creates dNBR (delta NBR) maps from pre- and post-fire satellite NBR (Normalized Burn Ratio) maps (Parsons et al. 2010; Miller et al. 2016), which are further converted to BARC256 (Burned Area Reflectance Classification of 256 unique classes) or BARC4 (4 classes) maps. The SBS maps are simply BARC4 maps that have been field-validated. Users can download BARC256 or SBS maps from a central National database (https://burnseverity.cr.usgs.gov/baer/baer-imagery-support-data-download). With 256-class maps, users specify break points to obtain four soil burn severity classes (see Fig. 2). Alternatively, where SBS maps are not available, users can download BARC4 maps from the Monitoring Trends in Burn Severity (https://www.mtbs.gov/) website, which hosts post-wildfire maps for the continental US, Alaska, Hawaii, and Puerto Rico from 1984 till present. When using BARC256 or BARC4 maps, users should be cautious as these reflect conditions of vegetation burn severity and not soil burn severity. Only the SBS maps are field validated and should be used for post-fire erosion management.

Several model interfaces exist on WEPPcloud (Table 1). These interfaces have been developed for specific geographic regions (i.e., United States, Australia, European Union) or site-specific regions in the US (i.e., Lake Tahoe Basin, California/Nevada; Seattle Public Utilities, Washington). The interfaces utilize configuration files to specify what soil, climate, and landcover databases are used for specific locales (Table 1). The WEPP model runs in the backend of all these interfaces (except RHEM) based on the input data created by *wepppy*.

2.3. *Other tools and utilities*

2.3.1. *Debris flow*

The risk of debris flows occurring, and the amount of sediment delivered from those debris flows is estimated by the Cannon et al. (2010) method based on burn severity, soil properties, topography, and weather (not shown). The method is intended for general guidance only, as the USGS currently carries out debris flow analyses for most large US wildfires using an advanced methodology (Staley et al., 2016, 2018).

2.3.2. *Combined watershed viewer*

The combined watershed viewer allows users to visualize the runoff and erosion predictions across multiple watershed runs (not shown). The Combined Watershed Viewer has a companion utility for creating hyperlinks to visualize a set of runs that can be easily shared.

2.3.3. *Export Projects/ArcMap*

The model runs use a file-based project structure in conjunction with Python model controllers serialized to JSON files. The projects can be exported from the interface as zip archives or downloaded using *wget*. WEPPcloud also has functionality for creating ESRI shapefiles containing sub-catchments with model output attributes. The shapefiles can be opened in GIS to merge multiple runs, develop GIS storyboards, or prepare maps for presentations, reports, or publications.

2.3.4. *ERMiT Batch exportation*

The Erosion Risk Management Tool (ERMiT) provides probabilistic predictions of delivered sediment from hillslopes for each of the five years following a wildfire (Robichaud et al., 2007). ERMiT has a batch processing tool that allows users to import hillslopes from WEPPcloud

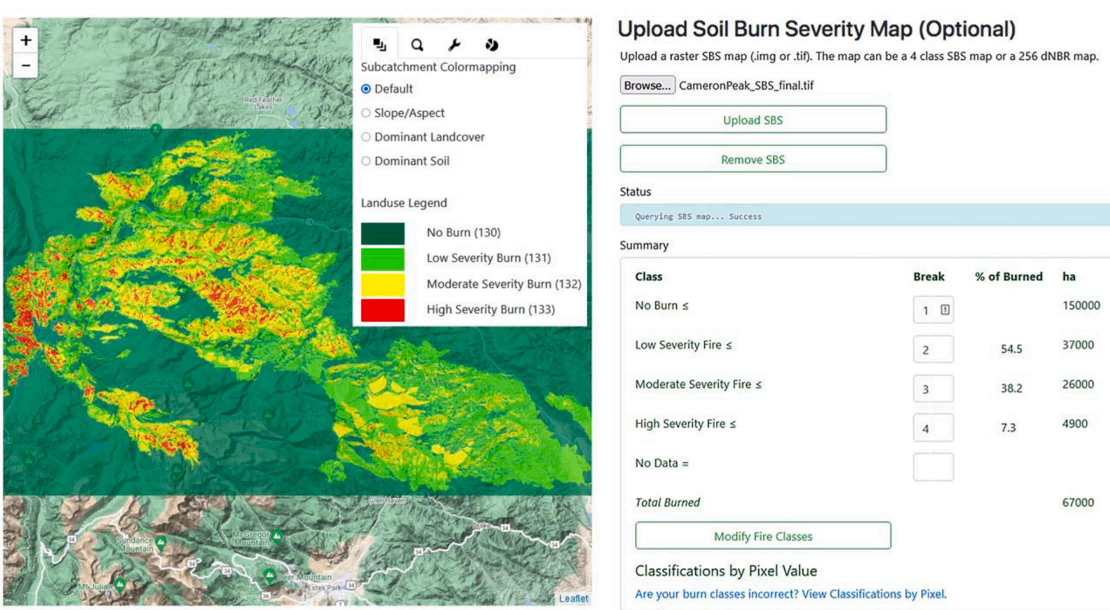


Fig. 2. Example of an SBS map and depiction of the Upload SBS Map control with the report for WEPPcloud (Un)Disturbed.

(https://forest.moscowfsl.wsu.edu/fswepp/batch/bERMiT.html). The ERMiT tool is particularly useful for evaluating the benefits of post-wildfire applications of mulch or seeding, or the installation of contour logs or straw wattles for erosion control. Results from the ERMiT Batch processor can be merged with the exported shapefile in a GIS should users want to present the ERMiT results spatially.

2.3.5. WEPPPY-win-bootstrap

Wepppy-win-bootstrap (Lew, 2021) is a lightweight open-source Python package available for advanced users that allows them to download previously run WEPPcloud projects and rerun them on Windows computers without installing *wepppy* and its dependencies. Users can download multiple runs at the same time in batch mode, make desired changes to the input files, and then rerun the desired projects. This is a useful and unique tool for experienced WEPP users that allows them to further parameterize individual model runs with additional site-specific data.

3. Modeled processes

The most important hydrology and erosion processes for the WEPPcloud simulations are summarized in Table 2, along with the data inputs and outputs associated with those processes. A detailed description of these processes can be found in Flanagan and Nearing (1995).

Table 2
Major hydrologic and erosion processes simulated with the WEPPcloud interface and WEPP model.

Hydrologic Process	Description
Surface hydrology	The surface hydrology component calculates infiltration, rainfall excess and saturation excess runoff, depression storage, and peak discharge.
Subsurface flow	Subsurface lateral flow from hillslopes is estimated using a kinematic form of Darcy's law with land slope as the driving hydraulic energy gradient (Dun et al., 2009, Boll et al., 2015).
Winter hydrology	Snow accumulation, snowmelt, frost and thaw are performed internally by the model on an hourly basis (Dun et al., 2010; Savabi et al., 1995a).
Percolation	Uses a cascading storage routing approach (Savabi et al., 1995b, Dun et al., 2009).
Hydraulics	Overland flow and peak runoff discharge from each hillslope are computed using a modified kinematic wave equation.
Plant growth	Model simulates biomass accumulation, senescence, canopy cover and height, Leaf Area Index, and root growth. Biomass accumulation is estimated based on heat units and photosynthetic active radiation.
Evapotranspiration	Uses Penman or FAO Penman-Monteith equations to calculate potential evapotranspiration (Wu and Dun, 2006).
Hillslope erosion	On a hillslope profile erosion is computed by estimating interrill detachment by raindrop impact and shallow sheet flow, and rill detachment by excess flow shear stress.
Channel erosion	The channel erosion routine is similar to rill erosion computations on hillslopes with the exception that the flow shear stress is calculated using regression equations that approximate the spatially-varied flow equations and only entrainment, transport, and deposition by concentrated flow are considered.
Baseflow†	Baseflow is calculated following linear reservoir theory, where the baseflow from an aquifer is calculated as a fixed percentage of the amount of water stored in the aquifer (Brooks et al., 2016; Sánchez-Murillo et al., 2014; Srivastava et al., 2013).
Pollutant†	This is an optional feature that estimates pollutant yield based on known pollutant concentrations provided by the user following the completion of the WEPP run (Dobre et al., 2022b; Dobre et al., 2022a; Elliot et al., 2015).
Ash Transport†	This optional selection uses the results of the WEPP watershed simulation to execute the WATAR program to estimate the probability of ash and associated pollutant delivery (Neris et al., 2021).

† Denotes processes that are available only in the WEPPcloud interface and not in the WEPP model.

4. Model input and simulations

4.1. Basic processing options

4.1.1. Watershed delineation

The first step for running the WEPPcloud interface requires delineating a watershed into representative hillslopes and channels (Fig. 3) and describing the structure that links hillslopes and channel segments to the overall stream network. WEPPcloud uses either TOPAZ or TauDEM to conduct topographic analysis with Digital Elevation Models (DEMs) to identify the sub-catchments and flowpaths within a watershed. A *wepppy* routine then abstracts hillslope profiles from the outputs by tracing and aggregating flowpaths as described by Cochrane (1999).

TOPAZ. WEPPcloud uses TOPAZ to abstract topographic data from Digital Elevation Models (DEMs). For the continental US, 30 or 10 m DEMs are available. Australia has a 30 m DEM, and Europe has a 25 m DEM. TOPAZ delineates a channel network from the DEM based on the steepest downslope path from each raster cell (pixel) from the 8 cells surrounding it (Garbrecht and Martz, 1997). Adjustments can be made to the detail of the channel network by changing values of the Minimum Source Channel Length (MSCL) and the Critical Source Area (CSA). Setting these to low values will increase the density of channels, which is useful when defining small watersheds (Cao et al., 2021).

TauDEM. Additionally, users can select the TauDEM (Terrain Analysis Using Digital Elevation Models; Tarboton and Baker, 2008; Wallis et al., 2009) tool for the extraction and analysis of hydrologic information from topography as represented by a DEM (to use TauDEM for delineation go to https://wepp.cloud/weppcloud/create). TauDEM is similar to TOPAZ but more recent in its implementation. TauDEM supports larger catchment areas and defines a binary channel network that eliminates more than three channels entering a single junction.

4.1.2. Landuse/managements

With the WEPP model, the most sensitive vegetation variables are the ground cover, Leaf Area Index (LAI) and canopy cover, as these all directly affect surface and subsurface hydrology and subsequently runoff and erosion (Miller et al., 2011; Nearing et al., 1990; Srivastava et al., 2018, 2020). The canopy and ground cover are specified in the WEPP management file. WEPP can simulate daily vegetation conditions in detail, including forest recovery following wildfire (Dun et al., 2009) or timber harvest followed by prescribed fire (Srivastava et al., 2020). Both Dun et al., (2009) and Srivastava et al., (2020) simulated regenerating forest vegetation using observed weather. However, should a user want to estimate erosion from a disturbance using a stochastic climate as typical of the applications on WEPPcloud, vegetation regeneration would quickly mask any effects of disturbance, and the erosion associated with that disturbance would likely be underestimated in all but the first year. If modeling with a stochastic climate, Miller et al. (2011) noted that erosivity of the CLIGEN stochastic climate in the first one to two years resulted in erosion rates less than the long-term average, further aggravating erosion underprediction if modeling with regenerating vegetation. To better understand the likely erosion associated with a given disturbance, the WEPPcloud interface assumes a fixed cover value for both canopy and ground cover for a WEPP run of 20–100 years, or more. Each simulation effectively represents another potential weather scenario that could occur following a disturbance. This allows the model to provide both long-term average output as well as output for any return period event that may occur with a given land cover or disturbance condition.

WEPPcloud is unique in that it supports several databases of management files. Each interface has crosswalk tables that specify which management file is used for each NLCD landuse class (or equivalent for non-US locales), and soil burn severity class. To assist the user in initiating a modeling run, the interface first determines the dominant landuse for each hillslope based on the 2016 NLCD map or uploaded soil burn severity map. The user can modify the canopy cover and ground

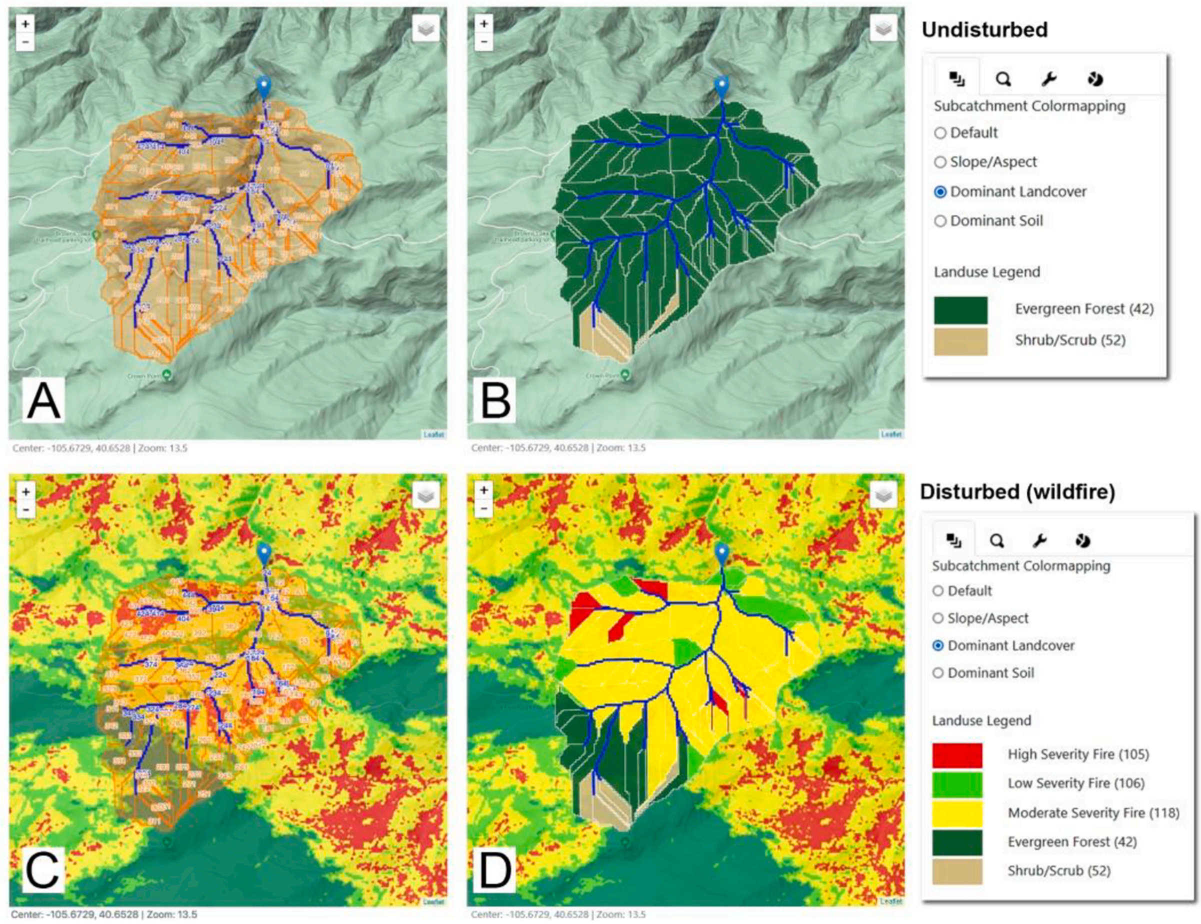


Fig. 3. Example of a watershed discretized into hillslopes and channels and the subsequent assignment of landcover based on undisturbed conditions (A, B) and wildfire (C, D) with the WEPPcloud interface. Hillslopes are outlined in orange, and channels are colored blue (Minimum Source Channel Length, MSCL = 100 m, Critical Source Area, CSA = 10 ha, 30-m DEM based on TOPAZ).

cover value from the default values if desired. This feature is particularly useful in the post-fire environment where ground cover is highly variable (Robichaud et al., 2007), or for fuel management operations where the disturbance from forest operations may not be the same as the default ground or canopy cover values provided by the interface. The user can also select a different land cover from the database and adjust the cover to describe a unique condition. Some of the WEPPcloud interfaces allow the user to apply treatments to specific hillslopes. For novel applications such as modeling vegetation regeneration, the user can download the entire run to WEPP Windows and use a custom-built management file (Alshantiri, 2011; Srivastava et al., 2020). In the future, WEPPcloud will allow users to provide or build their management files in a management editor.

4.1.3. Soils

For the US, two databases for soils are available in WEPPcloud: SSURGO and STATSGO2 (Reybold and TeSelle, 1989). The SSURGO database is used as default and is queried during the watershed delineation process. Alternatively, where the SSURGO database is not available, the STATSGO2 database is used to build the soil files. A WEPP soil file has two main categories, with one line describing the rill and interrill erodibility and hydraulic conductivity, and then several lines describing each layer in the soil profile (Flanagan and Livingston, 1995). The soil components (sand, clay, very fine sand, organic matter) and cation exchange capacity were used to estimate the hydraulic conductivity and erodibility properties for the topmost soil layer (Flanagan and Livingston, 1995). When the lateral flow routines within WEPP were modified by Dun et al. (2009), a second option was offered to allow users to specify the hydraulic conductivity, bulk density, anisotropy factor (i.e. ratio of lateral to vertical saturated hydraulic conductivity within a soil horizon), field capacity, and wilting point of each of the profile layers and called it the “7778” soil file format. The 7778 formatted files tend to result in better estimations of lateral flow (Boll et al., 2015). WEPPcloud is novel in its ability to generate 7778 soils from the SSURGO/STATSGO2 databases whereas the other interfaces still use the original soil file format.

4.1.4. Climate

The daily weather variables needed for the WEPP model are: daily precipitation depth *prcp* (mm); storm duration *dur* (h), ratio of time to peak intensity to total storm duration t_p (-); ratio of storm peak intensity to average intensity i_p (-), maximum T_{max} (°C) and minimum T_{min} (°C) daily air temperatures, dew point temperature T_{dew} (°C), solar radiation *rad* (Langleys/day), wind velocity *w-vl* (m/s), and wind direction *w-dir* (degrees) (Flanagan and Livingston, 1995). The WEPPcloud online interface offers users options for multiple climate data sources: CLIGEN, PRISM, Daymet, gridMET, Future, or Single storm. *CLIGEN* is a stochastic weather generator Nicks et al., 1995; Flanagan et al., 2001, Srivastava et al., 2019) that can be used to create weather input files formatted for WEPP based on the observed weather statistics from 2765 stations across the US and 7673 international stations. PRISM is a database that provides values for mean monthly precipitation, and maximum and minimum temperatures on an 800-m grid for the lower 48 US states. The values are interpolated from nearby weather stations and incorporate the effects of elevation and other topographic variables in estimating monthly values. Daymet and gridMET are gridded data sets based on interpolation of historic records available for the entire US at resolutions of 1 and 4 km, respectively. These datasets provide interpolated daily precipitation, and maximum and minimum temperatures from multiple weather stations between 1980 and present. The other weather variables needed by WEPP are stochastically generated based on the nearest CLIGEN weather station. The CLIGEN, Daymet, and gridMET weather files can be altered based on the PRISM's monthly values of precipitation, and maximum and minimum temperatures. The *Future* climate option uses Coupled Model Intercomparison Project Phase 5 (CMIP5) downscaled climate model daily series (Abatzoglou and Brown, 2012) to generate future climates between 2006 and 2099. For all climate options, users can adjust the precipitation and minimum and maximum temperatures based on 1980–2018 values from the PRISM data set. In addition to running in a continuous simulation mode using daily climate records, WEPPcloud also provides an option to run a single storm mode. WEPPcloud allows users to specify single storm climate files by defining a storm date, total precipitation, the duration of the storm, and intensity. Users can use the single storm option to assess how a watershed will respond to a storm of a specified intensity and duration.

4.1.5. Representing changes in landuse or management

The reasons for applying any erosion model are usually to evaluate erosion risk(s) for the current condition and then evaluate the impacts of alternative management practices on runoff, erosion, and sediment delivery. The WEPPcloud interfaces were mainly developed to support forest watershed management, however, some of the interfaces can also be used for rangelands and croplands, though additional management files may be needed for the relevant management practices.

Generally, forest erosion rates and sediment delivery are very low (Elliot, 2013), and it is only when disturbances occur that erosion increases. The four dominant forest disturbances are mechanical thinning or harvest, prescribed fire, wildfire, and roads (Elliot, 2013). The WEPPcloud interfaces do not include road erosion at this time, however, another FSWEPP interface (WEPP:Road) allows for road analysis.

Scenario testing and evaluation of treatment scenarios such as mulching after a wildfire, thinning, and even prescribed burns are vital components of land management. Land management not only alters vegetation but also soil properties (e.g. soil erodibility). Therefore, when modeling disturbances, it is important to modify management and soil properties in tandem to properly represent disturbances and treatments (Elliot, 2004). WEPPcloud (Un)Disturbed makes use of a parameter database with (Un)Disturbed classes and soil textures to parameterize WEPP managements and soils based on field validated measures (Elliot, 2004).

Modeling management alternatives with WEPPcloud usually starts with modeling undisturbed conditions followed by modifications to the land use to simulate disturbed conditions (Table 3). The (Un)Disturbed and WEPP-PEP interfaces allow users to alter individual hillslopes. The WEPPcloud interface provides functionality for cloning projects so current and treated conditions can be compared on a hillslope-by-hillslope basis. These results can be exported and compared using Desktop GIS applications or other tools, such as Pi-VAT (Prioritization, interactive Visualization, and Analysis Tool), a Shiny App companion tool for aggregating WEPPcloud results (Deval et al., 2022). For wildfire mitigation with mulching, users can change the high severity polygons by increasing the ground cover to the suggested value, or a value in line with field observations from previous mulch applications.

For a more detailed analysis of management practices, most of the WEPPcloud interfaces can export a file containing the information necessary to run every hillslope in a batch program for either the ERMiT model (Robichaud et al., 2007) for post-fire erosion mitigation analysis or Disturbed WEPP (Elliot, 2004) for timber harvest or fuel management analyses. Advanced GIS users will be able to combine the results of the ERMiT or Disturbed WEPP results in the ArcMap or QGIS programs that have downloaded the GIS files from WEPPcloud. The ERMiT model can evaluate the benefits of seeding, log erosion barriers, and mulching as well as predict the likelihood of sediment delivery from hillslopes for the five years following a wildfire. Disturbed WEPP can allow fuel managers to incorporate undisturbed riparian buffers and more easily evaluate the effects of different amounts of ground cover associated with mechanical treatments or the timing of prescribed burns.

Table 3
Suggested approach to modeling landuse change or post-fire mitigation with WEPPcloud, WEPPcloud (Un)Disturbed, or WEPP-PEP.

Condition	Soil	Management	
		Vegetation	Cover (%)
Undisturbed forest	Texture forest[†]	Forest	90–100
Thinned	Texture forest[†]	Forest	85–90
Prescribed fire	Texture low severity	Low severity fire	80–90
Wildfire	As per burn severity map	As per burn severity map	Default or alter after a ground survey
Post wildfire mulching 1 Mg ha^{-1}	As per burn severity map	As per burn severity map	65
Post wildfire mulching 2 Mg ha^{-1}	As per burn severity map	As per burn severity map	75
1-year post fire	Change low severity to short grass, and high severity to low severity	Change low severity to short grass, and high severity to low severity	Increase halfway to 100%

[†] There are four textures, and the interface will select the most appropriate texture and profile from the SSURGO or STATSGO2 database.

4.2. Advanced processing options

Extensive testing has demonstrated that WEPPcloud can consistently provide reasonable estimates (within a magnitude order) for areas with minimal site-specific knowledge or hydrologic expertise from the users (Part II, Dobre et al., 2022b). However, several advanced options are available to allow users to further adjust default parameters to calibrate models or obtain additional information.

4.2.1. Flowpath processing

WEPPcloud allows users to run simulations for each flowpath in the sub-catchments (similar to Cochrane and Flanagan, 1999; Flanagan et al., 2013, available in the Online GIS WEPP Interface). The outlet from one flowpath is assumed to exist for each pixel adjacent to a channel pixel. If the subsequent flow path up the hill splits into more than a single pixel width, the length of the flowpath is increased as the sum of the two combined lengths. This option will produce gridded output results that can be used by managers to identify areas prone to erosion within individual hillslopes (Fig. 4). For each flowpath, the distribution of erosion or deposition along that flowpath is generated by WEPP for at least 100 points. From this distribution, the erosion or deposition for each pixel is determined. If more than one flowpath runs through a particular pixel, the deposition/loss estimates are aggregated by taking the average of the non-zero values for that pixel. A GIS map of the erosion or deposition at each pixel is then generated (Fig. 4B). The number of flowpaths is 10 to 20 times the number of hillslope polygons, so frequently flow path runs are only done for one or two years to determine the distribution of soil erosion on the landscape, but not necessarily to get an accurate erosion estimate. The “watershed” output for part of a watershed after the 2020 Riverside Fire in Oregon indicates

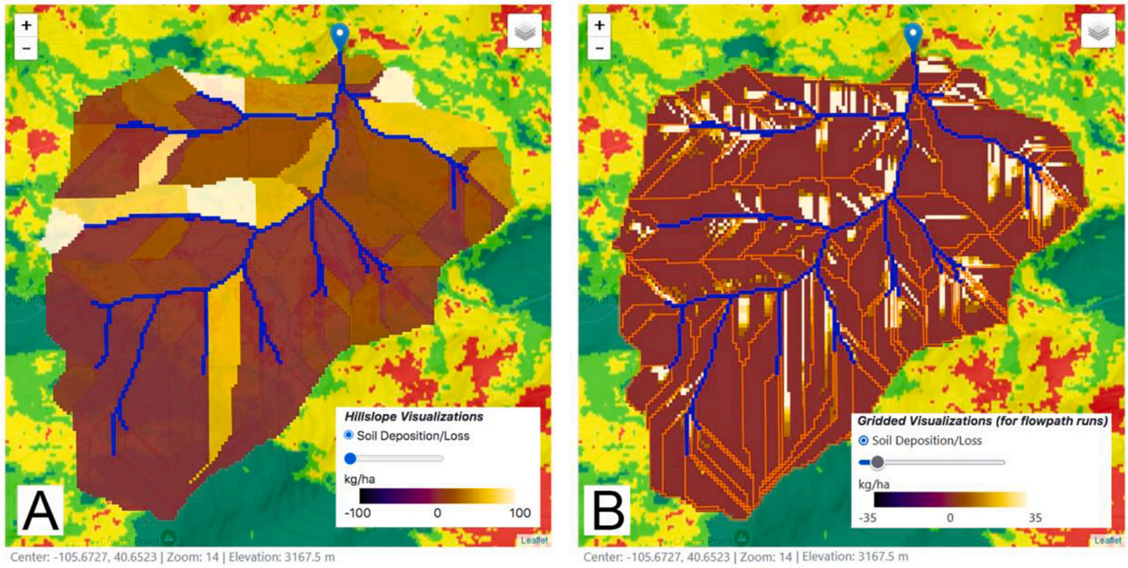


Fig. 4. Examples of the hillslope (A) and flowpath (B) soil loss and deposition maps for the 2020 Riverside Fire, OR. Lighter colors indicate soil loss and darker colors indicate soil deposition, and red indicates no soil loss or deposition.

which hillslope polygons may be at risk of erosion (Fig. 4A). The darker areas in the "flowpath" result (Fig. 4B) may help users target mitigation treatment.

4.2.2. *Hourly seepage computations*

The hourly seepage algorithms are based on the work of Boll et al. (2015) where it was demonstrated that drainage computed based on quasi-steady-state assumptions from particularly steep short hillslopes was not accurate and could lead to erroneous lateral flow and runoff predictions. The use of these options also triggers modified drainage routines, which assume unsaturated water flow is primarily vertical until the soil moisture of the soil layer exceeds field capacity moisture content. The net result is that the hourly routines tend to simulate the initiation of lateral flow at the deeper depths above a restricting soil layer instead of lateral flow initiating in near-surface soil layers under largely unsaturated conditions. This algorithm will slightly increase runtimes and therefore it continues to be an option for users who are particularly interested in steep shallow soil landscapes.

4.2.3. *Frost*

Users are provided with the option for simulating the reduction in infiltration due to soil freezing based on the work of Singh et al. (2009) and Dun et al. (2010). Soil freezing can greatly reduce infiltration rates, particularly in wet compacted fine-textured soils. In some landscapes, such as the loess soils in the dryland agricultural-dominated region of the Inland Pacific Northwest, hillslope profiles are highly susceptible to runoff and erosion from thawing soils (Singh et al., 2009; McCool and Roe, 2005; Brooks et al., 2012). With the thick insulating duff layers in forests, low soil bulk density, and porous soil structure, soil freezing does not necessarily reduce infiltration (Dingman, 1975). Therefore, we allow users to specifically determine whether or not they would like the model to simulate impacts of soil freezing.

4.2.4. *Baseflow processing*

Baseflow is estimated assuming a dynamic groundwater storage reservoir with a storage volume S (mm), where the input to the reservoir is from deep seepage from the soil profile estimated by the WEPP model, and daily flow from the reservoir into the stream channel as baseflow is a fraction of the total volume stored in the reservoir on the previous day (Brooks et al., 2016; Srivastava et al., 2013, 2020). In some geologies, there is water loss from the systems as deep seepage, which is estimated as a fraction lost from the reservoir each day that is not baseflow. The default parameters for the baseflow calculations are the initial groundwater storage (S_i; mm), baseflow coefficient (k_b; day^{-1}), deep seepage coefficient (k_s; day^{-1}), and the watershed groundwater baseflow threshold area (T_a; ha). The initial groundwater storage S_i is not a sensitive parameter in the model; a default value of 200 mm can be used in most applications. The linear coefficient k_b can be best estimated from the slope of the $\ln(time)$ vs. $\ln(flow)$ hydrograph for the falling limb of the hydrograph during dry periods for gauged streams in the area. The default parameter for the linear coefficient is 0.04 day^{-1}. In cases where the groundwater aquifer leaks water to a deeper regional aquifer or laterally across the watershed boundary, or below the stream gage, users can optionally define a secondary aquifer loss defined by a second deep seepage linear coefficient (k_s in day^{-1}) based on the same storage amount S. If the upslope area above a point in the stream network is greater than the user-defined critical watershed area, baseflow is then simulated both at the watershed outlet and within the stream network. The default critical area for baseflow is 1.0 ha. This value can be greater in more arid watersheds.

4.2.5. *Channel properties*

In WEPP, sediment detached from hillslopes will either be deposited downslope or will be routed to channels, where it can be deposited or transported to the watershed's outlet. Additionally, the model can estimate detachment and transport within the channel segments as well as the total sediment yield at the watershed's outlet. The most sensitive parameters for channel erosion are channel soil erodibility and channel critical shear. Srivastava et al. (2013, 2020) found that the WEPP model estimated reasonable results with a channel soil erodibility of 1.0×10^{-6} s m^{-1}. We found similar results while modeling 28 forested watersheds in the Pacific Northwest (Dobre et al., 2022b). Srivastava et al. (2020) also demonstrated that there is a direct relationship between the channel critical shear and the D_{50} particle size from pebble count data. To account for these findings, the WEPPcloud interface was designed to allow users to enter the channel bed median particle size (D_{50}), which is used to estimate a critical bed shear stress value following Berenbrock and Tranmer (2008).

4.2.6. Saturated hydraulic conductivity of the restrictive layer

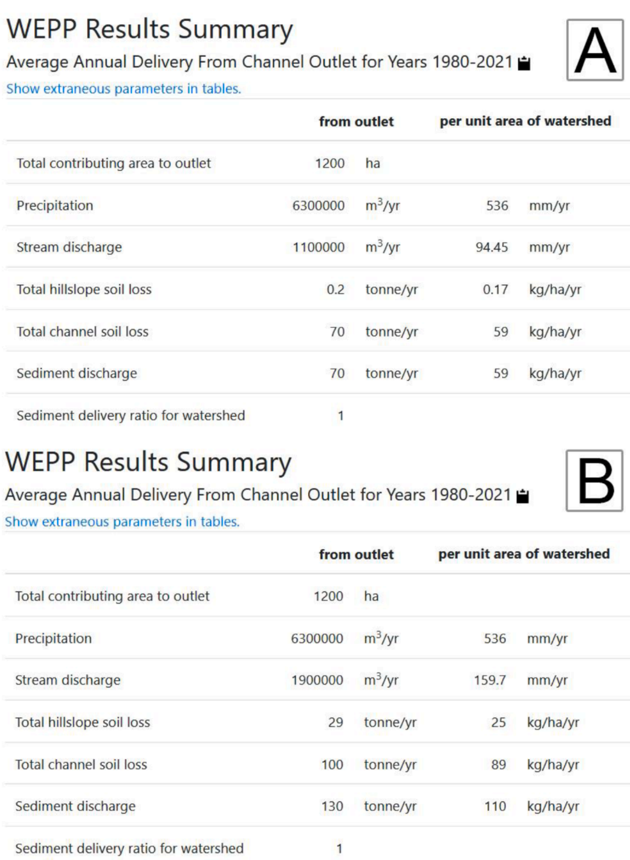
Most hydrologic models simulate runoff through infiltration excess runoff or Hortonian overland flow. However, in areas where soils have high hydraulic conductivity or where shallow soils are overlaying geologically restrictive layers, saturation excess runoff becomes an important runoff process. The saturated hydraulic conductivity of the restrictive layer (K_{sat}) is a critical parameter in WEPP to accurately capture the subsurface lateral flow in mountainous regions (Dobre et al., 2022b; Dun et al., 2009; Srivastava et al., 2013). This value depends on the type of the underlying geology and can be specified by the user based on additional knowledge of the geology of the watershed.

4.2.7. Pollutant processing

WEPPcloud uses a version of WEPP with pollutant load modeling. This is an optional selection that allows users to estimate pollutant losses based on known pollutant concentrations provided by the user (Dobre et al., 2022a; Dobre et al., 2022b; Elliot et al., 2015). The estimates are simplistic and do not account for sorption, desorption, mineralization, or immobilization. They only provide rough estimates of the pollutant being transported by both water (via surface runoff, lateral flow, and baseflow) and adsorbed to sediments.

4.3. Model outputs

The user is provided with the basic output from model simulations both at the hillslope and at the watershed scale. The raw outputs from WEPP (plain text files) are accessible via the online interface and the projects can be exported with all of the input and outputs included for further analyses or report preparation with a GIS, spreadsheet, database, or word processer. On WEPPcloud, model outputs such as water balance, soil erosion, sediment yield, return period analysis are summarized for users both in tabular and graphical format for decision-making. These are similar to outputs from the WEPP Online GIS interface (Frankenberger et al., 2011), except for the Water Balance report (see below), which is unique to WEPPcloud.



WEPP Results Summary

Average Annual Delivery From Channel Outlet for Years 1980-2021

Show extraneous parameters in tables.

A

	from outlet		per unit area of watershed	
Total contributing area to outlet	1200	ha		
Precipitation	6300000	m^3/yr	536	mm/yr
Stream discharge	1100000	m^3/yr	94.45	mm/yr
Total hillslope soil loss	0.2	tonne/yr	0.17	kg/ha/yr
Total channel soil loss	70	tonne/yr	59	kg/ha/yr
Sediment discharge	70	tonne/yr	59	kg/ha/yr
Sediment delivery ratio for watershed	1			

WEPP Results Summary

Average Annual Delivery From Channel Outlet for Years 1980-2021

Show extraneous parameters in tables.

B

	from outlet		per unit area of watershed	
Total contributing area to outlet	1200	ha		
Precipitation	6300000	m^3/yr	536	mm/yr
Stream discharge	1900000	m^3/yr	159.7	mm/yr
Total hillslope soil loss	29	tonne/yr	25	kg/ha/yr
Total channel soil loss	100	tonne/yr	89	kg/ha/yr
Sediment discharge	130	tonne/yr	110	kg/ha/yr
Sediment delivery ratio for watershed	1			

Fig. 5. Example of watershed summary at the outlet for both undisturbed forest conditions (A) and post-wildfire (B).

4.3.1. Watershed loss summary

The first table of this output page shows an average annual summary of precipitation amount, hillslope and channel soil loss, streamflow, sediment, and total phosphorus discharge (Fig. 5). The second and third output tables on the same page are average annual summaries of the above-mentioned variables for all hillslope and channel segments. This report utilizes WEPP's loss output but provides additional metrics as well as the ability to provide annual averages excluding the first couple of years when the simulation is stabilizing.

4.3.2. Return periods report

The return period of an event of a given magnitude is the average recurrence interval between events equaling or exceeding a specified magnitude (Chow et al., 1988). Return periods reports provide daily precipitation, runoff, sediment yield, and pollutant loads, and rainfall intensities and peak runoff rates for recurrence intervals up to half the length of run, for example, a 20-year run will generate 2-, 5-, and 10-year return period estimates. The return period report is not provided by WEPP but is provided by other WEPP interfaces including the Online GIS WEPP interface. The values are estimated from the annual maxima series of WEPP daily output values assuming a Weibull Distribution (Natural Resource Conservation Service NRCS, 2007). Other recurrence intervals can also be specified by the user. This report has an accompanying Culvert Diameter Sizing Spreadsheet Tool that assumes orifice flow at the inlet is limiting and is intended to be used with the Peak Runoff Rate estimates. Fig. 6 shows that the return periods for one parameter do not necessarily occur from the same event as another. For example, the 5-year return period peak discharge for undisturbed conditions occurred on May 15th 1984 (Fig. 6A), whereas the 5-year return period for sediment yield occurred on January 4th1980 (Fig. 6B).

4.3.3. Sediment characteristics report

WEPP internally routes sediment according to five class sizes: clay particles, silt particles, small aggregates (consisting of clay, silt, and organic matter), sand particles, and large aggregates (consisting of clay, silt, sand particles, and organic matter). The sediment characteristics report provides mean diameter, specific gravity, and composition (sand, silt, clay, organic matter) statistics for the sediments leaving the channel as well as the distribution of class sediment particles that are leaving the outlet (not shown). Separate statistics are provided to describe the sediment classes leaving the hillslopes. The sediment size distribution is used to improve estimates of particulate pollutant delivery and aid in evaluating the potential impacts of sand particles on aquatic health.

4.3.4. Water balance (water year)

WEPPcloud has a water balance report that provides precipitation, surface runoff, lateral flow, the sum of evaporation from the soil, ground cover and transpiration of the vegetation (ET), and percolation by hillslope averaged over the simulated water years. WEPPcloud also has interactive plotting for daily runoff, lateral flow, and baseflow time series (Fig. 7).

4.3.5. Spatial visualization

WEPPcloud uses Leaflet.js to provide interactive maps. For each model run, a map interface displays the location of the outlet, the channels, and the subcatchments. The interface can generate thematic maps to visualize landuse types, soil types, and topographic parameters (slope/aspect) (Fig. 8). Once WEPP has been run, choropleth maps for surface runoff, sediment yield, and pollutant loads are available. WEPPcloud also can combine maps of multiple watershed runs into a single map. These maps can be downloaded in a GIS format for further

Peak Discharge A

Recurrence Interval	Date	Peak Discharge
years	mm/dd/yyyy	m^3/s
2	05/17/1984	1.1
5	05/15/1984	1.8
10	04/23/1980	3.6
20	09/13/2013	4.3

Sediment Yield B

Recurrence Interval	Date	Sediment Yield
years	mm/dd/yyyy	tonne
2	01/11/1980	4.4
5	01/04/1980	5.5
10	01/01/1980	5.9
20	09/13/2013	6.8

Peak Discharge C

Recurrence Interval	Date	Peak Discharge
years	mm/dd/yyyy	m^3/s
2	04/30/1980	5.9
5	04/22/1980	7.9
10	03/08/1992	12
20	03/28/1992	31

Sediment Yield D

Recurrence Interval	Date	Sediment Yield
years	mm/dd/yyyy	tonne
2	05/08/2011	17
5	05/23/1995	46
10	05/12/1984	120
20	05/15/1984	140

Fig. 6. Example of return period results of peak discharge and sediment yield for undisturbed forest conditions (A, B) and post-wildfire condition (C, D).

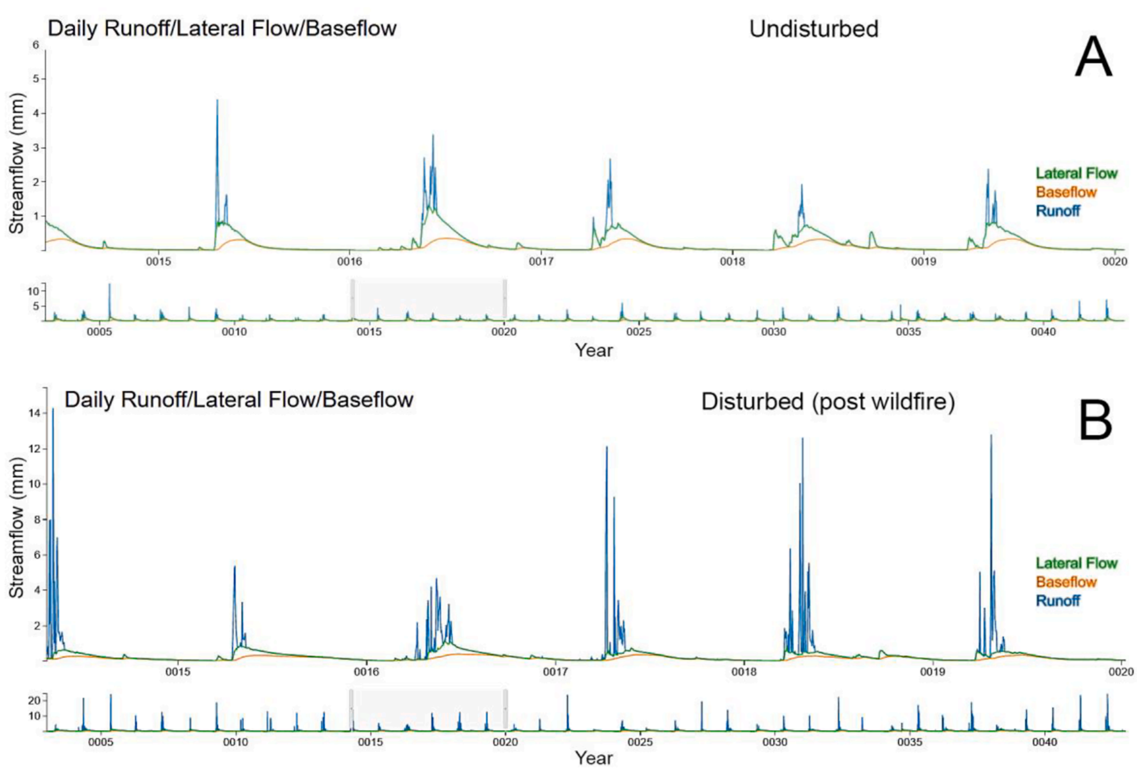


Fig. 7. Daily runoff, lateral flow, and baseflow graphs for undisturbed (A) and disturbed (B) conditions. The above panel in each of the figures shows the selected five-year hydrographs while the lower panel shows the entire simulation period of 40 years.

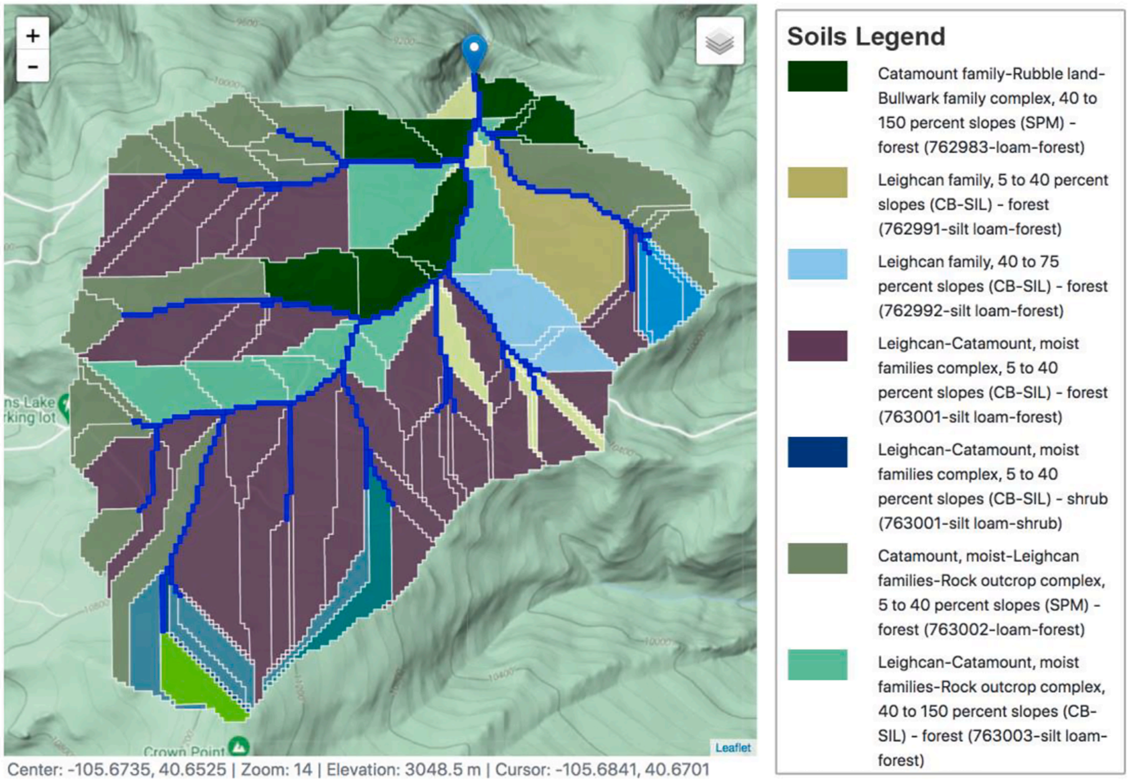


Fig. 8. Example of spatial visualization of soil series and textural characteristics.

manipulation for analysis or inclusion in reports or presentations.

5. Implications for management and applications

The WEPPcloud platform allows land managers to access a complex hydrologic and erosion model for land use decision-making at the watershed scale. The functionality of the interface and the various output options allow for comparing management scenarios. The modeling is beneficial for post-disturbance decision support, for assessing risks to climate change and natural hazards like fire, drought, and high-intensity storms. For example, undisturbed forest conditions can be compared to a forest thinning operation and its effect on stream discharge or sediment yield. Wildfire-affected watersheds can be evaluated by uploading a soil burn severity map into the WEPPcloud platform, and the effects of post-fire mulching on runoff and erosion can readily be evaluated. Post-fire results can be compared with an unburned condition with all other input conditions remaining the same to compare changes in runoff, peak flow, or sediment yield due to the wildfire and treatment.

Currently, WEPPcloud is used by the United States Forest Service (USFS) Burned Area Emergency Response (BAER) teams, Department of Interior (DOI) Emergency Stabilization teams (ES) teams, state agencies (e.g. California Department of Forestry and Fire Protection Watershed Emergency Response Team, CALFIRE WERT) to predict peak flows and the spatial distribution of erosion within watersheds and also to download hillslope-specific information (e.g. soil burn severity category, slope length, soil type, vegetation, etc.,), which are further imported into the ERMiT Batch tool to evaluate long-term post-fire treatments such as mulching. WEPPcloud has also been applied to site-specific locations to evaluate soil erosion from proposed future management scenarios or potential wildfires. For example, in the Lake Tahoe Basin, the model has been used to evaluate the risks from increasing mechanized thinning on slopes greater than 30% and the benefits of such treatments when compared to wildfire scenarios (Dobre et al., 2022a). Water utilities from areas that have not experienced historic wildfires (e.g. Seattle Public Utilities, Portland Water Bureau), are now using the model to better understand the potential increase in sediment yield from hypothetical fire scenarios. The newest model development (i.e. the ash transport model) will also be applicable to water utilities and watershed managers interested in the contamination of their drinking water supply reservoirs with ash and nutrients.

WEPPcloud supports basic hydrology and erosion research by enabling researchers to establish base simulations that can be calibrated and manipulated to test various hydrological models or modeling approaches. These findings are continuously integrated into *wepppy/* WEPPcloud to improve model estimates. WEPPcloud has primarily been used for forested areas but is also being used for croplands and rangelands. WEPPcloud and its ability to quickly acquire and process site-specific DEM, climate, soils, and landuse data are also useful for supporting models outside of WEPPcloud.

6. Future developments

The WEPPcloud interface has considerable potential for further supporting forested watershed management. Recent studies supporting advanced watershed analyses as presented in the WEPPcloud site-specific resources like Lake Tahoe in California included a simulated wildfire (or soil burn severity) for current conditions and treated conditions. We intend to add a simulated wildfire option similar to the proof of concept burn severity simulator developed by the Michigan Technological Research Institute (https://apps.mtri.org/burnsev/get; M. Miller personal communication).

In the absence of wildfire, the road network is usually the greatest source of sediment in a forest watershed. GIS methodologies have been developed to link GIS road layers to WEPP to estimate sediment delivery from road networks (Elliot et al., 2019). We intend to incorporate this advanced technology into WEPPcloud and link road erosion to overall watershed sediment delivery (Cao et al., 2020).

The interface also lends itself to supporting agricultural watershed analyses. Cropland applications will require a larger database of cropland management files to support the extremely diverse range of crops and tillage options that are common in the US. We will explore the ability to link WEPPcloud with the USDA-NRCS Conservation Resource Land Management Operations Database (CR_LMOD), developed during the past five years to be used with WEPP and WEPS (Wind Erosion Prediction System) in NRCS field applications of these models. CR_LMOD contains about 25,000 crop rotation templates across 75 crop management zones, about 120 crops, and 550 farming operations.

Just as applications have been developed from Western Europe and Australia, there is also the goal of expanding the applications to Asia, South America, and elsewhere in the western hemisphere if local collaborators can be found to assist in database development. Additional international collaboration can also be used to develop interfaces in other languages, such as Spanish or French.

Other developments are planned for the near future. WEPPcloud will incorporate multiple Overland Flow Elements (OFEs) to allow WEPP to provide better deposition and soil loss modeling for long hillslopes. Additionally, we intend to incorporate relationships between canopy cover, LAI, and above-ground live biomass similar to Srivastava et al. (2020) that will allow vegetation recovery following disturbance. We also plan on utilizing gridMET's daily climate time series (available up to yesterday) for near real-time prediction and erosion warning. WEPPcloud could also serve as a platform to readily expand the Daily Erosion Project (https://www.dailyerosion.org) well beyond the Midwest, allowing estimation of erosion every day based on the previous day's NEXRAD (Next Generation Weather Radar) precipitation data. Such a feature would be particularly useful for providing near real-time downstream estimates of post-fire flooding. We also plan on allowing users to select additional future climate models. WEPPcloud is also slated to offer the ability for users to utilize their management files for increased customization of watershed models.

7. Summary and conclusions

The WEPPcloud online suites of watershed interfaces are the latest development in online watershed modeling. These powerful tools provide managers with the ability to comprehensively examine impacts of site-specific management with a process-based hydrologic model driven by the most accurate publicly available soil, landuse, and topographic maps. Gridded climate inputs representing topographic variation across complex watersheds for historic, future, and near real-time weather data can be utilized. WEPPcloud does not require expensive software that needs to be upgraded every year, it runs and stores watershed simulations on a large server network avoiding issues with desktop memory and storage, synthesizes outputs into maps, tables, and figures that are readily available for end-users, and can currently be used to simulate the hydrology anywhere across multiple continents in a manner of minutes. The tools are intended to support forest and rangeland watershed management in evaluating the impacts of timber harvest, fuel management, and post-wildfire watershed management. In addition, the RHEM interface supports runoff and erosion analysis of rangeland hillslopes. Preliminary applications of the interface have been encouraging. The large databases covering the continental US, Western Europe, and Australia make the WEPPcloud interface readily usable in those regions. Future expansion to other erosion applications such as roads and croplands and other regions of the world are anticipated.

CRediT authorship contribution statement

Roger Lew: Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Mariana Dobre:** Conceptualization, Writing – original draft, Visualization, Funding acquisition. **Anurag Srivastava:** Conceptualization, Software, Writing – original draft. **Erin S. Brooks:** Conceptualization, Writing – review & editing, Funding acquisition. **William J. Elliot:** Conceptualization, Resources, Writing – original draft, Funding acquisition. **Peter R. Robichaud:** Conceptualization, Resources, Writing – review & editing, Funding acquisition. **Dennis C. Flanagan:** Software, 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.

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