Watershed-scale evaluation of the Water Erosion Prediction Project (WEPP) model in the Lake Tahoe basin

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SUMMARY

Forest managers need methods to evaluate the impacts of management at the watershed scale. The Water Erosion Prediction Project (WEPP) has the ability to model disturbed forested hillslopes, but has difficulty addressing some of the critical processes that are important at a watershed scale, including baseflow and water yield. In order to apply WEPP to forested watersheds, we developed and assessed new approaches for simulating streamflow and sediment transport from large watersheds using WEPP. We created specific algorithms to spatially distribute soil, climate, and management input files for all the subwatersheds within the basin. The model enhancements were tested on five geologically and climatically diverse watersheds in the Lake Tahoe basin, USA. The model was run with minimal calibration to assess WEPP's ability as a physically-based model to predict streamflow and sediment delivery. The performance of the model was examined against 17 years of observed snow water equivalent depth, streamflow, and sediment load data. Only region-wide baseflow recession parameters related to the geology of the basin were calibrated with observed streamflow data. Close agreement between simulated and observed snow water equivalent, streamflow, and the distribution of fine (<20 μm) and coarse (>20 μm) sediments was achieved at each of the major watersheds located in the high-precipitation regions of the basin. Sediment load was adequately simulated in the drier watersheds; however, annual streamflow was overestimated. With the exception of the drier eastern region, the model demonstrated no loss in accuracy when applied without calibration to multiple watersheds across Lake Tahoe basin demonstrating the utility of the model as a management tool in gauged and ungauged basins.

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1. Introduction

Site-specific, decision-support tools guide planning in watershed management, particularly in ungauged basins (Hrachowitz et al., 2013; Sivapalan, 2003). Such tools are needed to inform land use decisions related to water quantity and quality. Hydrologic models can be employed to address various water management problems. These models differ based on the simulated hydrologic processes, scale, applicability to the study domain, and computational time.

For example, catchment-scale models based on empirically-derived coefficients can be calibrated to match annual and monthly watershed outlet measurements (Grismer, 2012; Tetra Tech, Inc., 2007). Since catchment-scale models lump much of the spatial variability in soils, topography, and vegetation unique to each watershed, empirically-derived coefficients will vary from watershed to watershed, thus limiting the model transferability to other gauged and ungauged watersheds (Elliot et al., 2010). Moreover, without process-based algorithms appropriate for hillslope runoff generation and sediment transport, their application is limited to the catchment scale at these coarse time scales.

It is unlikely that calibrated models correctly predict all of the internal processes or if the calibration is masking fundamental structural problems (Grayson et al., 1992; Kirchner, 2006; Klemeš, 1986). As the conditions of a watershed change (e.g., increased urbanization, changes in climate), there is a risk that calibrated parameters (using historic data based on assumed

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stationarity) do not capture changes in the hydrologic regime and fail to adequately represent the impacts of management (Li et al., 2012; Razavi and Coulibaly, 2013; Seibert, 2003).

More detailed, complex process-based models may better describe hydrologic and pollutant transport mechanisms and overcome limitations associated with calibration. When mathematically describing the fundamental hydrological processes representative of a particular region, process-based models, parameterized with site-specific data, are more likely able to simulate hydrologic conditions in ungauged basins, and to capture the effects of climate change and management decisions on the watershed. However, because of their complexity, process-based models have not been widely used in many basin-scale studies.

Therefore, development of a hydrology-based decision support tool is challenging (Mulla et al., 2008) and requires that the model be:

(1) based fundamentally on the appropriate hydrologic process representative of the landscape (i.e., robust);
(2) sufficiently simple (i.e., parsimonious) to avoid the need for extensive calibration;
(3) valid at the scale of the management problem (e.g., hillslope, field, watershed);
(4) able to capture and incorporate spatial and temporal variability in input (precipitation, temperature, soil and vegetative properties); and
(5) able to predict water and pollutant transport from hillslopes as well as the cumulative response at the watershed outlet.

Meeting these requirements is daunting and some have questioned whether it is even possible (Beven, 2001; Grayson et al., 1992).

The Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995) is one example of a complex process-based hydrology and sediment transport model designed to assess the impact of management practices on runoff, erosion, and delivered sediment. The WEPP model was initially developed for simulations of hillslopes dominated by surface hydrology only (Ascough et al., 1997; Laflen et al., 1997) and has been successfully applied not only in the U.S., but also in agricultural fields from different parts of the world (Pandey et al., 2008; Pieri et al., 2007; Singh et al., 2011). The model was later enhanced to increase its applicability to small forested watersheds (Dun et al., 2009) and recent efforts have focused on improving the ability of the model to capture variable source area hydrology (Boll et al., 2015). Currently, the model can simulate processes such as infiltration, surface runoff, shallow lateral flow or interflow, soil detachment, deposition, transport and delivery across hillslope, in channel network, and through structural impoundment units (e.g., sediment basins, culverts) within a watershed (Boll et al., 2015; Dun et al., 2009; Flanagan and Livingston, 1995; Flanagan and Nearing, 1995). A particularly useful application of the WEPP model is its ability to partition sediment yield into three primary particle size classes, i.e., sand, silt, and clay, and two aggregate categories: small, containing silt, clay, and organic matter with a mean diameter of 0.03 mm, and large, containing sand, silt, clay, and organic matter with a mean diameter of 0.3 mm (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995). This application is especially valuable in areas that have been impacted by upland land-use activities with high risk of eutrophication, such as lakes or estuaries. Land managers need to know from where the fine sediments are generated in order to apply effective sediment reduction strategies and ultimately to reduce phosphorus loading to water bodies. WEPP, as a management tool, has seen applications through customized interfaces in predicting sediment delivery from burned forests or rangelands (ERMiT, Robichaud

et al., 2007), roads (WEPP Road; Elliot, 2004), and fuel management (WEPP FuME; Elliot et al., 2007) (http://forest.moscowfsl.wsu.edu/fswepp/).

At a watershed scale, WEPP can be applied using the GeoWEPP model (Renschler, 2003) or the online interface to the watershed version of the model (Frankenberger et al., 2011). Despite the increased use of the WEPP model to assess the impacts of management at the hillslope scale (Elliot, 2004), there have been very few applications and assessments of the model at the watershed scale (Amore et al., 2004; Defersha et al., 2012; Miller et al., 2011; Papanicolaou and Abaci, 2008; Srivastava et al., 2013). One of the primary limitations has been that the current stream channel algorithms were not developed for large river networks and therefore it has been recommended that the model only be applied to watershed areas less than 260 ha (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995; Wang et al., 2010). A channel-routing model to simulate water flow in channels has been developed for the WEPP model (Wang et al., 2010), however, this improvement has not been fully incorporated into the model. In addition, the model has not been developed to capture large scale variability in climate due to elevation gradients or to capture baseflow contributions and groundwater–surface water interactions. Larger watersheds also have the added challenge of capturing and representing spatial variability in land cover, management practices, and soil properties.

This paper describes an approach for applying the WEPP model to large watersheds and provides an overall assessment of the ability of the model to capture streamflow and sediment transport at multiple watersheds throughout a large basin. We were particularly interested in the ability of the model to represent the hydrology and sediment transport across the basin without re-calibration at each watershed as this is a true test for the use of the model for predictions in ungauged basins. Therefore, the overall objective of this paper was to critically assess the performance of the WEPP model as a potential tool for predicting watershed-scale hydrologic response and sediment delivery using readily available data and minimal calibration. Specific objectives include:

(1) developing automated approaches to capture variability in climate, soils, hillslope topography, and forest canopy, and to represent baseflow contributions in large watersheds,
(2) assessing the ability of the WEPP model with the enhanced algorithms to simulate streamflow and sediment loading from multiple gauged undisturbed watersheds using *publicly-available data* and *minimal calibration*, and
(3) identifying the extent to which the WEPP model can capture variability in hydrology across multiple watersheds before re-calibration is required and identify the key biophysical characteristics that trigger the need for re-calibration.

This multi-watershed approach provided the unique opportunity to assess the level to which the WEPP model can represent the hydrologic response from forested landscapes with complex climatic patterns, topography, and soil variability when limited to publicly available data. Applying the model without calibration to multiple watersheds allowed us to assess the ability of the model to make predictions in ungauged basins.

2. Study area

Lake Tahoe is an alpine lake situated at an altitude of 1898 m.a. s.l. along the state boundary between California and Nevada, US (Fig. 1). The basin area is 812 km^2 while the lake's surface area is 501 km^2, and is free of ice throughout the year. The basin was formed 2–3 million years ago by geologic faulting and, currently, there are three active large faults and several smaller faults that
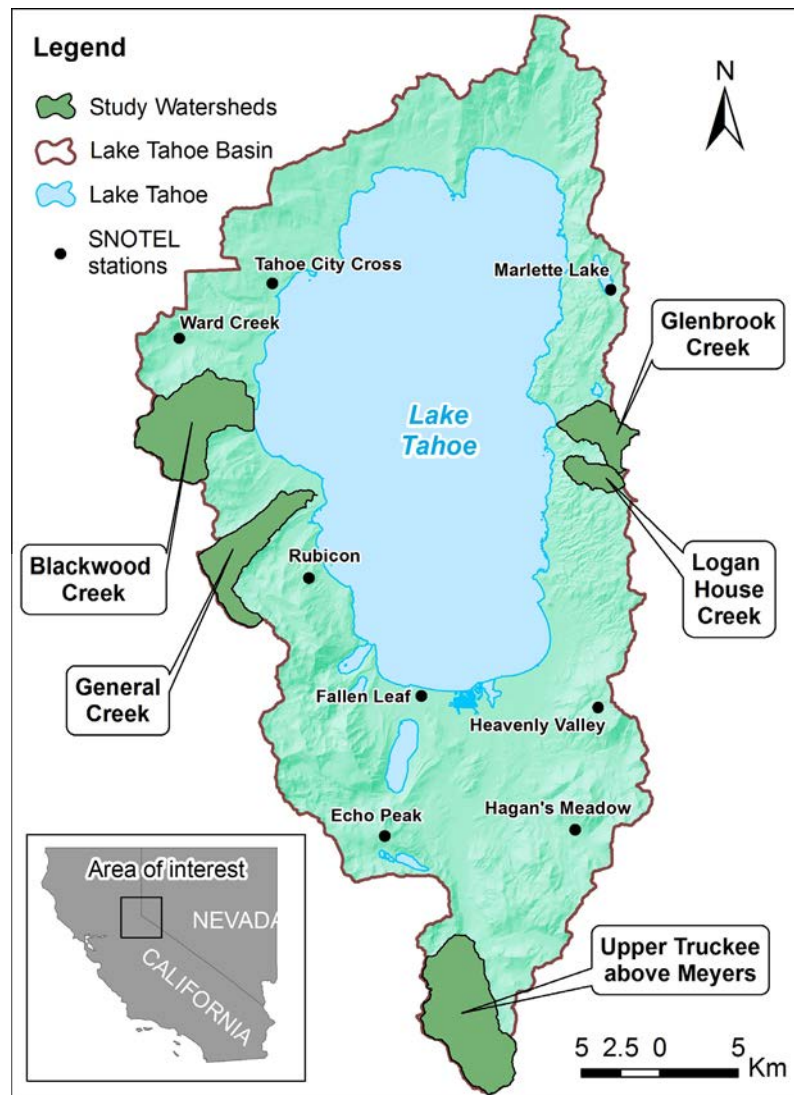
Fig. 1. Location of the study watersheds and SNOTEL stations, Lake Tahoe basin.

cross the basin and the lake floor. The geology and soils are mostly granitic except in the northern and northwestern part of the basin, where volcanic soil types predominate (Fig. 2). Glaciation shaped much of the current landscape in the western part of the basin by displacing soil and weathered rock derived from decomposed granite into the lake. The unglaciated eastern part of the basin contains a thick layer of weathered granite of high permeability (Thodal, 1997; Nolan and Hill, 1991). Four major aquifers exist below the basin in the north, west, and south, while only three very small ones exist in the eastern side. Vegetation is comprised of mixed conifer forest with significant areas covered by meadows, riparian areas, or bare granite outcrops (Coats et al., 2008; Nevada Division of Environmental Protection, 2011). Most streams flow over bedrock and a total of 63 tributaries drain directly into the lake (NDEP, 2011).

The climate is comprised of wet winters and dry summers. Influences from the Pacific Ocean and orographic effects result in extreme precipitation differences between the west and east-sides of the lake, with the wetter west-side of the basin receiving nearly five times more precipitation (Fig. 2). The basin's hydrology is dominated by snowfall accumulation and melt, especially at higher elevations, and rain-on-snow events, at lower elevations.

Lake Tahoe is well-known for its clarity and deep blue colors. These distinct properties have deteriorated during the last five decades likely as a result of anthropogenic activities in the basin. Besides an expansion in residential and commercial construction, other disturbances such as road building, lawn fertilizer application, golf courses, and atmospheric deposition have caused an increase in sediment transport and nutrient accumulation in the system (Goldman, 1988; Raumann and Cablk, 2008). Similarly, fire suppression through the 20th century in the Sierra Nevada region contributed to an accumulation of forest biomass. This resulted in more frequent and intense wildfires (McKelvey et al., 1996). More recently, prescribed fires and mechanical thinning have been used in the region to reduce fuel load and possibly decrease negative effects of high severity wildfires (Elliott-Fisk et al., 1996; Raumann and Cablk, 2008). These prescribed fires and timber harvesting activities have the potential to increase sediment loading to the lake, in particular fine sediment (<20 μm), which has been identified as one of the main factors contributing to the reduction in lake clarity over the last few decades (NDEP, 2011; Sahoo et al., 2013; Swift et al., 2006).

Watershed selection

To test the ability of WEPP to simulate the hydrology and sediment transport across the Lake Tahoe basin, we selected five watersheds representing diverse ecosystems. These watersheds
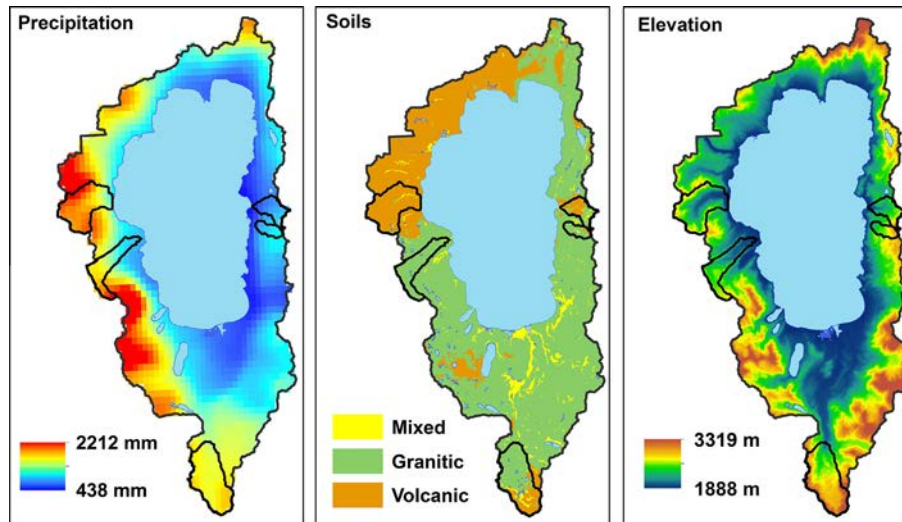
Fig. 2. Changes in precipitation, soils, and elevation within the Lake Tahoe basin.

provided an excellent location for this study because of the current environmental concerns with water clarity and quality, the climatic diversity between the west- and the east-side of the basin, and a long record of streamflow and sediment concentration for the major tributary streams (Table 1, Fig. 2). Undisturbed watersheds were selected in order to evaluate the ability of the model to perform with natural climate, soil, and vegetative variability, without the effects of anthropogenic disturbances (e.g., urban development) on output hydrographs. The selected watersheds were: the headwaters of the Upper Truckee River near Meyers (36.3 km^2), Logan House Creek (5.4 km^2), Glenbrook Creek (10.6 km^2), General Creek (19.2 km^2), and Blackwood Creek (28.5 km^2) (Table 1).

The Upper Truckee watershed is located in the southern part of the basin and is not influenced by the downstream city of South Lake Tahoe. However, the entire Upper Truckee River watershed, including the disturbed areas downstream of the town of Meyers, is known to contribute the majority of the sediment to Lake Tahoe. A large portion (38.3%) of Upper Truckee is composed of exposed rock (Fig. 3). General Creek and Blackwood Creek watersheds are both located on the wetter, west-side of the basin (Fig. 1). General Creek watershed is relatively undisturbed compared to Blackwood Creek watershed, which has been impacted by roads, grazing, gravel mining, anthropogenic channel modifications, and logging. General Creek is composed primarily of granitic soils, whereas Blackwood Creek is dominated by volcanic soils. Logan House Creek and Glenbrook Creek watersheds are located on the dry eastern side of the lake and are small with relatively low sediment loading, with primarily granitic soils in the former and a mixture of both granitic and volcanic in the latter (Fig. 2). Each of these watersheds has minimal residential or urban development. Hence, we were able to isolate upland- from urban responses.

Table 1
Watershed characteristics.

Watershed	USGS gauging station	Drainage area (ha)	Climate	Average elevation (m)
Blackwood	10336660	3110	Wet	2205
General	10336645	1912	Wet	2250
Upper Truckee River near Meyers	103366092	3675	Wet	2516
Logan House	10336730	541	Dry	2383
Glenbrook	10336740	1055	Dry	2250

3. Model parameterization and statistical assessment

3.1. Hillslope, climate, soil, forest canopy, and baseflow algorithms in WEPP

In order to apply WEPP to the Lake Tahoe basin, we made several modifications to the WEPP technology (Version 2006.5) to capture the spatial variability in climate, soil properties, hillslope topography, and canopy cover, as well as to account for baseflow contributions to overall streamflow. These modifications are reported below.

3.1.1. Hillslope topography
WEPP describes topographic variability within each hillslope using break points represented by slope steepness with horizontal length along the slope. Water flow is calculated on a per-unit hillslope width basis and therefore WEPP is able to represent profile convergence (i.e., topographic curvature along a flow path) but not contour curvature (i.e., planform curvature) within a specific hillslope. Each hillslope can be divided into up to 19 overland flow elements (OFEs) with unique combinations of vegetation and management characteristics. Mathematically, this characterization based on the OFEs is important to better represent the variable-source-area hydrology in complex topography (Boll et al., 2015; Crabtree et al., 2006). We used the GeoWEPP model (Renschler, 2003) to create hillslope files for each of the five study watersheds based on the 10-m digital elevation model (DEM) of the Tahoe basin. By default, the topography of all hillslopes generated by GeoWEPP is described as a single OFE with single soil and vegetation characteristics. In order to improve the variable source surface hydrology, a PERL script was written to automatically modify the topographic structure of each hillslope created by GeoWEPP to generate multiple OFEs. OFE length varied based on overall hillslope length and the spatial resolution of the DEM. For Lake Tahoe the OFE length was typically 30 m. Although users can manually assign unique soil and vegetative characteristics to each OFE within a hillslope, we made no attempt to capture this variability and used only the single management and soil file assigned to each hillslope by GeoWEPP.

3.1.2. Distributed weather input
With a 1400 m (4600 ft) difference in elevation and a strong orthographic effect resulting in a 1770 mm (70 in.) difference in precipitation across the basin (Fig. 2), it was important to capture variability in climate across the basin. The best available data for

Fig. 3. Example of outcrop rocks at Angora Lake. Source: http://www.aboutlaketahoe.com.

the basin were recorded on an hourly basis at eight SNOTEL stations (Fig. 1). The elevation difference between these stations was ~700 m with the lowest site being Fallen Leaf (1901 m.a.s.l) and the highest site being Heavenly Valley (2601 m.a.s.l.). Using weather data recorded at one elevation to represent the climate of an entire watershed can generate erroneous streamflow simulation results, especially in snow-dominated watersheds. Therefore, we developed an algorithm which assigned unique weather input data to each hillslope. Precipitation and temperature measured at the nearby SNOTEL stations were assigned to each hillslope using scaling factors calculated from 30-year average monthly PRISM raster maps of precipitation, and minimum and maximum temperatures. The PRISM maps have a high spatial resolution of 800 m and were developed by the PRISM Climate Group at Oregon State University (Copyright© 2006, http://prism.oregonstate.edu, Map created June, 2006).

The scaling factors were calculated between the raster pixel at the centroid of each hillslope polygon delineated by GeoWEPP and the raster pixel at the nearby SNOTEL station for each watershed. The precipitation scaling factor is a ratio of the mean monthly precipitation at the hillslope to the mean monthly precipitation at the weather station. The minimum and maximum air temperature scaling factors are simply the differences between the mean monthly air temperature at the hillslope and at the weather station (Eqs. (1)–(3)).

$$T_{\text{max\_rev}} = T_{\text{max}} - T_{\text{max\_ws}}[\text{month}] + T_{\text{max\_slope}}[\text{month}] \quad (1)$$

$$T_{\text{min\_rev}} = T_{\text{min}} - T_{\text{min\_ws}}[\text{month}] + T_{\text{min\_slope}}[\text{month}] \quad (2)$$

$$PP_{\text{rev}} = PP * PP_{\text{slope}}[\text{month}]/PP_{\text{ws}}[\text{month}] \quad (3)$$

where $T_{\text{max\_rev}}$, $T_{\text{min\_rev}}$, and PP_{rev} are the revised maximum and minimum temperature, and precipitation at the centroid of each hillslope, T_{max}, T_{min}, and PP are daily observed values of maximum and minimum temperature and precipitation at the SNOTEL station, $T_{\text{max\_ws}}$, $T_{\text{min\_ws}}$, and PP_{ws} are PRISM mean monthly maximum and minimum temperatures and precipitation for the PRISM pixels at the location of the SNOTEL weather station, and $T_{\text{max\_slope}}$, $T_{\text{min\_slope}}$, and PP_{slope} are mean maximum and minimum temperatures, and precipitation of the PRISM pixels at the centroid of each hillslope.

Hourly historic weather data at each of the eight SNOTEL sites (Riverson et al., 2012) were used to create WEPP hourly weather input files. The disadvantage of using hourly weather files is that high-intensity storms can have intense peaks that quickly burst and often last less than one hour, which cannot be adequately represented with an hourly weather file. Alternatively, we created eight datasets of daily weather by using the CLIGEN model, a complimentary daily weather generator program (Nicks and Lane, 1989), to correct the peak rainfall intensities of each precipitation event. Within CLIGEN, rainfall intensities are generated sub-hourly based on the long-term average monthly characteristics for a specific weather station; however, the stochastically-generated peak intensity assigned to a particular storm might not match reality. The accuracy of the model was assessed using both the hourly and daily weather data in the assessment of simulated streamflow and sediment loading.

3.1.3. Soil input

By default, WEPP uses pedotransfer functions to estimate soil porosity, field capacity moisture content, wilting point moisture

content, and saturated hydraulic conductivity based on soil texture and rock content (Boll et al., 2015). These pedotransfer functions were developed for cropland and rangeland soils, and were not considered appropriate for steep, rocky, forested soils. Rather than rely on the default soil properties based on soil texture in WEPP, we built WEPP soil files using the measured soil properties listed for each of the soils in the 2007 Tahoe Basin Soil Survey map (USDA, NRCS, http://soils.usda.gov/survey/printed_surveys). All soil properties were taken directly from the soil survey, except baseline erodibility parameters, which were not explicitly provided. Cropland undisturbed erodibility parameters were calculated using default algorithms in the WEPP model based on soil texture. WEPP soil files representing undisturbed soil conditions were created for all 55 soils listed in the soil survey of the Lake Tahoe basin.

3.1.4. Forest canopy files

Due to variability in climate and soil characteristics, the forest canopy cover varies widely within the Lake Tahoe basin. Since canopy cover influences the distribution of incoming radiation and snowmelt rates we used 30-m resolution maps of canopy cover, created from the National Land Cover Dataset for 2001 (http://www.mrlc.gov), to calculate the average percent cover for each hillslope. Algorithms were developed to automatically assign a unique canopy cover to each hillslope in the model.

3.1.5. Baseflow characterization

We included a post-processing algorithm to calculate baseflow at each watershed outlet. This was done based on simulated deep percolation losses from individual hillslopes within the watersheds, similar to the approach of Brooks et al. (2010), Frankenberger et al. (1999) and Srivastava et al. (2013). Water draining vertically below the root zone was assumed to feed an underground storage reservoir, which was then released back to the stream at the watershed outlet following a linear reservoir concept (Dooge, 1960). Daily baseflow (Q_b) in the stream was calculated as a fixed proportion of the total water stored in the groundwater reservoir (S) (Eq. (4)). This proportion is referred to as the baseflow recession coefficient k_b, which typically varies from 0.01 to 0.1 (Beck et al., 2013; Sánchez-Murillo et al., 2014).

$$Q_b = k_b \times S \tag{4}$$

where Q_b, k_b, and S are baseflow, baseflow recession coefficient, and storage, respectively.

Steep watersheds underlain by consolidated bedrock can generally be assumed to be "water tight"; however, it is possible in arid locations that deep percolation recharges a deep groundwater system or bypass below the stream gauge. In "water tight" watersheds, the linear reservoir coefficient can be determined by examining the rate of change in streamflow with time during drought conditions (Brutsaert and Nieber, 1977; Sánchez-Murillo et al., 2014). A second linear reservoir coefficient (k_s) was employed to represent deep groundwater losses or deep seepage (Q_s), the proportion of the total groundwater reservoir that does not return to the stream above the stream gauging station (Eq. (5)).

$$Q_s = k_s \times S \tag{5}$$

where Q_s, k_s, and S are deep seepage, deep seepage recession coefficient, and storage, respectively.

The Tahoe basin is underlain by consolidated bedrock, which generally does not support large subsurface aquifers. Consequently, we initially assumed that watersheds in the Tahoe basin were "water tight". In watersheds where annual water yield was overestimated we considered simulating deep groundwater losses.

3.2. Model assessment

WEPP was first applied to all five watersheds without calibration using 17 years of weather data between 1989 and 2005. The linear reservoir coefficient was derived from the recession portion of the observed hydrograph for Blackwood Creek. We initially assumed that this coefficient did not vary within the Tahoe basin and used it to simulate baseflow for all five study watersheds. The model was assessed in its ability to predict snow accumulation and melt, daily streamflow, and fine and coarse sediment transport at each of the watershed outlets. Since the Lake Tahoe basin has eight SNOTEL weather stations, we compared the sensitivity of model predictions to the base weather station used to scale the temperature and precipitation weather data. In locations where the overall streamflow was overestimated, we explored the use of a secondary linear reservoir groundwater loss. This allowed us to account for water losses to a deep groundwater system or to represent bypass flow below the stream gauge station.

3.2.1. Streamflow predictions

The ability to predict daily streamflow data was assessed at each of the study watersheds using daily observed streamflow records available through the USGS (http://waterdata.usgs.gov/nwis/sw) for the entire 17 years simulation period. We also compared the simulated proportion of water predicted to be delivered via surface runoff, lateral flow, and baseflow to assess the effect of soil variability on the dominant hydrologic flow delivery mechanism from each of the watersheds.

3.2.2. Identification of sources of sediment

In addition to watershed scale assessment of the hydrologic components of the WEPP model, we assessed the ability of WEPP to simulate sediment loading from upland sources. The existing stream channel algorithms in WEPP were designed for small (<2.6 km^2) catchments and therefore were not appropriate to simulate sediment detachment, deposition, and delivery through the existing channel network for the five watersheds in this study. Direct comparison between observed sediment loading at the watershed outlet was based on the relative magnitude and distribution of sediment by the model compared with existing observed data. The sediment load data were analyzed using both hourly and daily weather input. Observed sediment load was calculated using the sediment rating curves developed by Simon et al. (2003) from observed fine and coarse suspended sediment concentration and streamflow data collected at each watershed outlet location by the USGS.

3.2.3. Model performance evaluation

Model simulations of snowpack accumulation and ablation were compared to observed data from the eight SNOTEL stations located in the Tahoe basin. Each of these stations has been recording daily snow water equivalent (SWE) depth along with temperature and precipitation for a minimum of 20 years. Model accuracy was assessed using both long term (>15 years) continuous daily streamflow and event-based sediment concentration. These data are publicly available for the outlet of the watersheds through the US Geological Survey and include measurements of the percent fine sediment (<0.063 mm, silt and clay size) for water samples having high sediment concentrations.

Model assessment was performed using several goodness-of-fit statistics:

– the Nash–Sutcliffe Efficiency (NSE) statistic (Nash and Sutcliffe, 1970), shows the agreement between observed and predicted values; A NSE value of 1.0 indicates perfect agreement between simulated and observed data. A NSE value of 0.0 indicates the

model is no better than simply using the mean of the observed data. It is possible to have negative NSE values which indicate poor or no agreement with observed data. Although calibrated hydrology models can often be fit to provide NSE near 0.70–0.90 for streamflow, especially when comparing monthly predictions, a NSE above 0.30, when determined using daily output from an uncalibrated model, is a good indication that the fundamental mechanics of the model are correct. Similarly, Foglia et al. (2009) considered a NSE below 0.2 insufficient, 0.2–0.4 sufficient, 0.4–0.6 good, 0.6–0.8 very good, and greater than 0.8 excellent;

– the deviation of streamflow volume (D_v), which describes model underestimation or overestimation of the observed values; The values of D_v, expressed in percentage, are negative if the model underestimates and positive if it overestimates;
– the mean difference (MD), which describes the overall bias of the model;
– the root mean square error (RMSE), which is similar to the standard deviation of the error between model observations and predictions; and
– the coefficient of determination (R^2), which is the proportion of the measured data explained by the model (Foglia et al., 2009; Moriasi et al., 2007).

The equations used to calculate the NSE, D_v, MD, RMSE and statistics are given below.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{6}$$

$$D_v = \frac{\sum_{i=1}^{n}(y_i - x_i) \times 100}{\sum_{i=1}^{n}x_i} \tag{7}$$

$$MD = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2 \tag{8}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \tag{9}$$

where n is the number of data points, x_i is the observed value, y_i is the corresponding simulated value, and $\bar{x}$ is the average observed value for the study period.

4. Results and discussion

4.1. Comparison of model results using daily and hourly weather data

The models based on daily and hourly data showed agreeable results, with the hourly weather data giving slightly better results compared to the daily weather data (Table 2). Despite the "very good" agreement between simulated and observed streamflow for most years, WEPP greatly underestimated one large flood event on the 1st and 2nd of January, 1997 for all five watersheds. Fig. 4 illustrates an example of the underestimation for the Blackwood Creek.

This flood event was caused by a severe rain-on-snow event. WEPP's ability to capture this event appears to depend on the SNOTEL station used. For example, we used four nearby SNOTEL weather stations to represent the climate at the Upper Truckee watershed. We obtained the best overall modeling results (NSE = 0.52) with the Heavenly Valley SNOTEL station, located at a high elevation (2616 m.a.s.l.), but we underestimated the 1997 flood event. However, when using the Fallen Leaf SNOTEL station data, located below the Upper Truckee Watershed (1901 m.a.s.l.), we were able to capture the extreme flood event and only slightly overestimate the peak flow. This suggests that the hydrologic response of a watershed to large intense storms is highly sensitive to how well the storm pattern is represented in the input data.

Using static scaling indices based on monthly temperature and precipitation maps for a single weather station may not be sufficient for these intense storms. Weather records showed that the 1997 event was a very warm, wet storm, which raised the air temperature much more at lower elevations near the lake than at higher elevations. Since our modeling approach assumed that the temperature lapse rate can be distributed at each hillslope based on static mean monthly data from PRISM maps, there is the possibility of errors in the extrapolated air temperature depending upon which base weather station was used. Similarly, Srivastava et al. (2013) found that using a lower elevation weather station better modeled peak snowmelt events. The fact that WEPP was able to capture the extreme peak flow event using the lower elevation data suggests that the fundamental hydrological processes in the model can accurately represent these peak events, when appropriately distributed weather data are used.

4.2. Snow hydrology assessment

The WEPP model was able to closely simulate the observed accumulation and melt of the snow pack at each of the eight SNOTEL sites despite their substantial differences in climate (Fig. 5). Characteristics of each SNOTEL site and a statistical summary of the agreement between simulated and observed daily SWE depth are presented in Table 3. Based on the available 17 years of data, the average annual precipitation varied substantially between the west- and the east-side of the Lake. For example, Echo Peak and Hagan's Meadow stations (Fig. 1) are relatively close to each other and situated at similar elevations (2338 m and 2370 m, respectively). However, Echo Peak recorded almost double the amount of precipitation (1497 mm) as Hagan's Meadow (776 mm). On average, WEPP overestimated SWE by 37 mm with a RMSE of 105 mm. The normalized percent error, which is the RMSE divided by the maximum observed SWE, averaged 16% for all the sites (Table 3). Applying the criteria of Foglia et al. (2009) to snowmelt, we conclude the model agreement to range from "very good" for the sites with relatively shallow, transient snow packs (Fallen Leaf and Hagan's Meadow) to "excellent" at the remaining sites that have deeper snow packs.

4.3. Streamflow and water yield assessment

The WEPP model successfully simulated streamflow and water yield for the wetter, western and southern watersheds with no calibration but overestimated water yields from the drier eastern watersheds. The only parameter set based on observed streamflow data was the baseflow recession coefficient. This was calculated as 0.04 from observed streamflow records at Blackwood Creek and was applied to all other watersheds. The differences between simulated and observed streamflow and water yield suggest that there may be unique geologic features to the drier east-side watersheds that are not adequately represented by the WEPP model and post-processed baseflow. Because of these differences, the assessment of simulated daily streamflow and average annual water yield is presented in two sections. The first section describes simulations of the wetter west- and south-side watersheds, and the second describes simulations of the drier east-side watersheds. Discussions in both sections are based on modeling results using hourly weather data as they generated overall better results compared to the daily weather data.

4.3.1. West- and south-side watersheds

Overall, the agreement between simulated and observed streamflow was "good" to "very good" for both the west- and south-side watersheds, i.e., Blackwood Creek, General Creek, and Upper Truckee. The NSEs calculated for 17 years of simulated

Table 2
Streamflow model results for each watershed.

Watershed	Weather station	Time step	Reservoir coefficient	Aquifer coefficient	NSE	D_v	RMSE	R^2
Un-calibrated								
Blackwood	Ward	Daily	0.04	0	0.37	0.14	4.45	0.51
Blackwood	Ward	Hourly	0.04	0	0.41	1.57	4.31	0.51
Blackwood	Tahoe City	Daily	0.04	0	0.29	−9.57	4.71	0.43
Blackwood	Tahoe City	Hourly	0.04	0	0.40	−8.91	4.35	0.48
General	Ward	Daily	0.04	0	0.59	0.24	2.54	0.62
General	Ward	Hourly	0.04	0	0.61	2.16	2.47	0.63
General	Rubicon	Daily	0.04	0	0.32	2.93	3.25	0.46
General	Rubicon	Hourly	0.04	0	0.15	3.78	3.64	0.41
Upper Truckee	Echo Peak	Daily	0.04	0	0.46	−2.84	3.32	0.59
Upper Truckee	Echo Peak	Hourly	0.04	0	0.42	−0.56	3.44	0.54
Upper Truckee	Heavenly	Daily	0.04	0	0.50	−3.71	3.20	0.71
Upper Truckee	Heavenly	Hourly	0.04	0	0.52	−2.36	3.13	0.71
Upper Truckee	Fallen Leaf	Daily	0.04	0	0.22	14.13	3.99	0.69
Upper Truckee	Fallen Leaf	Hourly	0.04	0	0.34	15.96	3.68	0.72
Upper Truckee	Hagen	Daily	0.04	0	0.42	−16.04	3.45	0.49
Upper Truckee	Hagen	Hourly	0.04	0	0.37	−12.36	3.59	0.45
Logan House	Heavenly	Daily	0.04	0	−28.36	208.83	2.23	0.23
Logan House	Heavenly	Hourly	0.04	0	−23.02	249.19	2.02	0.25
Logan House	Marlette Lake	Daily	0.04	0	−15.88	161.19	1.69	0.40
Logan House	Marlette Lake	Hourly	0.04	0	−15.06	206.03	1.65	0.39
Logan House	Fallen Leaf	Daily	0.04	0	−37.24	329.29	2.54	0.23
Logan House	Fallen Leaf	Hourly	0.04	0	−35.35	334.16	2.48	0.26
Glenbrook	Heavenly	Daily	0.04	0	−3.61	79.99	1.35	0.37
Glenbrook	Heavenly	Hourly	0.04	0	−3.38	81.44	1.32	0.40
Glenbrook	Marlette Lake	Daily	0.04	0	−1.36	55.20	0.97	0.51
Glenbrook	Marlette Lake	Hourly	0.04	0	−1.54	58.23	1.00	0.51
Glenbrook	Fallen Leaf	Daily	0.04	0	−6.38	127.00	1.71	0.52
Glenbrook	Fallen Leaf	Hourly	0.04	0	−5.73	131.18	1.64	0.56
Calibrated[a]								
Logan House	Marlette Lake	Daily	0.00008	0.00016	−4.88	3.91	1.00	0.26
Logan House	Marlette Lake	Hourly	0.00044	0.00089	−0.63	6.57	0.53	0.21
Glenbrook	Marlette Lake	Daily	0.00159	0.00104	0.39	2.35	0.49	0.42
Glenbrook	Marlette Lake	Hourly	0.00149	0.00103	0.45	1.30	0.47	0.46

[a] Model calibration was performed only on the simulations with the weather stations that generated relatively better results.
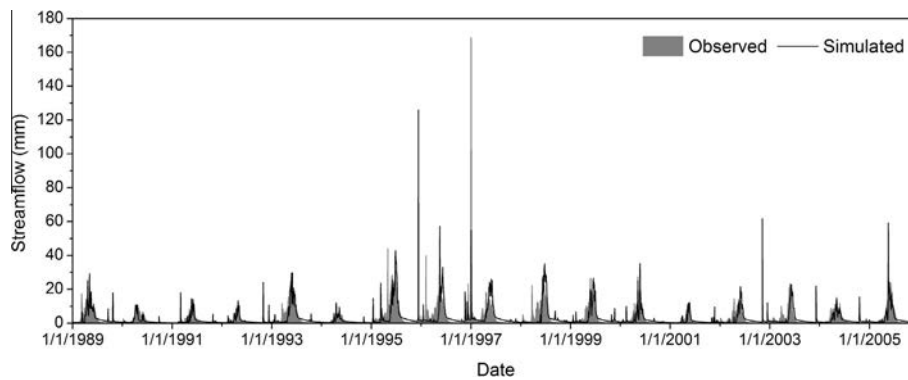

Fig. 4. Simulated and observed streamflow from the Blackwood Creek watershed, using the Ward SNOTEL station weather data.

streamflow were 0.41, 0.61, and 0.52 for the three watersheds, respectively (Table 2). The NSEs for individual years were as high as 0.80, 0.87, and 0.83 for Blackwood Creek, General Creek, and Upper Truckee, respectively, which would be considered "excellent" following the Foglia et al. (2009) criteria. Simulated average annual water yield fell into the "very good" category for all three watersheds (Table 4). It should be noted that none of these simulations involved any calibration.

4.3.2. East-side watersheds

The WEPP model substantially overestimated streamflow for both east-side watersheds of Logan House Creek and Glenbrook Creek, regardless of which weather station and time step were used (Table 2). The NSEs varied between −15.1 and −37.2 for

Logan House Creek and between −1.4 and −6.4 for Glenbrook Creek. The deviation of streamflow volume coefficient D_v showed overestimations as high as 334% and 131% for Logan House Creek and Glenbrook Creek watersheds, respectively.

One plausible explanation is that water that drains below the root zone enters a deep groundwater system that ultimately recharges the lake as groundwater flow. Alternatively, there exists a steep 470 m (1550 ft) drop in elevation from the lake surface to valley floor to the east at Carson City, NV and it is conceivable that groundwater could be draining eastward away from the basin. Tahoe basin has several known large geologic faults and the geology of the east-side of the basin has been documented to have high permeability rates (Nolan and Hill, 1991). We refer to this water as deep groundwater losses (Table 4). These deep groundwater losses
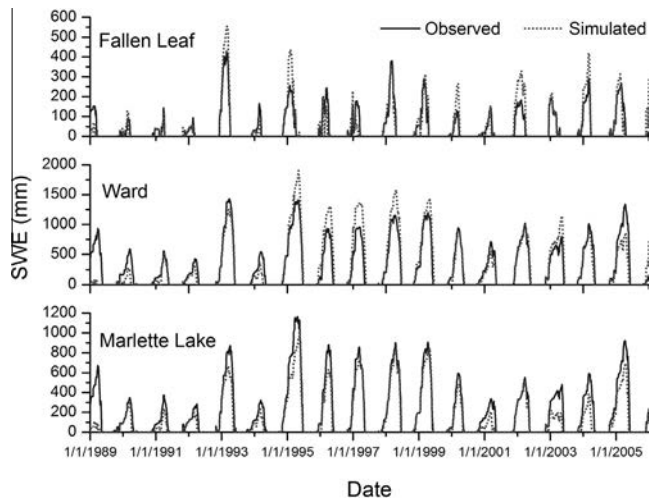
Fig. 5. Simulated and observed snow water equivalent (SWE) at three SNOTEL stations.

were simulated by calibrating the deep linear reservoir coefficient to optimize agreement between observed and simulated annual flow volumes at the watershed outlet.

4.3.2.1. Deep groundwater losses. When deep groundwater losses were included in the modeling, the NSE was greatly improved for Glenbrook Creek (0.45) and Logan House Creek (−0.63), although the latter remained a negative value. The NSE for Logan House Creek was largely biased by a few overestimated runoff events. We do not have sufficient information and data to quantify groundwater flow beneath the stream gauge, however, there is some compelling evidence that supports the idea that these watersheds have unique hydrogeologic flow processes.

The Logan House Creek stream gauge station is located more than 120 m above the average annual water surface elevation of

Lake Tahoe, just upstream of a steep region of rock outcroppings (Fig. 3), which have the potential for conducting flow through cracks and fissures. The stream gage in the Glenbrook Creek watershed, located north of Logan House Creek, was installed at the same elevation as Lake Tahoe, and therefore is likely less susceptible to subsurface groundwater losses beneath the station. If deep groundwater losses were related to the location of the stream gauge station and the geology directly below the stream gauge station, we would expect the groundwater losses in Glenbrook Creek to be less than the losses in Logan House Creek. This hypothesis is supported by our modeling results. The simulated groundwater loss required to match average annual water yield is 174 mm for Logan House Creek, more than two times greater than for Glenbrook Creek, which is 80 mm (Table 4). However, since there still seem to be groundwater losses in Glenbrook Creek additional geologic features may not be accounted for by the model.

Long-term summer streamflow recorded at both watersheds also points to the unique groundwater flow and storage in these east-side watersheds. During 1995–2000, the Tahoe region experienced above-normal precipitation, and the effect was evident on the summer streamflow in Glenbrook and Logan House Creeks but not so on the summer flow of west-side streams. Observed streamflow at the Logan House Creek stream gauge station remained well above 0.1 mm per day even during the driest summer months of these wet years. During the drier years, however, the flow would often drop to below 0.01 mm per day. Streamflow data of the Glenbrook Creek show the same response as Logan House Creek streamflow during these wet water years. In order for east-side streams to maintain high flows even during summer months a large source of subsurface spring flow must be present, suggesting a large groundwater storage, which discharges to the streams over time. It is worth noting that whether the deep groundwater losses are simulated or neglected, the WEPP model coupled with a baseflow component was able to capture the extreme differences in water yield between the east-side and west-side watersheds in the Lake Tahoe basin (Fig. 6).

Table 3
Characteristics of the eight SNOTEL sites in the Lake Tahoe basin and assessment of the snowmelt algorithms in WEPP. The Nash–Sutcliffe Efficiency (NSE), mean difference (MD), and root mean square error (RMSE) are calculated using simulated and observed daily snow water equivalent (SWE).

SNOTEL Site	Elevation (m)	Avg. annual precip. (mm)	Avg. annual T_{max} (°C)	Avg. annual T_{min} (°C)	Avg. annual peak obs. SWE (mm)	NSE	MD (mm)	RMSE (mm)	R^2	RMSE/Avg. annual peak obs. SWE (%)
Hagan's Meadow	2370	776	13.4	−4.3	472	0.72	−43	101	0.77	21
Fallen Leaf	1901	825	13.8	−2.6	218	0.73	6	40	0.84	18
Heavenly Valley	2616	844	9.6	−3.0	709	0.90	−51	92	0.96	13
Marlette Lake	2402	854	10.8	−1.3	650	0.88	−48	95	0.93	15
Tahoe City Cross	2072	879	12.8	−0.1	404	0.91	−16	47	0.93	12
Rubicon	2344	1044	10.4	1.0	781	0.84	−61	132	0.86	17
Echo Peak	2338	1497	12.0	1.1	1145	0.87	−94	170	0.94	15
Ward Creek	2028	1705	13.5	−2.6	938	0.82	14	159	0.89	17
Average	2259	1053	12.0	1.05	665	0.83	−37	105	0.89	16

Avg. = average.

Table 4
WEPP model performance for the five study watersheds (1989–2005). Simulated streamflow is separated into surface runoff, subsurface lateral flow, and baseflow. Values for Logan House and Glenbrook watersheds are after calibration by adding a second baseflow recession coefficient.

| Watershed	NSE Streamflow	Mean annual precipitation (mm yr^{-1})	Observed water yield (mm yr^{-1})	Simulated water yield (mm yr^{-1})	Simulated groundwater losses (mm yr^{-1})	Simulated % of total streamflow		
						Runoff	Subsurface lateral flow	Baseflow
Blackwood	0.41	1620	1045	1062	0	12.8	47.3	39.9
General	0.61	1281	738	753	0	28.2	10.3	61.5
UTR nr. Meyer	0.52	1315	894	873	0	43.8	25.3	31.0
Logan House	−0.63	807	96	102	174	7.7	9.3	83.0
Glenbrook	0.45	716	153	156	80	2.2	23.1	74.8
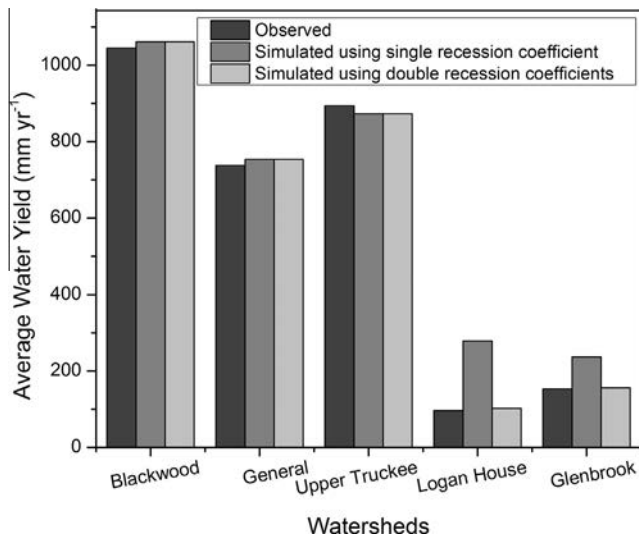
Fig. 6. Observed and simulated average water yield with a single recession coefficient (Blackwood, General, Upper Truckee) and observed and simulated water yield with two recession coefficients (Logan House and Glenbrook). Results are for a 17-year simulation period (1989–2005).

4.4. Total and fine sediment loading

A direct comparison between observed and simulated sediment load was not possible as instream sources were not simulated by the model. However, the relative magnitude, timing, and distribution of fine and course sediment simulated from upland sources matched well with observed sediment load data. As sediment load data are often skewed by a few extreme events, we present both average and median simulated sediment loadings. The observed data show that Blackwood Creek delivers considerably more sediment than each of the other watersheds (Table 5), followed by the Upper Truckee watershed, which on average contributes an order of magnitude less total sediment than Blackwood Creek. Similarly, WEPP simulated that the largest sediment load is delivered from Blackwood creek with minimal upland sediment transport from other watersheds.

The fact that the model simulated minimal upland soil loss from the rocky shallow soils in Upper Truckee suggests that the majority of observed sediment likely derives from instream sources. This generally agrees with Simon et al. (2003) who concluded that most of the sediment in the Upper Truckee River was due to bank erosion in flood plain regions downstream of Meyers near South Lake Tahoe City. The annual average observed sediment load from

east-side watersheds is minimal. Overall, simulated sediment loading using both the hourly and daily weather data was less than observed at the watershed outlets, suggesting that streams in the basin are a source of sediment rather than a net sink, which agrees with the findings of Simon et al. (2003). Simulated sediment delivery using daily weather data was greater than simulations using hourly data, indicating the potential for increased sediment load in the Tahoe basin from short duration storms. Simulated sediment transport was observed to occur during the peak runoff events, which coincided well with the periods of active transport in the observed data, see Fig. 7.

Simulated total sediment loading from WEPP was broken down into fine and coarse sediments, the former being more critical to water clarity in Lake Tahoe. The proportion of fine sediments in the total simulated sediment load delivered from upland sediments in Blackwood was simulated to be 55% (Table 5). This is greater, but relatively close, to the observed data, which indicates that roughly 40% of the total sediment load is composed of fine sediments (Fig. 8).

One advantage of using the WEPP model is its ability to provide average annual sediment load, runoff, and subsurface lateral flow for each of the soil types in the study watersheds. For example, Melody soils in Blackwood Creek, which are of volcanic origin and are often located in the steep, high elevation, "Badland" regions of the watershed, make up 14.9% of the total watershed yet deliver 65.8% of the total sediment load (Table 6). Areas with this soil type, therefore, would be important target areas for implementing erosion control practices in the Blackwood Creek watershed. For Ward Creek watershed with similar soils and situated to the north of Blackwood Creek, Stubblefield et al. (2009) estimated that the badlands contributed 10–39% of the total sediment load while occupying only 1.2% of the surface area of the watershed.

4.5. Hydrograph separation

Fig. 9 illustrates the three major components of the streamflow hydrograph: (1) surface runoff delivered directly to the stream, (2) subsurface lateral flow, and (3) baseflow for all five watersheds. The spatial variation across the watersheds is evident and adjacent watersheds exhibit rather distinct hydrologic responses. Blackwood Creek and General Creek, located on the west-side of the lake, have similar climates yet different hydrograph compositions, with the former contributed mostly from lateral flow while the latter from baseflow. Surface runoff is lower yet sediment load is greater in Blackwood Creek watershed than in General Creek. The primary factors controlling the proportion of surface runoff,

Table 5
Simulated average annual total and fine sediment (<20 μm) yield from upland hillslopes and observed sediment load at the watershed outlet.

Watershed	Weather input	NSE stream-flow	Sediment load (tonnes/yr)							
			Average				Median			
			Total		Fine		Total		Fine	
			Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.
Blackwood	Hourly	0.41	900	3098	487	1264	637	1990	356	771
General	Hourly	0.61	0	252	0	69	0	114	0	53
UTR nr. Meyer	Hourly	0.52	7	356	2	NA	0	287	0	NA
Logan House	Hourly	−0.63	0	4	0	NA	0	1	0	NA
Glenbrook	Hourly	0.45	0	5	0	NA	0	4	0	NA
Blackwood	Daily	0.37	2101	3098	1197	1264	794	1990	461	771
General	Daily	0.59	21	252	11	69	0	114	0	53
UTR nr. Meyer	Daily	0.50	41	356	24	NA	1	287	0	NA
Logan House	Daily	−4.88	191	4	167	NA	3	1	2	NA
Glenbrook	Daily	0.39	0	5	0	NA	0	4	0	NA

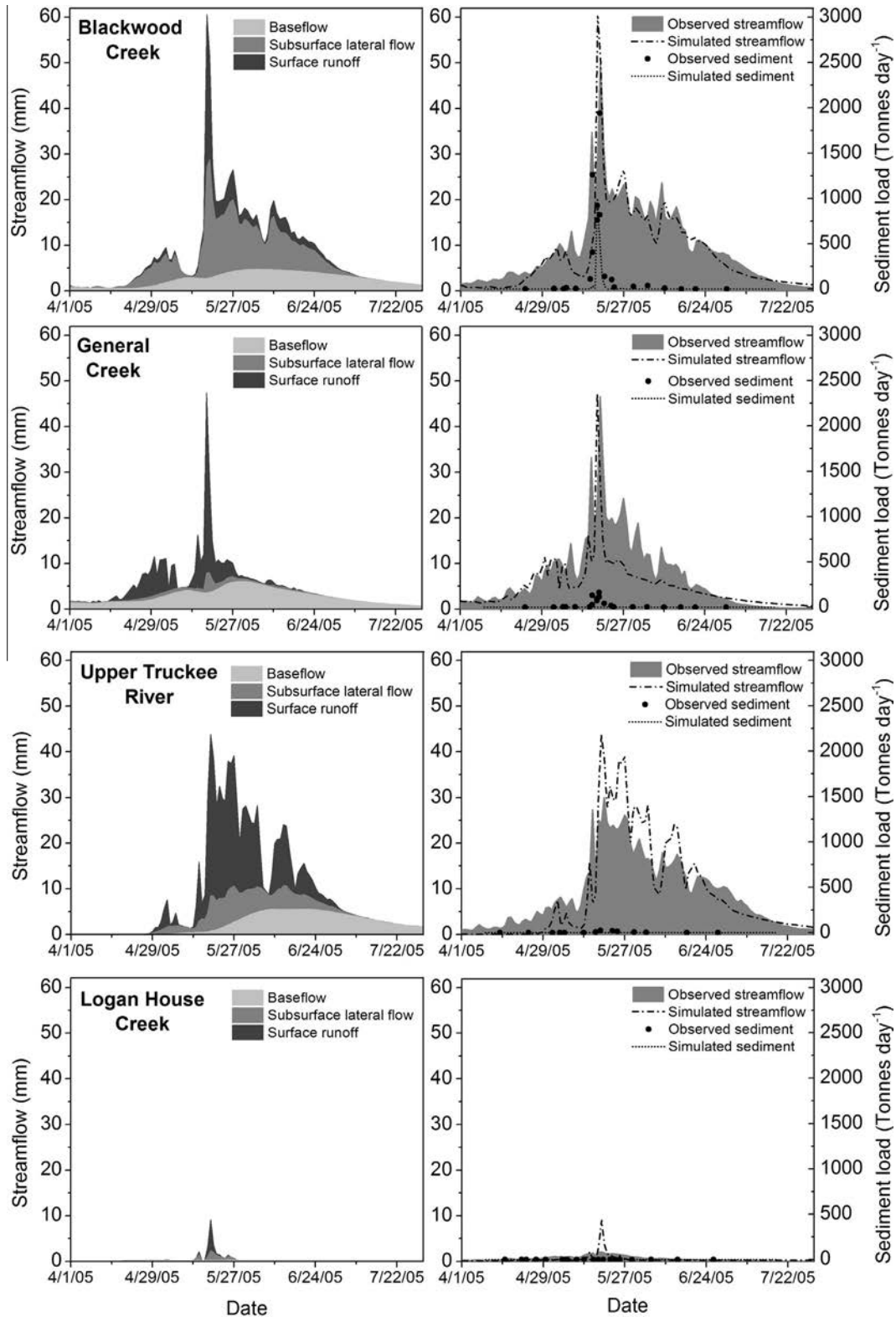NA = data Not Available; Sim., simulated; Obs., observed.

Fig. 7. Simulated and observed streamflow and sediment load (left) and simulated streamflow separated into baseflow, lateral flow, and runoff (right).

subsurface lateral flow, and baseflow in the hydrograph are the hillslope soil properties and topographic attributes within a watershed. The strong agreement between simulated and observed streamflow, in addition to the matching trends of simulated and observed sediment load, demonstrates WEPP's ability in characterizing different dominant hydrologic processes with minimal calibration.

A detailed breakdown of the simulated and observed streamflow and sediment loading for the 2005 season is presented in Fig. 7. We only show the results for four out of five watersheds since Logan House did not generate any sediments for the study period. The agreement between simulated and observed streamflow for each watershed is good. Blackwood Creek was the only watershed with upland contributions of total sediment. Suspended
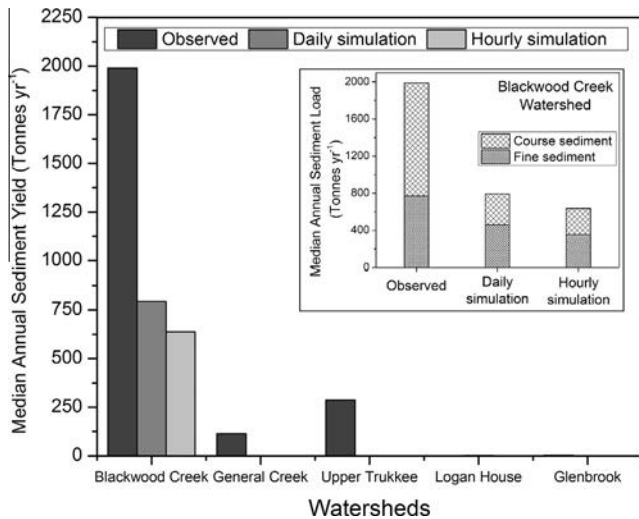
Fig. 8. Observed median annual sediment loading at the watershed outlet and simulated sediment loads delivered to the stream network using both hourly and daily weather data. Inset: Total sediment delivered to Blackwood Creek divided into fine (<20 μm) and coarse (>20 μm) particle sizes.

Table 6
Dominant hydrology and sediment loads for different soil types in Blackwood Creek.

| Soil type	Area (%)	Subsurface lateral flow (%)	Surface runoff (%)	Sediment delivery (%)	Parent material
Waca	31.3	7.7	6.4	8.9	Volcanic
Sky	26.7	21.2	31.6	0.7	Volcanic
Ellispeak	15.7	29.0	12.2	14.9	Volcanic
Melody	14.9	38.7	25.5	65.8	Volcanic
Kneeridge	6.5	1.0	1.6	0.0	Volcanic
Rock	2.5	0.6	14.2	9.2	Volcanic
Tahoe	1.3	0.7	1.9	0.0	Mixed
Tallac	0.6	0.1	0.2	0.3	Granitic
Pits	0.2	0.0	6.0	0.2	Granitic
Mountrose	0.2	0.0	0.2	0.1	Volcanic
Paige	0.1	0.2	0.0	0.0	Volcanic
Watah	0.1	0.7	0.0	0.0	Organic
Oxyaquic	0.0	0.0	0.2	0.0	Mixed
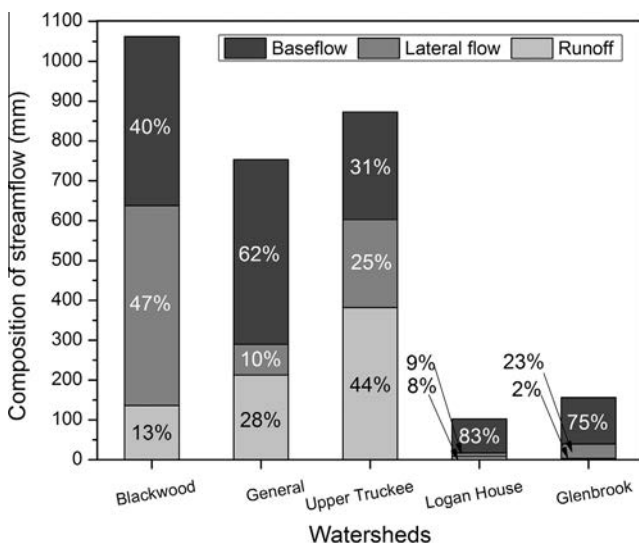
Fig. 9. Total simulated streamflow divided into baseflow, lateral flow, and runoff, and percentage of each relative to total streamflow.

sediment measurements by the USGS (http://cida.usgs.gov/sediment) indicate that General Creek was carrying sediment during this year; however, the WEPP simulations imply that the sediment was derived from streambeds and bank (Fig. 7). Notice that a large portion of the total streamflow in the Upper Truckee watershed was composed of surface runoff, yet both simulated and observed sediment loading from this watershed was negligible. The explanation for this discrepancy may be that the headwaters of the Upper Truckee River are composed mostly of rock outcrops with low infiltration rates, high runoff rates, and low erodibility. These rock outcrops (Fig. 3), which occupy 38.3% of the watershed, generate 72.8% of the total surface runoff yet only 2.8% of the total sediment load.

5. Summary and conclusions

A dense network of long-term climatic and stream gauging data in the Lake Tahoe basin provided a good opportunity to assess the predictive capabilities of the WEPP model and quantify the reliability of the model as a management tool for both gauged and ungauged regions of the basin. Specific input files and algorithms were developed to incorporate publicly available information on the spatial variability in climate, soils, and forest canopy, and to improve how steep, convergent topography is represented in the model. A list of the key sources of information incorporated into the model and the algorithms developed to represent the dominant hydrologic processes in Lake Tahoe are provided below.

– Each hillslope in the model was assigned a unique climate input file based on regional temperature and precipitation maps (PRISM) and measured data at SNOTEL stations.
– Publicly available soils (SSURGO), land use, and canopy cover maps were used to accurately represent the spatial variability within the study area.
– Soil hydrologic parameters were taken directly from the SSURGO soils database rather than from default parameters in the model.
– The topography of each hillslope was represented by multiple OFEs, which allowed the model to better represent flow convergence and variable source surface hydrology.
– Post-processing algorithms were developed to simulate baseflow using linear reservoir concepts.

We found excellent agreement between simulated and observed snow water equivalent for all eight SNOTEL sites located in the basin. We also found good to excellent agreement between simulated and observed streamflow and water yield for the wetter watersheds (Blackwood Creek, General Creek, and Upper Truckee River near Meyers) but the model overestimated water yield and streamflow for the drier eastern watersheds (Glenbrook Creek and Logan House Creek). Baseflow analysis revealed that this overestimation could potentially be caused by local groundwater leakage and storage processes in the east-side watersheds. This highlights the importance, limitations, and challenges of capturing the geologic variability with hydrologic models in ungauged basins. Despite the overestimation in streamflow, the general trends of simulated and observed sediment loading and annual volumes agree well.

It is critical in large mountainous watersheds to accurately capture spatial and subdaily temporal variability of weather input for accurate predictions of both rain-on-snow extreme events and sediment transport during short duration storms. Distributing temperature and precipitation using static monthly 30 year average precipitation and temperature data from local weather data was shown to be highly sensitive to the location of the weather station especially during peak rain-on-snow events. Simulated and observed streamflow matched well when both daily and hourly

weather data were used, with the hourly weather data resulting in slightly greater NSE and lower RMSE. Daily weather data are easier to access and simulations using daily time steps are shorter. However, for management purposes, and where data are available, the hourly time step will render more accurate results. Simulated sediment load was sensitive to whether storm events were simulated using the daily or hourly precipitation data. Simulated sediment load using daily weather data, where subdaily storm duration and intensity are estimated using stochastic algorithms, was larger and closer to the observed values than the simulated loads using hourly data.

Overall, we demonstrated that with the incorporation of these specific algorithms for climate, soil, canopy cover, and baseflow estimation, the WEPP model can successfully simulate streamflow and sediment transport in large upland watersheds with no or minimal calibration. The model was highly adaptable and transferable in the wetter, western and southern portions of the watersheds, however the model appears to be sensitive to geologic differences in the drier eastern portions of the watershed.

From these findings, we recommend that efforts be made to incorporate baseflow into the WEPP model, rather than carrying out post-processing calculations after the WEPP run is complete. The ability to model larger watersheds and obtain reasonable results for daily runoff leads us to also recommend that an improved channel routing and channel erosion capability be added to WEPP so that the channel sedimentation processes that are of greater importance on larger watersheds be more fully realized by the model.

The results from this study demonstrate that an adequate spatial representation of the input parameters can help improve overall streamflow predictions. Additionally, with the detailed level of representation of the input parameters, only minimal calibration (e.g., baseflow recession coefficient) was needed, suggesting that WEPP may be used for hydrological assessment in ungauged basins. WEPP's ability to differentiate between the three hydrologic components (surface runoff, subsurface lateral flow, and baseflow) provides unique opportunities for the management of watersheds affected by elevated pollutant loading. For the Lake Tahoe basin, isolating these three components can be especially helpful in understanding phosphorus movement through the landscape, and ultimately in improving the lake's water quality by identifying sensitive areas and decreasing the load of sediments and nutrients.

Acknowledgment

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