INCORPORATING GROUNDWATER FLOW INTO THE WEPP MODEL

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Abstract The water erosion prediction project (WEPP) model is a physically-based hydrology and erosion model. In recent years, the hydrology prediction within the model has been improved for forest watershed modeling by incorporating shallow lateral flow into watershed runoff prediction. This has greatly improved WEPP's hydrologic performance on small watersheds with seasonal flows, but the current version of WEPP is not capable of estimating base flow rates which are more important on larger watersheds. This paper presents a method under development to accumulate the daily deep seepage values estimated by WEPP, and return a fraction of that deep seepage to channel flow each day, resulting in reasonable base flow estimates. The modeling principles and processes will be described, suggested values for hydrologic parameters will be presented, and areas requiring additional research to support this approach will be presented. Examples of the application to forested watersheds in the Lake Tahoe Basin and northern Idaho will be presented.

INTRODUCTION

As populations shift to urban areas in the western U.S., there is an increasing demand for water for both domestic and commercial purposes. The main source of water in the western U.S. is surface water, and more than 60 million people depend on surface water from federal lands nationwide (Dissmeyer, 2000). Numerous empirical water yield models have been developed for forested watersheds (Troendle et al., 2009), but they are limited in their ability to address several current problems. These empirical models do not incorporate current forest management practices associated with low impact thinning and wildfire, they are not good at linking probabilities of low flows or high flows to water yields, and they do not lend themselves to incorporating future climate scenarios. New predictive tools are needed to address these current limitations to enable better planning and management of scarce water resources. This paper presents a proposed extension to the science in the physically-based Water Erosion Prediction Project (WEPP) model to overcome limitations on current water yield models.

BACKGROUND

Forest streams receive runoff from three main sources: surface, shallow lateral flow, and base flow (Ward and Elliot, 1995). Peak runoff rates are mainly influenced by surface runoff associated with large precipitation or snow melt events. The falling limb on hydrographs from upland forest watersheds is dominated by the lateral flow, and late summer flows often consist entirely of base flow.

The scale of the system is important in determining which runoff processes are most important. Three studies in Idaho and Montana help illustrate this point. When Elliot and Glaza (2009) installed weirs on twenty forested watersheds under 10 ha, they observed that only two of them generated long duration hydrographs typical of base flow, and another five generated hydrographs that lasted for several days during the snow melt season, typical of lateral flow. At this scale there was no apparent relationship between watershed size and runoff. Even when these watersheds were highly disturbed by logging or burning, there did not appear to be any surface runoff generated. Covert et al. (2005) reported on three forested watersheds following prescribed fire of 2, 7 and 9 ha, with observed runoff amounts of 28, 45, and 135 mm, where it appeared that runoff increased with the area of the watershed. Zhang et al. (2009) studied nested forested watersheds where a 110 ha watershed was nested within a 180 ha watershed. The smaller watershed generated 130 mm of runoff whereas the larger watershed generated 230 mm. In both cases, the runoff was seasonal, flowing from midwinter until July. These studies suggest that larger watersheds generate more runoff than small watersheds. One source of this variability is likely to be the differences in the dominant runoff processes, with surface runoff more important on the smallest watersheds, lateral flow on the middle-sized watersheds, and groundwater on the larger watersheds.

The WEPP model is a physically-based hydrology and soil erosion model (Flanagan and Nearing, 1995). It models hydrologic processes such as evapotranspiration, lateral flow, and deep seepage on a daily time step. Infiltration and surface runoff are modeled subhourly, and hillslope and channel sediment detachment, transport, deposition and delivery are predicted for each runoff event.

The 1995 release of the WEPP model only considered surface runoff from the hillslopes in water delivered to channels. Surface runoff was found to be a very poor predictor of runoff from small watersheds (under about 10 ha) modeled by both Covert et al. (2005) and Dun et al. (2009). For these small watersheds, the predicted runoff amounts and distributions were much closer to observed values when a new version of the WEPP model incorporating lateral flow was used. Yet when the same version of WEPP with surface runoff and lateral flow was applied to larger forested watersheds, in this case a nested pair of watersheds of 110 ha within 180 ha, Zhang et al. (2009) found that runoff was over predicted on the smaller watershed and under predicted on the larger watershed. They suggested that one of the likely reasons for the under prediction was that ground water processes were not included.

From the results of the modeling studies presented, we hypothesize that in order to improve the WEPP predictions for watersheds greater than about 10 ha, groundwater processes should be considered: the greater the size of the watershed, the more important to include groundwater. For example, Figure 1 is the prediction of the distribution of runoff in a hydrograph for Blackwood Creek in the Lake Tahoe Basin, using the method proposed in this paper for incorporating groundwater (Nash-Sutcliff Coeff compared to observed hydrograph = 0.4). This watershed has an area of 2861 ha, where the base flow is the only source of runoff after July 8. In this hydrograph, the surface runoff is 13 percent, the lateral flow is 47 percent, and the base flow is 40 percent of the total. This can be compared to Dun et al.'s (2009) where 100 percent of the runoff was attributed to lateral flow from a 9-ha forested watershed in the five years following a prescribed fire.

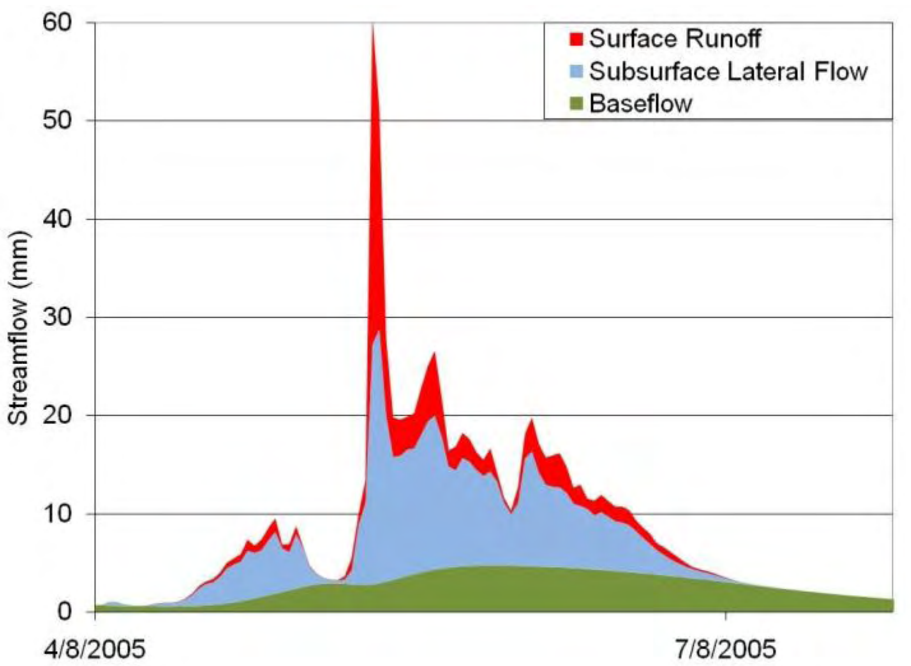

Figure 1 Predicted distribution of runoff from the Blackwood Creek Watershed in the Lake Tahoe Basin during the spring and early summer of 1995.

Several methods of modeling groundwater contributions to base flow have been developed. Highly complex finite element or finite difference models can be used if details of the geology are available (Ward and Elliot, 1995). Models have been developed that link surface and groundwater processes, but they usually require in-depth knowledge of aquifer properties and tend to be cumbersome to apply (Elliot et al., 2010). A simple way to consider ground water influence on stream channel flow in upland forest watersheds is a linear model that assumes that the base flow is a fraction of the amount of water in a fluctuating groundwater reservoir (Wittenberg, 1999):

$$q = k\,S \tag{1}$$

where q is the daily base flow (mm), k is the base flow coefficient, and S is the amount of water (mm) stored in a fluctuating groundwater reservoir. Barnes (1939) demonstrated that a streamflow recession curve could be separated into its three primary inflow components, surface runoff, interflow, and groundwater flow by plotting observed streamflow on semi-logarithmic paper. The steepest line after the peak described the runoff recession (i.e. the surface runoff coefficient), the intermediate slope represented the interflow recession (i.e. interflow coefficient) and the flattest slope near the end of the event represented the base flow recession (i.e. base flow coefficient). Brutsaert and Nieber (1977) described an alternative procedure for determining the base flow coefficient assuming both a linear and non-linear recession model based on the Boussinesq solution for drainage from large unconfined aquifers. In some cases the semi-logarithmic plot of individual recessions are curved (Wittenberg, 1999). These non-linear responses may be caused by multiple storages (e.g. wetlands, deep aquifers) that release water at slower rates than the near surface aquifers. It is also possible that water seeps into deep aquifers and does not reappear until further downstream below the stream gage. Deep seepage losses could be considered to be similar to equation 1, but the flow coefficient would likely vary with geology. There have been several studies which have attempted to describe variability in the base flow recession coefficients from neighboring watersheds using simple watershed characteristics such as soil depth, lateral hydraulic conductivity, and drainable porosity (Brutsaert and Lopez, 1998) or drainage density, geologic index and watershed slope (Vogel and Kroll, 1996, Brandes et al. 2005; Eng and Milly, 2007).

We believe that as the WEPP model is applied to larger areas, the importance of groundwater flows increases. In order to model this, it is necessary to accumulate the daily deep seepage predicted by WEPP in a groundwater reservoir. The outflow from that reservoir can then be routed daily to either base flow from the watershed, or into the ground water aquifer where it may be stored for long periods, may return to stream flows further downstream, or in coastal watershed, returned to the ocean. The remainder of this paper will describe two studies evaluating this approach for applying the WEPP model to larger watersheds.

ADDING GROUNDWATER CAPABILITY TO THE WEPP MODEL

Method When the WEPP model is applied to a watershed, the watershed is discretized into a series of stream segments and hillslope polygons on either side of those segments. The current watershed version of WEPP routes all predicted surface runoff and lateral flow through the stream network (Dun at al., 2009). For each hillslope polygon, it is possible to generate a separate daily water balance file and this file includes the values of surface runoff, lateral flow, and deep seepage. The deep seepage is mainly influenced by the soil profile and the hydraulic conductivity of the restrictive layer beneath the soil profile specified in the WEPP soil file. When the WEPP model is run, the user can specify that a daily “water file” be generated for that run. The water file contains the daily values for precipitation, snowmelt, surface runoff, lateral flow, “deep seepage” below the soil layers, and water content of the soil layers. In order to incorporate base flow from the fluctuating groundwater reservoir into the channel, the user can either use a single hillslope as representative of the watershed, or if greater geologic variation is to be modeled, the user can develop a script to access the water balance files for all hillslope polygons. This latter method, although slightly more complicated, will estimate a weighted average base flow accounting for the differences in the areas and geologic hydraulic conductivities of the watershed’s hillslope polygons. Once the WEPP run is complete, outside of the WEPP model, further analysis is currently required to add base flow to the watershed. This analysis can be done with any numerical processing tool that can read the text format of the water file. The Tahoe watershed analyses that follow were analyzed with a perl script program considering all hillslope polygons, whereas the Mica Creek analyses were carried out with a water file from a representative hillslope as the geology was more homogenous for that watershed. In both cases, an initial reservoir volume is assumed, base flow and deep seepage to groundwater are subtracted from it and deep seepage from the WEPP water file are added to it each day. The daily base flow estimate is added to the surface runoff and lateral flow in the water file to give a daily stream flow value as shown in Figure 1.

The predicted daily stream flows were compared to the observed flows graphically, and with the Nash-Sutcliff (N-S) efficiency statistic (Nash and Sutcliff, 1970). Coefficients for base flow and deep seepage to groundwater were manually altered for this study to maximize the N-S efficiency. On the Mica Creek Watershed, a sensitivity analysis was carried out on the base flow and deep seepage coefficients using the N-S efficiency to evaluate the relative sensitivity of the stream flow to these variables.

On the Tahoe watersheds, climate was varied within the large watersheds to account for variability of precipitation as predicted by the PRISM precipitation database.

The Lake Tahoe Basin Study The Lake Tahoe Basin is located on the eastern slopes of the Sierra Nevada Mountains, with the western and southern watersheds in California, and the eastern watersheds in Nevada. Five watersheds draining into Lake Tahoe were modeled using WEPP technology, three on the west or south side of the lake, and two on the east side (Figure 2 and Table 1). The size of the watersheds was large enough that groundwater processes would start to dominate the hydrologic response of the stream system and ranged from 546 ha (Logan House) to 3642 ha (Upper Truckee). Unique weather files were developed for each watershed, and the watersheds on the west required several climates to describe the variability of climate with elevation. There were two different geologic conditions in the Lake Tahoe Basin. On the west side of the basin, seepage losses to a deep aquifer were considered to be negligible. Assuming a linear reservoir, the base flow coefficient determined from observed streamflow recession hydrographs was 0.04. On the east side of the lake, however, it was readily apparent from the low observed water yield that there were significant deep seepage losses to the ground water aquifer (Table 1). Baseflow recessions were non-linear with extended periods of near constant flow during summer months (Figure 3).

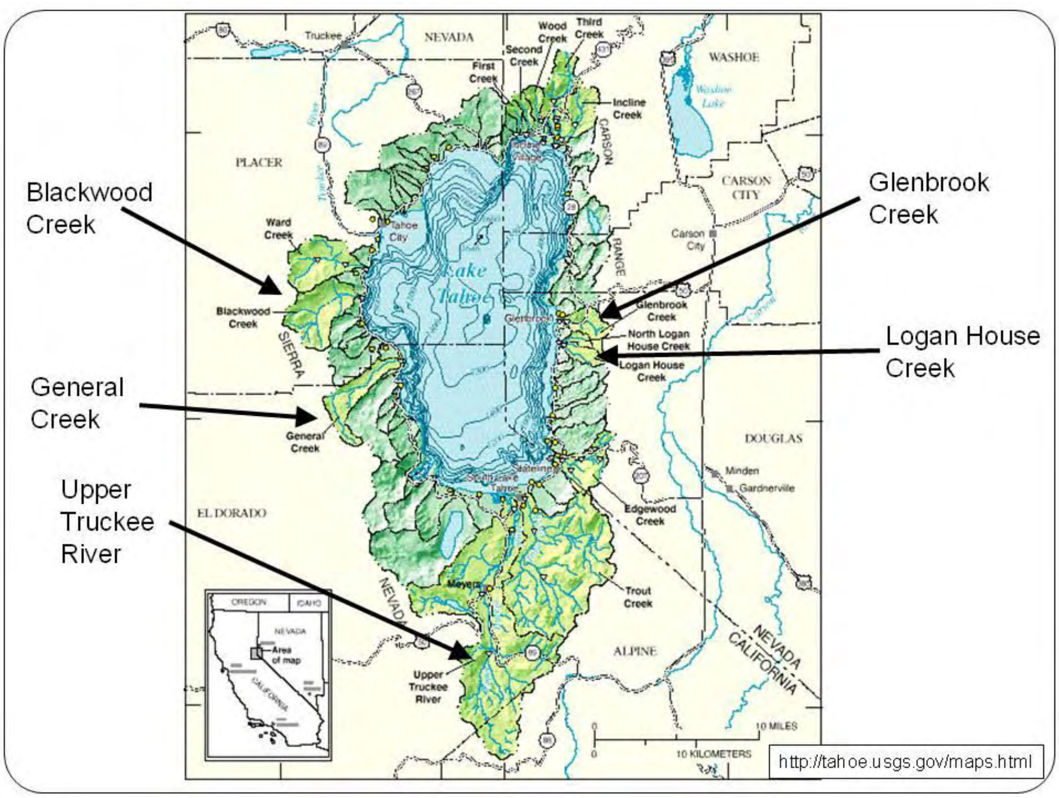

Figure 2 Watersheds analyzed for Lake Tahoe Basin study.

Table 1 Hydrologic assessment of the WEPP model for the five Lake Tahoe Basin watersheds. Averages are provided for the years 1989-2005. Simulated deep seepage represents flow that bypasses the stream gages station either recharging the lake directly, being stored in a groundwater aquifer, or being lost from the basin.

Watershed	Area (ha)	Mean Annual Precip. (mm/yr)	Obs. Water Yield (mm/yr)	Sim. Water Yield (mm/yr)	Simulated Percentage of Total Water Yield			Sim. Groundwater Losses (mm/yr)
					Surface	Lateral	Base	
Blackwood	2875	1620	1045	1062	12.8	47.3	39.9	0
General	1914	1281	738	753	28.2	10.3	61.5	0
Upper Truckee	3642	1315	894	873	43.8	25.3	31.0	0
Logan House	546	807	96	102	7.7	9.3	83.0	177
Glenbrook	1062	716	153	156	2.2	23.1	74.7	81

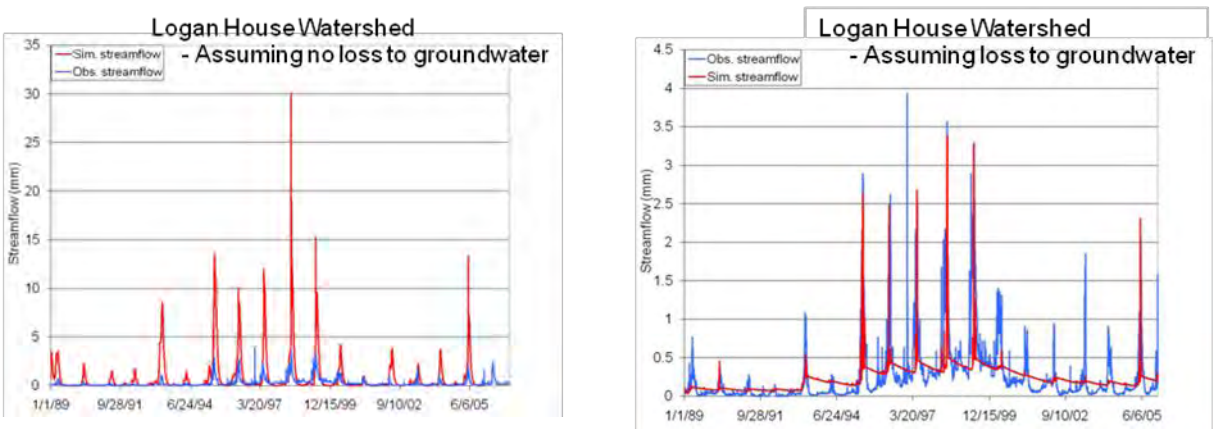

Figure 3 Predicted and observed hydrographs for Logan House Creek without and with losses to groundwater. Note the different vertical scales.

When the watershed runoffs were predicted with WEPP plus base flow, Nash-Sutcliffe (N-S) efficiencies were between 0.4 and 0.6 for all watersheds except Logan House where it was -0.4. The reason for this low value may be the limited number of runoff events on this low yielding watershed. It was also the smallest of the five watersheds. Comparing this to the smaller watersheds cited earlier, it is possible that the influence of groundwater was not so great in this watershed, and the hydrographs were more influenced by lateral flow processes. Other reasons for this may be due to poor prediction of the site-specific climate, or greater complexity in the groundwater processes than can be modeled by a simple linear model. The runoff predictions for Logan House Creek were significantly improved after losses to groundwater were incorporated in the model (Figure 3). For the Logan House watershed, the base flow coefficient was reduced to 0.0004 in order to maintain runoff well into the dry season as had been observed (Figure3), and a groundwater loss coefficient was found to be about 0.0012. Adding the groundwater loss improved the N-S efficiency from -0.4 to +0.42.

The greater percentage of surface runoff from the large Upper Truckee River watershed was due to the presence of rock outcrops in this watershed. For hillslope polygons dominated by rock outcrops, there would be little lateral flow or deep seepage. Figure 4 shows the observed and predicted hydrographs for General Creek on the west side of the lake. The base flow coefficient was 0.04 for this watershed, and the N-S efficiency for the hydrograph was 0.60 for this prediction.

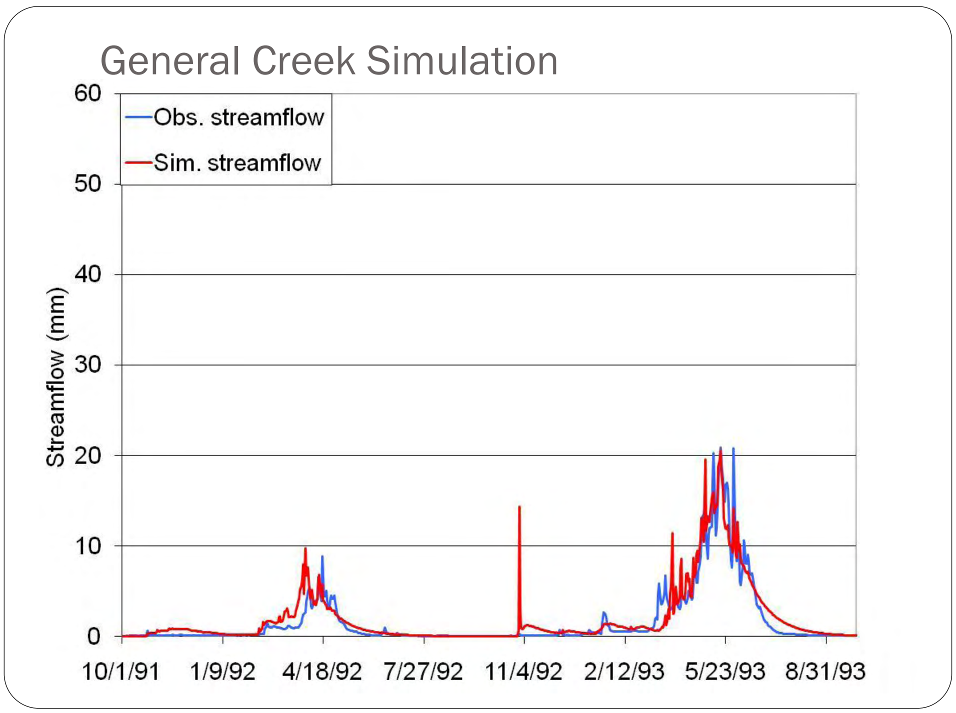

Figure 4 Observed and predicted daily stream flow from General Creek Watershed in the Lake Tahoe Basin.

Mica Creek Study Mica Creek Experimental Watershed is located at 47.176 latitude, 116.272 W longitude, approximately 95 km northeast of Moscow, Idaho. The paired and nested watersheds (Figure 5) were installed in 1990. Prior to the study, the watersheds had not been disturbed since they were logged in the 1930s. Roads were constructed in fall 1997 so the effects of the road construction could be monitored. In summer and fall 2001, half of watersheds one (139 ha) and two (177 ha) were harvested by the clear cut and partial cut methods, respectively. Watershed three (227 ha) was not disturbed leaving it as the control (Hubbart et al., 2007). For this study, we focused on watershed 4 (597 ha), which reflected the cumulative effects of treatments in watersheds 1, 2, and 3 plus an additional 54 ha of undisturbed forest.

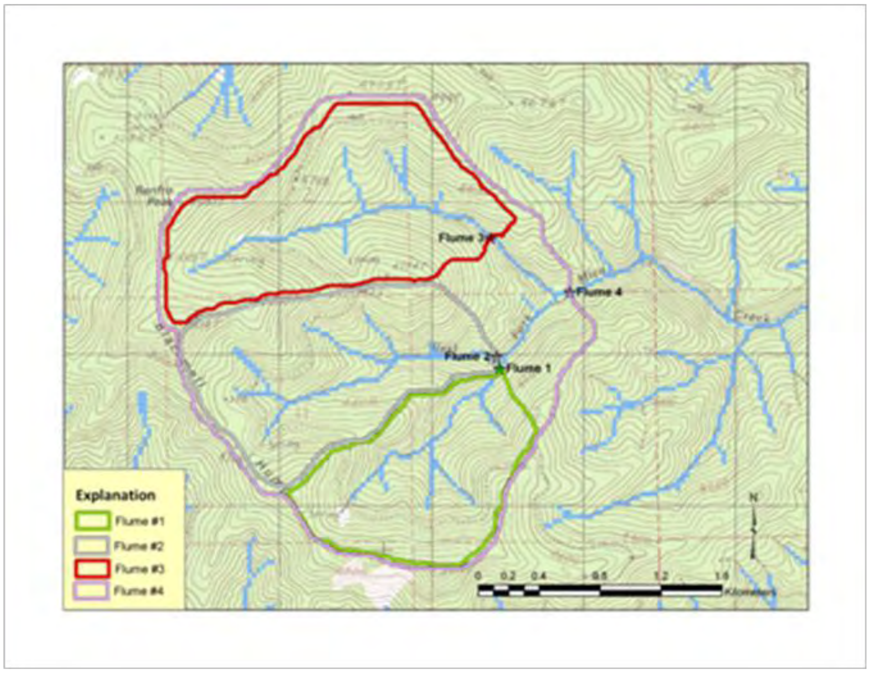

Figure 5 Watersheds and location of Flume 4 in the Mica Creek Experimental Watershed

Figure 6 shows the observed and predicted hydrographs for Watershed 4 using the observed climate, and Figure 7 using the climate with precipitation reduced by 200 mm to account for snow interception. Base flow and groundwater coefficients were 0.009 and 0.45 respectively, for both models.

The N-S efficiency for the runoff when using the observed climate was 0.33, while it increased to 0.55 for the reduced precipitation scenario. In both scenarios, the peak flow rates are similar, but the base flows are better predicted with the reduced precipitation scenario. Both Figures 6 and 7 show that there are challenges in predicting the magnitude of peak flows, which is the subject of further research. Peak flows in this climate are generally associated with rain on snow events. Both figures show that there were observed events that were not predicted in 1997, and predicted events that were not observed during the spring melt season in 1992. The recession curves are generally associated with lateral flow, and the base flows with the linear model, and both of these curves appear to be reasonably well predicted.

The results of the sensitivity of the hydrograph to the base flow and deep seepage coefficients are presented in Table 2 for the observed climate. Similar results were obtained for the reduced precipitation model. This analysis shows that the N-S efficiency is sensitive to variation in both coefficients, but is more responsive to changes in the groundwater coefficient. The reason for the smaller response in the N-S efficiency to changes in the base flow coefficient, particularly for the lowest groundwater coefficient, is that as the base flow coefficient is changed, the depth of water in the fluctuating groundwater reservoir changes. This can be seen in Table 3, where the amount of water in the fluctuating groundwater reservoir is highly dependent on both of the coefficients. When comparing Tables 2 and 3, it is apparent that there is some flexibility in selecting an appropriate base flow coefficient (within 50% of the normal value), as the fluctuating storage volume will adjust so that the base flow plus the deep seepage is equal to the

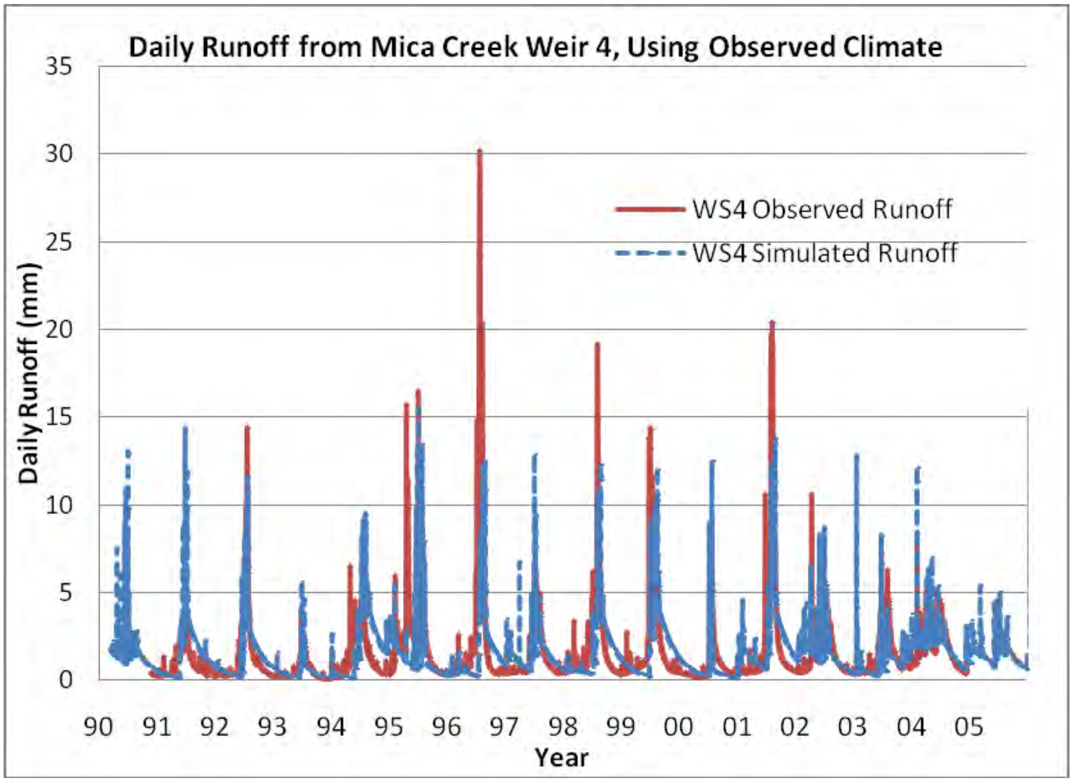

Figure 6 Observed and predicted runoff at weir 4 using the observed climate.

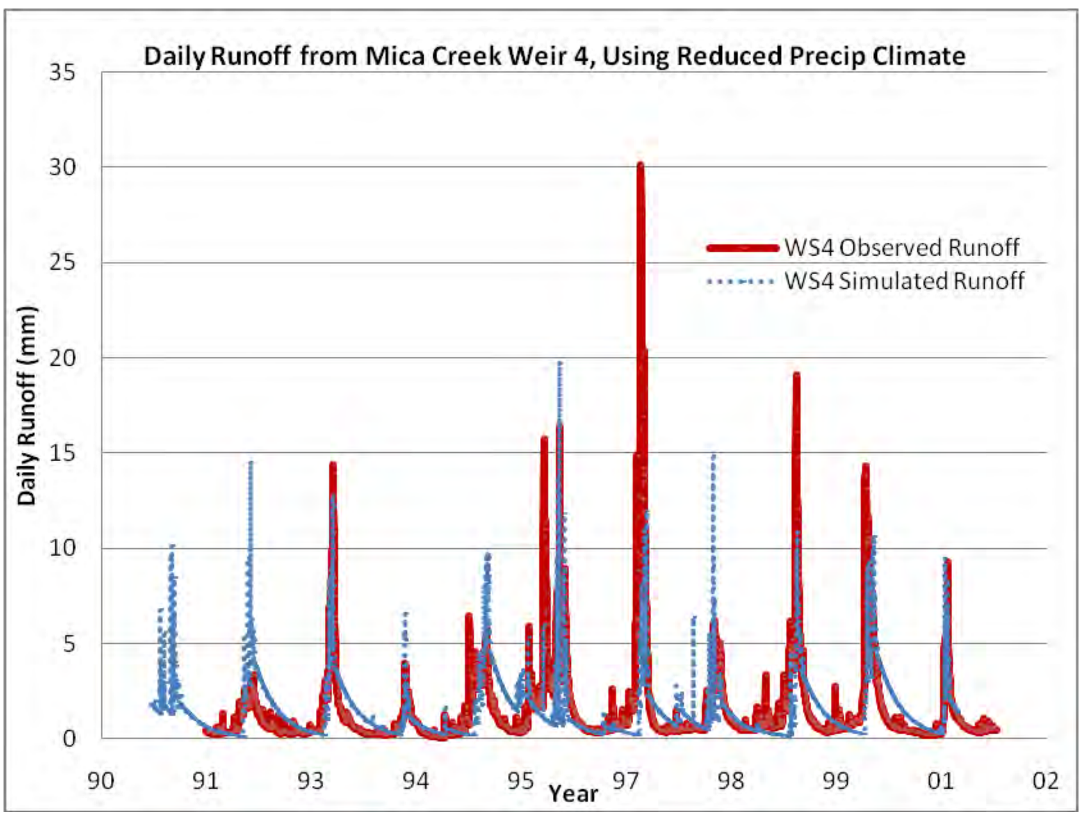

Figure 7 Observed and simulated runoff using a climate with precipitation reduced by 200 mm annually

deep seepage from the WEPP water file if the length of simulation is long enough. An error in estimating the correct groundwater coefficient, even within the 50% sensitivity window, can lead to a reduction in model accuracy.

Table 2 N-S efficiency table for sensitivity analysis for the normal precipitation model.

Groundwater Coefficient		Input values	Baseflow coefficient 50% < 0.005	Baseflow coefficient Middle 0.009	Baseflow coefficient 50% > 0.014
	50% <	0.18	0.34	0.34	0.34
	middle	0.35	0.37	0.33	0.29
	50% >	0.53	0.29	0.18	0.05

Table 3 Final value of storage in the temporary groundwater reservoir (mm) for the normal precipitation climate after 15 years of simulation.

Groundwater Coefficient		Input values	Baseflow coefficient 50% < 0.005	Baseflow coefficient Middle 0.009	Baseflow coefficient 50% > 0.014
	50% <	0.18	165	88	44
	Middle	0.35	320	171	86
	50% >	0.53	485	259	131

DISCUSSION

From the above two modeling exercises, it is clear that the addition of a linear ground water model will improve the WEPP model's accuracy for predicting runoff from larger watersheds. The watersheds on the western slopes of the Lake Tahoe Basin were relatively easy to model, probably because there was little opportunity for deep groundwater seepage. The challenge of getting a reasonable prediction for the Logan House Creek watershed was likely linked to the difficulty in establishing a groundwater coefficient value, and not in the base flow coefficient. The geology on the east slopes of the Tahoe Basin are reputed to be much more weathered, allowing greater water losses to deep seepage, and also allowing for a greater temporary storage volume to yield water after extended dry periods.

In the Tahoe watersheds, considerable care was taken in ensuring that the simulated climate was as close to the observed climate as possible. The importance of an accurate simulated climate was clear from the Mica Creek analysis where reducing the precipitation to mimic snow interception improved the model performance.

These two exercises show the importance of ensuring that accurate base flow and groundwater coefficients are determined for a given watershed. One of the questions raised from these two studies is why did such a large range in base flow coefficients occur (0.0004 to 0.04 for the Lake Tahoe Basin watersheds and 0.009 for the Mica Creek watershed)? With further inspection of the observed hydrographs, some of this variation can be explained. The lower base flow coefficients tend to support runoff further into the dry season, as was found to be the case for another study on a watershed about 100 km north of Lake Tahoe, where a base flow coefficient of 0.002 was needed to maintain base flow through two years of drought (Collins et al. 2010). The results in Table 3 suggest that this modeling approach tends to adjust the amount of water in the fluctuating reservoir in response to changes in the base flow coefficient. In all these watersheds, aquifer properties and topography play a major role in influencing the base flow. This initial study suggests that there is a need to evaluate base flow and groundwater seepage coefficients over a wide range of topographic and geologic conditions to see if typical values can be found that can be broadly applied to ungauged watersheds.

The deep seepage coefficient for the Mica Creek (0.45) analysis is larger than in the Tahoe Basin (0 to 0.0012). This may be due to the size of the watershed, as was originally hypothesized, that larger watersheds deliver greater amounts of groundwater than do small watersheds. In an earlier unpublished analysis of Mica Creek, deeper soils and a base flow coefficient of 0.007, similar to the results of this study, was necessary to obtain reasonable runoff hydrographs. Studies have shown that increasing soil depth decreases lateral flow and increases predicted evapotranspiration (Elliot and Wu, 2005). It is likely that the increased soil depth in the earlier study did not require losses to the aquifer because of this increased evapotranspiration.

These results suggest that additional modeling studies on watersheds with different climates, areas and geologies are needed to better understand the relative values and importance of the base flow and ground water coefficients.

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