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USING CCHE1D TO IMPROVE STREAM FLOW ROUTING CAPABILITIES OF THE WEPP MODEL

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ABSTRACT

Accurate assessment of forest management practices on sediment yield and delivery requires the use of physically based simulation models. Upland erosion rates are commonly simulated with the Water Erosion Prediction Project (WEPP) model. Since the WEPP was designed to evaluate erosion rates from fields and small watersheds without stream channels, it does not simulate hydrodynamics or sediment transport (especially important in watersheds larger than approximately one square mile). To resolve this problem, WEPP was linked via an interface program to CCHE1D, a one-dimensional, channel network, hydrodynamic-sediment transport model. The linked model was run with data from Caspar Creek Experimental Watershed, California, a long-term, U.S. Forest Service, experimental watershed. Calibration of the hydrodynamic and sediment transport capabilities of CCHE1D were completed separately and only the hydrodynamic results are presented here. A test simulation with 13 consecutive days of rainfall resulted in predicted runoff volume that was in very good agreement with observed runoff volume (less than 1% difference). However, due to limitations of the output data from the WEPP model, only daily, rectangular hydrographs could be generated. After routing the flows, daily peak discharge rates had an average relative error of 97% and a Nash-Sutcliffe coefficient of 0.41. These results are a marked improvement over the current method that WEPP uses for routing flows; with an average relative error of 1,110% and a Nash-Sutcliffe coefficient of -70.1. These results suggest that by using an appropriate hydrodynamic model to route flood-flows, the accuracy of peak flow estimates is increased by over two orders of magnitude.

KEYWORDS. WEPP, CCHE1D, forest management, TMDL, sediment, erosion

INTRODUCTION

Most total maximum daily load (TMDL) analyses make extensive use of computer models (U.S.E.P.A., 2002) because of the need to evaluate large areas with heterogeneous characteristics. The Water Erosion Prediction Project (WEPP) Model (Flanagan et al., 1995) is a physically based, erosion simulation model commonly used to assess management-related surface erosion in agricultural (Zhang et al., 2003) and forest (Foltz and Elliot, 1999) settings. Its ability to evaluate spatiotemporally distributed climatic and physiographic variables make it nearly ideal for use in site-specific, sediment TMDL evaluations. Although developed primarily for fields and small watersheds (area less than 2.6 km^2), the WEPP model has been extended for use in larger watersheds (area up to 130 km^2 (U.S.E.P.A., 1999)). As an upland erosion model, it has two limitations that need to be improved before the model can be used for simulations in larger watersheds: network hydrodynamics and sediment transport.

The WEPP Watershed model attempts to model hydrodynamics and sediment transport by using a simplified hydrologic model and a single, sediment transport capacity equation (Ascough et al., 1995). To move water from hillslopes, to and through a channel network, WEPP applies modifications to the Rational (McCuen, 1998) and Soil Conservation Service Curve Number (Soil Conservation Service, 1991) methods. These methods are not hydrodynamic modeling techniques, since they are only capable of determining the peak runoff and/or volume (U.S.A.C.E., 1994), and they ignore the physical processes governing open channel flow. The accuracy of watershed-scale runoff simulations is severely limited by not including a hydrodynamic procedure. This inadequacy also limits the accuracy of sediment transport rates which are highly dependent on the accuracy of discharge rates.

The second limitation of the WEPP model is its method for computing sediment transport. The WEPP model uses a modified form of Yalin's bedload equation (Yalin, 1963) to compute sediment transport capacity in rills, interrill areas, and channels. Yalin's equation has been successfully applied to overland flow sediment transport in interrill areas by several authors (Alonso et al., 1981; Ferro, 1998; Finkner et al., 1989; Wicks and Bathurst, 1996), but has been demonstrated as inadequate for bedload transport in rivers (Bravo-Espinosa et al., 2003). The purpose of this research project is to develop and implement a procedure to couple the WEPP model with the CCHE1D hydrodynamic and sediment transport model (Wu et al., 2004) such that current limitations of the WEPP model are reduced significantly.

METHODS

Study Area

The Caspar Creek Experimental Watershed (CCEW) is located on the Jackson Demonstration State Forest in northwestern, coastal California, approximately 15 km southeast of Fort Bragg, California. The CCEW consists of the 424-ha South Fork and the 473-ha North Fork sub-watersheds (Henry, 1998). These two tributary basins are located in the headwaters of the 2,167-ha Caspar Creek watershed, which discharge into the Pacific Ocean near the community of Caspar, CA. Hillslope gradients are generally less than 70 percent, but are frequently over 70 percent adjacent to deeply incised streams (Henry, 1998). The elevation of the watershed ranges from 37 to 320 m.a.m.s.l. (meters above mean sea level). The primary land-use/land-cover is coniferous forest, consisting mainly of dense stands of second-growth Douglas-fir (*Pseudotsuga menzieii*) and coast redwood (*Sequoia sempervirens*) (Henry, 1998). The soils in the study area are well-drained clay-loams 1 to 2 m in depth (Henry, 1998). Soils typically have high hydraulic conductivity (50-100 mm/hr), and subsurface stormflow is rapid, producing saturated areas of only limited extent and duration. CCEW experiences a Mediterranean climate, which is typical of low-elevation watersheds on the central North American Pacific coast (Henry, 1998). Mean annual precipitation is 1,190 mm, ranging between 305 to 2,007 mm, over the period 1962-1997. Streamflow follows the precipitation pattern; with winter maximum flows three orders of magnitude larger than summer minimum flows. Highest streamflow occurs generally in November through February low-intensity, long-duration rainfall events. The sediment transport regime is primarily sediments smaller than large gravels, including a significant sand and silt component (Henry, 1998).

Modeling Components

The WEPP model (version 2004.610, released June 2004) requires four input data files to run: 1) climate, 2) slope (landscape geometry), 3) soil, and 4) plant-management. The climate data required by the WEPP model were extracted from the CCEW databases, including daily values for temperature (max/min), solar radiation, and wind speed, and instantaneous values for precipitation. Landscape geometry data are automatically generated with TOPAZ (Garbrecht and Martz, 1995), a digital landscape evaluation tool that uses 30-meter digital elevation models (DEMs). All soil property data were extracted from the CCEW databases, including, depth, particle size gradation, organic matter content, and cation exchange capacity. The forest management files from the WEPP databases were used to describe plant/management conditions. These files were modified to adjust plant spacing, tree height, and leaf-area index based on typical growth and yield conditions for the region (Lindquist and Palley, 1967; McArdle et al., 1961).

The CCHE1D channel network model computes unsteady flows using either the dynamic or non-inertia wave approaches (Vieira and Wu, 2002). For all simulations discussed in this project, the dynamic wave simulation mode was used. The CCHE1D model provides several well-known equations for the determination of sediment transport capacity, which were temporarily disabled for this project to calibrate the hydrodynamic portion of the model. Otherwise, CCHE1D was used ‘as is’ for all flow simulation, in accordance with instructions provided by the model developers (Vieira and Wu, 2002).

CCHE1D needs the boundary conditions (inflow hydrographs) for each reach. All daily hydrographs obtained from WEPP were converted to continuous, time-series hydrographs for purposes of routing the flow with CCHE1D. For the project described in this report, it is assumed that daily runoff events are continuous as long as there are less than three (3) days separating consecutive events.

The Nash-Sutcliffe coefficient (NS) of model efficiency is used as a statistical criterion for evaluating hydrologic goodness of fit between measured and predicted values for each method (Nash and Sutcliffe, 1970). For this research, two output parameters will be evaluated: daily streamflow volume and peak streamflow discharge rate.

RESULTS

The TOPAZ-generated watershed structure contained 18 unique hillslopes and 7 channel segments. The erosion simulation was conducted using the WEPP Windows interface, for a 13-day simulation period from January 3, 1995 to January 15, 1995. Erosion simulations were conducted using input parameters developed from site-specific data. Since CCHE1D needs values for observed baseflow, and WEPP does not directly produce a value for baseflow, it was assumed that baseflow was the sum of the percolation and lateral subsurface flow depths (given in the daily water balance output file).

From the initial simulations, it was readily apparent that the WEPP Hillslope output data are inadequate to predict accurate outflow hydrographs. Since these data are daily summaries, the output cannot produce a true hydrograph. These data produce rectangular, step-function shaped hydrographs. The WEPP model assumes, for purposes of generating sediment loads from hillslopes, that the flow exiting the hillslope is constant at its peak rate for the entire duration of the storm event. To demonstrate this inadequacy, the rectangular hydrographs generated from WEPP, combined with daily baseflow, were routed through the South Fork Caspar Creek channel network using the time-series (Figure 1) hydrograph mode of CCHE1D. The observed daily runoff volume and peak rates were compared to those predicted by WEPP Watershed and CCHE1D.

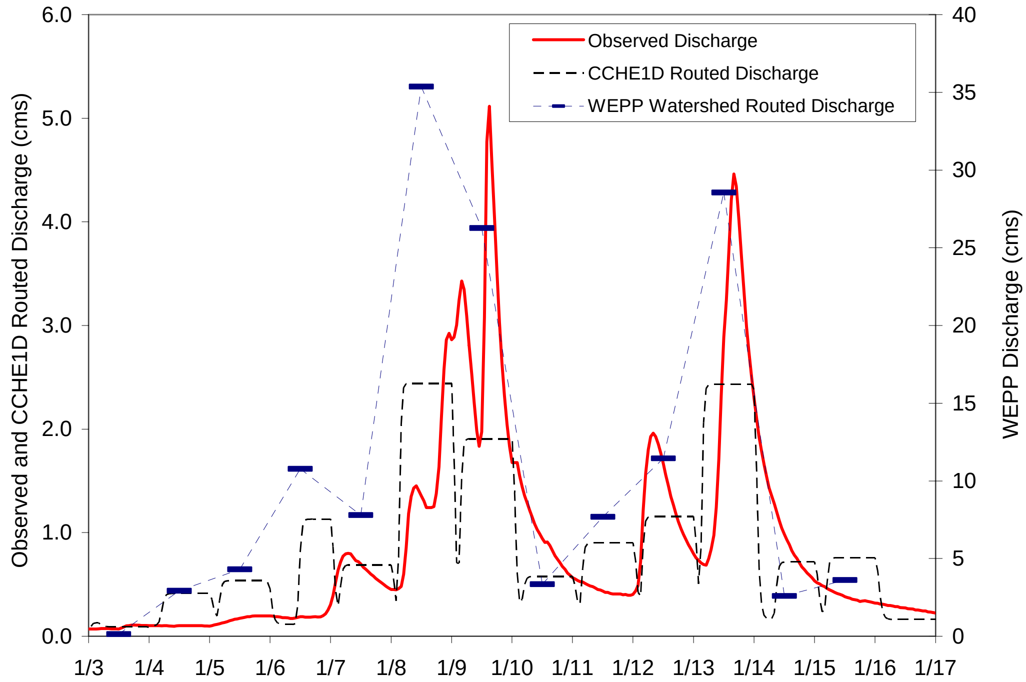

Figure 1. Observed discharge at South Fork Caspar Creek (January 3-18, 1995) vs. Predicted discharge (by WEPP Hillslope) routed with CCHE1D.

Both WEPP Watershed and CCHE1D adequately predict (within 0.5 and 0.8%, respectively) the observed runoff volume for the 13-day period illustrated in Figure 1. Visual inspection of Figure 1 clearly indicates that rectangular hydrographs created by WEPP Hillslope (and routed with CCHE1D) bear very little resemblance to the observed hydrographs. It also appears that when using CCHE1D to route WEPP Hillslope hydrographs, small events (e.g., Jan. 4, Jan. 5, Jan. 6, Jan. 11, Jan. 14, Jan 15) have over-predicted peak rates, and that larger events (e.g., Jan. 8, Jan. 9, Jan. 10 Jan. 12, and Jan. 13) have under-predicted peak rates. This observation is confirmed with data in Table 2. When using CCHE1D to route WEPP Hillslope hydrographs, peak rates are over-predicted by as much as 350% and under-predicted by as much as 69%, with a Nash-Sutcliffe ratio: NS = 0.41. When using WEPP Watershed, the estimated daily peak flow rates are uniformly over-predicted by a minimum of 13% and a maximum of 4,200%. The Nash-Sutcliffe ratio for these data is: NS = -70.1. This clearly indicates that using CCHE1D to route WEPP Hillslope hydrographs provides much improved estimates peak flow rates, over WEPP Watershed.

DISCUSSION

Based on the above analysis, it is clear that the current WEPP output data cannot be used to predict continuous runoff hydrographs, because the output data are daily summaries (providing inadequate sub-daily hydrograph information). Rectangular hydrographs, for this watershed (and likely many others), do not adequately represent the runoff hydrographs. When using only daily hydrograph information, several problems are apparent: 1) Trying to represent a continuous, single hydrograph produces discontinuities between daily events. Hydrograph ascension and recession limbs unrealistically rise and fall. 2) Daily events with multiple peaks cannot be evaluated. 3) Runoff events that span multiple days are not evaluated correctly. None of the flow generated on one day is carried over to the next day. 4) Closely spaced runoff events do not display auto-correlation and inter-dependence, as they should.

To generate a hydrograph that can be compared to observed data, the WEPP hillslope output pass files need to be modified in one of two ways. 1) Write the runoff volumes and rates for regular, sub-daily time intervals (hourly values would be adequate), such that the actual runoff hydrograph can be exported; or 2) include a value for Time-to-Peak, such that daily, triangular

(SCS-type) hydrographs can be created to approximate the actual hydrograph. It was beyond the scope of this project to re-write the WEPP program code to accomplish either of these tasks. However, this is certainly a viable project for future research

The interface developed for this study was more than just a data management algorithm. Although handling voluminous data is a significant task, there are two very important issues addressed in the interface algorithm: spatial continuity and time-step synchronization. Spatial continuity addresses the issues of differences in analytical scale and watershed network structure. As discussed previously, WEPP evaluates erosion processes at small scales (e.g., hillslope and sub-watershed), while CCHE1D evaluates hydrodynamic-sediment transport processes at both small (e.g., stream reach) and large (e.g., watershed network) scales.

CONCLUSIONS

Modeling upland erosion and in-channel sediment transport requires, at this time, two separate models. The WEPP model is used to generate upland hydrographs and sediment loads. These hydro- and sediment-graphs can then be routed through a watershed-channel network with a CCHE1D, a hydrodynamic-sediment transport model. However, to couple these two models, an interface program is required. The interface program created for this project uses the TOPAZ data generated by the CCHE1D and WEPP interfaces as a relational key for managing the runoff and sediment load databases.

Linking an upland erosion model like WEPP with a hydrodynamic-sediment transport model like CCHE1D is certainly viable. Results of this study demonstrate that the accuracy of peak flow estimates is increased by over two orders of magnitude when flow volumes are routed with an appropriate hydrodynamic model. However, to produce a linked model that is useful, the WEPP model needs to be updated. Without access to the sub-daily computations, it is very difficult to calibrate the model with observed flow data, and it is expected that similar difficulties will arise when calibrating sediment transport data. Future versions of WEPP should allow access to these data, either directly while the simulations are running, or indirectly through a series of output files that can be post-processed.

The objective of this project was to develop procedures for coupling a physically based upland erosion model (WEPP) with a fully dynamic, physically based hydrodynamic-sediment transport model (CCHE1D). Due to limitations of the WEPP model, this objective was not fully realized. However, with modifications to the WEPP model, it is expected that this goal could be realized. The resultant product would be a comprehensive, integrated watershed-scale, erosion simulation, and sediment transport model. This improvement is important for increasing the overall accuracy of surface runoff/erosion estimates associated with implementation of effective erosion control measures within ungaged watersheds. With the new procedures in place and validated, the hybrid CCHE1D-WEPP model would be available for use in modeling effectiveness of varying BMP systems used for sediment TMDL implementation, such that multiple, spatially varied management activities can be modeled and evaluated.

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