Extending WEPP Technology to Predict Fine Sediment and Phosphorus Delivery from Forested Hillslopes

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Abstract: In many watersheds, including the Great Lakes and Lake Tahoe Basins, two basins where the land cover is dominated by forests, the pollutants of concern are fine sediments and phosphorus. Forest runoff is generally low in nitrogen, and coarse sediment does not adversely impact the quality of lake waters. Predictive tools are needed to estimate not simply sediment, but fine sediment ($\leq$10 μm) and phosphorus delivery from forested hillslopes. We have been developing methods for making such predictions with the Water Erosion Prediction Project (WEPP) model. WEPP is a physically-based hydrology and erosion model that runs on a daily time step, with sub-daily runoff, erosion and sediment delivery predictions. The fine sediment delivery for forested hillslopes is relatively easy to estimate because WEPP provides a breakdown of primary particles (clay, silt and sand) and aggregates (silt size aggregates (30 μm) and sand size aggregates (300 μm)). The size distribution of eroded sediment is disaggregated to determine the amount of fine sediment below a user-specified size in each of the particle classes. Phosphorus transport is complex, as research has shown that in steeper forested watersheds, the dominant hydrologic flow paths are lateral flow and base flow. Surface runoff and sediment delivery are generally minimal unless the site has been disturbed by logging or fire, or the soil layer is thin (shallow to impermeable bedrock). Thus, in an undisturbed forest, the main phosphorus pathway will likely be in subsurface lateral flow as soluble reactive phosphorus (*SRP*), whereas in a disturbed forest, the dominant pathway may be in surface runoff as *SRP*, or as particulate phosphorus adsorbed to eroded sediment. Prediction is further complicated as research has shown that the *SRP* concentration in the soil water may be higher in undisturbed forests than in burned or harvested forests. Delivered sediment also is complicated in that preferential particle size sorting may occur, increasing the content of clay and organic matter in delivered sediment and thereby increasing the phosphorus concentration in delivered sediment above that in the forest. We have developed a way to use the current predictions within the WEPP technology to estimate not only the surface runoff and sediment delivery, but also delivery of fine sediment below a user-specified threshold, and phosphorus through both surface and subsurface lateral flow pathways.

BACKGROUND

In recent years, watershed managers have been challenged to determine the role of forest watersheds in generating phosphorus. Recent examples where watersheds with a significant fraction of the area in forests have concerns about phosphorus delivery include: Lake Tahoe (EPA, 2014), the Great Lakes (EPA, 2012), Big Bear Lake, CA (EPA, 2007), and Cascade Reservoir, ID (Idaho Division of Environmental Quality, 1996). In all of these cases, watershed managers were unable to evaluate the role of forests and forest management on phosphorus

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delivery from the forested parts of the watershed. Within the Lake Tahoe Basin we have received funding for three projects to develop phosphorus management tools to address these concerns. This paper focuses on the development of those tools for the Lake Tahoe Basin, but the principles can be applied to forested watersheds anywhere.

Phosphorus pathways in agricultural watersheds are associated mainly with surface runoff, detached sediments, lateral flow and tile drainage water (Sharpley et al., 1994). The dominant pathway in most cases is associated with detached sediments, while phosphorus dissolved in surface runoff and tile drainage are usually lesser important. Agricultural phosphorus delivery models have tended to focus on how management practices such as manure spreading, application of chemical fertilizers and minimum tillage affect the availability of soluble reactive phosphorus (*SRP*) for runoff, and the concentration of phosphorus adsorbed to soil aggregates and particles (particulate phosphorus, *PP*) (Sharpley et al., 1994). The concentrations of phosphorus in eroded sediments, surface runoff, and drain tile flows are then used in runoff and erosion models to predict phosphorus delivery (Withers and Jarvie, 2008).

In forested watersheds, surface runoff and erosion are frequently minimal, and generally are associated with wildfire. In the absence of wildfire, the dominant flow paths for water entering streams are either subsurface lateral flow or base flow (Elliot, 2013; Srivistava et al., 2013). Phosphorus concentrations in forest soils are usually much lower than in agricultural settings. Recent research has found that the concentration of *SRP* in the upper layers of soil water that are the source of shallow lateral flow are much greater than is measured in surface runoff (Miller et al., 2005). These observations suggest that a phosphorus delivery model is needed for forest watersheds that can include the current surface runoff and sediment delivery vectors, as well as delivery from shallow subsurface lateral flow.

In order to develop a model that can predict phosphorus delivery with lateral flow, a hydrologic model that includes shallow lateral flow as well as surface runoff and sediment delivery is needed. The Water Erosion Prediction Project (WEPP) model has such a capability (Dun et al., 2009; Srivistava et al., 2013). WEPP is a physically-based distributed hydrology and erosion model, and it uses a daily time step to predict evapotranspiration, plant growth, residue accumulation and decomposition, deep seepage, and shallow lateral flow. Whenever there is a runoff event from precipitation and/or snowmelt, WEPP predicts infiltration, runoff, sediment detachment and delivery (Flanagan and Nearing, 1995). WEPP has both a hillslope version and a watershed version. In recent years, the predicted deep seepage has been used to estimate groundwater base flow (Elliot et al., 2010, Srivastava et al., 2013), further increasing the model's hydrologic capabilities.

In addition to phosphorus, stakeholders in the Lake Tahoe Basin also are concerned about fine sediment delivery (Coats, 2004). In this context, "fine sediment" is generally considered to be sediment particles and aggregates less than 10 - 20 μm in diameter. Such particles can remain suspended in lakes for a considerable period of time as vertical currents due to surface wind shear and temperature gradients are sufficient to prevent the particles from settling (Coats, 2004). It is these small particles combined with increased algal growth due to phosphorus enrichment that have caused the lake to lose some of its clarity in recent decades.

This paper describes research and development activities that are ongoing to develop phosphorus and fine sediment prediction capabilities from forested watersheds using the WEPP model.

THE WEPP MODEL

The WEPP model was originally developed to predict surface runoff, upland erosion and sediment delivery from agricultural, forest and rangeland hillslopes and small watersheds (Laflen et al., 1997. Inputs for the model include daily climate, soil, topographic, and management or vegetation information. Within the model, WEPP completes a water balance at the end of every day by considering infiltration, runoff, deep seepage, subsurface lateral flow, evapotranspiration, and soil depth and horizon properties. Surface runoff is estimated on a sub-daily time step using an input hyetograph based on the daily precipitation depth, duration, and peak intensity and the soil water content, using a Green and Ampt Mein Larson infiltration algorithm (Flanagan and Nearing, 1995; Dun et al., 2009). The deep seepage is estimated when the soil exceeds field capacity for multiple soil layers, if desired, using Darcy's law. Evapotranspiration is estimated using either a Penman method or Ritchie's model. The lateral flow is estimated for layers that exceed field capacity using Darcy's law for unsaturated conditions as downslope conditions may not be saturated (Dun et al., 2009; Boll et al., 2015). Duration of surface runoff is dependent on storm duration and surface roughness (Flanagan and Nearing, 1995) and lateral flow duration is assumed to be 24 h on days when lateral flow is estimated. If requested by the user, WEPP generates a daily "water" file that contains modeled precipitation and snow melt, surface runoff, lateral flow, deep seepage, and soil water content (Flanagan and Livingston, 1995).

Table 1 shows part of the water file for the Tahoe City, CA climate for Julian days 70-78 (March 11-19). On day 70, precipitation (*P*) was all rain, with no snowmelt; on day 71 rainfall combined with melting snow, and days 77 and 78 were snowmelt only days. Daily runoff (*Q*) occurred only on day 78, while lateral flow occurred every day. The soil exceeded field capacity on day 72 so that deep percolation (*Dp*) began. During these 9 days, the total precipitation was 32 mm, total surface runoff was 15 mm, lateral flow was 19 mm, deep percolation was 0.1 mm, the soil water

Table 1 Example of information in the WEPP water output file. The climate is for Tahoe City, CA.

Day	*P* mm	*RM* mm	*Q* mm	*Ep* mm	*Es* mm	*Dp* mm	*latqcc* mm	*Total-Soil Water*(mm)	*frozwt* mm	*SWE* mm
70	8.4	8.4	0.00	0	2.05	0	0.28	129.73	0	258.79
71	2	42.68	0.00	0	3.09	0	0.88	168.43	0	218.12
72	0.3	17.74	0.00	0	3.2	0.01	1.89	181.08	0	200.67
73	6.9	30.09	0.00	0	2.35	0.02	2.77	206.03	0	177.49
74	13.7	4.57	0.00	0	2.08	0.02	2.77	205.69	0.04	186.62
75	0.3	0	0.00	0	1.27	0.02	2.54	201.89	0	186.92
76	0	0	0.00	0	3.52	0.02	2.26	196.09	0	186.92
77	0	11.48	0.00	0	1.73	0.02	2.77	203.06	0	175.44
78	0	22.69	14.73	0	1.12	0.02	2.77	207.11	0	152.75

Day=julian day; P= precipitation; RM=rainfall +snowmelt; Q=daily runoff; Ep=plant transpiration; Es=soil evaporation; Dp=deep percolation; latqcc=lateral subsurface flow; Total-Soil Water=unfrozen water in soil profile; frozwt=frozen water in soil profile; SWE=snow water equivalent on the surface content increased by 77.38 mm and the snow water equivalent on the surface decreased by 106 mm. Development is ongoing to add the deep seepage to a temporary groundwater reservoir, and from that to use a linear reservoir model to predict base flow from a sub-watershed as a fraction of the volume of that reservoir (Elliot et al., 2010; Srivastava et al., 2013).

WEPP predicts delivered sediment in five classes: primary clay, silt and sand particles, small aggregates made up of clay, silt and organic matter, and larger aggregates consisting of all three primary particles and organic matter. The sediment size classes and properties are summarized in Table 2 for a coarse sandy loam soil that is widespread in the Lake Tahoe Basin. The fraction of sediment in each size class delivered from a hillslope or a watershed is presented by WEPP. In addition, WEPP calculates a specific surface enrichment ratio (*SSR*), which is the ratio of the sediment surface area in the clay and organic matter fraction in the delivered sediment divided by this value for the soil on the hillslope. This ratio was intended to be used to assist water quality modelers in determining the increase in concentration of a pollutant in the delivered sediment compared to the sediment on the hillslope (Sharpley et al., 1994). For example, if the phosphorus content in the soil was 500 mg kg^{-1} and the enrichment ratio was 2.2, the concentration of phosphorus in the delivered sediment would be 1100 mg kg^{-1}.

THE LAKE TAHOE BASIN

Figure 1 is a map of the Lake Tahoe Basin showing the dominant geologic influences. The largest tributary is the Upper Truckee River flowing into the lake from the south. The overflow for the lake is in the northwest corner, where the Truckee River routes the overflow north, and then east toward Reno, NV. The dominant geologic processes in the basin were volcanic in the north and west, and decomposing granite in the south and east. There are also significant areas of exposed rock outcrops, particularly in the southern part of the basin. Some of the lower elevation lower gradient segments of the stream tributaries are alluvial. The lake has 63 tributaries, and the lake itself accounts for 38 percent of the total watershed area (Coats, 2004). Forests cover 57 percent of the watersheds, and shrubs 31 percent (Greenburg et al, 2006).

ESTIMATING PHOSPHORUS CONCENTRATIONS

Phosphorus delivery from a hillslope either will be adsorbed to eroded sediment (particulate phosphorus, or *PP*) or will be dissolved in surface runoff, subsurface lateral flow, or base flow (soluble reactive phosphorus, or *SRP*). Concentration of phosphorus in sediment depends on the

Table 2 For a forest sandy loam soil, properties of sediment size classes in eroded sediments estimated by the WEPP model.

Class	Mean Diameter (mm)	Specific Gravity	Particle Composition (%)			
			Sand	Silt	Clay	Organic Matter
1	0.002	2.60	0.0	0.0	100.0	250.0
2	0.010	2.65	0.0	100.0	0.0	0.0
3	0.030	1.80	0.0	80.0	20.0	50.0
4	0.300	1.60	85.4	7.1	7.5	18.8
5	0.200	2.65	100.0	0.0	0.0	0.0

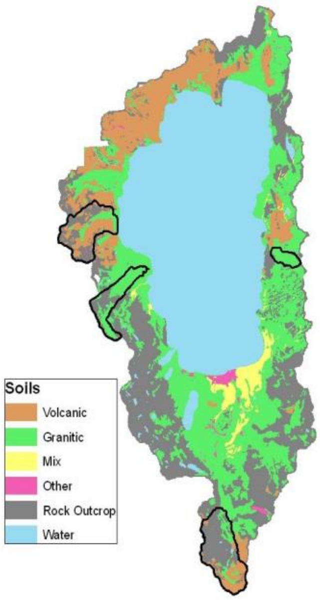

Figure 1 Major geologic categories within the Tahoe Basin.

mineralogy and particle size of the soil. Phosphorus dissolved in solution depends on the geology and the flow pathways (surface, lateral or base flow) that water follows.

For this paper, we focused on developing PP and SRP concentrations that are typical of the Lake Tahoe Basin. A similar procedure can be applied to other watersheds. Within the Lake Tahoe Basin, there is a long history of measuring total phosphorus (TP), SRP and suspended sediment concentration (SSC) in streams discharging to the lake. The number of water quality samples collected from the 13 major streams that flow into Lake Tahoe between 1989 and 2003 range from 129 samples collected from Trout Creek to 1414 at Incline Creek (Figure 2). The largest stream, the Upper Truckee, was sampled at multiple points within the watershed, and Incline Creek has two sample sites within its watershed (Figure 2) whereas the other streams were only sampled near their outlets. The analyses are available from the USGS (http://waterdata.usgs.gov/nwis/rt). Using observed TP (mg L^{-1}), SRP (mg L^{-1}) and SSC (mg L^{-1}) concentrations we calculated the Concentration of phosphorus sorbed to the suspended sediment (mg kg^{-1}) using equation 1.

$$\text{Concentration} = \frac{\text{TP}-\text{SRP}}{\text{SSC}} 10^6 \quad (1)$$

As seen in Figure 2, the median Concentration from each of the major stream in the Lake Tahoe Basin have a distinct regional pattern with Concentrations ranging from 1000 mg kg^{-1} in the wetter, western streams in the basin to ~1500 mg kg^{-1} delivered from the northern streams, to 1850 mg kg^{-1} from the high elevation streams in the southern setcion of the basin. These regional trends are likely associated with the underlying geology and the characteristics of the delivered sediment.

In order to capture seasonal trends in SRP delivered from Lake Tahoe streams, we applied a USGS model, LOADEST (Runkel et al., 2004), to the observed SRP data. The LOADEST model transforms point data into continuous time series of P loading and concentration as a function of stream flow and time using regression techniques. As seen in Figure 3, the SRP concentrations in Lake Tahoe streams vary seasonally with the highest concentrations (~0.022 mg L^{-1}) during low flow conditions in the fall and lowest concentrations (~0.015 mg L^{-1}) in the late spring during snowmelt. The LOADEST model was able to match these monthly trends fairly well (Figure 3).

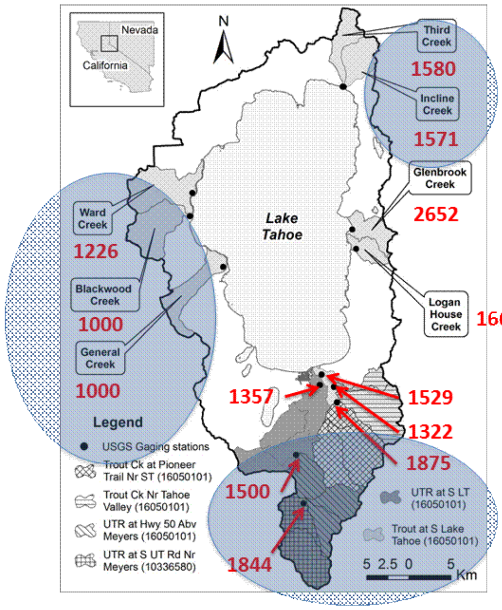

Figure 2 Concentration of phosphorus (mg kg^{-1}) adsorbed to delivered sediment from watersheds within the Lake Tahoe Basin shown in red. The concentrations tended to break down into three distinctive sets as shown by the gray circles, with the granitic soils in the Upper Truckee Basin having the larger concentrations, whereas the volcanic watersheds on the western side had lower concentrations of adsorbed *P*.

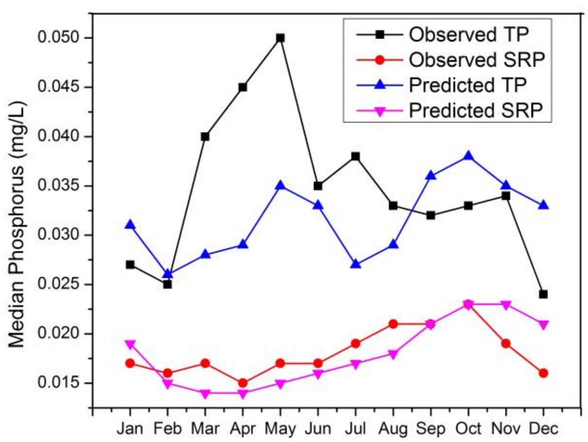

Figure 3 Observed and predicted phosphorus concentrations averaged across all years and all watersheds.

We also attempted to predict monthly TP concentrations with the LOADEST model; however the agreement was quite poor. Since the LOADEST model was not developed to use SSC as an independent variable in the regression analysis, but rather attempted to predict TP based on flow and time, it was not surprising the monthly TP concentrations simulated by LOADEST did not agree with observed patterns. This suggests that the TP concentration is largely influenced by the PP in the delivered sediment.

In addition to the sample concentrations we also generated daily hydrographs for each of the sampled streams. Figure 4 is a hydrograph for Blackwood Creek in which we have estimated the relative contribution of each of the flow paths (surface, lateral and base) using the WEPP model water file coupled to a linear groundwater flow model. Figure 4 shows that the base flow is the dominant flow path from July until snowmelt the following April, that surface runoff occurs only at times of peak flow rates, and that lateral flow is the dominant flow path during higher stream

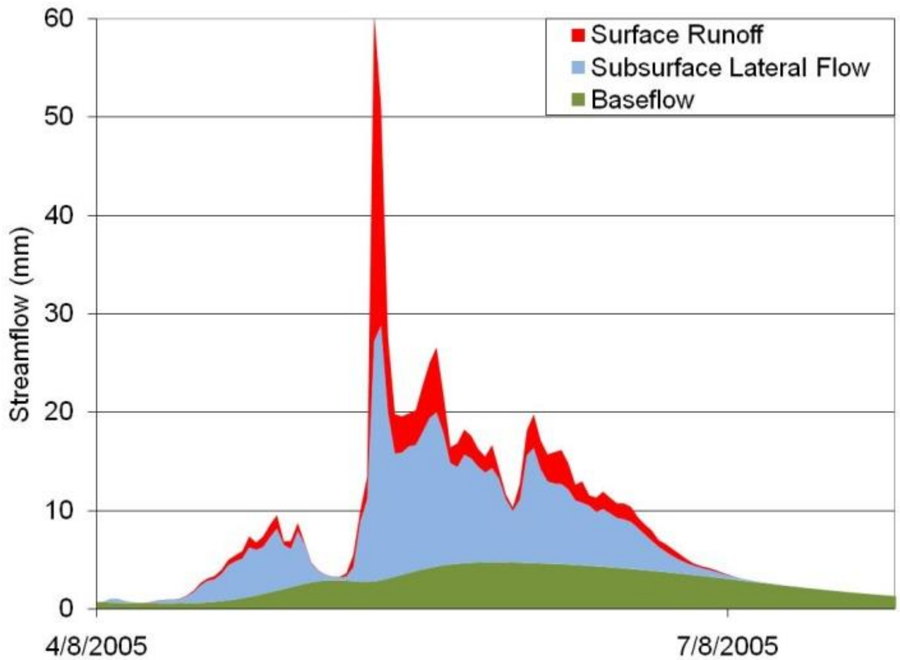

Figure 4 Example hydrograph based on WEPP hydrology for Blackwood Creek (Elliot et al., 2010).

flow rates in the late spring. Combining this information with the results shown in Figure 3, it is apparent that the SRP in surface runoff is likely less than 0.01 mg L^{-1}, whereas SRP concentrations in lateral flow and base flow are likely to be around 0.02 mg L^{-1}. Concentrations are the lowest during March and April when surface runoff is contributing to runoff and diluting lateral and base flow, but higher from June onward when lateral flow and base flow are the main sources of water in the stream system. Total phosphorus delivered, however, is likely to be the highest during the peak flow times associated with snow melt in April and May, which coincides with the greatest sediment transport as well.

ESTIMATING FINE SEDIMENT DELIVERY

The distribution of particle size delivery from hillslopes or watersheds given in the WEPP model output file can be parsed to determine the amount of each textural fraction in each particle size category by summing the delivery of a given size primary particle with the fraction of that particle contained in the aggregates. In WEPP, clay primary particles are ≤ 4 μm diameter, and silt particles are 4 - 62.5 μm diameter. To simplify modeling, we assumed that within the silt textural category the distribution of particle sizes was linear. Thus if the user needed to know the amount of sediment ≤ 10 μm, the number could be determined by adding all of the clay fraction as primary particles and in aggregates to the (10-4)/(62.5-4) fraction of the silt delivered as primary particles and in aggregates.

INTERFACES

In order to make this technology useful to managers, an interface was developed similar to the Forest Service Disturbed WEPP online interface for the WEPP model (Elliot, 2004). Figure 5

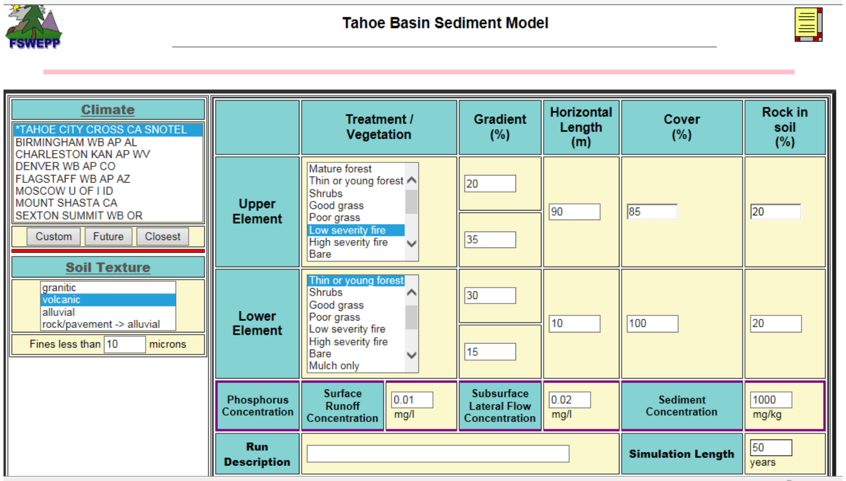

Figure 5a Input screen for the Tahoe Basin Sediment Model using a SNOTEL station from within the Lake Tahoe Basin for the weather and phosphorus concentrations from Figures 2 and 3.

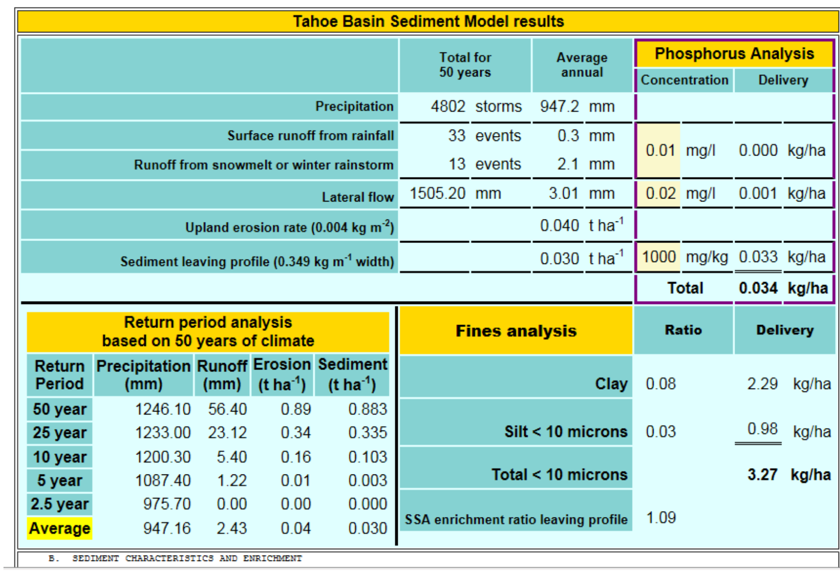

Figure 5b Output screen for the Tahoe Basin Sediment Model.

shows the input and output screens for the Tahoe Basin Sediment Model (TBSM, http://forest.moscowfsl.wsu.edu/fswepp). The user is asked to select a climate, dominant geology, vegetation conditions for the upper or treated part of a hill, and lower or stream side buffer part of the hill. In the case of an undisturbed condition, or a post-wildfire condition, the upper and lower portions of the hill may have the same vegetation.

The climate database for the TBSM includes one NOAA station within the Lake Tahoe Basin as well as five nearby weather stations. In addition, climate statistics have been added to the database for seven NRCS Snow Telemetry (SNOTEL) stations located within the Basin. Another feature unique to the TBSM interface is that future climate scenarios are available for the seven SNOTEL stations and the one NOAA station within the Basin.

The user is asked to provide the phosphorus concentrations in the surface runoff, lateral flow, and sediment. Earlier versions of the interface were designed for the user to enter the phosphorus concentration in the soil, and the model would then adjust this value using the specific surface enrichment ratio from the WEPP output. We found, however, that it was easier to obtain the concentration of total and soluble reactive phosphorus from in-stream monitoring rather than concentrations of phosphorus in the soils themselves, so the current interface is designed to use the concentrations shown in Figure 2 based on in-stream data. The interface could be altered for other applications where on-site particulate phosphorus concentrations are readily available and be designed to use delivered sediment with a delivery ratio as previously discussed.

Figure 5b shows the output screen for the TBSM. Each phosphorus path (sediment, surface runoff and lateral flow) is presented so that users will be able to determine the dominant pathway for the condition they are modeling. In the example shown in Figure 5b for a prescribed burn with a buffer, the greatest source of phosphorus is in the delivered sediment. This is often the case in disturbed forests (Stednick, 2010). In undisturbed forests, the greatest source of SRP is likely to be in the shallow subsurface lateral flow (Miller et al., 2005).

The fine sediment category between 4–62.5 μm is specified on the input page (Figure 5a) and the total delivery per unit area is calculated from the predicted sediment delivery, and presented on the output page.

DISCUSSION

This approach to modeling phosphorus and fine sediment delivery was developed for the Lake Tahoe Basin. The principles that are described here for estimating delivery of phosphorus can be applied to any condition where the input variables are known. For conditions where P concentrations are not known, sampling of a streams may be necessary to estimate the PP and SRP concentrations and their variability to apply this tool. The Tahoe Basin Sediment Model (TBSM) interface assumes a particulate phosphorus (PP) concentration attached to stream sediment. In other conditions, it may be more appropriate to link the PP concentration to the onsite concentration, and apply a specific surface enrichment ratio to the delivered sediment. With this interface, using the large PP concentrations in stream sediments (1000 – 2500 mg/kg), we may be over-predicting the delivery of PP to the stream. Elliot et al. (2012) reported onsite concentrations of 4–22 mg/kg and concentrations on coarse sediments collected from rainfall simulation of 160–475 mg/kg. The increasing concentrations of PP from soil to upland eroded sediments to stream sediments is due to the specific surface enrichment, and further work on the interface may be necessary to make sure the high instream concentrations are linked to the delivery of clay-size material. In the Tahoe basin, clay generally accounts for around 2 percent of the soil fraction.

An interesting hydrologic feature of coarse forest soils is that unless the soils are highly disturbed, there is little surface runoff. Comparing the hydrograph in Figure 4 to the SRP concentration variability in Figure 3 suggests that when surface runoff does occur, SRP concentrations are low, but when lateral flow or subsurface flow dominate the runoff, SRP concentrations increase. The net effect of integrating the runoff and concentration values in these two figures suggests that total SRP delivery is the greatest when runoff is the greatest. It also suggests an interesting twist to managers: if managers seek to minimize surface runoff, subsurface lateral flow is likely to increase (Srivastava, 2013), and so will the concentration of SRP leaving the hillslope. Surface runoff itself will deliver less SRP, but it will also be the mechanism that delivers sediment, so that PP will likely dominate the total phosphorus (TP) budget when there is surface runoff.

The TBSM does not consider channel processes. In steep forest watersheds, stream channels and banks tend to be coarse, minimally adsorbing or desorbing TP. Forests with finer textured or higher organic materials in stream beds or banks are more likely to influence TP delivery, adding to SRP during times of low stream SRP concentration and reducing SRP during times of high concentration (Withers and Jarvie, 2008).

The interface clearly shows the link between sediment delivery and TP delivery. Past watershed research has shown that sediment budgets from forest watersheds are dominated by wildfire, with sediment delivery following wildfire being as much as 100 times greater than that associated with undisturbed forests (Elliot, 2013). Such sediment pulses will likely dominate delivery of phosphorus in the same way as they dominate the sediment budget. Managers need to consider the effects of forest practices not only on immediate phosphorus delivery, but also on the effects that forest practices may have on phosphorus delivery following wildfire (Elliot, 2013).

If applying this tool to other basins, users need to be aware of several features of this interface that were customized for the basin. The soil categories, granitic, volcanic, alluvial and rock/pavement would correspond to coarse sandy loam, sandy loam, loam and rock/pavement in other watersheds. The PP concentrations were for sediment transported by suspension through the Tahoe Basin stream system, and not necessarily the concentration of eroded sediment leaving a hillslope. Careful thought needs to be given to decide whether to use the approach described here for suspended sediment, or to use the PP concentration in the field, and apply the specific surface enrichment ratio is PP concentrations of the soil are available. In impaired watersheds, however, it is often easier to obtain TP and SSC than it is upland soil concentrations and therefore use the interface in its current form.

CONCLUSIONS

We have described an approach to using the WEPP model to aid in predicting phosphorus and fine sediment delivery from steep forested watersheds. The approach is limited to hillslope processes, and does not consider channel impacts on phosphorus delivery. The tool that was developed, however, can be useful in aiding forest managers in evaluating the effects of forest management, including wildfire, on delivery of fine sediments and phosphorus.

REFERENCES

Boll, J., Brooks, E.S., Crabtree, B., and Dun, S. (2015). "Incorporation of variable source area hydrology in WEPP", Journal of the American Water Resources Association. In Press.

Coats, R. (2004). "Nutrient and sediment transport in streams of the Lake Tahoe Basin: A 30-year retrospective" General Technical Report PSW-GTR-193. Albany, CA: USDA Forest Service, Pacific Southwest Research Station, pp 143-147.

Dun, S., Wu, J.Q., Elliot, W.J., Robichaud, P.R., Flanagan, D.C., Frankenberger, J.R., Brown, R.E., and Xu, A.D. (2009). "Adapting the Water Erosion Prediction Project (WEPP) model for forest applications," Journal of Hydrology, 336(1-4) pp 45-54.

Elliot, W.J. (2004) "WEPP Internet interfaces for forest erosion prediction," Journal of the American Water Resources Association, 40, pp 299–309.

Elliot, W.J. (2013). "Erosion processes and prediction with WEPP technology in forests in the Northwestern U.S.," Transactions of the American Society of Agricultural and Biological Engineers, 56(2), pp 563-579.

Elliot, W., Brooks, E., Link, T., and Miller, S. (2010). "Incorporating groundwater flow into the WEPP model," Proceedings of the 2nd Joint Federal Interagency Conference, 17 June – 1 July, Las Vegas, Nevada. 12 p.

Elliot, W., Brooks, E., Traeumer, D., and Bruner, E. (2012). "Predicting phosphorus from forested areas in the Tahoe Basin," Conference on Environmental Restoration in a Changing Climate, Tahoe Science Conference, 22–24 May, Incline Village, Nevada.

Environmental Protection Agency (EPA). (2007). "TMDL document for Big Bear Lake nutrients (phosphorus)," Online at < http://iaspub.epa.gov/tmdl/attains_impaired_waters.tmdl_report?p_tmdl_id=33765&p_report_type= >. Accessed December 2014.

Environmental Protection Agency (EPA). (2012). "The Great Lakes today: Concerns," Online at <http://www.epa.gov/greatlakes/atlas/glat-ch4.html>. Accessed December 2014.

Environmental Protection Agency (EPA). (2014). "Watershed priorities: Lake Tahoe, California and Nevada." Online at <http://www.epa.gov/region9/water/watershed/tahoe>. Accessed December 2014.

Flanagan, D.C., and Livingston, S.J. (editors). (1995). WEPP User Summary NSERL Report No. 11. West Lafayette, Indiana: USDA Agricultural Research Service, National Soil Erosion Research Laboratory, 131 p.

Flanagan D.C., and Nearing, M.A. (1995). USDA – Water Erosion Prediction Project: Hillslope profile and watershed model documentation. NSERL Report No. 10. West Lafayette, Indiana: USDA Agricultural Research Service, National Soil Erosion Research Laboratory.

Greenberg, J.A., Dobrowski, S.Z., Ramierez, C.M., Tuil, J.L., Ustin, S.L. (2006). "A bottom-up approach to vegetation mapping of the Lake Tahoe Basin using hyperspatial image analysis", Photogrammetric Engineering & Remote Sensing 72(5), pp 581-589.

Idaho Division of Environmental Quality. (1996). Cascade Reservoir Phase 1 Watershed Management Plan Online at < http://www.epa.gov/waters/tmdldocs/Cascade%20Reservoir%20Phase%20I%20TMDL%20-%20Main%20Report.pdf >. Accessed December 2014. 97 p.

Laflen, J.M., Elliot, W.J., Flanagan, D.C., Meyer, C.R., and Nearing, M.A. (1997). "WEPP – predicting water erosion using a process-based model," Journal of Soil and Water Conservation, 52(2), pp 96-102.

Miller, W.W., Johnson, D.W., Denton, C., Verburg, P.S.J., Dana, G.L., and Walker, R.F. (2005). "Inconspicuous nutrient laden surface runoff from mature forest Sierran watersheds," Water, Air and Soil Pollution, 163, pp 3-17.

Runkel, R.L., Crawford, C.G., and Cohn, T.A. (2004). "Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers," Chapter A5 in U.S. Geological Survey Techniques and Methods Book 4, 69 p.

Sharpley, A.N., Chapra, S.C., Wedepohl, R., Sims, J.T., Daniel, T.C., and Reddy, K.R. (1994). "Managing agricultural phosphorus for protection of surface waters: Issues and options," Journal of Environmental Quality, 23(3), pp 437-451.

Srivastava, A. (2013). Modeling of hydrological processes in three mountainous watersheds in the U.S. Pacific Northwest. PhD Dissertation. Pullman, Washington: Washington State University. 170 p.

Srivastava, A., Dobre, M., Wu, J., Elliot, W., Bruner, E., Dun, S., Brooks, E., and Miller, I. (2013). “Modifying WEPP to improve streamflow simulation in a Pacific Northwest watershed,” Transactions of the American Society of Agricultural and Biological Engineers, 56(2), pp 603-611.

Stednick, J.D. (2010.) “Effects of fuel management practices on water quality,” Chapter 8 in Elliot, W.J., Miller, I.S., and Audin, L. (eds.). “Cumulative Watershed Effects of Fuel Management in the Western U.S.,” General Technical Report RMRS-GTR-231. Fort Collins, Colorado: USDA Forest Service, Rocky Mountain Research Station, pp 149-163.

Withers, P.J.A., and Jarvie, H.P. (2008). “Delivery and cycling of phosphorus in rivers: A review,” Science of the Total Environment, 400, pp 379-395.