Selection of Parameters Values to Model Post-fire Runoff and Sediment Transport at the Watershed Scale in Southwestern Forests

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Abstract

Erosion and runoff have been observed to increase following fire. Land managers and Burned Area Emergency Rehabilitation (BAER) teams must be able to estimate these post-fire changes. Studies of post-fire erosion on burned watersheds show that the concentrations of sediment eroded from burned rangeland and forested hillslopes in the southwestern United States can be extremely high. Since wildfire primarily impacts soils and vegetation cover on hillslopes, it is appropriate to assume that changes in hillslope conditions will result in changes in runoff peak, volume and sediment yield. The AGWA (Automated Geospatial Watershed Assessment www.tucson.ars.ag.gov/agwa) hydrologic modeling tool employs both an empirical model (SWAT) and a more process-based model (KINEROS2). In order to study how these models should be modified to provide land managers with a means to assess the impact of fire, the models were applied on two burned watersheds. Analysis of data from the Marshall Gulch watershed near Tucson, Arizona, indicates that changes in runoff volume are small compared to changes in peak runoff. The application of the KINEROS2 model to burned conditions at the Starmer Canyon near Los Alamos, New Mexico shows a pattern of change over time that is consistent with watershed recovery. Calibrated hillslope roughness values are consistent with independent estimates for roughness under bare conditions following the fire to roughness consistent with forested conditions three years later. The modeling also indicated that increasing hillslope roughness over time accounts for much of the change in runoff response.

Introduction

Following wildfire, runoff peak and volume have been observed to increase over pre-fire conditions (e.g. Robichaud, et al. 2000). Likewise, sediment discharge and sedimentation rates have been observed to increase. Therefore, runoff in post-fire conditions has the potential for downstream flooding and sedimentation that can degrade reservoirs used for drinking water supplies. For these reasons, the Burned Area Emergency Response (BAER) teams primarily address rehabilitation efforts to reduce runoff and erosion.

Some of the physical changes following fire that have been identified to contribute to changes in hydrologic response include (DeBano et al. 1998):

- removal of canopy cover, which decreases interception of rainfall and increases the portion of the rainfall that hits the ground, and eliminates the buffering effect of canopy on rainfall intensity, which is an important effect in the desert southwest subject to convective rainstorms,
- collapse of soil structure and consequent reduction of soil porosity,
- creation of hydrophobic soils which can reduce infiltration rates,
- creation of ash residues that can clog pores, thus resulting in decreased infiltration rates,
- removal of ground cover, which exposes soil, allowing sediment to be entrained by raindrop impact, reduces roughness and allows runoff to move more rapidly downslope, which reduces the time water is ponded on the hillslope and allowed to infiltrate, and produces higher runoff rates and flows with higher sediment concentration and transport capacity.

Observations show that these physical changes cause a major change in observed runoff volume, peak and sediment yield in the southwestern United States. Robichaud et al. (2000) summarized the available data on changes in runoff and erosion following fire. The increase in annual water yield following fire in southwestern conifer forests has been observed to be a factor of two or less. In contrast, southwestern conifer watersheds have been shown to experience a five to 100 fold increase in post-fire runoff peak flows (Anderson et al. 1976). Pre-fire sediment-yield on burned conifer forest watersheds in the southwest is almost too-small to measure (0.0003 t/ha: DeBano et al. 1996). However, post-fire sediment-yield on these watersheds has been measured to be some of the highest ever measured at 370 t/ha (Hendricks and Johnson, 1944), though it has also been observed to be only 1.6 t/ha in one study on a high severity burn (DeBano et al. 1996). These large differences indicate that post-fire erosion rates are highly variable, but can be extremely high.

The Automated Geospatial Watershed Assessment tool

BAER teams must predict the potential impact of fire on runoff and erosion in order to target vulnerable locations for remediation. The USDA-ARS Southwest Watershed Research Center, in cooperation with the U.S. EPA Office of Research and Development, has developed a geographic information system (GIS) tool to facilitate this process. The Automated Geospatial Watershed Assessment tool (AGWA www.tucson.ars.ag.gov/agwa/) uses widely available standardized spatial datasets that can be obtained via the internet. The data are used to develop input parameter files for two watershed runoff and erosion models: KINEROS2 (www.tucson.ars.ag.gov/kineros) and SWAT (www.brc.tamus.edu/swat). More details about AGWA and the two hydrologic models are described in a companion paper (Goodrich et al. this volume) that includes an application of AGWA to post-fire runoff assessment.

The SWAT model (Arnold et al. 1994) calculates runoff volume using the SCS Curve Number method (USDA 1986) and runoff peak using the rational formula. Previous attempts to use a unit hydrograph approach have been unable to accurately estimate post-fire runoff peaks without overestimating runoff volume (McLin et al 2001).

KINEROS2 (Smith et al. 1995; Smith and Quinton 2000), is a distributed runoff-erosion model based on Hortonian overland flow theory, and, therefore, is well-suited to describing the hydrodynamics of runoff and erosion processes on burned southwestern watersheds, where infiltration rates are low and rainfall is infrequent but intense. Runoff is described with a one-dimensional continuity equation applicable to both overland and channel flow: Sediment entrainment and transport on hillslopes and channels is treated as an unsteady, one-dimensional convective transport phenomenon, using a continuity equation similar to that for runoff. Sediment flux on a hillslope has two independent sources, raindrop-induced entrainment and flow-induced entrainment. Sediment transport for up to five independent particle sizes is described using the Engelund and Hansen (1967) total load equation.

Objective

The objective of this study is to determine how model inputs to the KINEROS2 and SWAT models need to be modified to account for post-fire conditions.

Methods

Site Descriptions

Data for this study comes from two burned conifer watersheds in the mountains of the southwest United States; the Marshall Gulch station which drains 830 ha in Pima County, AZ burned by the Aspen Fire in June 2003; and the Starmer Canyon watershed, a 212 ha. watershed draining into Pajarito Canyon in Los Alamos County, NM burned during the 2000 Cerro Grande Fire. A separate paper in this proceedings more thoroughly describes the Starmer Canyon dataset (Springer and Hawkins this issue); previous model calibration using Starmer Canyon data are also described by McLin et al. (2001).

Historical data exist for the Marshall Gulch site from 1951 to 1959. Following the fire, the gauge was reestablished. Because rainfall and runoff data are rarely available from burned watersheds for before and after a fire, the Marshall Gulch data offers an opportunity to examine changes in runoff peak and volume following fire. Currently, rainfall data is recorded at three different gauging stations on or near the watershed. However, during the 1950s, rainfall was collected at only one location on the watershed. The burn upstream of the Marshall Gulch station was spotty. Most of the watershed was burned, but high, moderate and low severity burns were observed (Figure 4 in Goodrich et al. this volume). Soils on the watershed are sandy loam developed in weathered granite bedrock.

Curve Number and Peak Runoff to Average Runoff Calculation for Marshall Gulch

Using these data from Marshall Gulch, rainfall and runoff pairs were selected from the 1950s and after the fire. Curve Numbers were calculated from these data using the methods of Hawkins (1993). Furthermore, Hawkins (2004 pers. comm.) has suggested plotting peak discharge rate (Qpeak) vs average discharge rate for the event (Qavg) (calculated by dividing runoff volume by time of base of the hydrograph) for each storm, because a consistent ratio between these two is often observed, and this ratio may provide insights into changes in runoff response.

Calibration of KINEROS2 at Starmer Canyon

At Starmer Canyon, the KINEROS2 model was parameterized using the AGWA tool, and an optimal parameter set was selected by calibrating the observed discharge rate with the simulated discharge rate for each storm. The USGS 10m DEM was used in AGWA to delineate the watershed. Default cover values derived from the National Land Cover Dataset (NLCD) and the STATSGO soils database. Erosion parameters were selected by AGWA for KINEROS2, based on USDA soil classification and empirical relationships developed from the USLE soil erodibility factor (Woolhiser et al, 1990). The only change in initial parameterization to account for fire was to decrease the canopy cover values selected in AGWA by an order of magnitude from 0.5 to 0.05.

Optimal parameter values were selected for saturated hydraulic conductivity (Ks), Manning roughness in the channel (n Ch) and Manning's roughness on the hillslope (n HS) using the SCEUA (Duan et al 1992). Methods used to calibrate KINEROS2 using SECEUA are described in Canfield and Lopes (2004). The objective function maximized the Nash Sutcliffe (1970) statistic calculated using each point along the hydrograph for each event.

Results and Discussion

Observed Changes in Peak and Volume at Marshall Gulch, Az

Using rainfall and runoff depths for summer monsoon events that occurred on Marshall Gulch during the 1950s and after the fire in 2003 and 2004, Curve Number (CN) values were calculated (Hawkins, 1993). Curve numbers are plotted against rainfall in Figure 1.

Evaluation of this figure shows that there is no apparent increase in CN in post-fire conditions, and therefore no obvious change in runoff volume production in post-fire conditions. The lack of clear differences between the CNs in burned and unburned situations can be attributed to errors in rainfall and runoff measurement, as well as the comparison of data sets separated in time by forty years. However, the trends support the findings of Springer and Hawkins (this volume), which show small change in post-fire Curve Numbers at Starmer Canyon, and increasingly declining CNs with rainfall, indicative of the 'complacent' watershed response (Hawkins, 1993). Such 'complacent' behavior indicates that a single CN may be inappropriate for estimating runoff volume in forested conditions either before or after the fire.

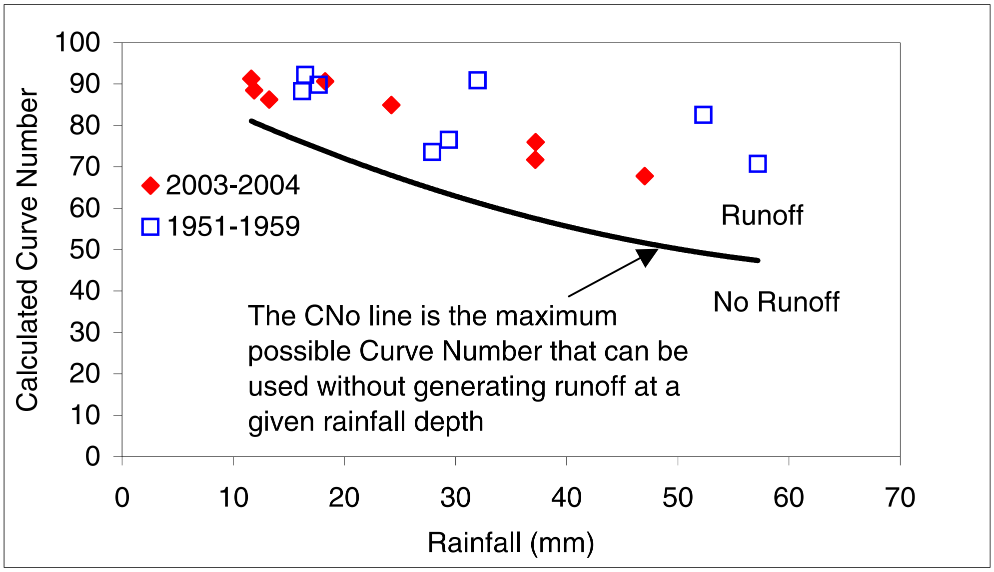

Figure 1 – Calculation of Curve Numbers before and After the Marshall Gulch Fire

While the volume and CN estimates suggest little change in runoff following the fire at Marshall Gulch, a clear change can be observed in the hydrograph peaks and hydrograph base time. Review of the data show that following a rainfall event in the 1950s, a runoff event could continue for several days. However, following the fire, the time of base often was no longer than a few hours. Hawkins (2004 pers. comm.) has suggested plotting Qpeak vs Qavg. Using this method a clear change can be seen as shown in Figure 2.

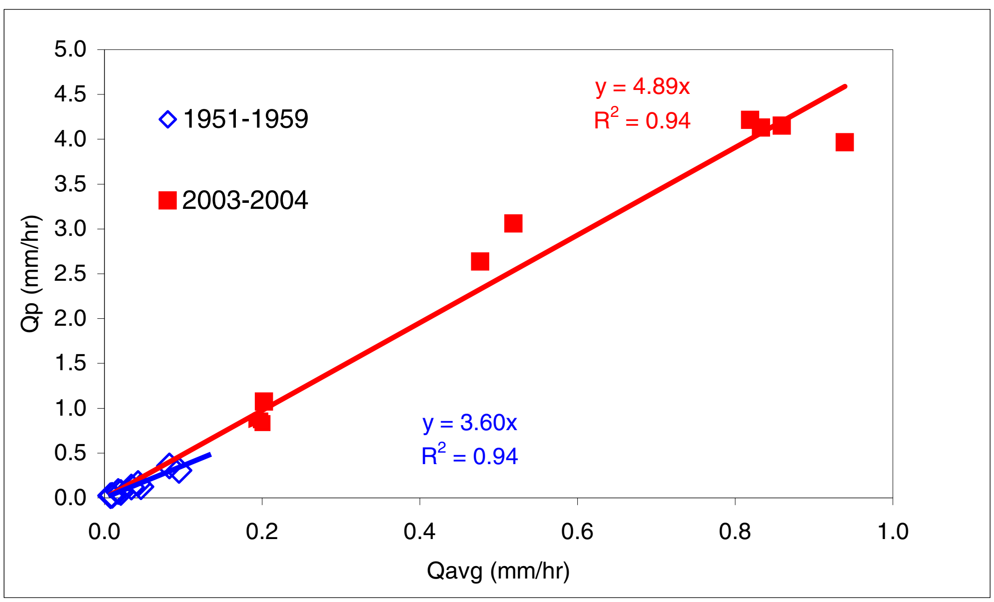

Figure 2 – Peak Discharge plotted against Average Discharge for Before and After the Marshall Gulch Fire

Post-fire peaks are clearly much greater than pre-fire peaks. Furthermore, while a strong correlation of the form Qp = coeffiecient * Qavg exists for both datasets, the coefficients are different, which suggests the hydrograph generation mechanisms may have changed producing a hydrograph of a different shape.

Evaluation of the peak and volume data from Marshall Gulch shows a relatively large change in peak runoff and relatively little change in runoff volume. This finding is consistent with the observations of Anderson et al. (1976) and Robichaud et al. (2000). Therefore, analysis of this data set suggests that post-fire prediction tools must be modified to produce much higher post-fire runoff peaks, without a commensurate increase in predicted runoff volume.

KINEROS2 Modeling at Starmer Canyon

The available rainfall and runoff data were used to select optimal model parameter estimates for the KINEROS2 model at Starmer Canyon. The optimized model fit is summarized in Table 1. While data are available for more events, only hydrographs that could be modeled well (as determined by a Nash-Suttcliffe statistic greater than 0.7) using KINEROS2 were used in this analysis. The fact that some events could not be modeled well may be attributed to errors in rainfall and runoff measurement.

Table 1 – Optimal Parameter Values for Selected Events at Starmer Canyon

Event	Rainfall Depth (mm)	Days Since Fire	Ks (mm/hr)	n Channnel	n Hillslope	Nash-Sutcliffe
6/28/2000	11.3	37	3.361	0.193	0.014	0.89
7/9/2000	14.3	48	0.390	0.013	0.213	0.74
10/22/2000a	14.1	154	1.183	0.151	0.430	0.85
10/22/2000b	12.3	154	0.866	0.150	0.087	0.85
8/9/2001	9.8	444	2.172	0.008	0.716	0.88
7/14/2002	9.8	783	3.312	0.041	1.175	0.95
8/11/2003	22.6	1176	7.540	0.117	1.053	0.90

The poorest fit hydrograph (7/9/00) used in this simulation is shown in Figure 3.

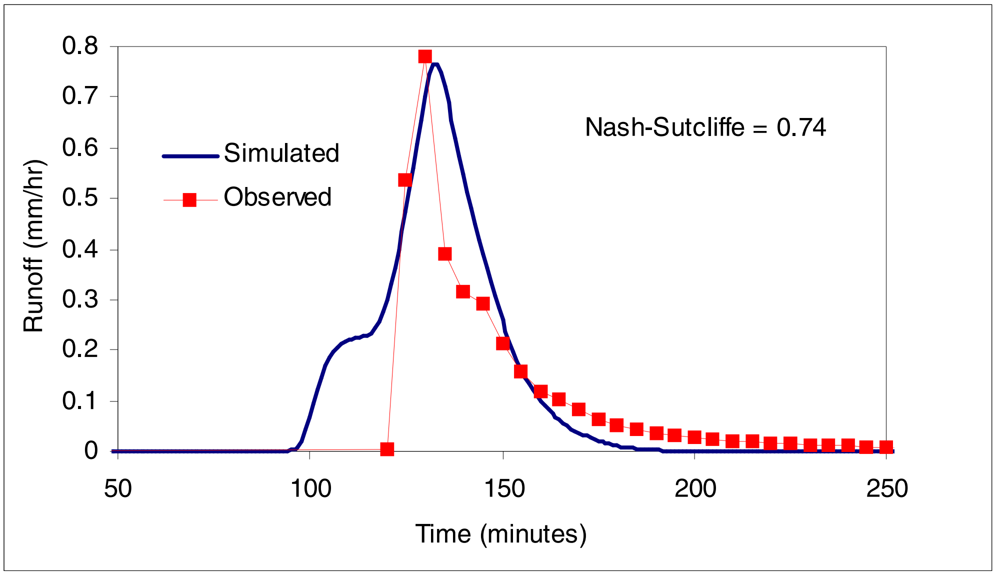

Figure 3 – Comparison of Observed and Simulated Hydrograph for the Poorest fit Hydrograph Used in the Analysis at Starmer

Using these data, an interesting trend is observed in optimal hillslope roughness (Figure 4). For the first event, the optimal hillslope roughness was 0.014, which is very close to the value of 0.011 recommended for bare soil by Engman (1986). For the last event the optimal hillslope roughness value is 1.05, which does not differ greatly from the value of 0.8 for wooded conditions recommended by Engman.

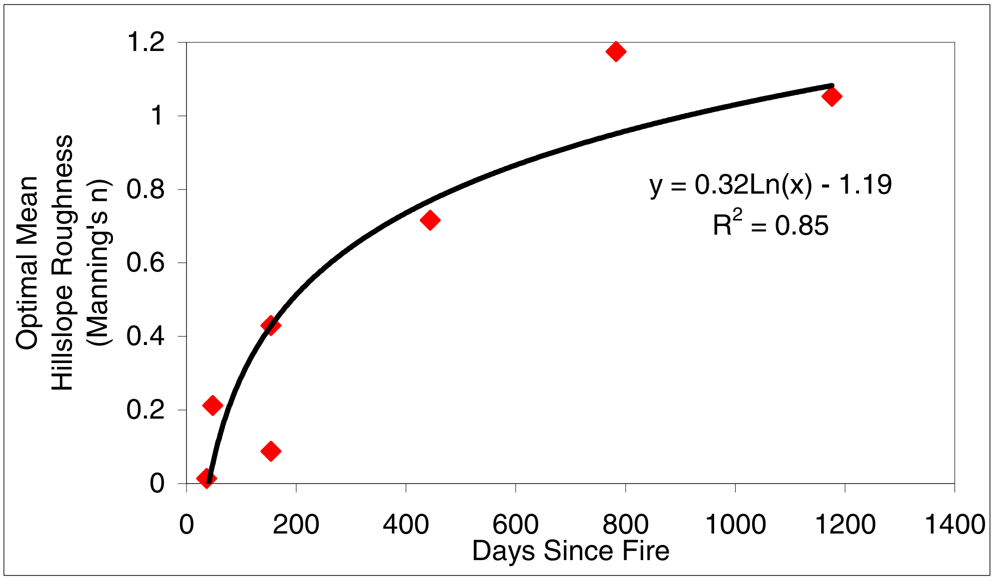

Figure 4 – Optimal Hillslope Roughness for Events that Occurred after the Cerro Grande Fire at Starmer Canyon Plotted vs Time

The trend of increasing hillslope roughness over time is to be expected because vegetation will begin to grow. In addition, soil compaction will be reduced by the development of a root system and processes such as freeze-thaw, which can further increase the porosity in the soil. The effects of these changes can also be observed in the changes in the optimal saturated hydraulic conductivity (Ks) over time as shown in Figure 5.

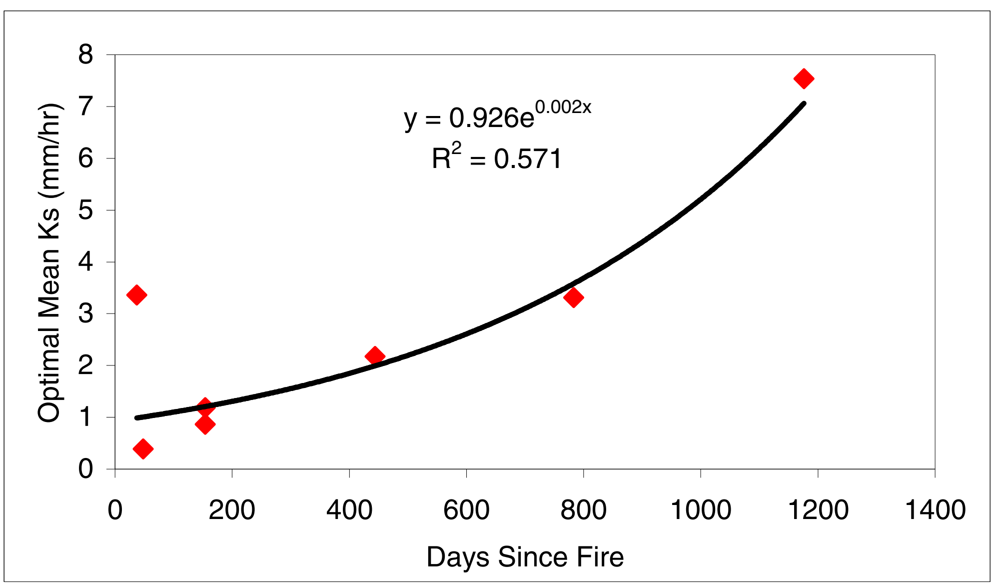

Figure 5 – Optimal Hillslope Hydraulic Conductivity Following the Cerro Grande Fire at Starmer Canyon Plotted vs. Time

Simulated Changes in Runoff Peak as a Result of Changes in Roughness

Of the three parameters optimized, the modeled peak runoff predictions are most sensitive to hillslope roughness. Figure 6 shows how changes in hillslope roughness can impact runoff peak for a 95 m long hillslope in Starmer Canyon subject to an 11 mm rainfall event with a peak 15-minute intensity of 19.7 mm/hr. In this case, a change from bare to forested roughness results in a six-fold change in runoff peak and a three-fold change in runoff volume.

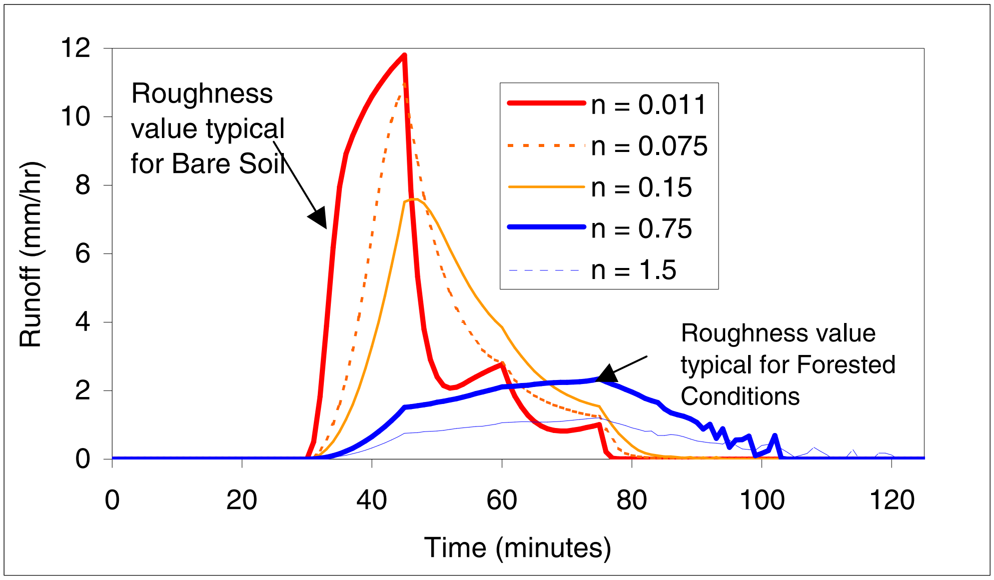

Figure 6 – Hillslope Runoff Plotted vs time for DifferentH Hillslope Roughness Values

Runoff on bare soil is often assumed to produce Hortonian overland flow, which is the runoff mechanism described in KINEROS2. While Engman (1986) has determined a roughness value for forested conditions that can be used to estimate hillslope roughness under Hortonian conditions, runoff in forested watersheds is generally thought to be dominated by subsurface storm flow and return flow (Dunne and Leopold, 1978), conditions not simulated in KINEROS2. Furthermore, with highest roughness rates (n= 0.75 and 1.5) the Hortonian processes simulated in KINEROS2 may produce instability on the recessional limb of the hydrograph at low flow rates (Figure 6). Therefore, while KINEROS2 may provide a reasonable description of runoff for post-fire conditions, it does not simulate the processes generally assumed to produce runoff in pre-fire conditions or in fully recovered forested watersheds. These model deficiencies will be addressed in future versions of KINEROS2.

By necessity, most simulation models are unable to simulate all processes inherent in watershed rainfall-runoff response. However, they can provide useful approximations. While KINEROS2 does not describe the runoff producing processes in forested conditions, the erosion from Hortonian overland flow simulated by KINEROS2 should be greater than the erosion generated by subsurface storm flow and return flow. Therefore, it can be considered to be a conservatively high value.

Simulated Impact of Roughness Change on Sediment Discharge at the Base of a Hillslope

Using erosion parameters selected by AGWA for KINEROS2 based on USDA soil classification and empirical relationships developed from the USLE soil erodibility factor (Woolhiser et al, 1990), the impact of hillslope roughness on erosion can be illustrated in Figure 7.

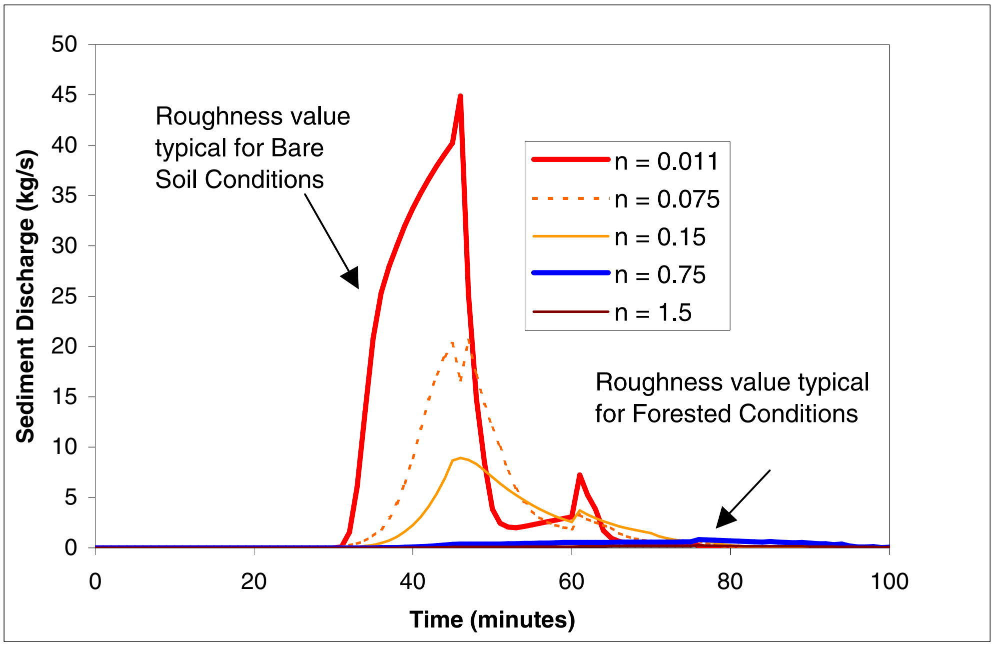

Figure 7 – Hillslope Sediment Discharge Plotted vs Time for Different Hhillslope Roughness Values

Since erosion parameters are unchanged in these simulations, and sediment entrainment by raindrop impact should be relatively unchanged, the simulated change in sediment discharge rates can be attributed to the change in sediment transport associated with the increased flow rates that occur on hillslopes with lower roughness.

Comparison of the hillslope runoff and hillslope sediment delivery show that hillslope roughness has a relatively greater increase in sediment delivery as indicated in Figure 8. This example shows a two-fold decrease in runoff volume from bare to wooded conditions. As mentioned previously, there was a six-fold change in peak runoff rate from bare to wooded conditions. However, the factor of twenty decrease in sediment delivered from the hillslope to the channel indicates that for this simulation, sediment is more sensitive to this change in roughness than either runoff peak or runoff volume. Furthermore, the unburned estimates are likely to be high because KINEROS2 describes Hortonian overland flow for unburned conditions when subsurface storm flow and return flow are likely to be more appropriate. Therefore, the relative change estimate may be low.

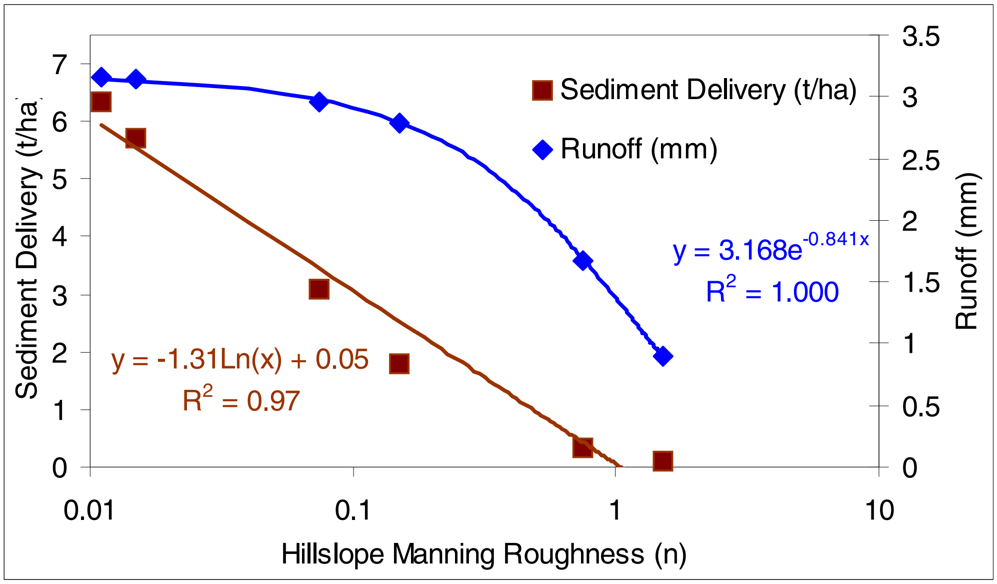

Figure 8 – Hillslope Sediment Delivery and Runoff Volume Plotted vs hillslope roughness values

Conclusions

This study shows that peak runoff rates in post-fire conditions can be several hundred percent greater than pre-fire conditions, and that modeled peak discharge and sediment delivery are strongly dependent on hillslope roughness. Optimal parameter sets for of a series of events at the Starmer Canyon watershed suggest an increase in hillslope roughness from bare conditions after the fire to hillslope roughness similar to wooded conditions three years later, which is consistent with watershed recovery. The fact that these roughness values are consistent with independent estimates for these values for these conditions suggests that the KINEROS2 model may provide useful estimates of relative change in peak runoff when physically-realistic values of roughness are used. Therefore, initial post-fire roughness will need to be reduced to bare, or near bare conditions to produce realistic estimates of runoff peak.

This and other studies have found that observed changes in runoff volume following fire are less pronounced than the changes in peak runoff rates on forested watersheds. Unfortunately, change analysis is hampered by a lack of pre-fire data on burned watersheds. At Marshall Gulch, data from before and after the Aspen fire supported the findings of Springer and Hawkins (this volume) that showed limited change in runoff volume and a watershed with 'complacent' behavior whereby CN values increase with increasing rainfall rates. An accompanying paper, Goodrich et al (this volume), suggests some possible Curve Number values for post-fire conditions based on changes in cover that result in smaller changes in CNs than are currently selected by experience.

Large changes were observed in discharge rates following the Aspen Fire at Marshall Gulch. Furthermore, the fact that the ratio of runoff peak to runoff average was observed to change from 3.6 pre-fire to 4.9 after the fire suggests that the runoff generating mechanisms at Marshall Gulch have been changed by the fire.

While KINEROS2 is not structured to simulate the runoff processes observed in heavily forested conditions, the erosion estimated by simulating Hortonian overland flow should provide an estimate that would be higher than the hillslope erosion that would occur as a result of subsurface storm flow and return flow under forested conditions.

One area requiring further study is the change in peak discharge to average ratio noted at Marshall Gulch. What physical processes control this ratio and why should they change in post-fire conditions? Another area needing further investigation is an analysis of the geometric partitioning effect on runoff peak and sediment discharge. Studies indicate that there can be scale dependence under some conditions (Goodrich, 1990; Canfield and Goodrich (in press)).

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