Suggested Changes to AGWA to Account for Fire (V 2.1)

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1.0 Introduction:

Wildfires can, and have had, a profound impact on the nature of watershed response to precipitation (DeBano et al. 1998). Increases in peak runoff rate and volume, as well as sediment discharge, typically increase following fires, (Robichaud, et al. 2000; Anderson et al. 1976). Mitigating these effects is one of the primary objectives of the Burned Area Emergency Response (BAER) teams. Weather and climatic conditions often force these teams to make rapid post-fire assessments for decision-making on how and where to deploy remediation measures. Building and running distributed hydrological models to predict potential impacts of fire on runoff and erosion can be a time-consuming and tedious task. The USDA-ARS Southwest Watershed Research Center, in cooperation with the U.S. EPA Office of Research and Development, and the University of Arizona have developed the AGWA geographic information system (GIS) based tool to facilitate this process. A GIS provides the framework within which spatially-distributed data are collected and used to prepare model input files and evaluate model results in a spatially explicit context.

The AGWA (Automated Geospatial Watershed Assessment) Tool

AGWA provides the functionality to conduct pre- and post-fire watershed assessments for two widely used watershed hydrologic models using readily available standardized spatial datasets. The two models currently incorporated into AGWA are the Soil & Water Assessment Tool (SWAT; Arnold et al. 1994; www.brc.tamus.edu/swat) and the KINematic Runoff and EROSion Model (KINEROS2; Smith et al., 1995; www.tucson.ars.ag.gov/kineros). SWAT is a continuous-simulation model for use in large (river-basin scale) watersheds. KINEROS2 is an event-driven model developed for small (<100 km^2) arid, semi-arid, and urban watersheds. The AGWA tool combines these models in an intuitive interface for performing multi-scale watershed assessments.

AGWA is an extension for the ArcView versions 3.X (ESRI, 2001). ArcGIS 9.0 and web versions of AGWA are currently under development. AGWA is distributed freely via the Internet as a modular, open-source suite of programs (www.tucson.ars.ag.gov/agwa). Data requirements to run AGWA include elevation (USGS DEM data), land cover (EPA MLRC), soils (USDA STATSGO, USDA SURRGO, FAO) and precipitation data (observed or design storms), all of which are typically available at no cost over the Internet for the conterminous United States. A fundamental assumption of AGWA is that the user has previously gathered the necessary GIS data layers for the area of interest. All of these data layers are easily obtained for the conterminous United States. Pre-processing of the DEM to ensure hydrologic connectivity within the study area is required, and tools are provided in AGWA to aid in this task. These tasks can be done relatively rapidly within AGWA but could also be completed for forests and land areas prior to a fire. By doing so the BAER teams would only have to deal with preparing a post-fire burn-severity map for the area of interest when time is of the essence.

Once an AGWA session has been initiated, the program is designed to lead the user in a stepwise fashion through the transformation of GIS data into simulation results. A conceptualization of the steps necessary to apply AGWA is presented in Figure 1. The AGWA Tools menu is designed to reflect the order of tasks necessary to conduct a watershed assessment. This process consists of five major steps: (1) watershed outlet identification and watershed delineation; (2) watershed subdivision by topographically controlled contributing areas; (3) model parameterization based on topography, land cover, and soils; (4) preparation of parameter and rainfall input files; and, (5) model execution and visualization, and comparison of results.

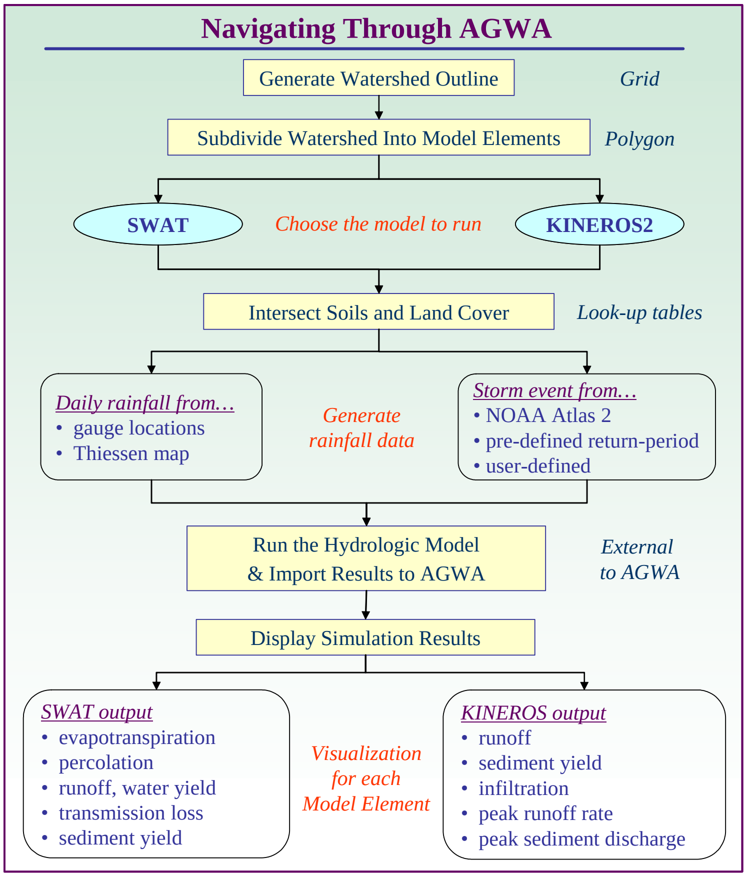

Figure 1.1 Conceptualized and sequence of steps in the use of AGWA for hydrologic modeling

In step (2), the geometric complexity of a watershed model representation is controlled by the user-defined contributing source area (CSA). This is the drainage area required to initiate a first-order channel and represents the transition where runoff is better treated as concentrated channel flow versus overland flow. Methods to automatically select the appropriate CSA across a broad range of basin morphologies are not clearly defined in the literature, but based on prior experience a default CSA of 2.5% of the total watershed drainage area is typically sufficient for preliminary watershed analysis. The user can modify this value, with a smaller CSA resulting in a more complex representation of the watershed (e.g. a greater number of model elements).

In regards to step (3), geometric model parameters (slope, flow length, etc.) are derived directly from the topographic data. Infiltration, interception, and erosion parameters are derived from look-up table relationships between these variables and the soil and land-cover attribute information in the input data sets (e.g. soil texture, soil group, vegetation type). These look-up table relationships are based on the literature and limited model calibration from highly instrumented experimental watershed data. However, the user can modify them if local observations enable model calibration. A critical element in using AGWA for post-fire assessments is establishing relations that can be used to translate burn severity into changes in the infiltration, hydraulic roughness, and erosion model parameters.

After hydrologic model execution (SWAT or KINEROS2), AGWA will automatically import the model results and add them to the polygon and stream map tables for spatial, color-ramped displays (step 5). A separate module controls the visualization of model results. The user can toggle among viewing various model outputs for both upland and channel model elements, enabling the problem areas to be identified visually. If multiple land-cover scenes exist, the user can parameterize either or both of the two models and attach the results to a given watershed. Results can then be compared on either an absolute or percent change basis for each model element. Model results can also be overlaid with other digital data layers to further prioritize management activities. Examples of AGWA applications for assessments of the hydrologic impacts of past land-cover change, as well as of alternative futures land-use change, can be found in Hernandez et al. (2000), Miller et al. (2002), and Kepner et al. (2004).

Hydrologic Models

Key components of AGWA are the hydrologic models used to evaluate the effects of land cover and land use on watershed response. Both the KINEROS2 and SWAT models are able to process complex watershed representations to explicitly account for spatial variability of soils, rainfall distribution patterns, and vegetation.

KINEROS2

KINEROS2 is an event-oriented, physically based model describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds, and is based on Hortonian overland flow theory (Smith et al., 1995). In this model, watersheds are represented by discretizing contributing areas into a cascade of one-dimensional overland flow and channel elements using topographic information. Surface flow in both overland and channel elements is modeled using a finite difference approximation of the one-dimensional kinematic wave equations in which upslope supply, rainfall rates, and infiltration rates are considered simultaneously at each finite difference node. The infiltration component is based on the simplification of the Richard's equation posed by Smith and Parlange (1978). It is relatively 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. Sediment transport is treated using unsteady, one-dimensional convective-transport equations similar to those used for runoff. Entrainment of sediment is modeled as resulting from raindrop impact or flow-induced entrainment. Sediment transport for up to five, non-interacting particle sizes is described using the Engelund and Hansen (1967) total load equation.

SWAT

SWAT is a river basin scale model developed to predict the impact of land-management practices on water, sediment, and agricultural chemical yields for large, complex watersheds with varying soils, land use, and management conditions over long periods of time (Arnold et al. 1994). The model combines empirical and physically-based equations, uses readily available inputs, and enables users to study long-term impacts. The hydrology model is based on the water balance equation:

$$SW_t = SW + \sum_{i=1}^{t} \left(R_i - Q_i - ET_i - P_i - QR_i \right) \qquad (1)$$

where *SW* is the soil water content minus the 15-bar water content, *t* is the time in days, and *R*, *Q*, *ET*, *P*, and *QR* are the daily amounts of precipitation, runoff, evapotranspiration, percolation, and return flow, respectively; all the units are in millimeters. Since the model maintains a continuous water balance, complex basins are subdivided to reflect differences in ET for various crops, soils, etc. Thus, runoff is predicted separately for each sub area and routed to obtain the total runoff for the basin.

2.0 Populating Parameter Values in AGWA

The basis of the modifications to assume that the majority of the changes in burned situations occur on the hillslopes rather than the channels. The means by which runoff and peak are implemented in SWAT and KINEROS in AGWA are the cover tables associated with the different cover mapping systems. The table for the MRLC classification is as follows:

Table 2.1 Existing MRLC Tables

Class	Name	A	B	C	D	Cover	Int	n
11	Open Water	100	100	100	100	0	0.00	0.000
12	Perrenial Ice/Snow	98	98	98	98	0	0.00	0.000
21	Low Intensity Residential	77	85	90	92	15	0.10	0.150
22	High Intensity Residential	81	88	91	93	10	0.08	0.120
23	Commercial/Industrial/ Transportation	89	92	94	95	2	0.05	0.010
31	Bare Rock/Sand/Clay	96	96	96	96	2	0.00	0.010
32	Quarries/Strip Mines/Gravel Pits	78	85	90	92	2	0.00	0.010
33	Transitional	72	82	87	90	20	0.00	0.010
41	Deciduous Forest	55	55	75	80	50	1.15	0.015
42	Evergreen Forest	55	55	70	77	50	1.15	0.015
43	Mixed Forest	55	55	75	80	50	1.15	0.015
51	Shrubland	63	77	85	88	25	3.00	0.055
61	Orchards/Vinyards/Other	77	77	84	88	70	2.80	0.040
71	Grasslands/Herbaceous	49	69	79	84	25	2.00	0.015
81	Pasture/Hay	68	79	86	89	70	2.80	0.040
82	Row Crops	72	81	88	91	50	0.76	0.040
83	Small Grains	65	76	84	88	90	4.00	0.040
84	Fallow	76	85	90	93	30	0.50	0.040
85	Urban/Recreational Grasses	68	79	86	89	90	2.50	0.040
91	Woody Wetlands	85	85	90	92	70	1.15	0.060
92	Emergent Herbaceous Wetlands	77	77	84	90	70	1.15	0.060

In reviewing this table, it is clear that the CN estimates are basically from the TR55 manual. However, the manning roughness values are excessively small. In order to prepare a tool that can do change analysis, more reasonable roughness values must be substituted on the table for the unburned condition. A revised estimate of baseline roughness values can be derived from the KINEROS documentation, TR-55 and other studies. While categories in the KINEROS documentation and TR-55 may not fit exactly with the categories on this table, the values are a reasonable approximation for the tables in the category. For the riparian classifications, I found no estimates of roughness, so these have been approximated.

Table 2.2 Revised MRLC Table with Revised Roughness Values

Class	Name	A	B	C	D	Cover	Int	n
11	Open Water	100	100	100	100	0	0.00	0.000
12	Perrenial Ice/Snow	98	98	98	98	0	0.00	0.000
21	Low Intensity Residential	77	85	90	92	15	0.10	0.150
22	High Intensity Residential	81	88	91	93	10	0.08	0.120
23	Commercial/Industrial/ Transportation	89	92	94	95	2	0.05	0.011*
31	Bare Rock/Sand/Clay	96	96	96	96	2	0.00	0.011*
32	Quarries/Strip Mines/Gravel Pits	78	85	90	92	2	0.00	0.010
33	Transitional	72	82	87	90	20	0.00	0.010
41	Deciduous Forest	55	55	75	80	50	1.15	0.4#
42	Evergreen Forest	55	55	70	77	50	1.15	0.8#
43	Mixed Forest	55	55	75	80	50	1.15	0.6#
51	Shrubland	63	77	85	88	25	3.00	0.055
61	Orchards/Vinyards/Other	77	77	84	88	70	2.80	0.040
71	Grasslands/Herbaceous	49	69	79	84	25	2.00	0.13*
81	Pasture/Hay	68	79	86	89	70	2.80	0.40*
82	Row Crops	72	81	88	91	50	0.76	0.17#
83	Small Grains	65	76	84	88	90	4.00	0.17#
84	Fallow	76	85	90	93	30	0.50	0.05*
85	Urban/Recreational Grasses	68	79	86	89	90	2.50	0.41*
91	Woody Wetlands	85	85	90	92	70	1.15	0.60@
92	Emergent Herbaceous Wetlands	77	77	84	90	70	1.15	0.60@

@ - estimated based on covers with similar CN and cover values
# - From TR 55
* - From KINEROS web site

In order to apply KINEROS2, the values for parameters for infiltration and soil erodibility as a function of rainsplash and sediment transport capacity need to be entered into the model. Table 1.3 shows a subset of the parameter values used to populate the parameters in KINEROS2 as a function of texture.

TEXTURE	KS	G	POR	SMAX	CV	SAND	SILT	CLAY	DIST	KFF
CL	2.300	259.000	0.464	0.840	0.940	32.000	34.000	34.000	0.240	0.390
S	210.000	46.000	0.437	0.950	0.690	91.000	1.000	8.000	0.690	0.180
SC	1.200	302.000	0.430	0.750	1.000	50.000	4.000	46.000	0.340	0.360
SCL	4.300	263.000	0.398	0.830	0.600	59.000	11.000	30.000	0.400	0.360
SI	3.000	260.000	0.450	0.920	0.550	8.000	81.000	11.000	0.130	0.430
SIC	0.900	375.000	0.479	0.880	0.920	9.000	45.000	46.000	0.150	0.310
SICL	1.500	345.000	0.471	0.920	0.480	12.000	54.000	34.000	0.180	0.400
SIL	6.800	203.000	0.501	0.970	0.500	23.000	61.000	16.000	0.230	0.490
SL	26.000	127.000	0.453	0.910	1.900	65.000	23.000	12.000	0.380	0.320

3.0 Burn Severity Assessment by Burned Area Emergency Rehabilitation Teams

BAER Team Assessments and burn severity classifications. Review of burn severity maps and potential burn severities under different cover types. In general, the following characterization describes burn severity:

> High –Ground cover is almost completely consumed; the ash layer may be up to two inches deep; tree crowns are completely consumed; few to no leaves or needles remain on trees; tree mortality may be close to 100 percent.
>
> Moderate –Shrub canopy may be all or partly consumed; shrubs skeletons and root crowns may remain; some identifiable char and litter are beneath a thin ash layer; soil structure is intact; fine and very fine roots remain; scorched brown needles or leaves remain on trees; tree mortality is 40-80 percent.
>
> Low –Vegetation is lightly scorched; large trees are mostly alive; very small fuels have been consumed.

A more quantitative summary is presented in table 3.1.

	- - - - - - - - Burn severity - - - - - - -		
Soil and litter parameter	Low	Moderate	High
Litter	Scorched, charred, consumed	Consumed	Consumed
Duff	Intact, surface char	Deep char, consumed	Consumed
Woody debris - small	Partly consumed, charred	Consumed	Consumed
Woody debris - logs	Charred	Charred	Consumed, deeply charred
Ash color	Black	Light colored	Reddish, orange
Mineral soil	Not changed	Not changed	Altered structure, porosity, etc
Soil temp. at 0.4 inch (1 cm)	<120 °F (<50 ^{o}C)	210-390 °F (100-200 ^{o}C)	>480 °F (>250 ^{o}C)
Soil organism lethal temp.	To 0.4 inch (1 cm)	To 2 inches (5 cm)	To 6 inches (16 cm)

Burn severity classification based on postfire appearances of litter and soil and soil temperature profiles (Hungerford 1996; DeBano and others 1998).

4.0 A Review of the Impact of Fire on Runoff Volume, Peak and Sediment Yield

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.

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 4.1.

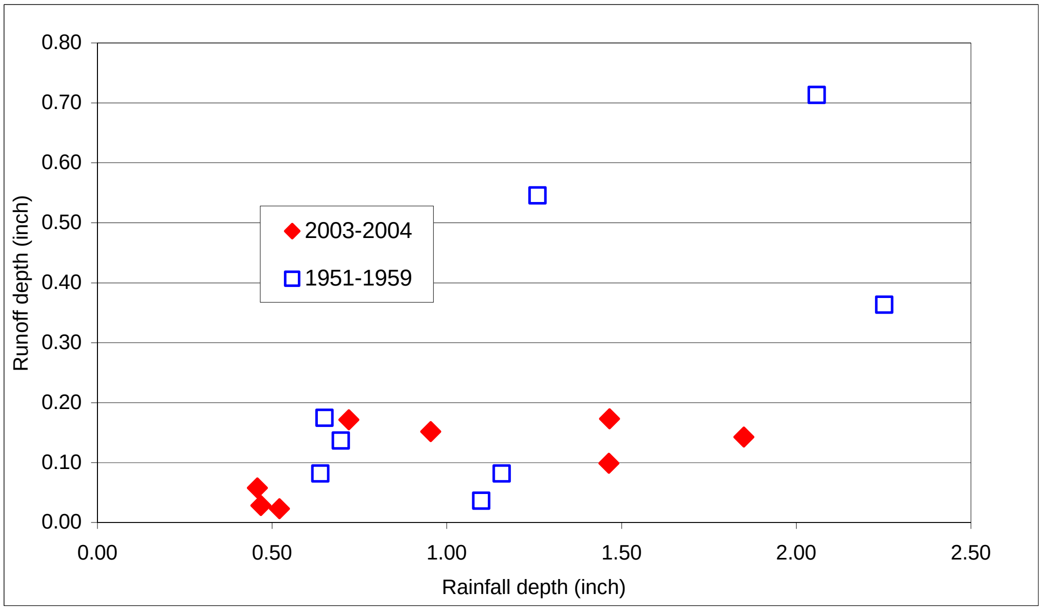

Figure 4.1 – Rainfall Plotted Against Runoff for Events from Before and After the Aspen Fire

Using these data, it is possible to calculate Curve Numbers for before and after the fire as shown in Figure 4.2:

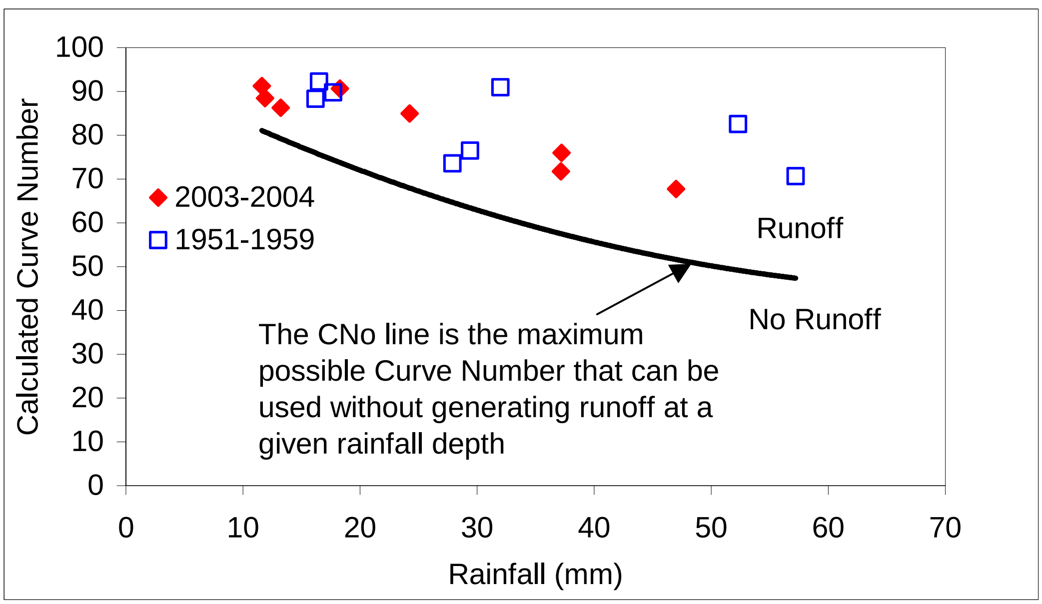

Figure 4.2 – Curve Number Plotted Against Rainfall Depth

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.

Surface runoff in SWAT is estimated with a modification of the SCS Curve Number method (U. S. Department of Agriculture, 1986). A survey of Burned Area Emergency Response (BAER) plans showed that the Curve Number (CN) approach is often used in post-fire assessment. Currently, many BAER teams select post-fire CNs based on experience, without the value of careful post-fire data analysis. Two papers in this volume calculated post-fire CNs and found a small change in post-fire runoff volume (Canfield et al; Springer and Hawkins). However, Canfield et al. (2005) found that change in post-fire peak was approximately an order of magnitude higher after the Aspen Fire in Pima County, AZ, even though there was no significant change in post-fire CN (i.e. little change in total post-fire runoff volume). McLin et al. (2001) also noted that post-fire runoff peaks can be very high, while runoff volumes are less changed. Therefore users of unit hydrographs have chosen to overestimate volume in order to accurately predict peak runoff rates.

5.0 Estimating Post-Fire Runoff Volume Change Using Curve Numbers

Surface runoff in SWAT is estimated with a modification of the SCS Curve Number method (U. S. Department of Agriculture, 1986). A survey of Burned Area Emergency Response (BAER) plans showed that the Curve Number (CN) approach is often used in post-fire assessment. Currently, many BAER teams select post-fire CNs based on experience, without the value of careful post-fire data analysis. Two papers in this volume calculated post-fire CNs and found a small change in post-fire runoff volume (Canfield et al; Springer and Hawkins). However, Canfield et al. (2005) found that change in post-fire peak was approximately an order of magnitude higher after the Aspen Fire in Pima County, AZ, even though there was no significant change in post-fire CN (i.e. little change in total post-fire runoff volume). McLin et al. (2001) also noted that post-fire runoff peaks can be very high, while runoff volumes are less changed. Therefore users of unit hydrographs have chosen to overestimate volume in order to accurately predict peak runoff rates.

Analysis of post-fire CNs from BAER team reports for several burn severities on fires in the Southwest (Hayman, CO; Cerro Grande, NM; and, Oracle Hill, AZ) and modeled runoff from a fifty mm storm indicate up to two orders of magnitude change in runoff volume, which is inconsistent with observations. To select a CN that more accurately reflects the calculated post-fire CNs described in other studies in this volume, (Canfield et al; Springer and Hawkins), we employed a relationship between CN and cover.

The National Land Cover Dataset (NLCD) includes an estimate of percent cover for each land-cover type. CNs for each of these have been estimated based on Hydrologic Soils Group classes A, B, C, and D, and cover conditions (USDA, 1986). For natural land covers (excluding wetlands and most agricultural classes areas), and urbanized areas, relatively strong relationships exist between percent cover and CN (Figure 5.1). If we employ these regression relationships, a revised post-fire CN can be estimated using a post-fire estimate of cover for each hydrologic soil group. By assuming a 15% reduction

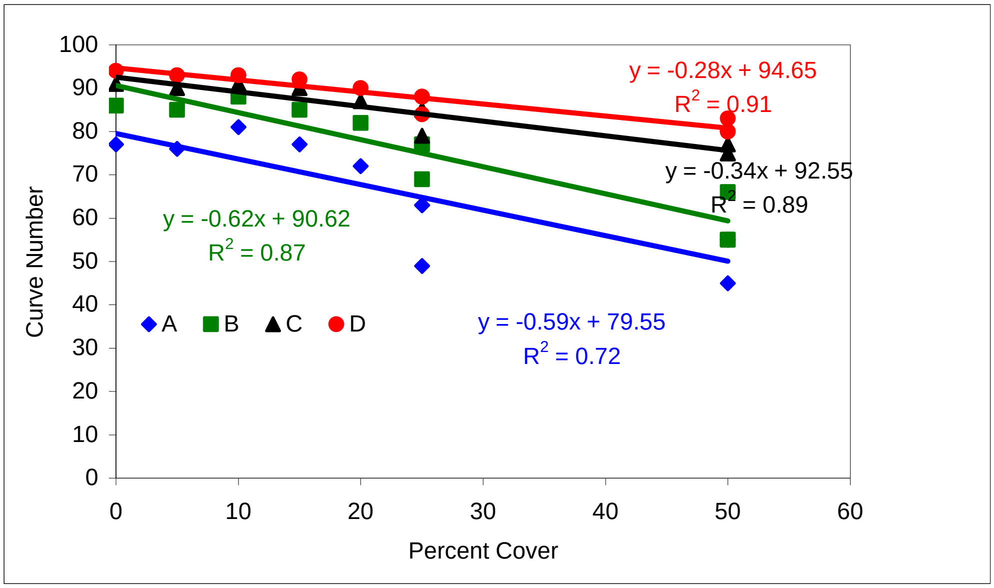

Figure 5.1 – Relationship Between Cover and Curve Number for Each Hydrologic Soils Group

in cover for low-severity burns, a 50% reduction for high-severity burns (as is assumed in Disturbed WEPP - http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/wd/weppdist.pl, and a 32% reduction for moderate-severity burns, we can obtain revised estimates of post-fire CNs (Table 5.1).

Table 5.1: Original and revised AGWA-based Curve Number estimates as a function of hydrologic soil group, land-cover class and burn severity (low, moderate or high)

Class	Name	Cover	A	B	C	D
84a	Bare	0	77	86	91	94
84	Fallow	5	76	85	90	93
22	High Intensity Residential	10	81	88	91	93
21	Low Intensity Residential	15	77	85	90	92
33	Transitional	20	72	82	87	90
51	Shrubland	25	63	77	85	88
71	Grasslands/Herbaceous	25	49	69	79	84
41	Deciduous Forest	50	55	55	75	80
42	Evergreen Forest	50	45	66	77	83
43	Mixed Forest	50	55	55	75	80
51	Shrubland	25	63	77	85	88
41l	Deciduous Forest	43	59	60	78	82
42l	Evergreen Forest	43	49	71	80	85
43l	Mixed Forest	43	59	60	78	82

51l	Shrubland	21	65	79	86	89
41m	Deciduous Forest	34	65	65	80	85
42m	Evergreen Forest	34	55	76	82	88
43m	Mixed Forest	34	65	65	80	85
51m	Shrubland	17	68	82	88	90
41h	Deciduous Forest	25	70	71	83	87
42h	Evergreen Forest	25	60	82	85	90
43h	Mixed Forest	25	70	71	83	87
51h	Shrubland	12	73	88	91	91

Note: l - low severity burn
m - moderate severity burn
h - high severity burn

Several trends in the Table 5.1 AGWA-derived CNs can be noted in comparison to BAER team estimates (not shown). The estimated CNs in Table 5.1 are generally higher for unburned conditions and lower for burned conditions than estimates used by BAER teams. This results in higher runoff depths for pre-fire conditions and lower runoff depths for post-fire conditions. To illustrate these differences, runoff depth has been estimated using the CNs in Table 5.1, and using CNs from BAER team reports on the Cerro Grande (Evergreen), and Oracle Hill Fires (Deciduous Forest and Shrubland) using a 40-mm rainfall event.

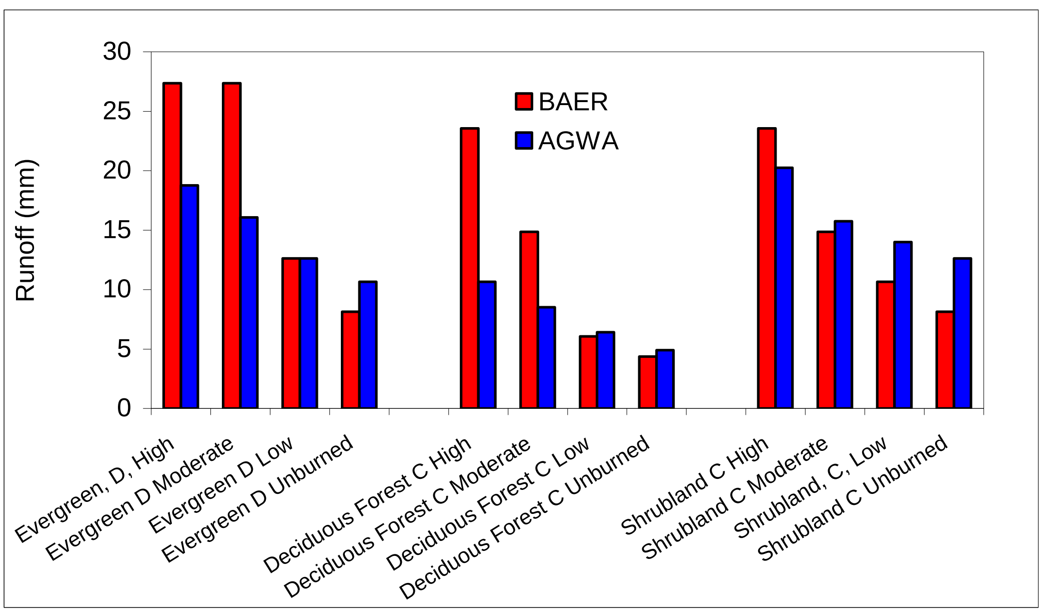

Figure 5.2 – Calculated Runoff from a 40 mm storm using AGWA and BAER team estimates (cover, hydrologic soil group, burn severity)

The values in Figure 5.2 show that the AGWA estimates tend to produce a higher runoff volume for unburned conditions and a lower runoff volume for burned conditions. This results in a smaller estimate of runoff-volume change as a result of wildfire. This is consistent with the results described in the Curve Number estimates for Marshall Gulch described in chapter 8, and Springer and Hawkins (2005), which show that observed post-fire runoff-volume change is small relative to the large change in runoff peak rates. Note that the 40-mm storm event is quite large; and the differences demonstrated in Figure 5.2 would be greater for smaller events because a higher fraction of the rainfall will go to the initial abstraction. .

6.0 Estimating Post-Fire Peak Runoff Rates

Data are available from a burned conifer watershed at the Marshall Gulch station which drains 830 ha in Pima County, AZ burned by the Aspen Fire in June 2003. 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 (see chapter 8). Soils on the watershed are sandy loam developed in weathered granite bedrock. In the pre-fire condition, runoff could occur days after an event as illustrated by Figure 6.1.

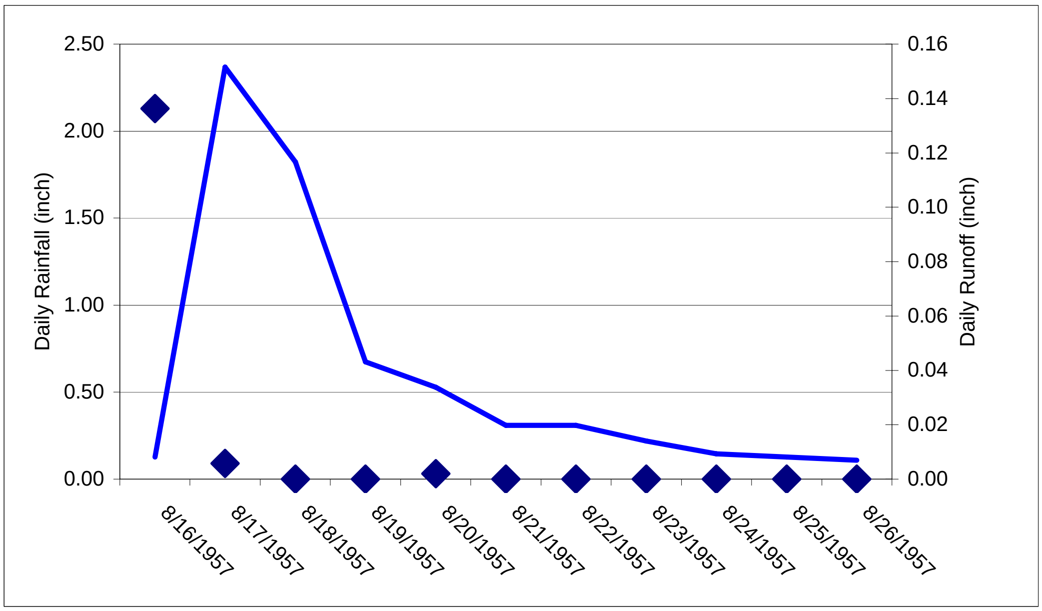

Figure 6.1- Rainfall (left axis) and Runoff (right axis) vs Time (days)

In contrast, in post-fire conditions, event duration was much shorter as indicated for the July 23, 2003 event in Figure 6.2.

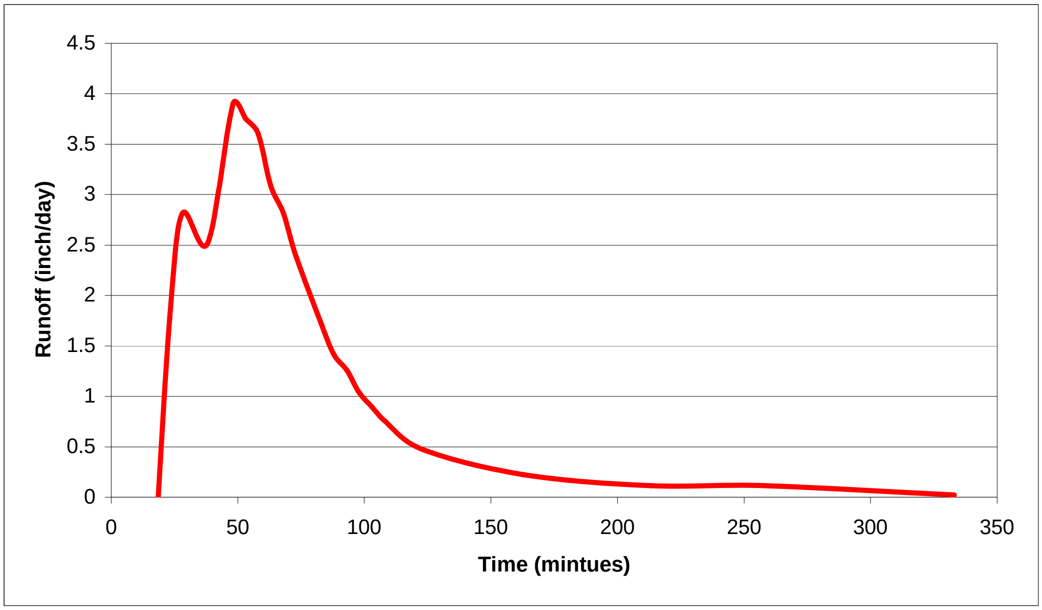

Figure 6.2 - Runoff (right axis) vs Time (minutes)

The fact that the event durations were so long under pre-fire conditions and so short under post-fire conditions illustrates that the most profound impact of fire is to reduce runoff travel times and increase peak. 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 6.3.

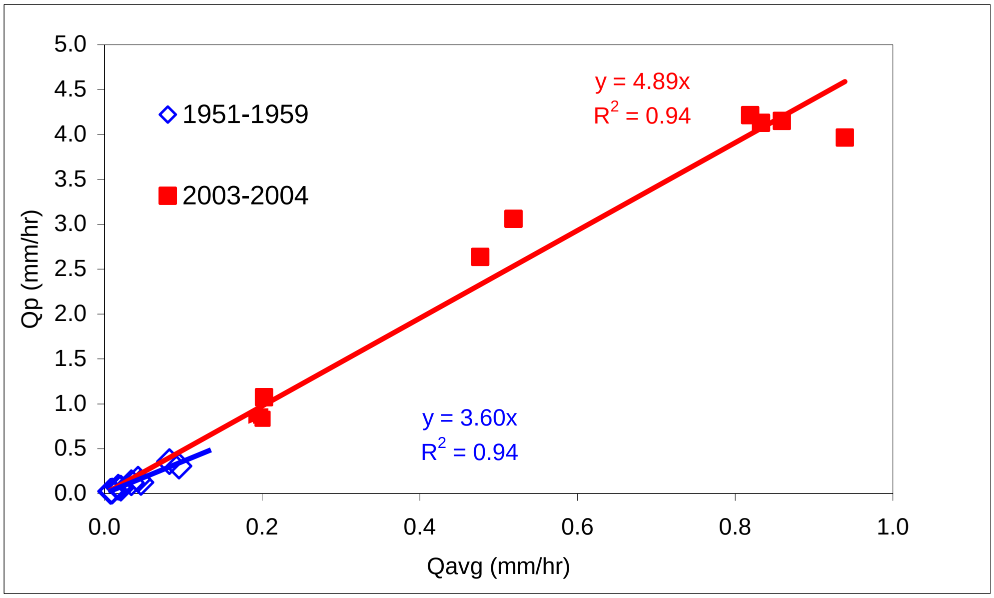

Figure 6.3 – Peak Discharge plotted against Average Discharge for Before and After the Marshall Gulch Fire

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.

What is clear from evaluation of the peak and volume data is that the most profound impact in runoff is in peak runoff rather than runoff volume, which has been seen before. Other studies of changes in post-fire hydrology have shown increases in runoff volume (e.g. see Robichaud et al 2000 table 3). Therefore, it would not be appropriate to conclude that there is never a change in volume, but rather that the most profound impact of fire is to increase runoff peaks, which this data set clearly illustrates.

7.0 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 7.1 – 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 7.1.

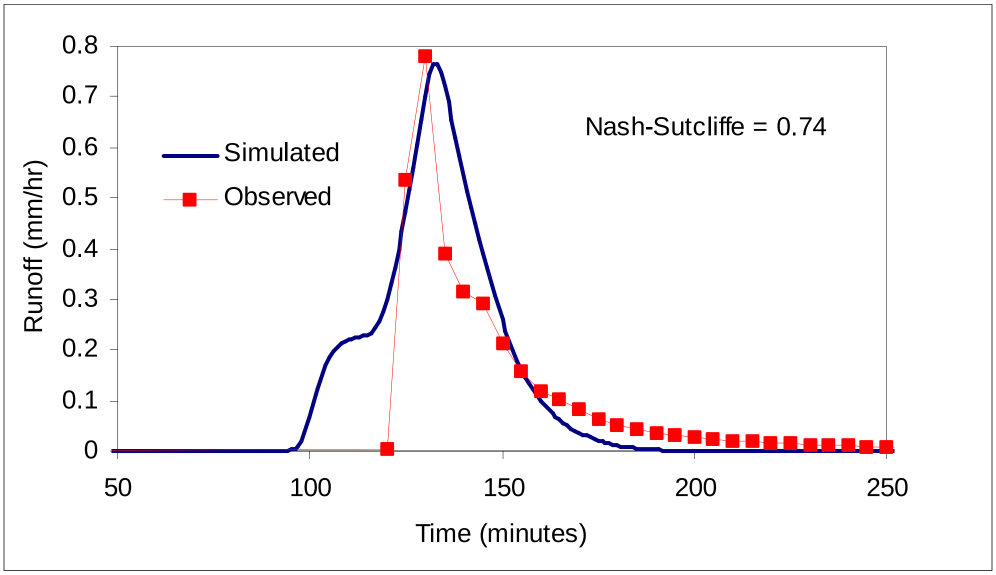

Figure 7.1 – Comparison of Observed and Simulated Hydrograph for the Poorest fit Hydrograph Used in the Analysis at Starmer Canyon

Using these data, an interesting trend is observed in optimal hillslope roughness (Figure 7.2). 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.

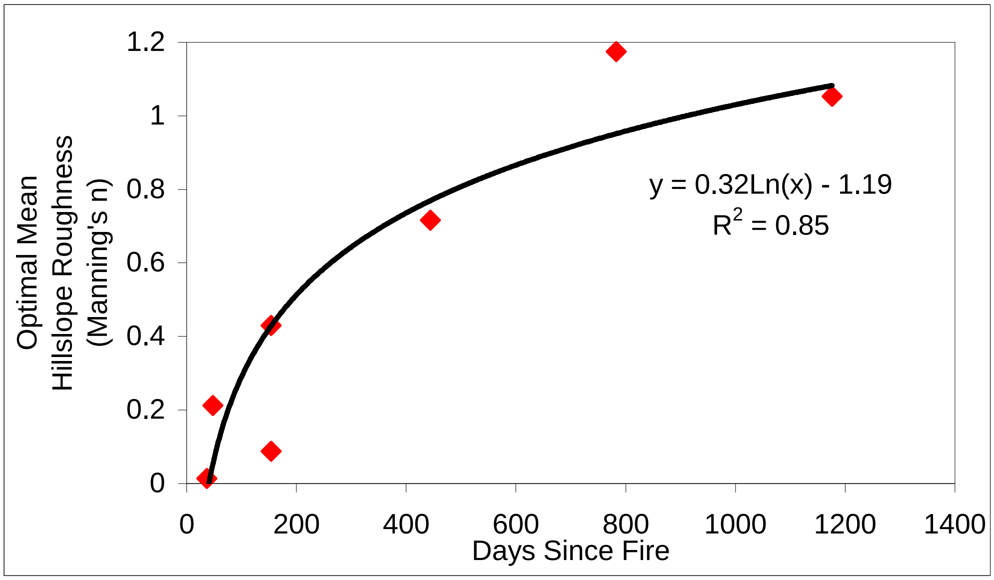

Figure 7.2 – Optimal Hillslope Roughness for Events that Occurred after the Cerro Grande Fire at Starmer Canyon Plotted vs Time

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.

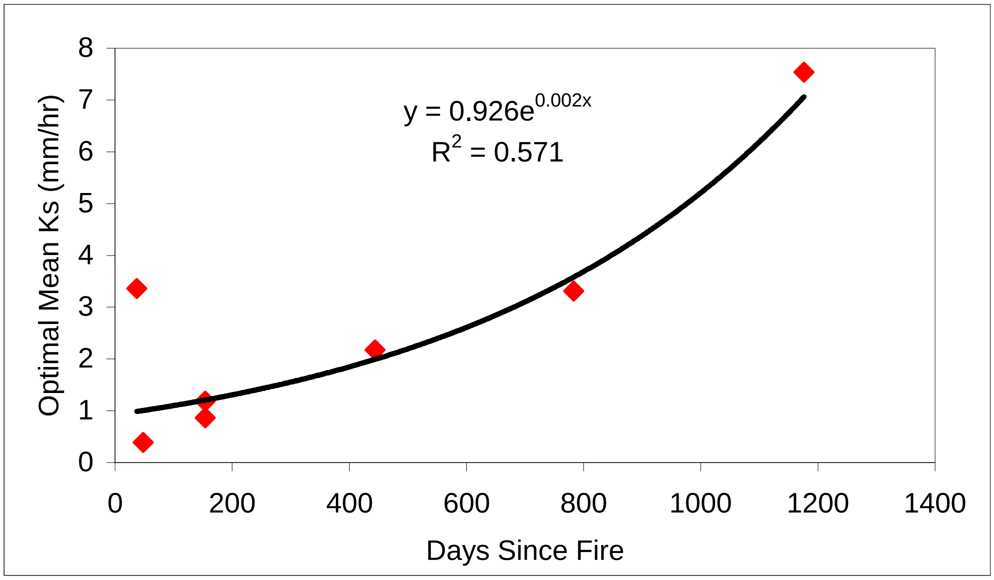

Figure 7.3 – Optimal Hillslope Hydraulic Conductivity Following the Cerro Grande Fire at Starmer Canyon Plotted vs. Time

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 7.3.

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 7.4 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.

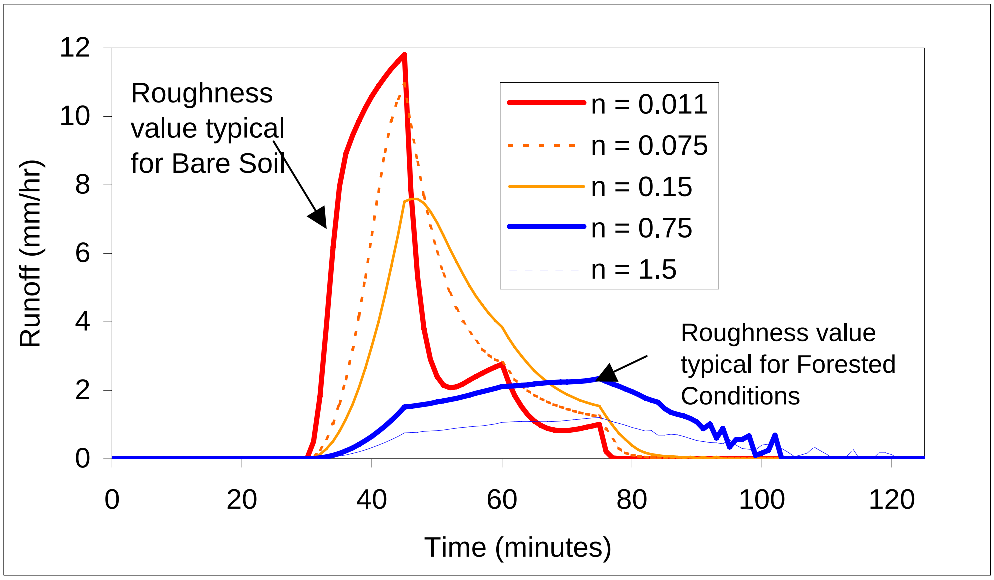

Figure 7.4 – Hillslope Runoff Plotted vs time for DifferentH Hillslope Roughness Values

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 7.5). 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 7.5.

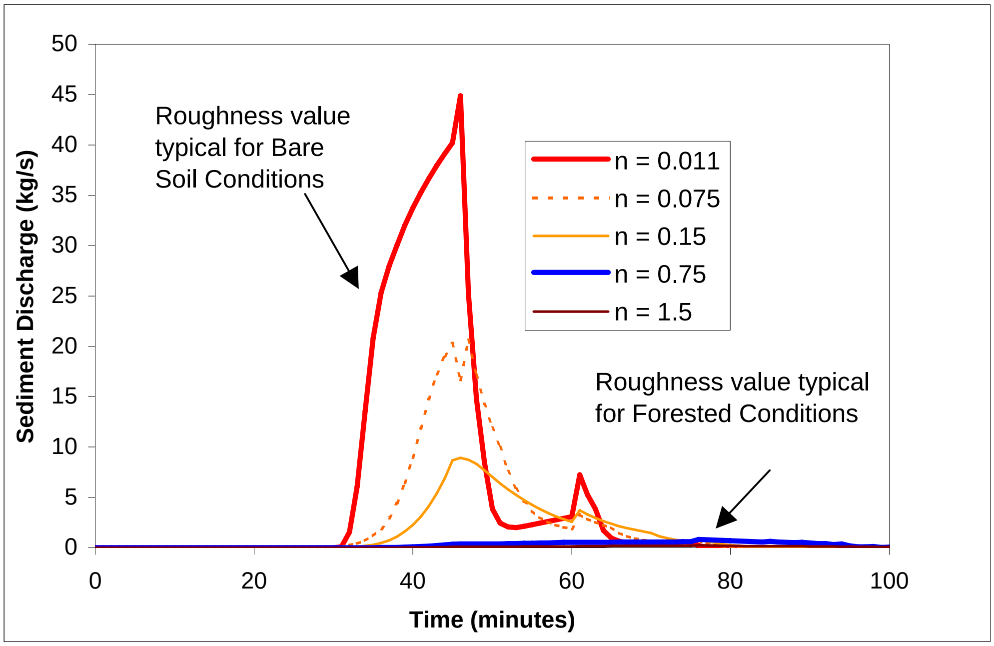

Figure 7.5 – Hillslope Sediment Discharge Plotted vs Time for Different Hhillslope Roughness Values

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 7.6. 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.

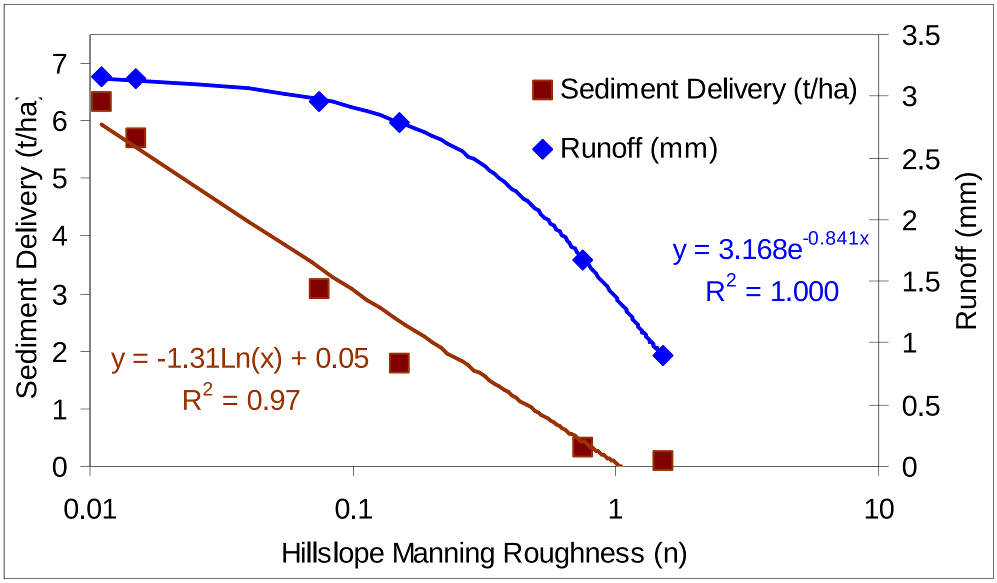

Figure 7.6 – Hillslope Sediment Delivery and Runoff Volume Plotted vs hillslope roughness values

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)).

8.0 AGWA-SWAT Application to the 2003 Aspen Fire near Tucson, Arizona

The overlay of land cover and soils allows AGWA to select a parameter set appropriate for that given land cover on that soil. The addition of a burn-severity map allows further characterization of hydrologic response based on the land cover, soils classification and burn severity. A critical element in using AGWA for post-fire assessments is translating a burn severity map into relationships that can be used to alter infiltration and erosion model parameters. This issue is discussed in more detail in a companion paper by Canfield et al. (this volume). In hydrologic-model terms, different CN values, and different post-fire roughness values can be selected based on the new classification. The burn severity map for the 2003 Aspen fire (Figure 8.1) illustrates a complex mosaic of low, moderate, and high severity burns.

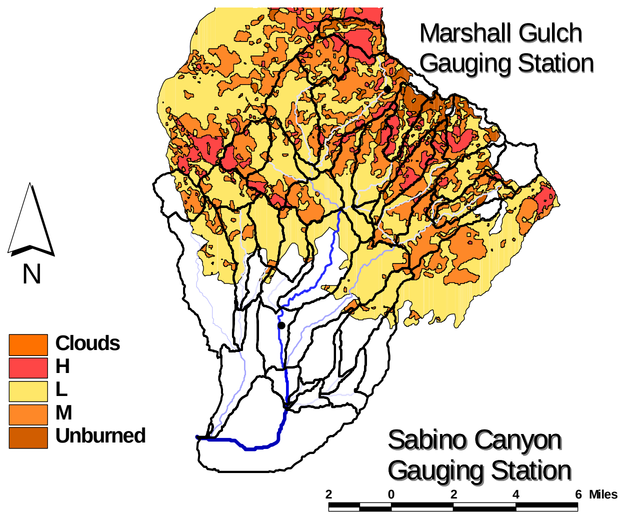

Figure 8.1– Burn Severity Map of Aspen Fire on the Sabino Canyon Watershed

By using a GIS, this information can be used to develop a complex mosaic of CNs, which can allow users to more accurately reflect hydrologic conditions within the model representation. The traditional method of implementing the CN technique (USDA, 1986) uses a spatially-weighted average CN, which can be used to describe the hydrologic response of a watershed. Since runoff is highly sensitive to CN, small differences in CN can result in big differences in runoff (Hawkins, 1975). A revised post-fire CN map for the Sabino Canyon watershed is given in Figure 8.2.

To fully utilize the revised CN map, the watershed must be partitioned into model elements small enough to represent a single hydrologic soil group, land-cover and burn-severity classification. Therefore, AGWA should not be used to partition a watershed at a more coarse level than the default 2.5%, and there may be situations, where this level is too coarse.

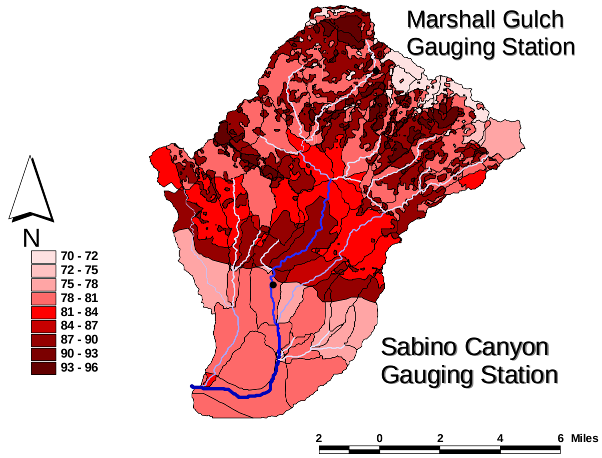

Figure 8.2 – Revised Curve Number Map of Aspen Fire on the Sabino Canyon Watershed

A second change that occurs on hillslopes is a change in hillslope roughness. Evaluation of roughness in the companion paper (Canfield et al, this volume) indicates that post-fire roughness on hillslopes can be over an order of magnitude lower in forested areas following fire. Rather than fix roughness separately for all soil/cover/complexes, the post-fire evaluation with AGWA sets roughness at a value reasonable for bare soil (n = 0.011; Engman, 1986). Selection of this value allows for more than an order of magnitude change in extremely rough environments, such as conifer forests.

The revised CN map in Figure 8.2 was used to generate SWAT model parameters for a one year simulation driven by a historical observed climatic record. The resulting difference in annual water yield by subwatershed area is illustrated in Figure 8.3. For this simulation, watershed roughness and infiltration parameters were held constant. This is unrealistic as the watershed recovers over time, but the objective is to evaluate how average annual runoff would change in a post-fire regime. Chapter 7 presents time-

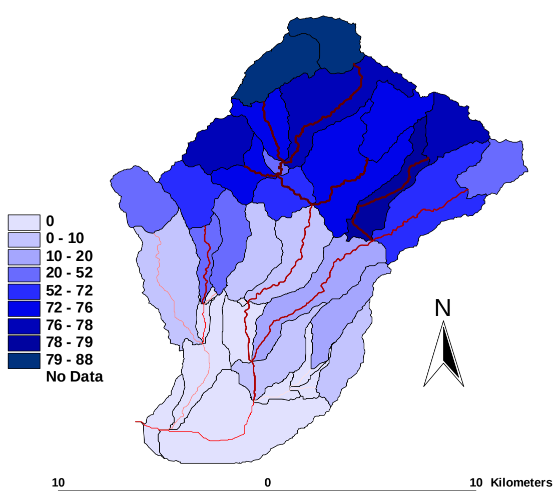

Figure 8.3 – First Year Post-fire Water Yield Difference Modeled by SWAT-AGWA (% change)

varying relationships (first post-fire day equals day one) for KINEROS2 parameters of hillslope hydraulic roughness and saturated hydraulic conductivity based on optimized post-fire observations at Starmer Canyon near Los Alamos, New Mexico.

Post-fire simulations from design or observed storms can also be spatially compared to pre-fire simulations driven with the same climate for various simulation outputs (e.g. peak runoff rate, total storm volume, total sediment transport, erosion, etc.). These differences can be displayed in percentage difference terms from the pre-fire case, or in terms of absolute differences.

Conclusions

Estimation of post-fire hydrologic response and change analysis is an important step in developing a plan to remediate potential post-fire flooding and erosion. The GIS-based AGWA tool (www.tucson.ars.ag.gov/agwa) allows the use of readily available spatial datasets to perform pre-fire hydrologic analysis using empirical (SWAT) and process-based (KINEROS2) hydrological models. If a burn-severity map is available, estimates of runoff volume can be made by modifying post-fire CNs. An application of AGWA-SWAT is illustrated using available data sets and a burn-severity map on the 2003 ASPEN fire near Tucson, AZ. A relationship between cover and CN provides a basis for estimating post-fire changes in CNs. The estimated changes in CNs are smaller than those derived from experience and used in many post-fire BAER analyses. However, they agree more with the observed changes in post-fire runoff volume, which show that the change in runoff volume is small relative to the large change in post-fire peak runoff. Therefore, a second modification in AGWA is to drastically decrease hillslope roughness, which increases peaks without a large increase in runoff volume. An application of KINEROS to the Starmer Canyon dataset at Los Alamos (Canfield et al, this volume) shows that hillslope roughness approximates bare conditions following the fire, and rapidly recovers. In summary the AGWA tool offers the capability of rapid post-fire watershed assessments to more effectively target remediation efforts. We would welcome, and assist in, the application of AGWA by resource managers and BAER teams.

9.0 Suggested Modifications to KINEROS2 to Account for Fire

Estimated Post-Fire Roughness Values

Using the cover values for natural covers and estimated hillslope roughness for those covers as listed in table 1.2, the relationship illustrated in Figure 9.1 was determined for roughness value as a function of cover values.

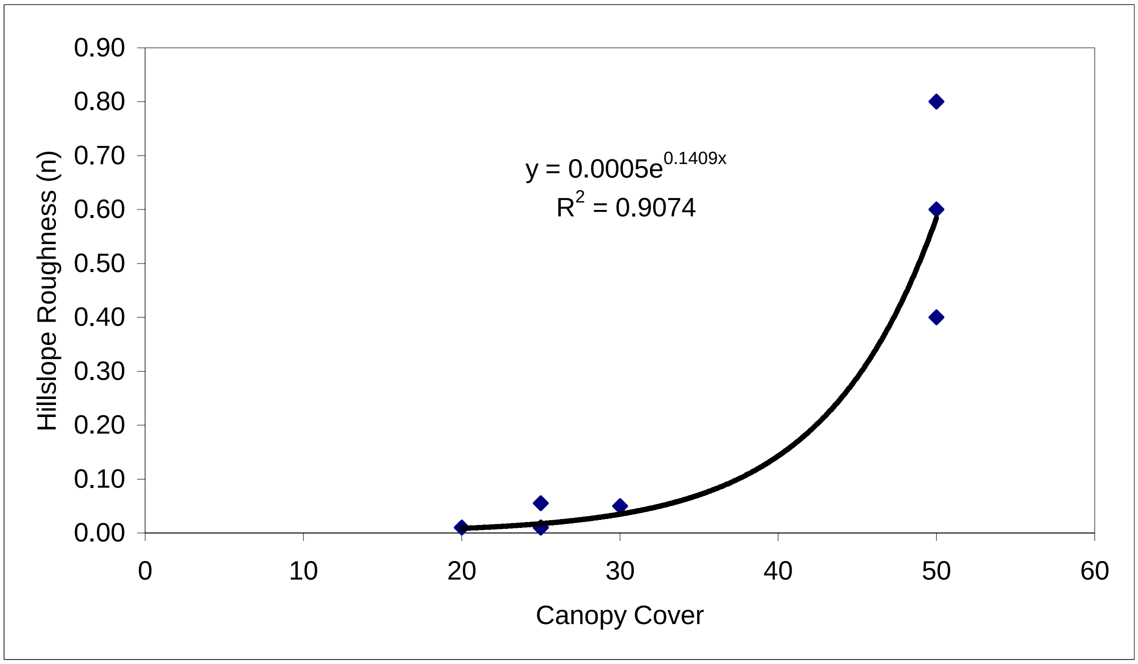

Figure 9.1 – Hillslope Roughness as a Function of Canopy Cover

Using these, values, table 5.1 could be updated to estimate post-fire hillslope roughness values as a function of canopy cover. It should be noted that hillslope roughness is related to ground cover and litter, but that litter is produced by the canopy, and one would expect environments with more canopy cover to also have more ground cover.

Table 9.1 Estimated Curve Number, Cover, Roughness and Interception Values for Burned and Unburned Conditions

Class	Name	A	B	C	D	Cover	Int	n
11	Open Water	100	100	100	100	0	0	0.000
12	Perrenial Ice/Snow	98	98	98	98	0	0	0.000
21	Low Intensity Residential	77	85	90	92	15	0.1	0.150
22	High Intensity Residential	81	88	91	93	10	0.08	0.120
23	Commercial/Industrial/ Transportation	89	92	94	95	2	0.05	0.011
31	Bare Rock/Sand/Clay	96	96	96	96	2	0	0.011
32	Quarries/Strip Mines/Gravel Pits	78	85	90	92	2	0	0.010
33	Transitional	72	82	87	90	20	0	0.010

41	Deciduous Forest	55	55	75	80	50	1.15	0.400
42	Evergreen Forest	55	55	70	77	50	1.15	0.800
43	Mixed Forest	55	55	75	80	50	1.15	0.600
51	Shrubland	63	77	85	88	25	3	0.055
61	Orchards/Vinyards/Other	77	77	84	88	70	2.8	0.040
71	Grasslands/Herbaceous	49	69	79	84	25	2	0.130
81	Pasture/Hay	68	79	86	89	70	2.8	0.400
82	Row Crops	72	81	88	91	50	0.76	0.170
83	Small Grains	65	76	84	88	90	4	0.170
84	Fallow	76	85	90	93	30	0.5	0.050
85	Urban/Recreational Grasses	68	79	86	89	90	2.5	0.410
91	Woody Wetlands	85	85	90	92	70	1.15	0.600
92	Emergent Herbaceous Wetlands	77	77	84	90	70	1.15	0.600
41l	Deciduous Forest	59	60	78	82	43	1.15	0.199
42l	Evergreen Forest	49	71	80	85	43	1.15	0.199
43l	Mixed Forest	59	60	78	82	43	1.15	0.199
51l	Shrubland	65	79	86	89	21	1.15	0.010
41m	Deciduous Forest	65	65	80	85	34	1.15	0.060
42m	Evergreen Forest	55	76	82	88	34	1.15	0.058
43m	Mixed Forest	65	65	80	85	34	1.15	0.058
51m	Shrubland	68	82	88	90	17	1.15	0.005
41h	Deciduous Forest	70	71	83	87	25	1.15	0.017
42h	Evergreen Forest	60	82	85	90	25	1.15	0.017
43h	Mixed Forest	70	71	83	87	25	1.15	0.017
51h	Shrubland	73	88	91	91	12	1.15	0.017

Note: l - low severity burn
m - moderate severity burn
h - high severity burn

It should be noted that the estimated roughness values for high severity burn approach the value for bare conditions. Therefore, the values of the table seem reasonable for forested conditions, and may be appropriate for estimating moderate and low severity burned forest conditions. However, the calculated values for shrubland are unrealistically low, and so should be set to a value no lower than bare conditions.

Post-Fire Ks Estimates

At this point, Ks values have not been estimated based on burn severity and cover estimates.

10. Suggested Modifications to AGWA-SWAT to Account for Fire

Modifications to AGWA SWAT

The estimated changes in CN and roughness for burned conditions described in Table 9.1 should serve as a basis for implementing SWAT in AGWA for burned conditions. However, since runoff velocities in SWAT assume a given rainfall excess, the estimates of peak runoff and erosion may be underestimated.

Impact of SWAT Overland Flow Calculation on Runoff Velocity

Estimates of Overland Flow Travel Time in SWAT: In the SWAT model overland flow can be described by the following equation:

$$v = \frac{q_{ov}^{\ 0.4} * slp^{0.3}}{n^{0.6}}$$

Where v is the overland flow velocity (m/s), q_{ov} is the average overland discharge rate (m^3/s), slp is the hillslope slope, and n is the manning roughness value. This is simply the solution of the kinematic wave for overland flow ( ). In SWAT, 6.35 mm/hr (1/4 inch/hr) is assumed to be rainfall excess rate, the q_{ov} value can be calculated for the length of the slope, and the following formulation can be used.

$$v = \frac{0.005 L^{0.4} * slp^{0.3}}{n^{0.6}}$$

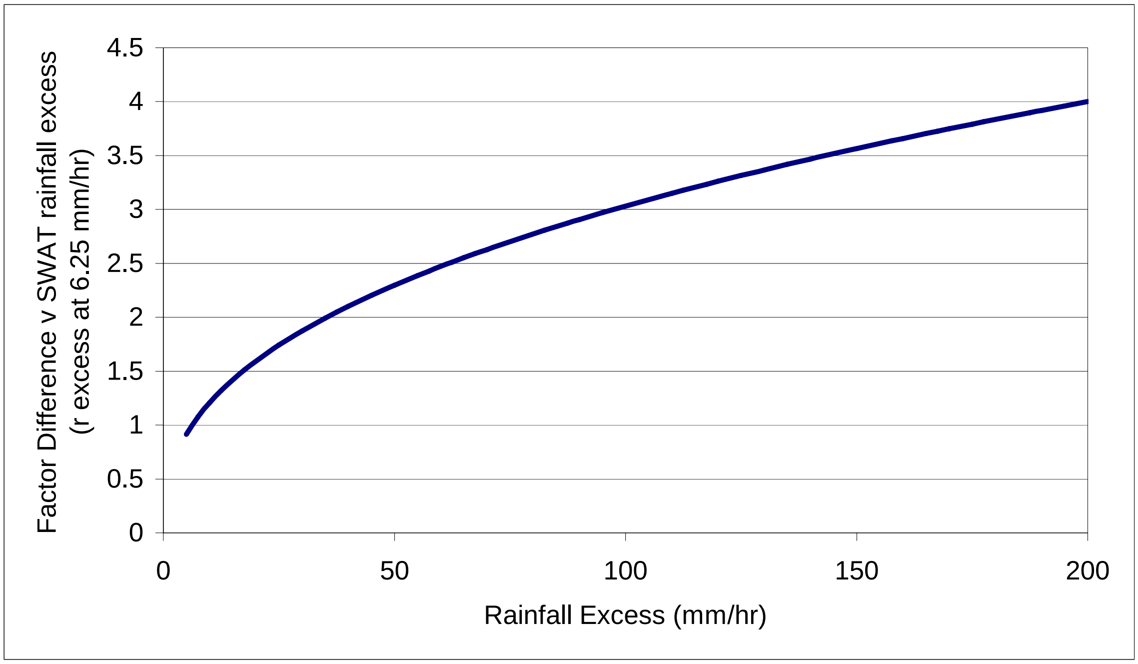

Figure 10.1 Relative Difference In Rainfall Excess on Overland Flow Velocity

SWAT uses rainfall excess calculated at 6.25 mm/hr in order to calculate runoff rate. Using the formulation of runoff velocity calculated in SWAT, runoff rate increases as a function of rainfall excess rate to the 0.4 power. In the southwest, rainfall excess can exceed 100 mm/hr in some situations. As noted in figure 10.1, the velocity of overland flow can be three times greater than the rate calculated in SWAT for rainfall excess of 100 mm/hr. Furthermore, at rainfall excess rates of 35 mm/hr, which are commonly exceeded in the desert southwest, the SWAT-calculated runoff rate is off by a factor of two. Therefore, SWAT-calculated peak runoff rate may be below the value calculated using the kinematic wave formulation for dynamic rainfall excess calculation.

11.0 Acknowledgements

Everett Springer provided the data set from Starmer Canyon at Los Alamos. The insights of Everett and Richard Hawkins were invaluable in understanding the hydrologic response of these burned watersheds. Hoshin Gupta provided valuable insight into calibration of hydrologic models and supplied the FORTRAN SCEUA code that was used for optimization of the KINEROS2 runs at Starmer Canyon. Andy Wigg from Pima County, (Arizona) Flood Control District provided rainfall and runoff data for Marshall Gulch. Salek Shafiqullah, USFS-Coronado National Forest, provided a burn severity map for the Aspen and Bullock fires and valuable insight into the USFS BAER approach. Support for this research was provided by the USDA-ARS Headquarters Post Doctoral Program, the US-EPA Landscape Ecology Branch, and in part by SAHRA under the STC Program of the National Science Foundation, Agreement No. EAR-9876800. This support is gratefully acknowledged

Disclaimer

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