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# Predicting Increased Sediment Delivery From the Cerro Grande Fire Using a Distributed Profile-Based Hillslope Erosion and Deposition Model in a GIS Framework

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## *Abstract*

A profile-based, analytical Hillslope Erosion Model (HEM) was integrated into a GIS framework to assess the impact of the Cerro Grande fire on erosion and sediment delivery to the many streams draining the burn area. The model, HEM-GIS, calculates rill and interrill erosion, transport and deposition along digital flow-pathways generated with the ArcInfo GIS software. This new erosion and sediment yield technology accounts for complex terrain attributes and their impact on the connectivity of sediment transport pathways from source areas to streams. GIS digital spatial data including: elevation, vegetation cover, burn severity and soil type are used as input to the model. Output includes spatially distributed predictions of total event-based sediment yield (tons or kg/m$^2$). The model was applied across an 800 km$^2$ region of the Pajarito Plateau watershed to assess the sedimentation risks associated with a 100-year design rain event. For this storm, the model predicted that the fire will cause runoff to increase from 3 to 6 times, and sediment yield will increase by more than order of magnitude.

## *Introduction*

In May 2000 the Cerro Grande Fire burned about 85% of the steep forested lands in the headwaters of streams that flow through Los Alamos County, the Los Alamos National Laboratory (LANL) and Native American lands located on the Pajarito Plateau in Northern New Mexico. The fire preceded the summer monsoon season, which is characterized by intense convective rain events. Landholders on the Pajarito Plateau were very concerned about the increased risk of flooding, hillslope erosion and channel scour and aggradation that was expected following the fire. Floods following previous fires in the region indicated that historic peak discharge values of less than a cubic meter per second to tens of cubic meters per second could increase by one to two orders of magnitude. (BAER Cerro Grande unpublished report, June 2000, Cannon and Reneau, 2000). Roads and buildings, as well as power, water and sewer lines located in canyon bottoms are in the direct path of floods. In addition, floodplain sediments in some of the canyons downstream of LANL facilities contain low levels of residual contaminants from weapons related activities during and following the Manhattan Project (Reneau *et al.*, 1998). Concern over the impact of post-fire hydrologic processes on human health, facilities and infrastructure prompted the development and application of models to assess, in a rapid response mode, the magnitude of post-fire flood and sediment transport events that might result from the approaching monsoon rain storms.

The post-fire erosion and sediment transport modeling aimed to address issues of stream water quality, culvert blockages and breaches, and channel stability near facilities and infrastructure. To address these issues a model was required that could route sediment eroded from burned hillslopes into stream systems across a large area of the Pajarito Plateau (800km$^2$). Though a number of models exist to predict hillslope erosion and or sediment transport such as USLE, WEPP, and KINEROS, these models have limitations relating to sediment routing (USLE), parameterization and set up time.

We required a model that could be adapted and applied rapidly to the Cerro Grande fire area. However, it was critical that the model account for the impact of complex topography and terrain attributes on the connectivity of sediment transport pathways and the delivery of sediment from hillslope sources to streams. In this paper we report on the development and application of a watershed erosion and sediment delivery model with these capabilities. The model integrates a validated, hillslope erosion, sediment transport and deposition model into a Geographical Information System (GIS) framework. This new integrated model takes advantage of the spatial data layers that existed for the Pajarito Plateau prior to the Cerro Grande Fire, as well as those that emerged during and after the fire.

## Site Description

### Geography

The Cerro Grande fire swept across the eastern face and flanks of the Jemez Mountains from May 4th to June 6th 2000. The Jemez Mountains form much of the Valles Caldera and rise from an elevation of about 2380 m on the Pajarito Plateau to 3183 m at Pajarito Mountain. The mountains are characterized by long, steep hillslopes draining into confined bedrock and alluvial stream channels. Prior to the fire the hillslopes were vegetated with dense mixed-conifer forest and had a thick surface duff layer. The fire burned approximately 17,240 ha of forest and woodland. Approximately 34% of the burn area was classified as high burn severity, which is characterized by the complete burning of all ground cover, tree foliage and branches, as well as many trunks. Exposed bedrock in these areas are discolored and exfoliating due to the intense heat on the ground. Soils are typically classified as sandy to silty loams with areas of outcropping bedrock (Nyhan *et al.* 1978, Benally, 1991). Post-fire observations indicate that many hillslope soils have a large coarse fragment component. After the fire these soils were observed to be water repellent and were classified as hydrophobic by the Burn Area Emergency Response (BAER) team.

### *Climate*

Annual precipitation varies with elevation, ranging from 51cm in the Jemez Mountains to 33 cm at the lower elevations of the Pajarito Plateau (Bowen, 1990). About 40% of this falls during intense short thunderstorms during the summer monsoon season (Bowen, 1990). These storms are highly variable in space. McLin (1992) estimates precipitation depths of about 3.4, 4.9 and 6.6 cm for storms with return periods of 2, 10 and 100 years (6 hr duration) in Los Alamos at an elevation of 2250 m. Following the fire the Bureau of Land Management (BLM) set up a network of Remote Area Weather Stations (RAWS) stations as part of flood warning system. During the months following the fire the maximum observed precipitation depth was 4.4cm at the Garcia Canyon RAWS station, well north of the town of Los Alamos and LANL, on July 16th 2000. The next largest event dropped 2.8 cm in Quemazon Canyon on July 18th 2000. All other rain events monitored at the Cerro Grande RAWS sites were much smaller.

### *Hydrology*

The streams in the Jemez Mountains drain through canyons that alternate with the many finger mesas comprising the Pajarito Plateau. The canyons are on the order of 50m to 100m deep, 100m to 200m wide and about 10km long (Bowen, 1990). The alluvial channels in the canyons are small, on the order of a couple of meters wide and 0.5m to 1m deep for drainage areas of around 25km$^2$. LANL runs a stream water quality and flow monitoring program at about 60 stations throughout the Pajarito Plateau. Many of the streams on the Pajarito Plateau lose water through the canyons reaches, and prior to the fire few summer runoff events originating in the Jemez Mountains or on the Plateau reached the Rio Grande. Peak discharge values in many canyons were an order of magnitude higher than the peak of record, and storm flow to the Rio Grande from the burn area was significant.

Runoff generation prior the fire occurred by both saturation excess and infiltration excess processes. Subsurface flow is dominant during snowmelt in the Spring and can account for up to 30% of annual runoff from plots located on the mesa top during years with high winter precipitation (Wilcox *et al.*, 1997, Newman *et al.*, 1998). Infiltration excess processes occur during intense summer rain events, but typically less than 10% of summer precipitation ran off the monitored mesa plots (Wilcox *et al.*, 1997, Newman *et al.*, 1998). Following the fire even small events (< 2yr return period) produced significant hillslope runoff (Cannon *et al.*, this volume).

## Methods

### Overview

In this paper we describe the development and application of an erosion and sediment yield model, HEM-GIS, to evaluate flood and sedimentation hazards to facilities and infrastructure in a 300km$^2$ area of the Jemez Mountains and Pajarito Plateau. In particular, we examined the impact of a 6hr rain event with a 100 year return period across this region for pre-fire and post-fire conditions. A watershed approach was required to determine the cumulative impact of hillslope erosion from burned and unburned areas on sediment delivery to streams. HEM-GIS was developed to integrate existing watershed runoff models with existing hillslope erosion and sediment transport models. The version of HEM-GIS described here integrates a simple, curve number based rainfall-runoff model with the profile-based Hillslope Erosion Model (HEM) (Lane *et al.*, 1988, 1995) in an ArcInfo Geographical Information System (GIS) framework.

A key feature of HEM-GIS is that it enables the routing of sediment from eroded hillslopes into the streams. The model takes into account the changing conditions that runoff encounters along a pathway to the stream. For instance, if runoff from a burned hillslope passes through an unburned area, the model predicts a decrease in sediment concentration and will deposit sediment in the unburned area where ground cover increases. Changes in gradient, vegetation cover, and soil erodiblity along the hillslope transport pathway impact sediment delivery to the stream. This is in contrast to USLE-based GIS erosion models, which typically only predict an erosion potential for a given grid cell.

### Hillslope Erosion Model

HEM was developed and tested by Lane and others (1988, 1995) at the USDA ARS Watershed Research Center in Tucson, AZ. This model was chosen because it was relatively easy to parameterize with existing and emerging (post-fire) spatial data, and it could be directly applied on flow pathways generated on Digital Elevation Models (DEMs). The erosion and overland flow equations are coupled and solved to predict sediment concentrations and yields along a hillslope profile for a runoff event. The hillslope profile is comprised of connected segments, each with its own gradient, soil erodibility, and vegetative canopy and ground cover. The model represents rill and interrill erosion, and sediment transport and deposition processes. Input data includes a runoff volume per unit area for each hillslope profile in addition to the segment information listed above. (Run HEM on-line at http://eisnr.tucson.ars.ag.gov/hillslopeerosionmodel/ .)

HEM couples runoff and sediment continuity equations to predict sediment yield along each hillslope profile for a runoff event. Runoff is represented by the kinematic wave equation for overland flow per unit width on a plane:

$$\frac{\partial(h)}{\partial t}+\frac{\partial(q)}{\partial x}=r \qquad (1)$$

In equation (1) $h$ is flow depth (m), $t$ is time (s), $q$ is discharge ($m^2/s$), $x$ is distance (m) and $r$ is rainfall excess (m/s). In this model we represent discharge as:

$$q = Kh^m \qquad (2)$$

where $K$ is the stage-discharge coefficient. The exponent, $m$, is 3/2 when

$$K = C\sqrt{S} \qquad (3)$$

where $C$ is the Chezy hydraulic resistance coefficient for turbulent flow and $S$ is the dimensionless slope of the land surface.

The sediment continuity equation for overland flow is:

$$\frac{\partial(ch)}{\partial t} + \frac{\partial(cq)}{\partial x} = E_i + E_r \qquad (4).$$

In equation (4) $c$ is the sediment concentration, $Ei$ is the interrill erosion rate per unit area per unit time and $Er$ is the net rill erosion (or deposition) rate. The simplifying assumptions for rill and interrill erosion rates are given as:

$$E_i = K_i r \qquad (5)$$

where $Ki$ is the interrill coefficient (kg/m3), and

$$E_r = K_r(T_c - cq) = K_r[(B/K)q - cq] \qquad (6)$$

where $Kr$ is the rill coefficient (1/m), $Tc$ is the transport capacity (kg/s/m) and is assumed equal to $(B/K)q$, $B$ is a transport-capacity coefficient (kg/s/m2.5)

The solution to the sediment continuity equation for the case of constant rainfall excess was integrated through time (Shirley and Lane, 1978) to produce a sediment-yield equation for a runoff event as:

$$Q_s(x) = QC_b = Q\{B/K + (K_i - B/K)[1 - \exp(-K_r x)]/K_r x\} \qquad (7).$$

Here $Qs$ is total sediment yield for the entire amount of runoff per unit width of the plane (kg/m), $Q$ is the total storm runoff volume per unit width (m3/m), $Cb$ is mean sediment concentration over the entire hydrograph (kg/m3) and $x$ is distance in the direction of flow (m). This equation is the analytical solution to the coupled runoff and sediment continuity equations described above. It can be applied to, and solved on, multi-segment hillslope profiles with varying slope and cover charcacteritics.

HEM-GIS applies the profile-based HEM across the whole burn area and its affected watersheds in an automated manner. Input data are extracted from GIS spatial data coverages that include elevation, ground and canopy cover, erodibility and runoff volume per unit area for a precipitation event. Output values for sediment yields are also distributed across the whole watershed. The runoff volumes can be calculated within HEM-GIS from SCS curve numbers, or from dynamic, deterministic rainfall/runoff models such as SPLASH (Beeson, *et al.*, this volume). The derivation of the HEM-GIS input data, and the methods for applying HEM in the GIS framework are described below.

### *Precipitation and Runoff*

Runoff per unit area was calculated for each grid cell using the Soil Conservation Service (SCS) curve number approach. The SCS approach relates total rainfall excess or runoff, $R_E$(in), to precipitation, $P_E$(in), through an empirical coefficient CN, the curve number. The equation used for runoff production is as follows:

$$R_E = (P_E - I)^2/(P_E - I + S), \quad S = (1000/CN) - 10, \text{ and } I = 0.2S \qquad (8)$$

This approach was used by the BAER team to estimate flood risk following the fire. It is also the approach used by McLin (1992) to calculate pre-fire flood risks in the canyons of the Pajarito Plateau. Note that the equation depends on units of inches. Runoff in inches is converted in HEM-GIS to millimeters for input into the erosion equations.

Precipitation increases with elevation in this region, and a spatial coverage of precipitation as a function of elevation, El(m), was developed from data at the Los Alamos and White Rock rain gages which are separated in elevation by about 200m. We used Mclin's (1992) 100 year, 6hr design storms to develop a simple linear interpolation between the two stations to give precipitation depth P(cm):

$$P = 0.008El - 12.0 \qquad (9)$$

This distribution of P is shown in figure 2a.

### *Other Spatial Data*

The spatially distributed input data required for HEM-GIS were developed from diverse data sources within and outside LANL. The model required parameter values that were functions of three base spatial data sets: burn severity (figure 2b), soil type and vegetation type. Spatial data sets such as percent ground (figure 2c) and canopy-cover, erodibility (figure 2d) and curve numbers were derived from these base data.

Burn severity was obtained from the BAER burn severity map (May 27, 2000 version). The soil type data set was developed from Nyhan *et al.* (1978), the U.S. Forest Service (Benally, 1991) and STATSGO data. Curve number values used in this application were derived from BAER estimates and existing pre-fire data (McLin, 1992) that were modified to reflect observed runoff data in June 2000 (Andrew Earles, Wright Water Engineers, July, 2000).

Percent canopy cover and ground cover were derived from existing LANL vegetation type data, the BAER burn severity map and unpublished (J. Nyhan and D. Breshears, May 2000) and published data (Wilcox, 1994; Wilcox *et al.*, 1997, Martens *et al.*, 2000). The latter data sets are summarized in Table 1, and link vegetation type with percent canopy cover and ground cover before and after the fire. Percent cover within the burn area was calculated from a few ground observations at sites classified as high, moderate and low burn severity in vegetation categories of Ponderosa Pine forest, mixed conifer forest and Pinon-Juniper woodland (Randy Balice, LANL, *pers.com.*, May 2000). The few observations were converted into a percent reduction in cover by burn severity and vegetation type, and applied across the burn area.

Soil erodibility was derived from the composite soil type map that was extended to include soil texture data. Erodibility values were assigned to grid cells based on the soil texture of the cells. The erodibility values were derived from the USDA WEPP database by L.Lane for use in HEM. Erodibility values were taken from the HEM web site given above. These values are summarized in Table 2.

### *GIS Analysis*

The runoff and erosion models were linked and applied in HEM-GIS in a sub-watershed mode. Hillslope erosion and sediment delivery to the stream were calculated for each sub-watershed. These were generated using Arc Info commands to compute the Strahler stream order for the whole stream network, and identify the sub-watersheds to streams of each Strahler order. The size and number of the sub-watersheds was determined by the user-defined size of the hillslope drainage area that is required to support a stream channel. In this model run we chose 200 cells (18 ha) of hillslope contributing area. This is somewhat larger than indicated by field observations. However, contributing areas for channel formation are very large, even in steep zero-order basins. The 200 cell value was chosen so that: 1) the hillslopes within any given sub-watershed would have reasonable geomorphic similarity, 2) most of the flow paths within a sub-watershed did not converge until entering the stream line and 3) a manageable number of sub-watersheds were created for this large geographic region. We did not have sufficient data to apply a slope-area method (Montgomery and Dietrich 1992; Dietrich *et al.* 1993) to define the channel network. The analysis resulted in 747 sub-watersheds that were processed by the model (figure 3).

The HEM component of the model runs on individual hillslope profiles. The model applies HEM on a selection of hillslope profiles from each sub-watershed. An example sub-watershed with its selected profiles is shown in Figure 3. The profiles are extracted along Arc Info flow paths from ridge grid cells (sub-watershed boundaries) to the stream grid cells within each ordered polygon. The segments of each profile are comprised of the 30m x 30m grid cells in the Digital Elevation Model (DEM) for the watershed. Each segment has the length, gradient, ground cover, canopy cover and erodibility values of its grid cell within the spatial data layers in Arc Info.

HEM is applied on each extracted profile using an event-based total runoff depth. HEM calculates the sediment yield delivered into the stream from each profile for the runoff event. The total sediment yield (metric tons) to the stream in each sub-watershed is the sum of the area-weighted sediment yield from each profile. Sediment yield is also expressed as a rate, kg $m^{-2}$, which is applied to all cells in the sub-watershed to calculate accumulated sediment delivery to and along the stream network.

## *Results*

### *Runoff*

Runoff depth for the 100-year storm was calculated in every grid cells for both pre-fire and post-fire conditions. Pre-fire predicted runoff shows limited spatial variation with typical local runoff depths of <1.0cm to 3.0cm (figure 4a). In contrast, post-fire predicted runoff is highly spatially variable, ranging in depth from <1.0cm to 11.6cm (figure 4b). The predicted storm runoff depths directly reflect the curve number values and the precipitation gradient, with the highest runoff values occurring in the high severity burn areas in headwater locations. Our runoff depths, computed using a distributed curve number approach, agree well with runoff depths from rainfall simulator experiments on burned and unburned plots (Johansen et. al., this volume), and those computed using the SPLASH (Beeson et al., this volume) and HEC (McLin et. al., this volume) models.

The distributed runoff depth values were converted to runoff volume using the Arc Info flow accumulation command with runoff depth as a weighting grid. Table 3 shows runoff volumes resulting from the 100-year event are predicted to be 3 to 8 times larger for the post-fire scenario than the pre-fire scenario. The values in Table 3 were extracted from the runoff volume grid where several streams cross highway 501 (figure 1). The Highway marks the boundary between the Jemez Mountains and Pajarito Plateau as well as the boundary between LANL and USFS land. The highway blocked high flows in Pajarito Canyon, Canyon De Valle and Water Canyon during a big runoff event on June 28th 2000, when less than 2 cm of rain and hail resulted in peak flows greater than $30m^3s^{-1}$, resulting in culvert blockages, flooding on the road and several feet of sedimentation behind culverts.

### *Coupled Runoff and Erosion*

Erosion and sediment yield to stream segments were calculated in HEM-GIS using the runoff depth, erodibility and cover values described in the above sections. Total sediment yield was calculated for each sub-watershed in the model area for both pre-fire and post-fire conditions. Although runoff depth and cover differed between the two simulations, erodibility was held constant. For pre-fire conditions, HEM-GIS predicted typical sediment yield values of 50 to 500 tons (metric) in upland sub-watersheds (figure 4c). In contrast, the model predicted sediment yield values of 500 to 15,000 tons in the same sub-watersheds using post-fire runoff and cover input data (figure 4d). Variations in sediment yield on the unburned mesas results from mapped variation in vegetation type and cover under unburned conditions.

The total sediment yield values for the sub-watersheds are strongly dependent on the size of the sub-watershed, and it is hard to compare these results to other data sets. We can better assess the impact of the fire on sediment yield as a rate per unit area. Typical sediment yield rates for the pre-fire condition were predicted to range from 0.01 to 1.0 kg $m^{-2}$ in the upland sub-watersheds (figure 4e). Sediment yield rates predicted for the post-fire condition were one to two orders of magnitude greater than the pre-fire rates, ranging from about 3.5 to 16 kg $m^{-2}$ (figure 4f).

The sediment yield rate values were used to produce grids of accumulated sediment delivery to the stream from all upstream eroding hillslope sources. Figure 5 shows the post-fire predicted total sediment yield in the vicinity of Upper Los Alamos and Pueblo Canyons. The post-fire100 year design storm delivers between 16,000 and 64,000 tons (metric) of sediment to the streams above highway 501 (Table 3). This is 3 to 27 times the sediment delivery predicted for the pre-fire scenario. Within-channel sediment transport was calculated for these streams using APOINT98 (Lane and Nichols 1997). The APOINT98 calculations suggest that the flood hydrograph resulting from the 100-year storm will transport anywhere from 30% to 100% of the hillslope derived sediment for a given stream system. The variation in transport is due to uncertainty in channel roughness and bed grain size during the large flood.

## Discussion

HEM-GIS represents a significant advance in erosion prediction technology in that it applies a robust flow-path based erosion and sediment transport model across large watersheds in an automated manner. Good digital elevation models are now available for many regions of the world, and HEM-GIS takes advantage of digital topography and GIS technology to automate the process of defining the geometry of hillslopes and sub-watersheds for routing sediment into channels. Changes in local gradient along a runoff pathway can exert strong control on runoff and sediment transport. The connectivity of sediment sources to sinks depends on the existence of benches, footslopes, floodplains and fans located along flow pathways (Herron and Wilson, 2001). Our ability to predict sediment delivery depends on our ability to represent those features in our models (Butterworth et. al. 2000). HEM-GIS enables representation of these features at the level of the resolution of a given DEM.

In this application we were able to assess the potential impact of the Cerro Grande fire on runoff and sediment delivery for a large storm event, across the complex terrain of the Jemez Mountains and Pajarito Plateau. Runoff from the 100-year design storm was predicted to be about 85% and 35% of the precipitation in the upland and mesa-top burn areas respectively. Under pre-fire conditions predicted runoff was about 15-20% of rainfall in both the upland and mesa-top areas. In general, the model suggests that runoff doubles under post-fire conditions for a 100–year design storm. The predicted values compare well to those observed by Johansen et al. (this volume) on rainfall simulator plots. Although stream flow was observed to increase by one to two orders of magnitude for small events, the large volume of precipitation during the 100-year event will greatly exceed the infiltration and storage capacities of both the burned and unburned soils. The dynamics of this behavior is explored by Beeson *et al.*(this volume).

The upland runoff in the post-fire scenario was only 3 to 6 times the pre-fire scenario, but sediment delivery increased by greater than an order of magnitude. The sensitivity of the model to the cover parameter is high, resulting in high erosion rates in severely burned areas. Though the model has not been properly tested against field data, predicted sediment yield rates correspond well with those observed during rainfall simulator experiments conducted by Johansen *et al.* (this volume) after the Cerro Grande fire. His work shows that a severely burned plot in Ponderosa Pine forest on the mesa top produced 25 times more sediment per unit of runoff than the unburned plot. Our model predicted that the burned mesa areas delivered about 30 times more sediment to the adjacent streams than the unburned areas per unit of runoff. In upland areas the model predicted that burned areas delivered about 10 times more sediment to streams per unit of runoff than unburned areas.

Although HEM-GIS takes advantage of DEM and GIS technology to predict sediment yield throughout watersheds, the current implementation has several important limitations. First, the model routes sediment along selected flowpaths (automated selection) within sub-watersheds and uses only these selected profiles to calculate an average sediment yield to the stream segment. This procedure requires many GIS computations, and does not use all the topographic information available in the DEM. The need for selective profile processing arises from the assumption of constant rainfall excess in the analytical solution to the runoff-erosion equations. Total runoff can not change along a profile, so converging and diverging flowpaths calculated on a DEM surface violate the constant runoff assumption. We attempt to correct for this by truncating HEM profiles at stream cells and sub-watershed boundaries, and by choosing a channel network density that limits the number of convergent flow paths within sub-watersheds.

The constant rainfall excess assumption gives rise to a second limitation; we do not accurately represent the impact of the runoff hydrograph on sediment transport. To do this however, would require a dynamic, numerical, coupled runoff and erosion model. Finally, We know from field observations that the soil surface texture has changed after large runoff events, and it is likely that the surface may be armoring during the erosion event. The armoring process will reduce total erosion and transport due to changes in surface protective cover and roughness.

Development and application of this profile or flow-path based runoff , erosion and yield model highlighted the need to carry out additional work. We need to parameterize and test the model against better field data, and we are now setting up hillslope scale field monitoring sites for this purpose. We would like to improve model performance by eliminating the need to sub-divide the model region into sub-watersheds, a step that is required to generate non-convergent flow-paths on the DEM. We would prefer to apply HEM on all flow pathways. This will require reformulation of the constant rainfall excess assumption, and an analytical solution may be difficult to formulate.

An important advantage of the current model formulation is that it is very easy to parameterize, and it has no errors or instabilities inherent in many numerical models. However, it may not adequately represent important processes that more complex models represent. An initial comparison between the curve-number runoff generation method and SPLASH indicated that total runoff production on a sub-watershed basis was similar for both models. Future work includes comparing the analytical erosion and sediment delivery component of the model against more sophisticated, dynamic, erosion and transport models. These tests should help to identify the conditions under which HEM-GIS performs best.

Finally, we are working toward coupling the HEM-GIS model to a channel sediment routing model which will enable us to identify areas susceptible to sedimentation and scour within the channel as sediment delivery from hillslope sources varies throughout the network.

## *Conclusions*

Current hillslope erosion prediction technology is limited by either 1) the inability to apply technology across large tracts of diverse terrain in an automated manner or 2) the inability to route eroded sediment from source areas into streams along hillslope flow-pathways. The HEM-GIS model overcomes both of these limitations by linking a profile-based, analytical erosion and sediment transport model into a GIS framework. The advantage of this model is that it predicts the impact of complex topography and other terrain attributes on the delivery of sediment from source areas to the streams. The approach enhances our ability to examine the connectivity of sediment transport pathways through landscapes. When the model was applied on the Pajarito Plateau to assess the impact of the Cerro Grande fire on hillslope sediment yield resulting from a 100-year design storm, predicted runoff and erosion corresponded well with observations from rainfall simulator experiments. Though the model has some limitations, it paves the way to better watershed-based erosion and sediment delivery predictions.

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Table 1. Cover values are a function of pre-burn cover properties for different vegetation types modified by burn intensity. Ground cover includes pebbles.

| Cover Type | Canopy Cover, % | Ground Cover, % |
|---|---|---|
| Developed | 10 | 90 |
| Grassland | 90 | 90 |
| Ponderosa Pine | 80 | 90 |
| Mixed Conifer | 80 | 90 |
| Aspen | 80 | 90 |
| Pinon/Juniper | 35 | 80 |
| Water/Shadows | 80 | 90 |
| Bare Ground | 5 | 50 |
| Juniper Woodland | 20 | 70 |
| low burn Developed | 9 | 73 |
| low burn Grassland | 77 | 73 |
| low burn Ponderosa Pine | 68 | 73 |
| low burn Mixed Conifer | 68 | 73 |
| low burn Aspen | 68 | 73 |
| low burn Pinon/Juniper | 30 | 65 |
| low burn Water/Shadows | 68 | 73 |
| low burn Bare Ground | 4 | 43 |
| low burn Juniper Woodland | 17 | 58 |
| mod burn Developed | 4 | 55 |
| mod burn Grassland | 38 | 55 |
| mod burn Ponderosa Pine | 34 | 55 |
| mod burn Mixed Conifer | 34 | 55 |
| mod burn Aspen | 34 | 55 |
| mod burn Pinon/Juniper | 15 | 50 |
| mod burn Water/Shadows | 34 | 55 |
| mod burn Bare Ground | 2 | 35 |
| mod burn Juniper Woodland | 9 | 45 |
| high burn Developed | 0 | 24 |
| high burn Grassland | 2 | 24 |
| high burn Ponderosa Pine | 2 | 24 |
| high burn Mixed Conifer | 2 | 24 |
| high burn Aspen | 2 | 24 |
| high burn Pinon/Juniper | 1 | 23 |
| high burn Water/Shadows | 2 | 24 |
| high burn Bare Ground | 0 | 22 |
| high burn Juniper Woodland | 0 | 23 |

Table 2. Soil data used in HEM-GIS. Soil texture information was extracted from soil survey reports for the region (Nyhan *et al.*, 1978, Benally, 1991). Soil erodibility values were assigned on the basis of texture.

| **Texture** | **Erodibility** |
|---|---|
| sandy loam | 2.3 |
| fine sandy loam | 2.1 |
| loam | 1.8 |
| loamy sand | 2.0 |
| silty loam | 3.3 |
| sand | 2.0 |

Table 3. Comparison of predicted pre-fire and post-fire sediment yield and runoff at Hwy 501.

| | Sediment (tons) | | | Runoff (m^3) | | |
|---|---|---|---|---|---|---|
| | post-fire | pre-fire | x increase | post-fire | pre-fire | x increase |
| Pueblo Canyon | 34983 | 1287 | 27 | 353470 | 63083 | 6 |
| Los Alamos Canyon | 64453 | 7352 | 9 | 791501 | 248356 | 3 |
| Pajarito Canyon | 30435 | 1734 | 18 | 342185 | 67856 | 5 |
| Canyon De Valle | 15971 | 3517 | 5 | 271273 | 96815 | 3 |
| Water Canyon | 33935 | 2809 | 12 | 506646 | 105501 | 5 |

## 6. Figure Captions

*Figures shown here are jpeg files. These figures will be submitted in post-script file format for greater clarity in publication.*

Figure 1. Location map showing the general area affected by the fire. The Los Alamos National Laboratory is shown in the shaded region. The fire started in the Northwest corner of Bandelier National Monument and swept Northeast across the Santa Fe National Forest and Santa Clara Pueblo, as well East onto LANL land and into the city of Los Alamos.

Figure 2. Spatial data sets used to parameterize the model included: a) precipitation depth used as input to the curve number runoff calculation, b) the BAER team, May 27, 2000, burn severity map was used to derive post-burn canopy and ground cover maps, c) percent ground cover, where the amount of ground cover including litter, ground vegetation, stones, burned tree stumps and limbs is a function of original vegetation type and the burn severity, d) erodibility index derived from USDA rainfall simulator experiments for soils of different textures (pers. com. L. Lane, USDA, ARS, Tucson, May 2000, Get Lane reference).

Figure 3. The HEM erosion and sediment transport model was applied to hillslope profiles corresponding to ArcInfo generated flowpaths in sub-watersheds. The sub-watersheds were generated by imposing the drainage density shown in a). (The contour interval in a) is xxx. Bold watershed boundaries are not used in the calculations and are shown only to indicate the structure of the watershed.) The drainage network was used in a Strahler ordering scheme to define the sub-watersheds shown in b). The hatched area in b) shows a sub-watershed bounding a 2nd order stream segment. An algorithm traces around each sub-watershed boundary to select the starting cells for the 17 flow-pathways shown in c), which were used in the HEM calculations. The profile segments are comprised of the 30 by 30 meter grid cells from the DEM.

Figure 4. Predicted runoff and sediment yield for the 100-year, 6-hour design storm event. Total event runoff (mm) is shown distributed across the grid of 30m x 30m cells for the for a) the pre-fire and b) post-fire conditions. Total sediment yield (metric tons) on a sub-watershed basis as predicted for c) pre-fire and d) post-fire conditions. Sediment yield to sub-watershed stream segments is shown as a rate of delivery (kg $m^{-2}$) for e) pre-fire and f) post-fire conditions.

Figure 5. The post-fire sediment yield in figure 4f) is accumulated using the ArcInfo flow accumulation algorithm. The accumulated value at a given point represents the total amount of hillslope sediment delivered to the length of stream above that point during the design storm event. It does not reflect the transport of hillslope sediment through the stream. In the upland streams the flood hydrographs generated by the design storm have enough transport capacity to transport between 30 % and 100 % of the sediment yield from the hillslopes.

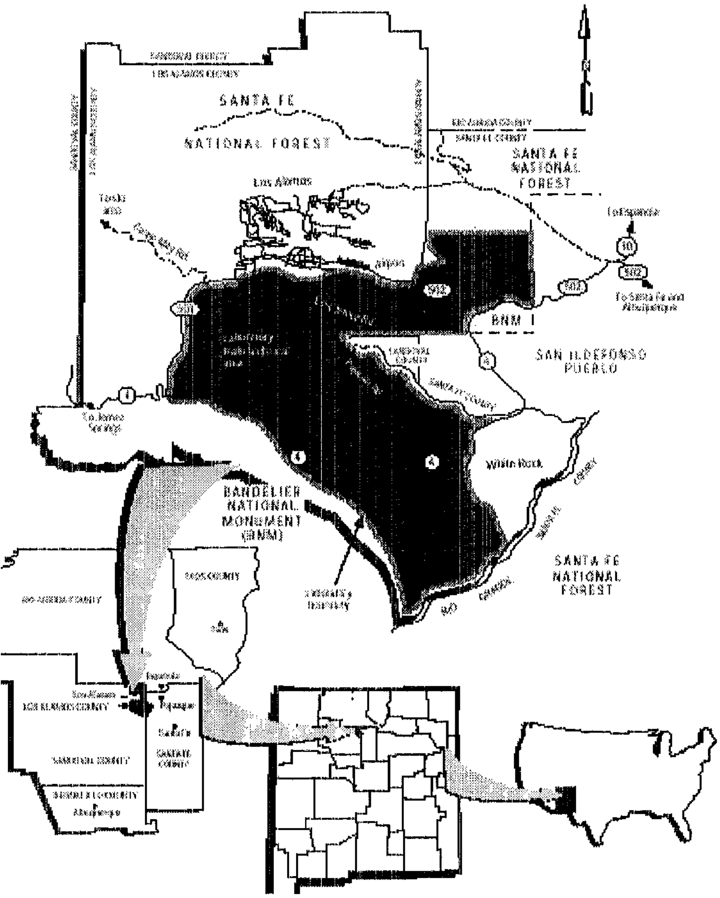

N
SANTA FE
NATIONAL FOREST
SANDOVAL COUNTY
LOS ALAMOS COUNTY
SANTA FE
NATIONAL
FOREST
Los Alamos
To Espanola
30
502
502
To Santa Fe and
Albuquerque
BNM
SAN ILDEFONSO
PUEBLO
4
4
4
501
To Jemez
Springs
White Rock
BANDELIER
NATIONAL
MONUMENT
(BNM)
SANTA FE
NATIONAL
FOREST
RIO
GRANDE
SANTA FE COUNTY
TAOS COUNTY
Taos
RIO ARRIBA COUNTY
Espanola
Los Alamos
LOS ALAMOS COUNTY
Pojoaque
Santa Fe
SANTA FE
COUNTY
SANDOVAL COUNTY
BERNALILLO COUNTY
Albuquerque

Figure 1.

Figure 2.

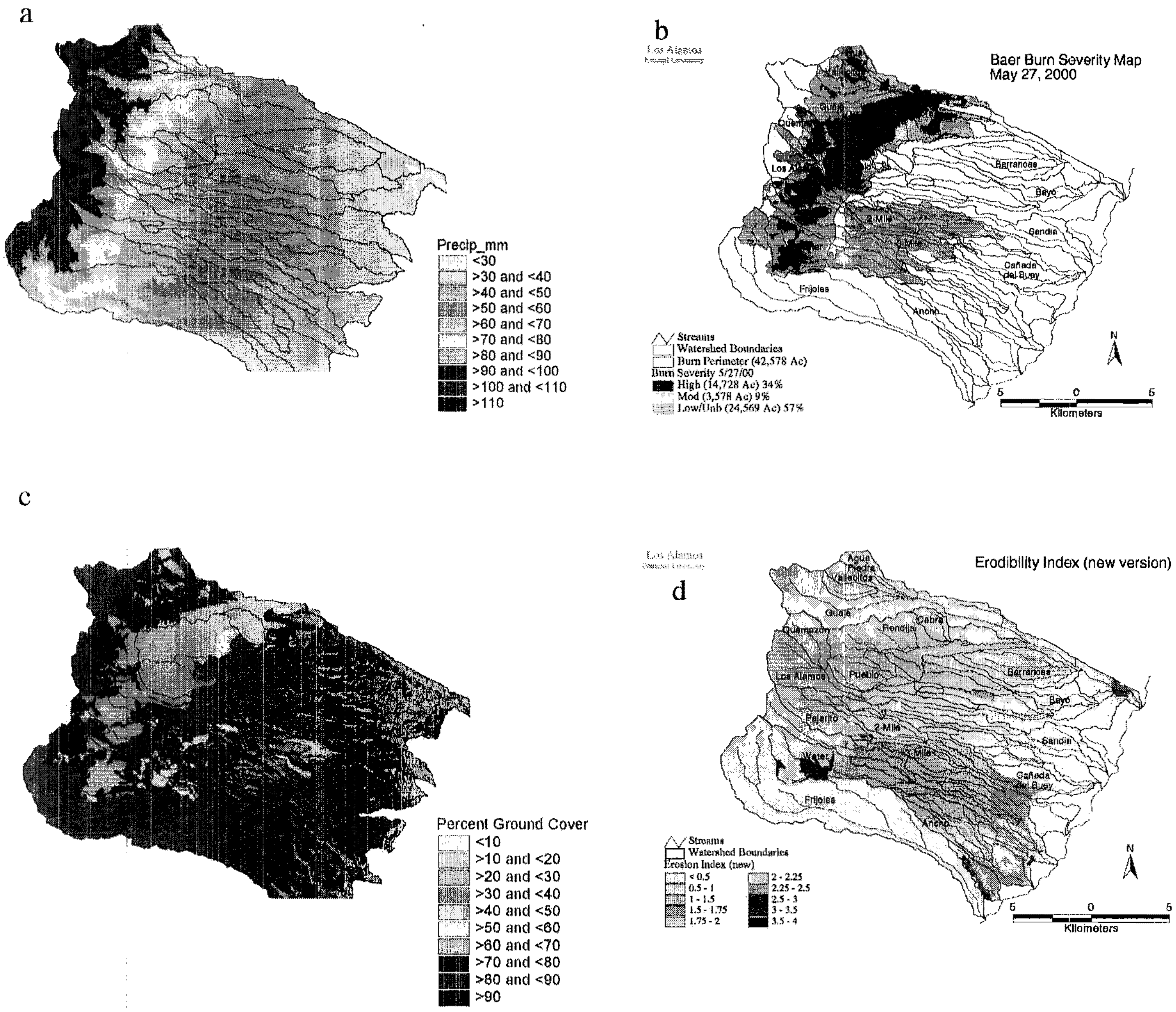

a
Precip_mm
<30
>30 and <40
>40 and <50
>50 and <60
>60 and <70
>70 and <80
>80 and <90
>90 and <100
>100 and <110
>110
b
Los Alamos
Baer Burn Severity Map
May 27, 2000
Guaje
Quemazon
Los Alamos
Barrancas
Bayo
2-Mile
3-Mile
Sandia
Cañada del Buey
Frijoles
Ancho
Streams
Watershed Boundaries
Burn Perimeter (42,578 Ac)
Burn Severity 5/27/00
High (14,728 Ac) 34%
Mod (3,578 Ac) 9%
Low/Unb (24,569 Ac) 57%
N
5
0
5
Kilometers
c
Percent Ground Cover
<10
>10 and <20
>20 and <30
>30 and <40
>40 and <50
>50 and <60
>60 and <70
>70 and <80
>80 and <90
>90
Los Alamos
d
Erodibility Index (new version)
Agua Piedra
Vallecitos
Guaje
Quemazon
Rendija
Cabra
Los Alamos
Pueblo
Barrancas
Bayo
Pajarito
2-Mile
3-Mile
Water
Sandia
Cañada del Buey
Frijoles
Ancho
Streams
Watershed Boundaries
Erosion Index (new)
< 0.5
0.5 - 1
1 - 1.5
1.5 - 1.75
1.75 - 2
2 - 2.25
2.25 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
N
5
0
5
Kilometers

Figure 3.

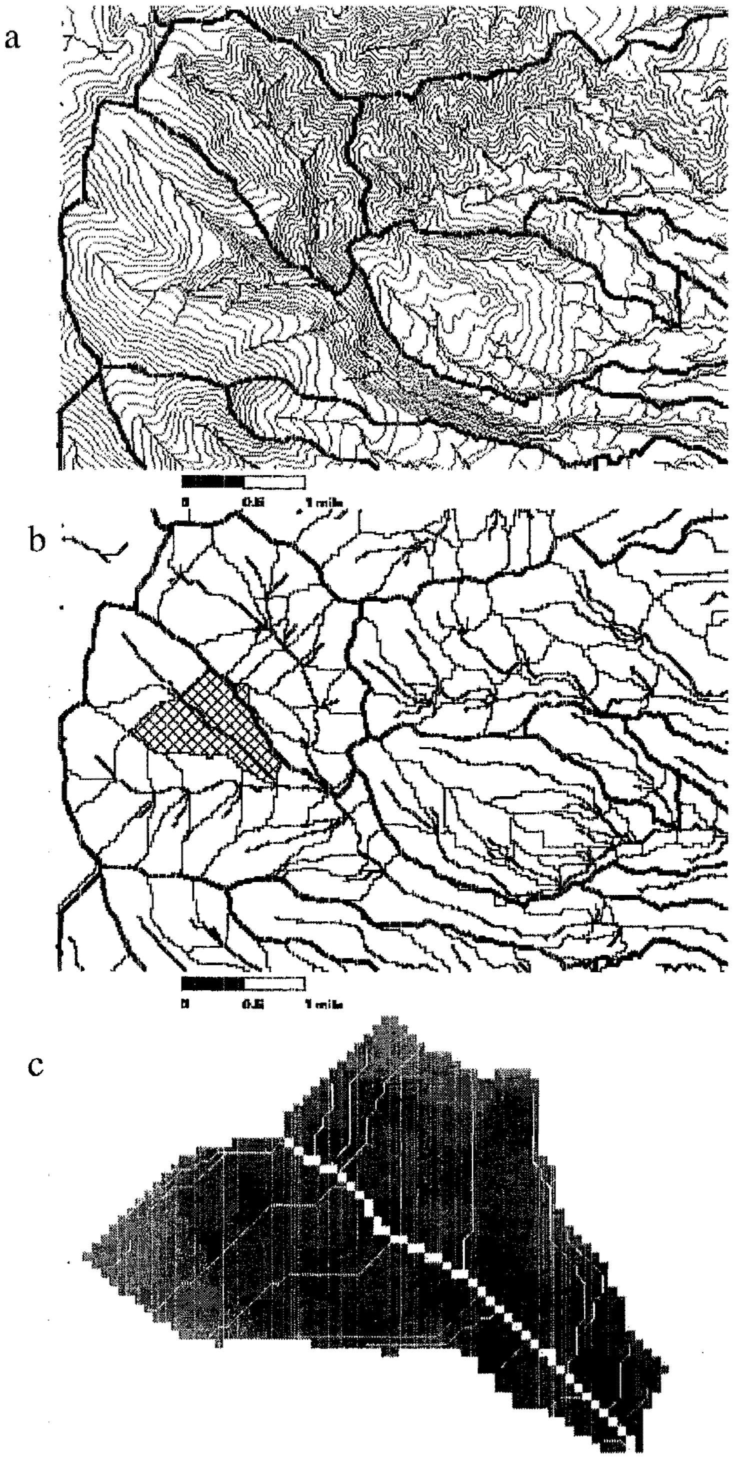


Figure 4.

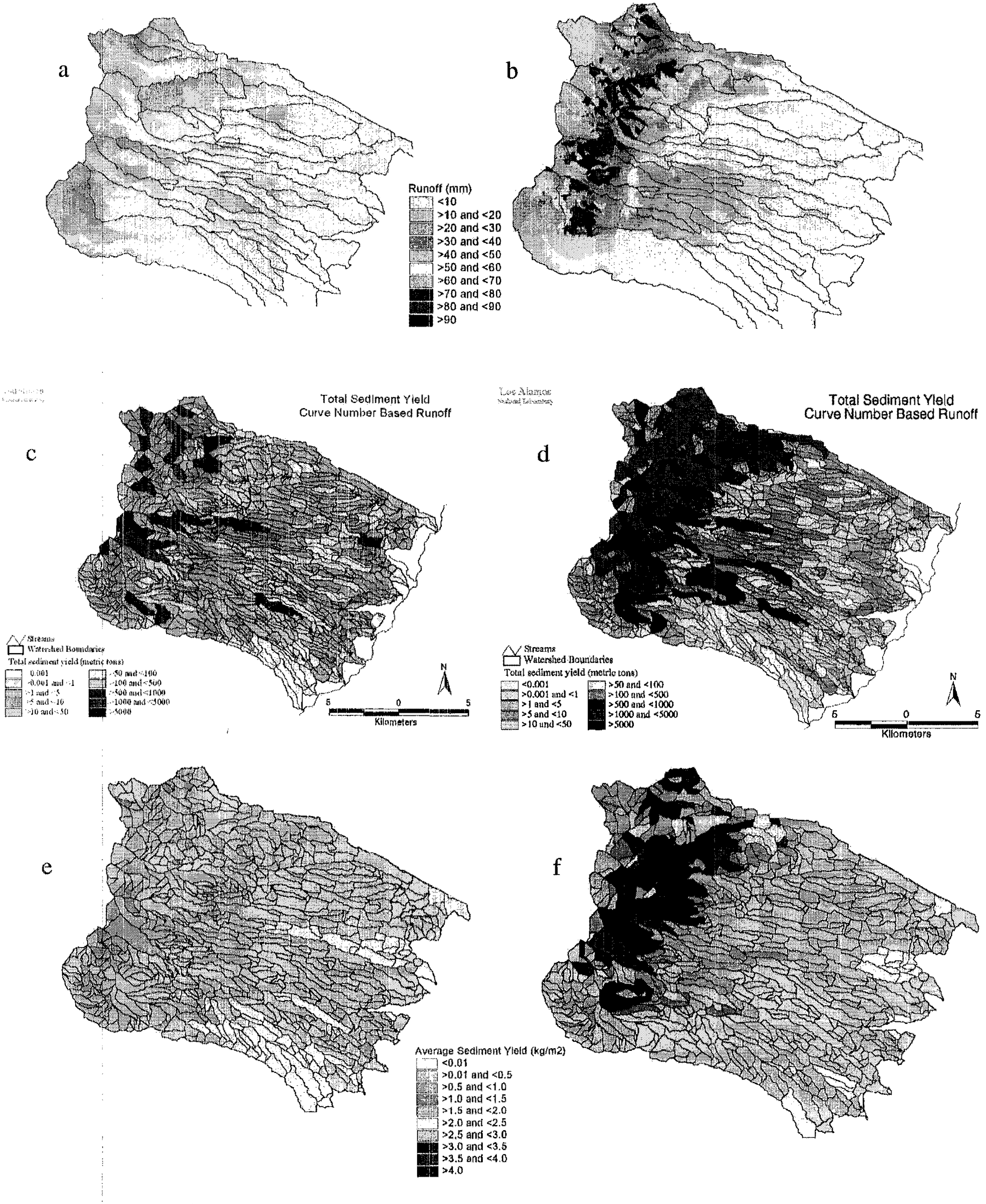
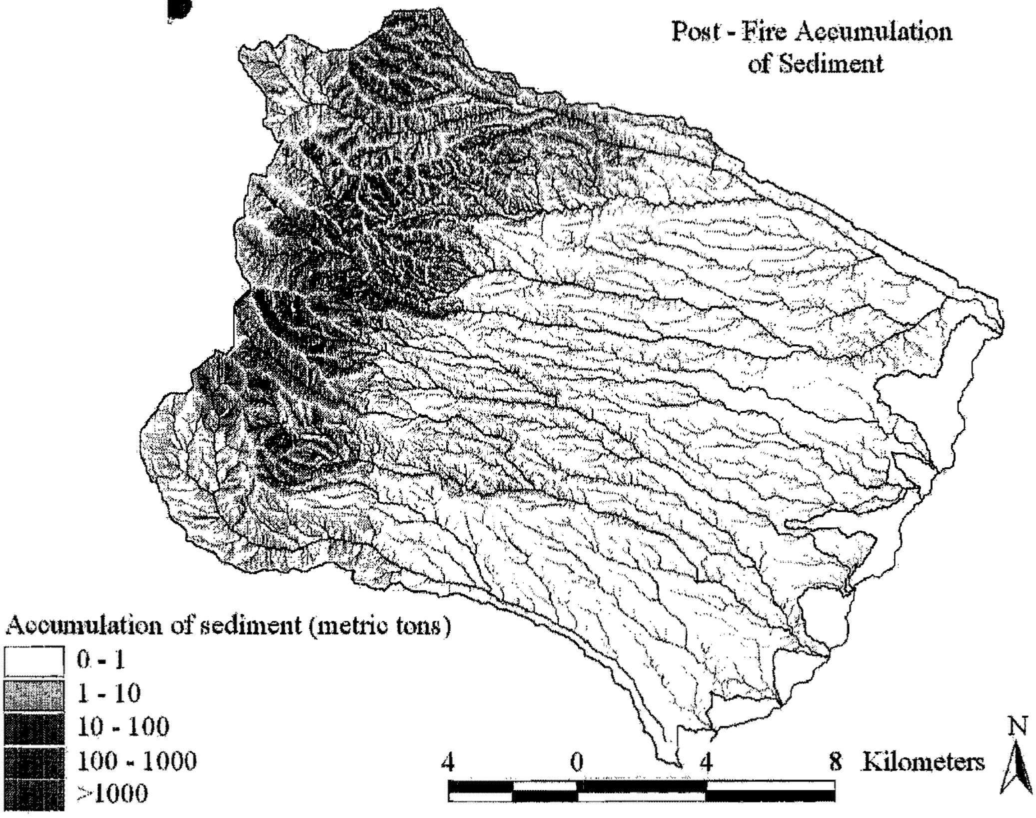

a
b
Runoff (mm)
<10
>10 and <20
>20 and <30
>30 and <40
>40 and <50
>50 and <60
>60 and <70
>70 and <80
>80 and <90
>90
c
Total Sediment Yield
Curve Number Based Runoff
Streams
Watershed Boundaries
Total sediment yield (metric tons)
0.001
>0.001 and <1
>1 and <5
>5 and <10
>10 and <50
>50 and <100
>100 and <500
>500 and <1000
>1000 and <5000
>5000
N
5
0
5
Kilometers
d
Los Alamos
National Laboratory
Total Sediment Yield
Curve Number Based Runoff
Streams
Watershed Boundaries
Total sediment yield (metric tons)
<0.001
>0.001 and <1
>1 and <5
>5 and <10
>10 and <50
>50 and <100
>100 and <500
>500 and <1000
>1000 and <5000
>5000
N
5
0
5
Kilometers
e
f
Average Sediment Yield (kg/m2)
<0.01
>0.01 and <0.5
>0.5 and <1.0
>1.0 and <1.5
>1.5 and <2.0
>2.0 and <2.5
>2.5 and <3.0
>3.0 and <3.5
>3.5 and <4.0
>4.0

Figure 5.


Post - Fire Accumulation of Sediment
Accumulation of sediment (metric tons)
0 - 1
1 - 10
10 - 100
100 - 1000
>1000
4
0
4
8
Kilometers
N