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Predicting floodplain boundary changes following the Cerro Grande wildfire

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Abstract:

A combined ArcView GIS–HEC modelling application for floodplain analysis of pre- and post-burned watersheds is described. The burned study area is located on Pajarito Plateau near Los Alamos National Laboratory (the Laboratory), where the Cerro Grande Wildfire burned 42 878 acres (17 352 ha) in May 2000. This area is dominated by rugged mountains that are dissected by numerous steep canyons having both ephemeral and perennial channel reaches. Vegetation consists of pinon–juniper woodlands located between 6000 and 7000 ft (1829–2134 m) above mean sea level (MSL), and Ponderosa pine stands between 7000 and 10000 ft MSL (2134–3048 m). Approximately 17% of the burned area is located within the Laboratory, and the remainder is located in upstream or adjacent watersheds. Pre-burn floodplains were previously mapped in 1990–91 using early HEC models as part of the hazardous waste site permitting process. Precipitation and stream gauge data provide essential information characterizing rainfall–runoff relationships before and after the fire. They also provide a means of monitoring spatial and temporal changes as forest recovery progresses. The 2000 summer monsoon began in late June and provided several significant runoff events for model calibration. HEC–HMS modelled responses were sequentially refined so that observed and predicted hydrograph peaks were matched at numerous channel locations. The 100 year, 6 h design storm was eventually used to predict peak hydrographs at critical sites. These results were compared with pre-fire simulations so that new flood-prone areas could be systematically identified. Stream channel cross-sectional geometries were extracted from a gridded 1 ft (0·3 m) digital elevation model (DEM) using ArcView GIS. Then floodpool topwidths, depths, and flow velocities were remapped using the HEC–RAS model. Finally, numerous surveyed channel sections were selectively made at crucial sites for DEM verification. These evaluations provided timely guidance that influenced the decision to construct several flood detention structures that were completed in September 2000. Published in 2001 by John Wiley & Sons, Ltd.

KEY WORDS ArcView GIS; HEC–HMS; HEC–RAS; floodplain modelling; wildfires

INTRODUCTION

The Los Alamos National Laboratory (the Laboratory) was established in 1943 as part of the Manhattan Project. It is located (35° 52′ N, 106° 19′ W) in north-central New Mexico (USA) about 60 miles (97 km) north-northeast of Albuquerque, and 25 miles (40 km) northwest of Santa Fe (Figure 1). Los Alamos has a semiarid, temperate mountain climate. This 43 mile^2 (111 km^2) facility is situated on Pajarito Plateau between the Jemez Mountains on the west and the Rio Grande Valley to the east. The plateau slopes east-southeast for more than 15 channel miles (24 km), where it terminates along the Rio Grande in White Rock Canyon. Topography ranges from 7800 ft (2377 m) above mean sea level (MSL) along the western Laboratory margin to about 6400 ft MSL (1951 m) at the canyon rim. The plateau is dissected by a system of gauged and ungauged watersheds that are dominated by ephemeral stream drainage. Here we define a gauged watershed as one having at least one rain gauge (input) and one stream gauge (output) so that

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the system response can be estimated (Dooge, 1959, 1973). Some perennial channel reaches are also locally defined. All of these watersheds are elongated in the west-to-east flow direction along Pajarito Plateau, and are extremely narrow in the north–south direction. In total, there are 13 separate watersheds draining Laboratory lands that contain over 100 channel miles (161 km) requiring floodplain identification. These floodplains are defined at approximately 200 ft (61 m) intervals using topographic data obtained from a 1 ft (0·3 m) gridded digital elevation model (DEM). These data were obtained from a 1992 aerial photogrammetric survey of the Laboratory and surrounding areas.

The Cerro Grande wildfire began as a US National Park Service prescribed burn on May 4, 2000. It quickly spread out of control because of high winds and extremely dry conditions. The fire was contained on June 6, 2000, after consuming approximately 42 878 acres (17 352 ha), including 7439 acres (3010 ha) within the Laboratory. The fire continued to burn inside the containment line throughout July, as seen in Figure 1. A complete summary of fire-related events is available (BAER, 2000).

Although the Laboratory has maintained a comprehensive environmental monitoring program since 1949, it became a permitted hazardous waste treatment, storage, and disposal facility in 1990. Permit conditions stipulate that these Resource Conservation and Recovery Act (RCRA) facilities must delineate all 100 year floodplain elevations within their boundaries [40 CFR 270·14(b)(11)(iii)]. These floodplains were originally mapped (McLin, 1992) using the US Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) computer-based Flood Hydrograph Package (HEC-1) and the Water Surface Profiles Package (HEC-2). These techniques are well documented and routinely used for floodplain analyses (USACE, 1982, 1985; Hoggan, 1996). Updated models (USACE, 2001a,b) now include HEC–HMS (Hydrologic Modelling System) and HEC–RAS (River Analysis System). The Laboratory's RCRA operating permit is subject to renewal in 2001. All floodplain boundaries will be remapped for this renewal because they have expanded following the fire. These changes are in direct response to fire-related modifications in the rainfall-runoff process due to reductions in watershed vegetation cover and development of hydrophobic soil conditions. As the forest around the Laboratory recovers over the next several decades, these floodplain boundaries are expected to recede slowly back toward their pre-fire boundaries at some undetermined rate.

The US Geological Survey (USGS) has produced probabilistic techniques to estimate peak discharges in New Mexico streams (Thomas and Gold, 1982; Waltemeyer, 1986). These studies define the regional magnitude and flood frequency within stream channels using multiple regression techniques for the 2, 5, 10, 25, 50, and 100 year storm events. However, as seen in Figures 2 and 3, these empirical equations produce significantly larger pre-fire hydrograph peaks for ungauged watersheds compared with observed peaks or HEC–HMS simulations (McLin, 1992). The observed peaks in Figure 2 were obtained from backwater calculations (Veenhuis, 2000), whereas the observed peaks in Figure 3 were recorded at stream gauges (Shaull *et al.*, 2000). The USGS procedure yields peaks that are typically one to two orders of magnitude larger than physical observations or HEC–HMS simulated peaks using equivalent subbasin parameters. More importantly, there is no known methodology to extrapolate the USGS technique to post-fire watershed conditions. Hence, these probabilistic techniques are not used in this evaluation.

HEC–HMS is a single event, rainfall-runoff model that can be used to simulate real or hypothetical storm hydrographs in gauged or ungauged watersheds in response to user-specified rainfall hyetographs (USACE, 2001a). As used here, HEC–HMS employs traditional 50, 100, or 500 year, 6 h design storm events for Los Alamos. These representative design storms are hypothetical events that were constructed using historical precipitation patterns from six Pajarito Plateau recording rain gauges (McLin, 1992). Predicted HEC–HMS hydrograph peaks, along with stream channel geometry and watershed drainage characteristics, are then utilized by the HEC–RAS model to compute either 50, 100, or 500 year floodplain boundaries. This procedure is well established in modern engineering practice.

For the modelling efforts described here, stream channel cross-sections at varying locations were obtained from the Laboratory's computer-based graphical information system (ArcView GIS) and is similar to an earlier GIS–HEC topographic data extraction procedure (McLin, 1993). For this study, cross-sections are located approximately every 200 ft (61 m) along each reach. Topographic data are automatically extracted from the

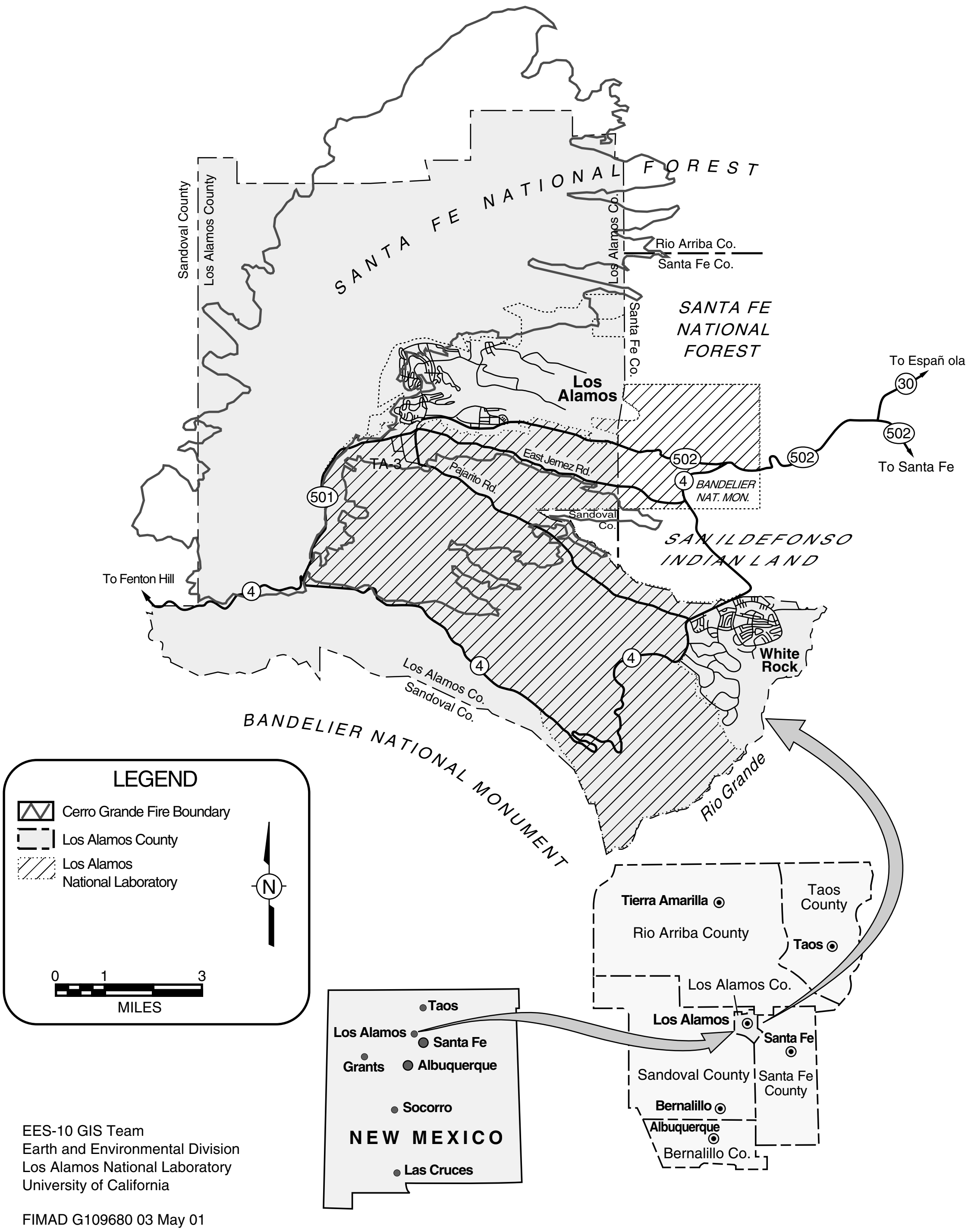

Figure 1. Location map showing Cerro Grande burn area near Los Alamos, New Mexico (USA)

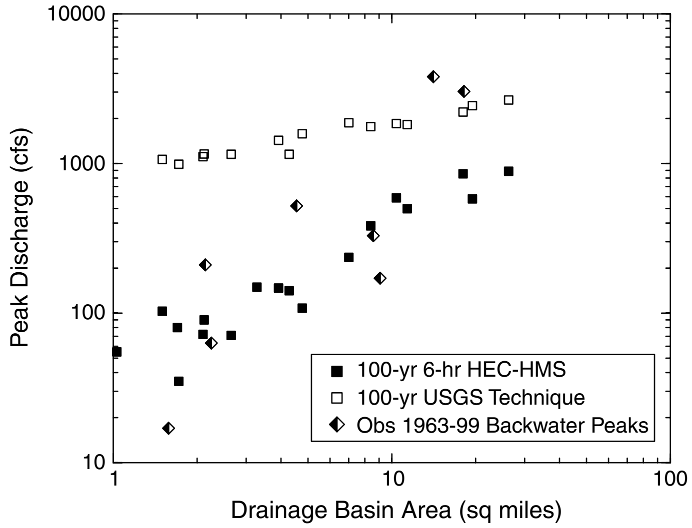

Figure 2. Comparison of simulated HEC–HMS and USGS 100 year pre-fire peak discharges at eastern Laboratory boundary. Observed peaks are from backwater calculations

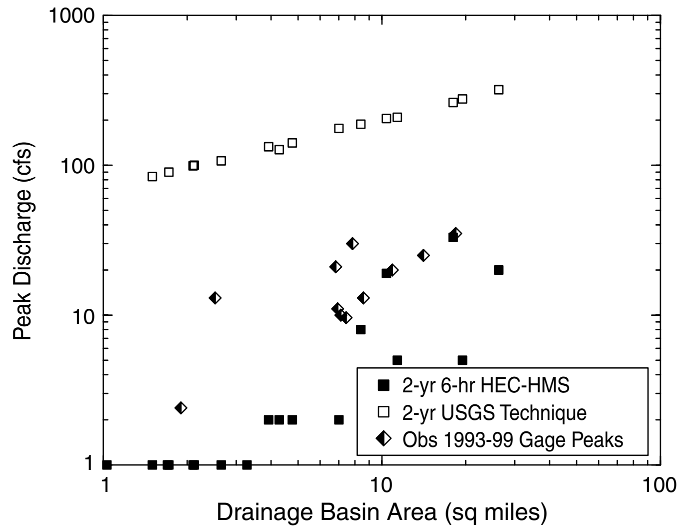

Figure 3. Comparison of simulated HEC–HMS and USGS 2 year pre-fire peak discharges at eastern Laboratory boundary. Observed peaks are from gauging records

DEM database in order to minimize channel-surveying tasks. This procedure is performed for each cross-section following the pre-selected channel reach pathway. Each DEM point along the cross-section forms an (x, y, z) topographic point that is geo-referenced to the New Mexico State Plane coordinate system. A typical 100 ft (30 m) long cross-section contains between 15 and 50 data points. These cross-sectional features are exported to the HEC–RAS model using HEC–geoRAS, an ArcView extension capability developed by the USACE–HEC. In order to verify this data extraction process, approximately 1% of all channel sections were surveyed. Differences between minimum DEM and surveyed channel elevations were typically less than 1 ft (0·3 m).

The independently executed HEC–RAS model employs an HEC–HMS hydrograph peak to simulate a water surface elevation at each channel section using a steady, gradually varied flow approximation. Here the water surface elevation is computed as a function of channel distance using an iterative standard-step method (USACE, 2001b). The model computes a pair of left and right overbank floodpool coordinates for each section that identifies where the DEM land surface and computed floodpool intersect. Coordinate pairs from adjacent channel sections are imported back into ArcView GIS and linked together using the geo-referenced New Mexico State Plane coordinate system. These linked coordinates define the floodplain over the entire channel reach. Parameter estimation procedures and construction of input data files for pre- and post-fire conditions are described in the sections below. Finally, scale maps depicting the Laboratory boundary and all floodplains can be generated (e.g. McLin, 2001).

DESIGN STORM FOR LOS ALAMOS

An observed storm hydrograph for a given watershed is closely related to the spatial and temporal storm distribution that generated it. However, observed large recurrence interval storms are generally unavailable, so hypothetical design storms must be used in most engineering applications. In this paper, we describe the 100 year, 6 h design storm event for Los Alamos that is assumed to produce the 100 year floodplain. The reader should note that other 100 year storm events (e.g. the 100 year, 24 h event) will produce different 100 year floodplain definitions. Other design storm construction methodologies also exist (e.g. Miller *et al.*, 1973; USBR, 1977; Chow *et al.*, 1988) and depend on availability of precipitation records.

In constructing a design storm event, several important steps are required, including (1) storm frequency or return period; (2) storm duration, total rainfall depth, and watershed area adjustment; and (3) storm time distribution and duration of rainfall excess. In our case, the US Environmental Protection Agency (EPA) stipulates that RCRA permitted facilities must use the 100 year storm to define all floodplains. The USACE recommends (M. Magnuson, USACE Albuquerque District Office, personal communication, 1989) that a 6 h storm event should be used for northern New Mexico in most 100 year flood simulations. Bowen (1990, 1996) has tabulated statistically based rainfall depths for various storms. No areal adjustment was made for rainfall depths because individual subbasins are less than about 3 miles^2 (8 km^2). Hence, factors (1) and (2) above are fixed *via* institutional constraints and rainfall observations. The selection rationale for factor (3) is described below.

A representative rainfall hyetograph must be selected that is based either on the worst possible storm pattern or from recorded storm distribution patterns. This hyetograph will significantly affect the shape and peak value of the resulting runoff hydrograph for a given watershed. Daily precipitation depths have been measured in Los Alamos since 1911 (Bowen, 1990, 1996). Individual storm patterns have been recorded at 15 min intervals beginning in 1964. These data were used to develop intensity–duration–frequency (IDF) relationships (McLin, 1992, 2001). These IDF curves (Figure 4) were used to establish individual 6 h design storm distributions for the 2, 5, 10, 25, 50, 100, and 500 year events.

Once IDF curves are constructed, then a 6 h design storm hyetograph can be developed for each return period event using the alternating block method (Chow *et al.*, 1988, 454–466). Results for the dimensionless 2 and 100 year instantaneous storm events are shown in Figure 5. The Soil Conservation Service (SCS, now the Natural Resources Conservation Service) 100 year, 6 h design storm distribution (SCS, 1993) is also shown for comparison. Note that the SCS curve will produce a more uniform rainfall distribution, and lower corresponding hydrograph peak. As seen in Figure 5, the 6 h instantaneous design storm distributions used here are bell-shaped with a midpoint peak intensity at 3 h. These distributions imply gradually increasing and decreasing intensities preceding and following peak values. This design storm pattern essentially satisfies soil infiltration and other abstraction loss requirements with low rainfall intensity, and generates higher hydrographs in response to higher rainfall intensities later. Observed New Mexico summer thunderstorms typically result from intense prefrontal squall lines moving south to north. These thunderstorms are exceptionally localized

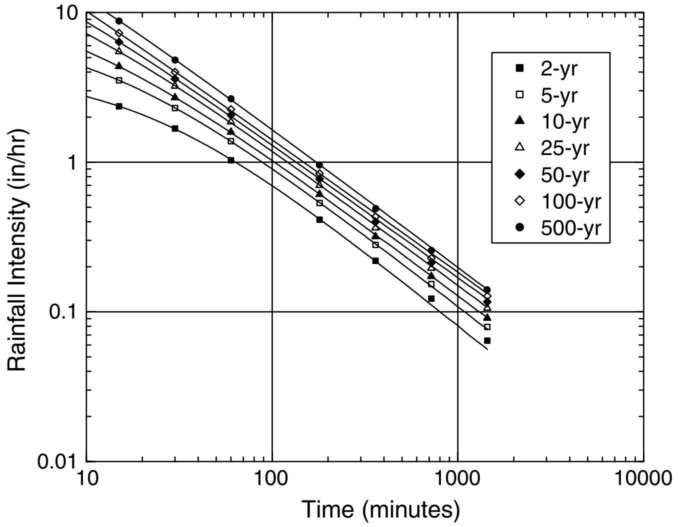

Figure 4. Intensity–duration–frequency curves for Los Alamos, New Mexico (USA)

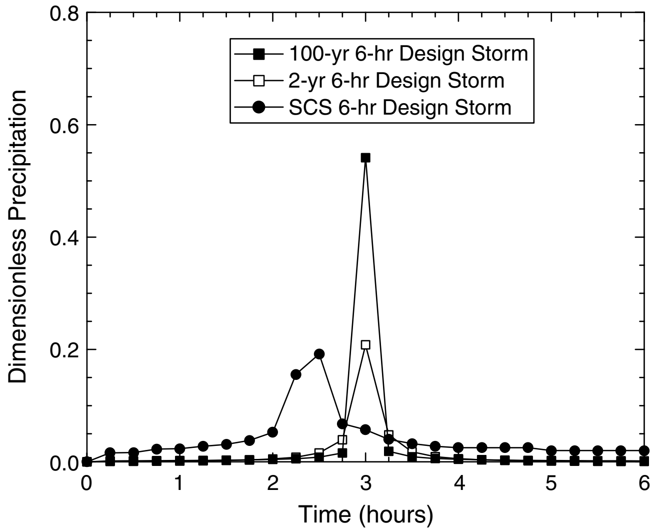

Figure 5. The 6 h design storms for Los Alamos; the SCS 6 h storm is shown for comparison

events that rarely cover more than about 0·5 miles^2 (1·3 km^2). Hence, our design is conservative, since it is simultaneously applied to all subbasins within the west–east-oriented watersheds.

Each of the 6 h design storm distributions described above contains all of the shorter duration events with the same recurrence interval. For example, the 100 year, 6 h design storm contains the 100 year, 15 min storm in its central 15 min interval. Likewise, the 100 year, 1 h storm is contained within the central 60 min interval of the 100 year, 6 h design distribution. In other words, the 100 year, 6 h design storm incorporates all 100 year events with storm durations of 6 h or less. This observation is directly related to the alternating block method used to construct the design storm. Hence, the 6 h design storm will produce larger hydrographs than shorter duration design storms with the same recurrence interval because it has a longer period of low intensity rainfall before its central peak. For example, the 6 h design storm will yield larger hydrograph peaks than its 1 h counterpart. This is a significant point that is often overlooked.

As employed here, the HEC–HMS simulations used the total rainfall depths reported by Bowen (1990, 1996) and the cumulative design storm distributions computed from the instantaneous distributions described above. Rainfall depths from Bowen (1990) were also adjusted for elevation differences between subbasin centroids using a least-squares linear regression of rain gauge elevations and recorded precipitation depths (McLin, 1992). This was done to account for orthographic effects across Pajarito Plateau.

HEC–HMS MODEL

HEC–HMS is a general-purpose model that can predict the optimal unit hydrograph, channel loss rate, stream flow routing parameters, snowmelt computations, unit hydrograph computations, hydrograph routing and combinations, and hydrograph balancing operations. HEC–HMS can be used to forecast both pre- and post-burn flooding impacts associated with these changing land-use patterns. Output from the model includes the design storm hydrograph for each subbasin. Hydrograph peaks are then utilized in the HEC–RAS model as input data.

HEC–HMS can utilize five different unit hydrographs (UHs) to simulate runoff, including a user specified UH, kinematic wave, Clark, Snyder, or SCS UH. The SCS UH was selected in this study to characterize the relationship between rainfall-runoff and peak discharge. The SCS rainfall abstraction loss rate was also utilized as explained later. Finally, HEC–HMS can route computed flood flows through downstream subbasins using a variety of techniques, including modified Puls, Muskingum, Muskingum–Cunge, kinematic wave, and level-pool reservoir routing. The Muskingum method was selected for this option because channel losses and flood-wave attenuation in individual watersheds have not been fully characterized. Hence these losses were assumed to be zero even though they are known to be relatively high in certain pre-fire stream channel reaches (e.g. those channel reaches with relatively thick alluvial deposits). Muskingum routing parameters were computed from average channel flow velocities using Manning's equation. In addition, level-pool reservoir routing was selected to move water through road culverts with high embankments and for flood detention structures.

Obviously, not all rainfall from a storm contributes to direct runoff, since some is lost during the overland flow process. These abstractions include vegetation interception, depression storage, soil infiltration, evaporation, and other minor losses. Five theoretical rainfall loss calculation techniques are incorporated in HEC–HMS, including the initial and uniform, HEC exponential, Green–Ampt, Holton, and SCS curve number (CN). However, the SCS CN loss method provides a systematic method for computing composite CN values that can account for changing impervious areas or dramatic land-use alterations. The SCS synthetic UH expresses the ratio of discharge to peak discharge against the ratio of time to basin lag time. Here lag time is given by (Viessman *et al.*, 1977):

$$t_p = D/2 + t_l \quad \text{and} \quad t_l = [l^{0.8}(S+1)^{0.7}]/(1900Y^{0.5}) \tag{1}$$

where t_p is the time (hours) from rainfall beginning to peak discharge, D is rainfall duration (hours), t_l is subbasin lag time (hours), l is the longest water course length (feet) from the subbasin outflow toward the upstream watershed divide, S is the potential maximum retention after rainfall begins (inches), and Y is the average watershed slope (percent) along the flowpath. Note that in (1) the lag time is directly related to CN since $S = 1000/\text{CN} - 10$. Once rainfall excess has been determined, a unit hydrograph can be computed for each subbasin.

In Figure 6, pre-fire Los Alamos watershed data are used to show SCS basin lag times from Equation (1) as a function of Snyder lag times (Viessman *et al.*, 1977). Empirical coefficients used in the Snyder technique were obtained from USACE studies (M. Magnuson, USACE Albuquerque District Office, personal communication, 1989) from the Rio Puerco in New Mexico and Rio Grande near El Paso, Texas (lower curve). Synder lag

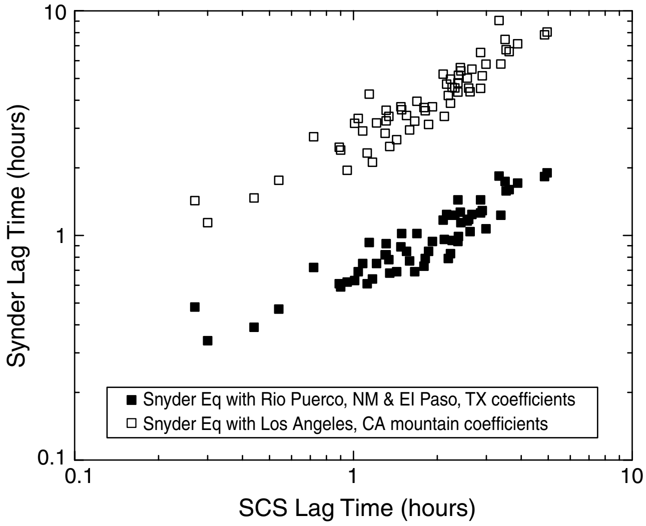

Figure 6. Comparison of SCS and Snyder pre-fire basin lag times for Los Alamos using equivalent basin parameters

times for the upper curve were obtained using a modified form of the Snyder relationship and coefficients for mountainous watersheds near Los Angeles, California (Linsley *et al.*, 1982, 223–225). Figure 6 clearly shows that SCS basin lag times used in this study are bracketed by extremes produced with the Snyder technique. Computation of post-fire changes in Snyder lag times was not possible because changes in empirical coefficients associated with the fire could not be evaluated.

Figure 7 shows a plot of changes in pre- and post-fire SCS CN values and lag times for impacted watersheds. Note that t_1 values from Equation (1) have been dramatically reduced in upland subbasins where CN values have increased the most. Fire impacts are also the most pronounced in these same locations (see Wilson *et al.*, 2001). In some headwater subbasins, lag time has been reduced from 90 min to under 33 min. This implies

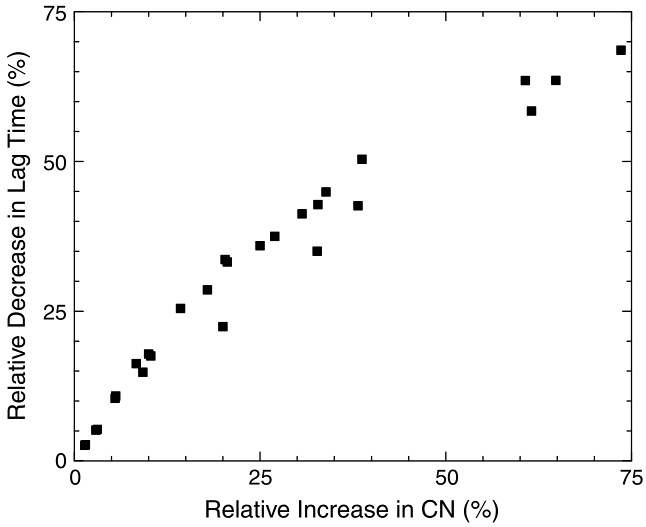

Figure 7. Cerro Grande wildfire changes in CN and basin lag times. Here a relative change is defined as (pre-fire value − post-fire value)/(pre-fire value)

that both recording rain and stream gauges need to be collecting data every 15 min or less in order to capture the dynamic nature of the rainfall-runoff process. In other words, data acquisition rates for systems inputs and outputs need to be less than one-half the system response time (approximated here by t_l) in order to avoid data aliasing (Jenkins and Watts, 1968, 285).

In addition to ease of use, Equation (1) has the advantage that impacts of development within a given watershed can be evaluated, since changes in CN over time are easily estimated. These same impacts cannot be systematically evaluated with the kinematic wave, Snyder, or Clark UH methods.

Pre-fire CN values were determined for all watersheds (McLin, 1992) and formed a starting point for post-fire simulations. These pre-fire values typically ranged from the mid-50s and 60s for wooded alpine forests, to 70s and 80s for mountain brush and pinon–juniper woodlands. These values were originally obtained using a quasi-model calibration procedure for ungauged watersheds, as discussed below.

Once all pre-fire basin characteristic parameters had been estimated, then individual watershed hydrographs could be generated. Before this was done, however, a parameter sensitivity analysis was made. All model parameters were constrained to a vary narrow range of observed values, except for composite subbasin CN numbers. These CN values were estimated from county soil maps (Nyhan *et al.*, 1978) and standard tables (Hoggan, 1996), although alternative methodologies are available (Hjelmfelt, 1980; Hawkins, 1993). To evaluate the uncertainty in estimated pre-fire CN values, hydrograph peaks produced by the 2 year, 6 h design storm event for Los Alamos were examined for all subbasins. The logic for this design procedure is straightforward: one can quickly develop a general appreciation for flood magnitudes associated with individual pre-fire 2 year storm events from physical observation. These qualitative observations suggest that pre-fire 2 year flood peaks in Los Alamos County are only slightly larger than zero. This same appreciation cannot be easily developed for pre-fire 100 year magnitude events, because these events are rarely observed. Following this logic, all HEC–HMS simulations should accurately reflect observed pre-fire 2 year events if one is to have confidence in large recurrence-interval flood predictions. One should recognize that once all pre-fire subbasin characteristic parameters have been determined, then one only needs to change subbasin rainfall totals and design storm distribution patterns in order to generate larger recurrence interval hydrographs.

Each pre-fire watershed simulation was made for the 2 year, 6 h Los Alamos design storm event. If a given subbasin yielded a hydrograph peak that was unreasonably high or low, then the composite CN was adjusted either downward or upward respectively and a new simulation was made. Recall that a change in CN implies a corresponding change in basin lag time, as suggested by Equation (1). This iterative process was repeated several times for each watershed. Individual composite CN values were typically adjusted less than 3% until the predicted 2 year hydrograph peak was greater than zero but less than about 3 $ft^3\ s^{-1}$ ($85\ l\ s^{-1}$) for an average size subbasin. Approximately half of all subbasins required a composite CN adjustment; these adjustments were nearly equally divided between increases and decreases in CN values. Once these CN values were fixed, then the larger recurrence interval hydrographs were computed using the 6 h rainfall totals and the design storm distribution patterns developed earlier.

The post-fire CN values were initially modified from original values using weighting factors based on the percent of subbasin areas that were burned. These burned areas were subdivided into low-(57% of total burn area), medium-(8% of total), and high-severity (34% of total) burned areas as defined by the Burned Area Emergency Rehabilitation team (BAER, 2000). This classification is qualitatively linked to changes in soil texture and infiltration capacity. High burn-severity areas are located in those areas where the surficial soil structure has been altered. These soils typically have a hydrophobic layer that was formed during the fire. This layer is located approximately 0·25 in (6·4 mm) below the surface and is between 0·25 and 3·0 in thick (6·4 to 76 mm). These hydrophobic soils develop when high-temperature fires produce heavy volatile organics that migrate into soils and condense (Imeson *et al.*, 1992; Dekker and Ritsema, 1994). For the Cerro Grande wildfire, these hydrophobic soils are preferentially located on north-facing canyon slopes with heavy ponderosa pine forests. They occur on approximately 22% of the total burn area. Medium-severity burn areas show little or no hydrophobicity and are concentrated on south-facing canyon slopes with sparser vegetation, on mesa tops, and in canyon bottoms. Low-severity burn areas are generally located along the perimeter of more severely burned areas. This hydrophobic soil distribution is related to the distribution of fuels, temperature, and heavy winds during the fire. Quantitative evaluation of infiltration capacity changes in these hydrophobic soils is currently underway.

The BAER team originally assigned CN values of 65, 85, and 90 to the low-, medium-, and high-severity burn areas respectively. We modified these CN values to include a range of values for each severity classification. Thus, for low-severity burns, we estimated CN values range from a low of 65 to a high of 85, with an expected value of 75. For moderate-severity burned areas, we estimated than CN values range from a low of 80 to a high of 90, with an expected value of 85. Finally, for high-severity burned areas, we estimated that CN values range from a low of 85 to a high of 95, with an expected value of 90. Unburned areas retained their original pre-fire CN values; however, we assumed these values could range four CN points above and below this original value. A composite CN value was computed for each subbasin using these four burn-severity weight factors and four expected CN values. These weight factors were computed according to the fraction of burned area within each subbasin area (i.e. unburned, low, medium, or high severity). Each respective weight factor was multiplied by each respective CN value and the results were summed to obtain the composite CN value. This process was then repeated for the low and high CN estimates to establish lower and upper limits on these CN composites. These calibration efforts will also be repeated as forest recovery progresses to document the time rate of change in calibrated CN values. The procedure described here was necessary, however, because public safety and environmental questions needed addressing before the summer (2000) monsoon season created flooding hazards in the Laboratory.

Figure 8 shows a dramatic increase between pre- and post-fire hydrograph peaks per unit area for both observed and simulated storm events. The observed data in Figure 8 were obtained from stream gauges (Cerro Grande fire) and backwater calculations (La Mesa and Domes fires) for several regional wildfires (Veenhuis, 2000; Cannon and Reneau, 2000; McLin, 2001). Simulated values were obtained with the HEC–HMS model using the pre- and post-burn CN values described earlier. In addition, the 2 year, 1 h design storm distribution was used for these simulations because this pattern best represented the observed rainfall pattern following each of the fires. Figure 8 suggests that the final CN values for the post–burn areas yield simulated hydrograph peaks that compare favourably with observed values.

Figure 9 shows a comparison between observed and HEC–HMS predicted hydrographs for Starmer Canyon, a small tributary watershed located in the Santa Fe National Forest along the western Laboratory perimeter.

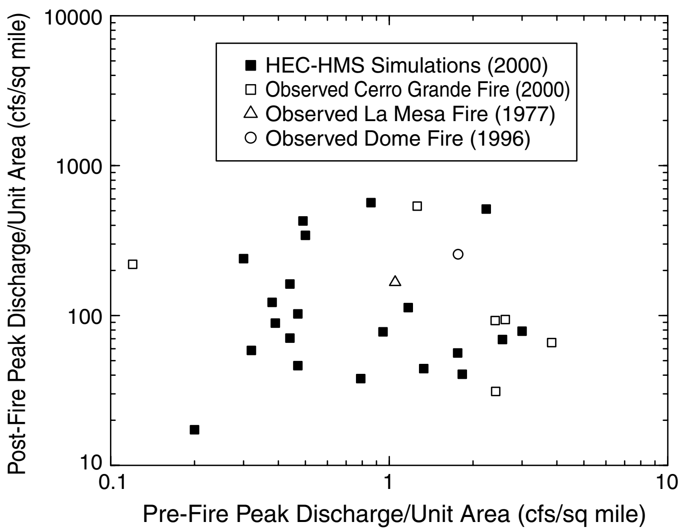

Figure 8. Comparison of observed and simulated pre- and post-fire peak discharges per unit drainage basin area. The La Mesa and Dome wildfires occurred south of the Cerro Grande wildfire in the years indicated

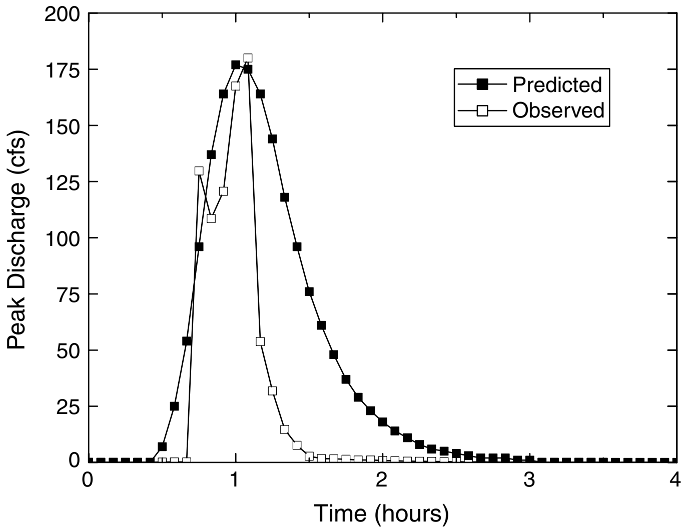

Figure 9. Observed and simulated hydrographs for the Starmer Canyon watershed following a small thunderstorm on June 28, 2000

This watershed was severely burned during the Cerro Grande wildfire. The observed hydrograph was in response to approximately 0·69 in (17·5 mm) of rain that fell in less than 45 min on June 28, 2000. The observed and predicted hydrograph peaks match well. However, total observed runoff volume is considerably less than the predicted volume. Five additional observed and predicted hydrographs for other small watersheds follow a similar pattern. These comparisons suggest that the shape of the SCS unit hydrograph may not completely represent Pajarito Plateau watersheds or that channel infiltration losses are significant. These preliminary results are encouraging, however.

HEC–RAS FLOODPLAIN MAPPING

The HEC–RAS model calculates and plots water surface profiles for subcritical, critical, and supercritical gradually varied, steady flows in channels of any cross-sectional configuration. Surface-water profile analyses are commonly used to map floodplains at RCRA sites, determine flood protection levee heights, and establish flood hazard zones for insurance purposes. The HEC–HMS and HEC–RAS models are typically used in conjunction with one another for these floodplain assessment studies.

Flow regime boundary geometry is defined in the HEC–RAS model with cross-sections and reach distances between adjacent cross-sections. These cross-sections are located at user-specified intervals along the stream channel so that the flow capacity in the channel and overbank areas can be characterized. Reducing the distance between adjacent sections will increase the model's accuracy, because erratic fluctuations in energy losses between sections can be minimized. Manning's equation is initially used to determine how much of the cross-sectional flow is in the channel and how much is in the overbank areas. Values for subarea conveyance (i.e. all terms in Manning's equation except the friction slope term) are known if the friction slope is assumed constant throughout a given cross-section. A starting water surface elevation at either the downstream (subcritical) or upstream (supercritical) end of the watercourse, expansion or contraction coefficients, Manning's roughness factor n, and stream discharge are specified as input data.

This floodplain mapping procedure implies that natural channels meet uniform flow conditions, that the energy grade is approximately equal to the average channel bed slope, and that water surface elevations can be obtained from a normal-depth calculation. These assumptions are conservative in most natural channels. Figure 10 depicts the predicted post-fire 100 year floodpools in Pajarito Canyon before and after construction of the flood detention structure. The pre-fire 100 year floodplain is not shown in Figure 10 because it is nearly identical to the post-construction floodpool.

DISCUSSION AND CONCLUSIONS

The successful integration of modern GIS databases and hydrologic models is an emerging technology (Maidment and Djokic, 2000). Most federal, and many State, facilities already have significant GIS topographic coverage. This paper describes an application of HEC–HMS and HEC–RAS floodplain models to complex terrain using ArcView GIS extracted topographic data. These models are recognized by the EPA, USACE, and others as the best available technology for floodplain definition in ungauged watersheds. Combining these models with a GIS capability represents a refinement in their continued use.

The SCS CN method was used in this study to predict runoff. The relative merits of this empirical approach versus physically based representations have been openly debated in the literature for years. However, Loague and Freeze (1985) have shown that physically based models generally do not predict runoff any better than the relatively simple approach used here. In addition, extension of physical models to ungauged watersheds retains many limitations of simple approaches. Furthermore, the SCS method has the advantage that future changes in land use patterns (e.g. pre- and post-fire watershed alterations or urbanization) are easily addressed.

Most event simulation models represent the rainfall-runoff process as a linear input–output system. This implies that model calibration studies can utilize data from low recurrence-interval storm and runoff events to

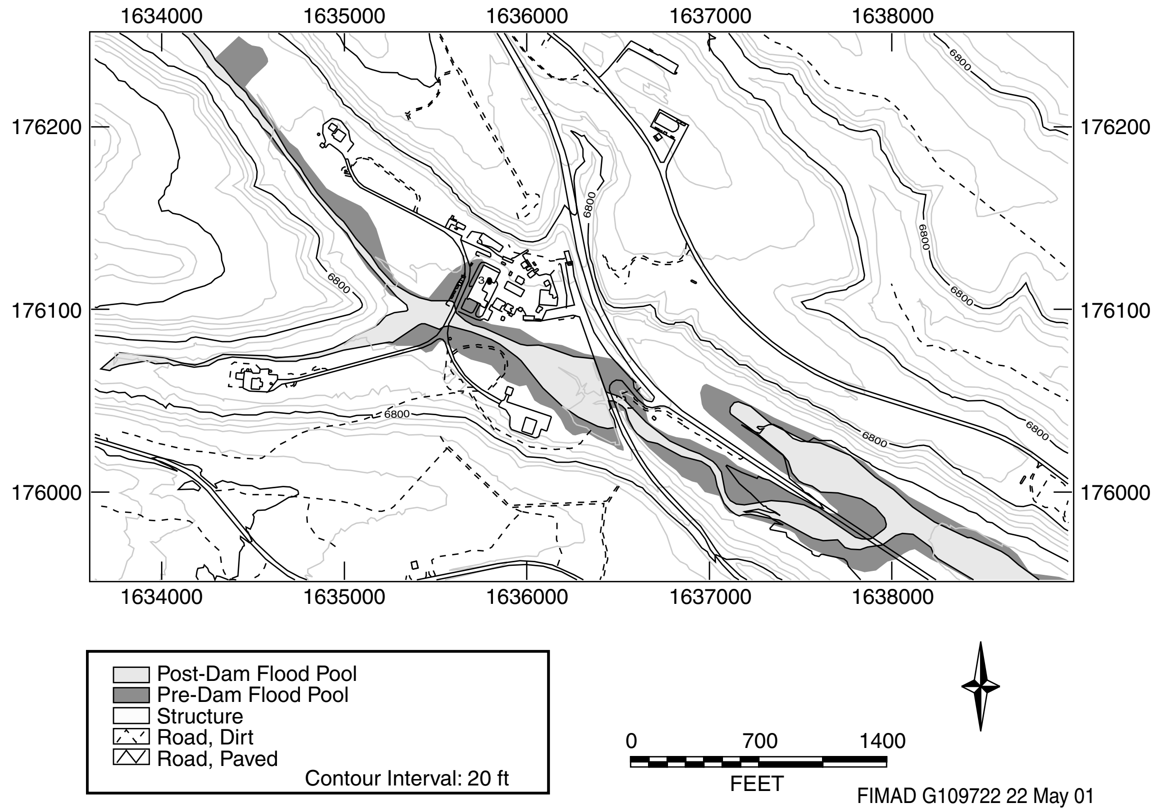

Figure 10. Predicted post-fire 100 year floodpool map at Technical Area 18 before and following construction of the upstream Pajarito flood control structure

characterize the watershed response. Typically, these calibration results are then extended to large recurrence-interval events. This well-established practice is far from perfect, because the system response may not be linear over this entire range. For example, the calibration efforts described here utilize convective summer thunderstorm data that rarely exceed 3 h in duration. However, large recurrence-interval storms in the southwest are often associated with long-duration hurricanes that move inland from the Gulf of Mexico or the Baja Peninsula. One practical solution to this problem is to use a 6 or 24 h design storm with peak rainfall intensities near the middle of the storm distribution to mimic these rare events.

Finally, observed increases in hydrograph peaks and total runoff volume following wildfires are well documented in the literature. For northern New Mexico, these increases in peak flow appear to be in the range of one to two orders of magnitude per unit drainage basin area. Furthermore, recording rain and stream gauges should collect data at less than one-half the post-fire system response time, or basin lag time, to capture the dynamic nature of the rainfall-runoff process.

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