PREDICTING EVENT BASED PEAK DISCHARGES RESULTING FROM THINNING AND WILDFIRE FOR THE UPPER RIO DE FLAG WATERSHED, FLAGSTAFF, ARIZONA

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The upper Rio de Flag watershed in Flagstaff, Arizona (Figure 1) is drained by an ephemeral stream, the Rio de Flag, and its tributaries. During storms, the Rio de Flag gathers surface flows from a number of parallel sub-basins that descend more than 5000 feet from the top of the San Francisco Peaks to the city of Flagstaff. The steepness of the San Francisco Peaks induces rapid downstream movement of surface water runoff, resulting in flooding along the Rio de Flag within the city (Hill et al. 1988). During the winter, spring, and monsoon (summer) seasons of the last two centuries, peak discharges entering into downtown Flagstaff have caused extensive property damage (Murray 1974).

For a period of 11 years (1969–1980) the city of Flagstaff and the USGS operated three crest-stage gauging stations in the 32,000-acre Upper Rio de Flag watershed to determine discharges with recurrence intervals of 2, 5, 10, and 25 years (Hill et al. 1988). Although the gauging stations are no longer in operation, they provided important information to city planners who anticipated future development in the watershed and surrounding areas.

While development continues throughout the watershed, there is another threat to the health of the watershed and downstream property. This threat comes from several years of drought, current and future insect outbreaks, and heavy accumulations of fuels that can lead to a possible stand replacing wildfire and the destruction of homes and other properties in the wildland-urban interface as well as in the forest. In addition, because fire is known to decrease the rate of water infiltration into soil and thus cause an increase in surface runoff, large-scale flooding is an immediate post-fire concern (Neary et al. 2003; Fisher and Binkley 2000; Robichaud et al. 2000; Robichaud 2000; Robichaud and Hungerford 2000; DeBano et al. 1998). The effects of forest disturbance through burning on stream peak discharges are highly variable and complex. In the Southwest, post-fire peak discharge increases of 500–9600 percent are common due to intense monsoon rainfalls at the end of the summer fire season, steep terrain, shallow skeletal soils, and water repellency (Robichaud et al. 2000).

To decrease the risk of a stand-replacing fire, forest thinning operations are being conducted in the watershed within open forest stands and in the wildland-urban interface (Fort Valley Ecosystem Restoration Project 2002). Many studies have shown that forest thinning can increase water yield and peak discharges from watersheds (Nyland 1996; Gottfried 1991; Tecle 1991; Baker 1984; Brown et al. 1974). A long-term study of forest thinning in the Beaver Creek Experimental Watershed, located within 30 miles southeast of the Rio de Flag watershed, showed significant increases in stream discharge (Brown et al. 1974). Baker (1984) showed a 63 percent increase in annual water yield in the ponderosa pine vegetation type after intensive tree removal. In addition, Burton (1997) reported a 66 percent increase in peak discharge after thinning in Brownie Creek, Utah. The causes for the increased flow are thought to be more saturated soils, soil compaction, road construction, and snow accumulation and snowmelt in the thinned areas (Chang 2003). Gottfried (1991) reported that in mixed conifer stands within the Thomas Creek watershed in the White Mountains of Arizona, annual runoff increased by 45 percent and mean peak discharges increased by 60 percent in thinned areas in the winter. These increases were attributed to lower evapotranspiration and greater snow accumulation and melting rates than in pre-thinned and harvested stands. According to Ffolliott and Fogel

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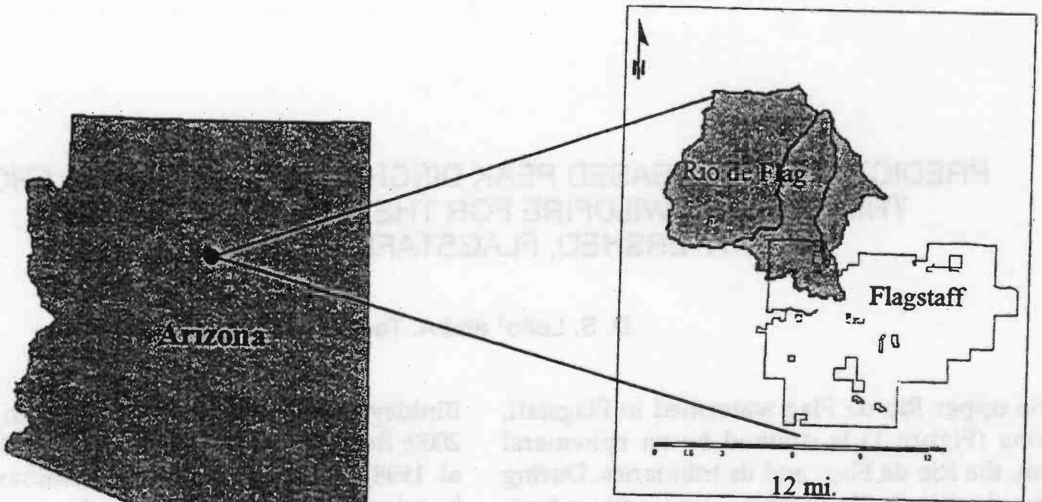

Figure 1. Location of the upper Rio de Flag watershed within Arizona and Flagstaff.

(2003), the relationships between watershed management practices such as thinning and peak discharge are difficult to isolate and quantify. Peak discharges can decrease or can remain unchanged after thinning, depending on thinning intensity, location in the watershed, regrowth of vegetation, and climatic patterns (Chang 2003).

Study Objectives

Our objective was to compare the predicted peak discharges under various simulations of severe wildfire with a simulation of forest thinning in the Rio de Flag watershed using the U.S. Army Corp of Engineers, Hydrologic Engineering Center's Hydrologic Modeling Software (HEC-HMS; Scharffenburg 2001). We also compared the scale of the predicted peak discharges relative to actual historic floods in Flagstaff. We expected modeling results to show that wildfire produces significantly higher peak discharges than forest thinning during larger storm events. Also, a wildfire over the entire watershed could produce peak discharges of a magnitude never seen before in Flagstaff.

Forest Thinning

Scenarios for forest thinning incorporated the current stand treatments in 10,000 acres of the Fort Valley Experimental Forest as a part of the Greater Flagstaff Forests Partnership. The purpose of these treatments is to facilitate the restoration of ecosystem health as it relates to tree vigor, threatened and endangered species, diseases and pathogens, riparian resources, and fire hazard. As a result, forest thinning goals include the removal of suppressed and intermediate trees to open up forest stands and restore the forest condition to near pre-European densities, structure, composition, and function (Fort Valley Ecosystem Restoration Project 2002). In addition, prescribed fire will be incorporated on 2990 acres after certain stands are thinned (Newbauer, personal communication 2004). The current rate of thinning in the forest is less than 1000 acres per year, or approximately 3 percent of the total watershed area, due to deferrals for wildlife, research projects, and inoperable areas. In addition, managers are thinning stands to varying degrees of density. Stand treatments include light, moderate, and intense thinning to approximately 120, 90, and 60 sq ft of residual basal area respectively. Newbauer (personal communication 2004) predicts that treatments in the watershed may not be completed until 2009.

To err on the side of not underestimating peak discharge, we assumed that a total of 10,000 acres in Fort Valley was treated to the intense level within a short time period of 3 years. Reasons for this were (1) 10,000 acres is the expected area of treatment, (2) water yield should increase in cases where basal area reduction is greater than 20 percent and understory vegetation recovery is limited (Chang 2003), and (3) forest thinning activities must cover large areas for any impact on peak discharge to occur (Hewlett 1982). Therefore, we assumed that if about 30 percent of the watershed would be thinned promptly, the subsequent peak discharges from thinning would not be influenced by factors such as the reestablishment of understory vegetation or human development.

Wildfire

Forest conditions in the area indicate a potential for an ignition of a wildfire within the watershed or outside of it (Neary et al. 2003). The probability of a certain size event occurring depends on factors such as weather, fuel conditions, and topography. Severe wildfires can consume much of the forest vegetation, reducing both rainfall interception by the forest canopy and evapotranspiration (Robichaud and Waldrop 1994). While current drought conditions increase the probability for a severe fire, it is extremely difficult to predict a specific fire event and the degree at which vegetation and soils are affected.

The effects of fire on peak discharges are mostly determined by fire severity and post-fire precipitation regime, making it impossible to determine changes in peak discharge from all conceivable situations (DeBano et al. 1998). Therefore, we created three generic wildfire scenarios related to watershed area burned at the highly severe level. These scenarios were one-quarter, one-half, and the entire watershed burned under a severe, stand-replacing fire event.

METHODS

The upper Rio de Flag watershed was first delineated using a 10 m Digital Elevation Model (DEM) obtained from the Arizona Regional Image Archive (http://aria.arizona.edu/; accessed in 2004), and the CRWR Preprocessor extension in ArcView (ESRI 2002; Maidment and Djokic 2000). Three subwatersheds gauged by the U.S. Geological Survey (USGS) for 11 years were also delineated in order to help calibrate the surface runoff model. Watershed characteristics such as soil type, stream patterns, vegetation type, slope, and land use characteristics were obtained in the form of shapefiles from the Arizona Land Resource Information Service and Coconino National Forest databases. After all watershed data were gathered, we used the Army Corp of Engineers surface runoff modeling software, HEC-HMS. With this software we employed Natural Resource Conservation Service (NRCS, formerly Soil Conservation Service) methods (Scharffenburg 2001; NRCS 1986; McCuen 1982) to determine the event-based surface runoff from the thinning and three wildfire scenarios under dry, average, and wet moisture conditions. The NRCS models are categorized as event, lumped, empirical, or fitted parameter models (Scharffenburg 2001). We used NRCS methods because they are easy to apply, are the most widely used by hydrologists, and were developed to evaluate downstream impacts from various management treatments (Woodward et al. 2002). The NRCS Curve Number Loss Model, taken from Scharffenburg (2001) and NRCS (1986), estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture using the following equation:

$$Q = (P - I_a)^2 / P - I_a + S$$

where Q = accumulated precipitation excess (runoff); P = accumulated precipitation depth; I_a = initial abstraction (initial loss); and S = potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation. Until the accumulated rainfall exceeds the initial abstraction, the precipitation excess, and hence runoff, will be zero.

An empirical relationship of I_a and S is

$$I_a = 0.2S.$$

The maximum retention, S, and watershed characteristics are related through an intermediate parameter, the curve number (CN) where

$$S = (1000 / \mathrm{CN}) - 10.$$

The curve number for a watershed can be estimated as a function of land use, soil type, and antecedent soil moisture. The curve numbers for this study are shown in Table 1. Curve numbers in AMC II can be converted using the following equations:

$$\mathrm{CN(I)} = 4.2\mathrm{CN(II)} / 10 - 0.058\mathrm{CN(II)}$$

and $$\mathrm{CN(III)} = 23\mathrm{CN(II)} / 10 + 0.13\mathrm{CN(II)}.$$

Hydrologic soil groups are defined in Table 2. Antecedent moisture conditions (AMCs), which reflect seasonality and 5-day antecedent precipitation conditions, are described in Table 3.

Although findings from Johnson (1998) show that the use of NRCS methods on some watersheds in excess of 96.5 can be appropriate, Ponce (1989) recommended using careful judgment when applying NRCS methods in excess of this limit and suggested subdivision of larger watersheds. The area of the subwatersheds in this study is sufficient to determine peak discharge because the variability in curve number for the largest subwatershed

Table 1. Runoff curve numbers for AMC II (NRCS 1986).

Cover Type	Hydrologic Condition	Impervious Area (%)	Hydrologic Soil Group A	B	C	D
Forest[1]	Poor	–	45	66	77	83
	Fair	–	36	60	73	89
	Good	–	25	55	70	77
Pasture, grassland, or range[2]	Poor	–	68	79	86	89
	Fair	–	49	69	79	84
	Good	–	39	61	74	80
Meadow – continuous grass, no grzing	–	–	30	58	71	78
Farmsteads	–	–	59	74	82	86
Streets and roads	–	–	98	98	98	98
Paved	–	–	76	85	89	91
Gravel	–	–	72	82	87	89
Dirt	–	–	–	–	–	–
Commercial and business	–	85	89	92	94	95
Residential lots	–	–	–	–	–	–
1/8 acre or less	–	65	77	85	90	92
1/4 acre	–	38	61	75	83	87
1/3 acre	–	30	57	72	81	86
1/2 acre	–	25	54	70	80	85
1 acre	–	20	51	68	79	84
2 acre	–	12	46	65	77	82

[1]Poor: Forest litter, small trees, and brush are destroyed by disturbance or regular burning. Fair: Evidence of grazing but no burning, and some forest litter covers the soil. Good: No evidence of grazing, and litter and brush adequately cover the soil.
[2]Poor: < 50% ground cover or heavily grazed with no mulch. Fair: 50–75% ground cover and moderately grazed. Good: > 75% ground cover and lightly grazed.

Table 2. NRCS hydrologic soil groups (Scharffenburg 2001).

Soil Group	Description	Minimum Infiltration Rate (in/hr)
A	Deep sand, deep loess, aggregated silts	0.30–0.45
B	Shallow loess, sandy loam	0.15–0.30
C	Clay loams, shallow sandy loam, soils low in organic content, soils high in clay	0.05–0.15
D	Soils that swell significantly when wet, heavy plastic clays	0.00–0.05

Table 3. Definitions of the three AMC (Antecedent Moisture Condition) groups (NRCS 1986).

AMC Group	Total 5-day antecedent rainfall (in) Dormant Season	Growing Season
I	< 0.5	< 1.4
II	0.5–1.1	1.4–2.1
III	> 1.1	> 2.1

(29.9 sq mi) is relatively small, which fails to discourage application of NRCS methods over large areas (Hawkins, personal communication 2004).

Description of Subwatersheds

It is important to point out that most of the peak discharge data and general watershed description information we gathered for the three subwatersheds comes from the USGS Water Resources Investigations Report 87-4210. In this report Hill et al. (1988) give regression functions for peak discharges, historically estimated and recorded peak discharges, vegetation characteristics, channel characteristics, and hydrologic soil groups. The three subwatersheds gauged by the USGS used for this study are Hidden Hollow, Schultz Canyon, and Crescent Drive.

Hidden Hollow

The Hidden Hollow watershed encompasses 29.9 square miles (Figure 2). As the largest subwatershed, Hidden Hollow consists of a large forested and rural valley bounded by mountains to the north and south. The main stream channel is

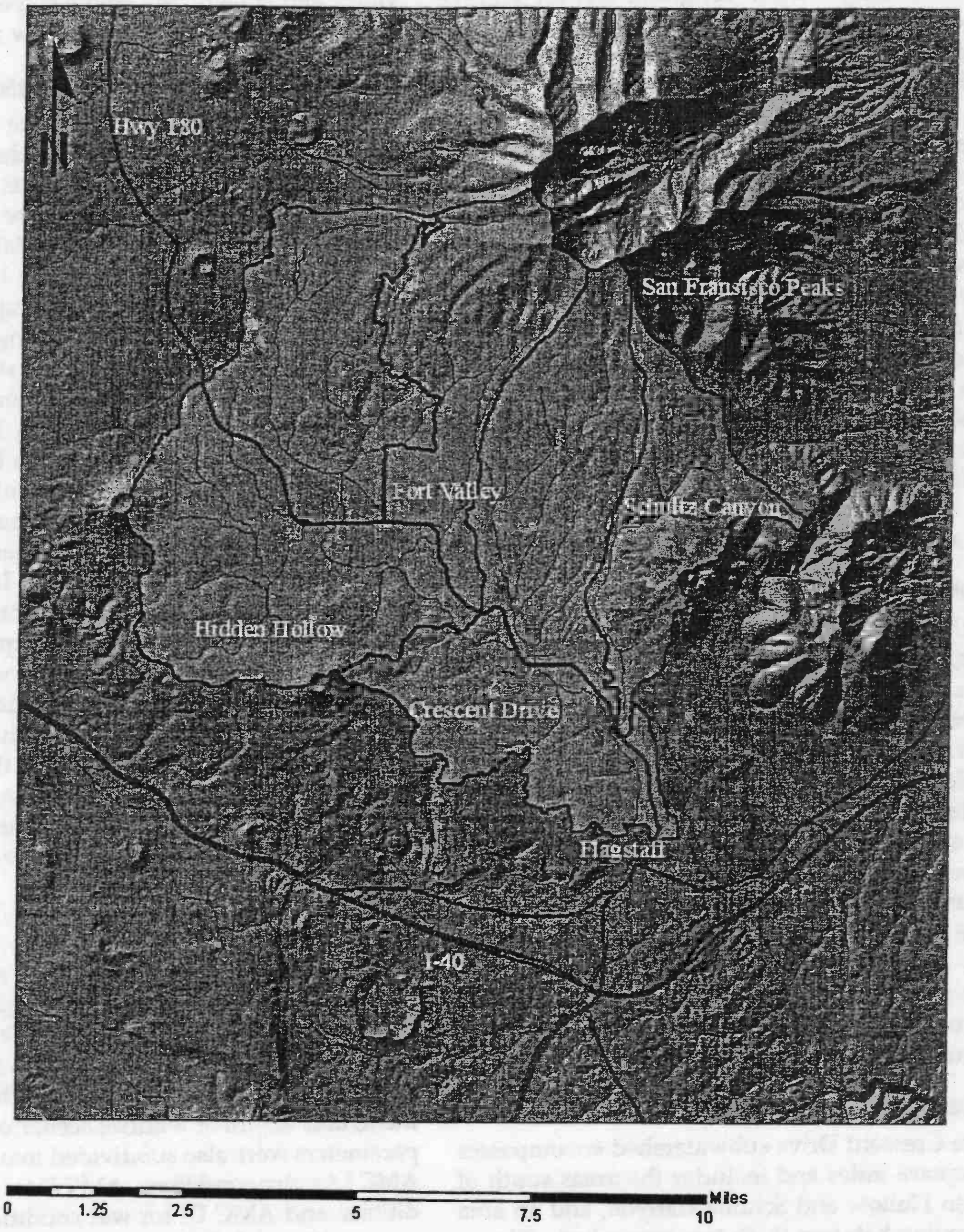

Figure 2. Map of the Rio de Flag watershed showing the three subwatersheds and their juxtaposition with respect to the San Francisco Peaks, Flagstaff, Fort Valley, and Interstate 40 and Highway 180.

approximately 8 miles long and has an average slope of 2.4 percent. About three-quarters of the vegetation in the area is ponderosa pine and pine/oak forest. Meadows covered with grasses and herbaceous plants are the next-abundant vegetation type. In the higher elevations, mixed conifer and subalpine conifer stands are present. Land use in the watershed consists mostly of small ranches, scattered residential areas, and national forest land. The amount of impervious area in the watershed is estimated, using Geographic Information Systems (GIS) software, to be approximately 2 percent. Hydrologic soil groups range anywhere from B to D, with B soils dominating areas along the stream. Soils in group B have a moderate to high rate of infiltration when thoroughly wet (Van Mullem et al. 2002; NRCS 1986), and according to Hill et al. (1988), this watershed produces very little runoff.

Schultz Canyon

Schultz Canyon, which encompasses 6.4 square miles, drains a rural pine forest on the steep southeast slope of the San Francisco Peaks (Figure 2). The main tributary to the Rio de Flag is about 6 miles long with an average slope of 5.6 percent. The Schultz Canyon tributary meets the main Rio de Flag stream channel near the northwest Flagstaff city limits. Despite steep slopes, little runoff occurs from Schultz Canyon. The vegetation types are similar to Hidden Hollow vegetation. Land use in the watershed consists of scattered residential areas and national forest land. The impervious cover in the watershed is estimated at 1 percent. Hydrologic soil groups are of the B and C types and are highly pervious.

Crescent Drive

The Crescent Drive subwatershed encompasses 16.9 square miles and includes the areas south of Hidden Hollow and Schultz Canyon, and an area intervening between these two watersheds (Figure 2). The intervening area is forested with the same vegetation as Hidden Hollow and Schultz Canyon. Housing developments and urban development are abundant at the lower end of the watershed. The main channel length is about 4 miles with an average slope of 2 percent. Land use in the watershed includes more than 1000 acres of residential and urban development; the rest is national forest land consisting of roads, trails, and recreation areas. The impervious cover in the watershed is estimated at about 4 percent. Soil groups are mostly C, but B soils are commonly found along the valley and stream. The gentle slopes and pervious soils along the stream produce low runoff.

Surface Runoff Modeling

The construction of a surface runoff model begins with the selection of model components. These are then assembled as parts of the overall model, following a logical sequence that resembles that of the natural processes. Rainfall and snowfall are considered first, followed by hydrologic abstractions, subwatershed hydrograph generation, stream channel routing, and hydrograph aggregation in a cascading manner at the stream network confluences (Scharffenburg 2001; Ponce 1989).

Surface runoff modeling using HEC-HMS requires three general components: a basin model, a meteorological model, and a control specification. The basin model requires information such as watershed area, infiltration capacities, NRCS curve numbers, surface imperviousness, lag time, baseflow, and channel roughness or routing parameters. The meteorological model requires information such as storm type and duration, and rainfall depth. When basin and meteorological models are complete, a control specification can be set and an event is generated to determine the event discharge. The control specification depicts the resolution of the hydrograph calculation (Ponce 1989). The control specifications we used were at 15 minute intervals.

Establishing Current Conditions

Using information from Hill et al. (1988) and GIS data, we determined NRCS parameters to be used in the HEC-HMS model. Table 4 shows watershed parameters using NRCS methodology for current conditions, the intense thinning treatment, and the three wildfire scenarios. Watershed parameters were also subdivided into three AMCs: AMC I for dry conditions, AMC II for average conditions, and AMC III for wet conditions to reflect seasonality and 5-day antecedent precipitation conditions (NRCS 1986; Ward and Elliot 1995). Testing the model under all AMCs is significant to this study because (1) return intervals for discharge and rainfall events published by Hill et al. (1988) and the Army Corp of Engineers (2000) do not coincide (Tables 4 and 5), and (2) AMC is a consistent factor in explaining deviations from the central trend of runoff. For example, precipitation from the previous 5 days may help explain the reason why a rainfall event with a 25 yr return interval produced a 100 yr flood in September 1923.

Table 4. NRCS parameters used for the HEC-HMS surface runoff model for the current watershed condition, wildfire scenarios, and the intense thinning treatment. The parameter values were generated for all three AMCs. The three wildfire scenarios are severe burning to the entire area, to half, and to a quarter of the watershed. Intense thinning treatment is thinning all 10,000 acres of the Fort Valley area in the watershed to 60 sq ft of basal area.

	Initial Loss (inches)			SCS Curve Number			Imperviousness (%)	Transform: SCS Lag Time (min)
	AMC I	AMC II	AMC III	AMC I	AMC II	AMC III		
Current Condition								
Hidden Hollow	1.97	1.75	1.25	33	52	68	2	120
Schultz Canyon	2.7	2.5	1.6	31	50	66	1	75
Crescent Drive	1.97	1.75	1.25	33	53	69	4	100
Wildfire (entire)								
Hidden Hollow	1.35	1.05	0.85	54	73	79	2	100
Schultz Canyon	1.7	1.5	1.1	51	70	77	1	70
Crescent Drive	1.35	1.05	0.85	56	74	78	4	85
Wildfire (half)								
Hidden Hollow	1.72	1.49	1	40	60	73	2	110
Schultz Canyon	2.6	2.1	1.4	38	58	70	1	72
Crescent Drive	1.72	1.49	1	41	61	72	4	92
Wildfire (quarter)								
Hidden Hollow	1.9	1.62	1.15	36	56	71	2	115
Schultz Canyon	2.65	2.3	1.45	34	54	70	1	74
Crescent Drive	1.9	1.62	1.15	37	57	71	4	95
Intense Thinning								
Hidden Hollow	1.94	1.7	1.2	39	59	70	2	117
Schultz Canyon	2.7	2.5	1.6	32	51	68	1	75
Crescent Drive	1.95	1.73	1.22	38	58	71	4	98

Parameters for the watershed were first determined for the current conditions under AMC II and then adjusted according to historic peak discharges on record. The basic procedure in calibrating the model was one of selective parameter value manipulation and comparison of simulated flow values against recorded peak discharges. For example, if the simulated discharge was less than recorded, the value of initial loss was adjusted to a smaller value to increase the simulated runoff. We used initial loss to describe surface storage, interception, and infiltration in inches prior to runoff (Ward and Elliot 1995).

Other parameters were manipulated as well. An important consideration in determining the parameters for the current watershed condition is the spatial modification of the watershed since the last large flood in 1993. Since 1993, there have been numerous housing and road developments in the area. As a result, impervious areas in the study area have increased. This may reduce infiltration rates and lag times, resulting in higher peak discharges than previous floods having similar storm events (Riley 1998). We used lag time as the time interval from the maximum rainfall rate to the peak rate of runoff (Viessman and Lewis 1996). The amount of impervious area was determined using total area of development and average impervious values for the area taken from McCuen (1982). The impervious portion in developed areas ranges from 12 to 85 percent. Baseflow estimates were not necessary because the streams in the study area are ephemeral and do not have baseflow (Hill et al. 1988). After determining flow characteristics under the current conditions, we used watershed parameter values that explain forest watershed conditions under thinning and wildfire for input into the NRCS model.

Thinning Scenario

Based on the NRCS hydrologic soil complexes for forest land in the fair condition vegetation cover class, the curve number was increased from the current condition to reflect the possible change in runoff characteristics in the thinning scenario (Chang 2003). It is important to note that the soils

Table 5. Historic peak flows and complementing rainfall depth with corresponding return interval (RI), antecedent soil moisture[1] depth (ASM) from previous 5 days, antecedent moisture condition (AMC), and event type in Fort Valley.[2] Peak discharges ranged from 3 to 1200 cfs (1920–1993).

Date	Peak Flow (cfs)/RI (yr)	Event Rainfall Depth (in)/RI (yr)	ASM	AMC	Event Type
02/20/1993	900/50	2.5/25	1.04	II	Rain on snow
03/12/1982	240/10	2.3/25	0	I	Snowmelt
07/26/1980	104/5	0.8/2	0.34	I	Rain
05/21/1979	90/5	0.6/2	0	I	Rain
04/02/1978	128/10	0.75/2	1.07	I	Rain
05/15/1977	10/2	0.45/2	0.53	I	Rain
02/09/1976	40/2	1.1/2	1.64	III	Snowmelt
04/08/1975	10 /2	0.3/2	0.38	I	Rain on snow
04/03/1974	3/2	0.11/2	0.43	I	Rain
04/28/1973	235/ 10	0.6/2	0	I	Rain on snow
09/30/1971	10/2	1.52/5	0.33	I	Rain
08/30/1970	10/2	0.15/2	0.07	I	Rain
08/05/1963	300/25	0.5/2	1.33	I	Rain
03/24/1960	11/2	0.45/2	0	I	Rain
04/20/1958	56/2	0.15/2	0	I	Rain
03/04/1938	600/50	1.45/5	1.4	III	Rain
09/18/1923	1200/100	2.33/25	1.5	II	Rain
02/22/1920	600/50	1.42/5	1.48	III	Rain on snow

[1]ASM is the precipitation depth within 5 days leading up to the storm. ASM determines AMC. AMC I = Dormant season ASM less than 0.5 in; growing season ASM less than 1.4 in. AMC II = Dormant season ASM between 0.5 and 1.1 in; growing season ASM between 1.4 and 2.1 in. AMC III = Dormant season ASM greater than 1.1 in; growing season ASM greater than 2.1 in.
[2]Precipitation depths and event types are for the Fort Valley weather station.

in study subwatersheds do not belong to one soil group, and the current thinning treatment is not conducted in the entire watershed. As a result, the curve number generated is an estimation of what may actually occur in the watershed from intense thinning. Other parameters such as initial loss and lag time were decreased accordingly. The Schultz subwatershed received minor adjustment in its curve number because the actual thinning taking place in the subwatershed involves mostly urban interface thinning, not open forest thinning. As a result the curve number was increased by 1 to 2 points because thinning affects a minimal area.

Wildfire Scenarios

Parameters for the wildfire scenarios in Table 4 were decreased for initial loss and lag time and increased for the curve number. The initial loss was used as the main factor in determining wildfire impacts because experiments performed by Robichaud (2000) suggested that infiltration rates can decrease up to 40 percent, and this value was used to estimate the initial loss. Lag time was decreased because a lack of vegetation would cause an increase in the velocity of overland flow that enters stream channels (DeBano et al. 1998). The curve number generated for wildfire burned areas was based on NRCS hydrologic soil complexes for forest land in poor condition because wildfire can destroy much of the vegetation, leaving the soil bare and dry. In dry soil conditions, water repellency occurs at shallow depths (Robichaud and Hungerford 2000).

Meteorological Model

According to Viessman and Lewis (1996) and Ponce (1989), an appropriate model of rainfall distribution pattern for the study area is the Type II SCS 24 hr rainfall distribution (Figure 3), which we used for this study. The Type II rainfall distribution is representative of storm systems that occur in the southwestern United States (Ponce 1989). Twenty-four hour, basin-wide precipitation depths of 2, 5, 10, 25, 50, and 100 yr return periods for the area were obtained from the U.S. Army Corp of Engineers feasibility report for the Rio de Flag (2000). Figure 4 shows the 24 hr precipitation depth for each of the six return periods. The depth

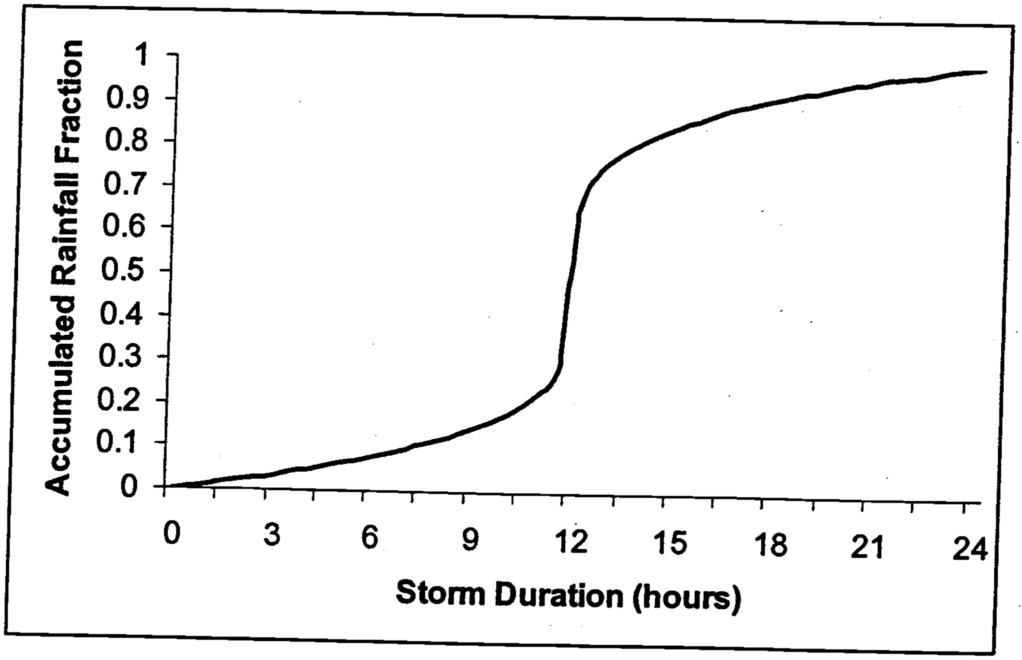

Figure 3. SCS Type II rainfall distribution model for a 24 hour storm (ordinates taken from McCuen 1982).

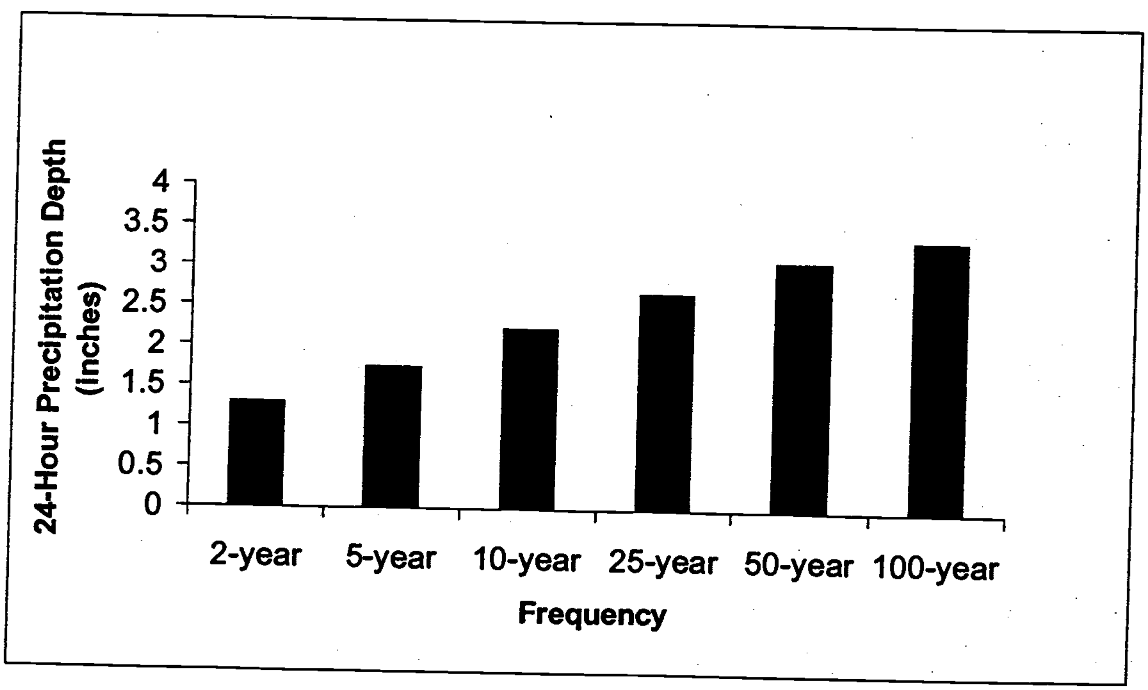

Figure 4. Twenty-four hour, basin-wide precipitation depths for 2, 5, 10, 25, 50, and 100 yr return periods in Flagstaff, Arizona (Army Corp of Engineers 2000).

of rainfall ranges from 1.3 inches for a 2 yr storm event to 3.4 inches for a 100 yr storm event.

Reconstruction of Historical Floods with Respect to Thinning and Wildfire

To reconstruct historical floods with respect to thinning and wildfire we employed the basin and meteorological models described previously; however, we used the actual storm depth from past storms (Table 5) instead of return period depths. One historical storm from each storm type was chosen. Storm events selected include heavy winter runoff from the February 1993 flood, intense monsoon moisture from the July 1980 flood, and a tropical storm from the September 1923 flood. After choosing historical storm events for the meteorological model, we computed the peak discharge using HEC-HMS based on the appropriate parameters in the basin model (Table 4). For example, in the 1923 storm event we used 2.33 inches of precipitation as the storm depth (meteorological model) and loss rates, curve numbers, and lag times for AMC II under the thinning and wildfire scenarios. Reconstruction for the February 1993 storm was a special case for modeling because antecedent snowmelt occurred prior to the storm period, resulting in baseflow. Therefore, for simulation purposes we included baseflow in the model at the rate of 6 cu ft/sec/sq mi. This rate, which was suggested by the Army Corp of Engineers (2000) in their reproduction of the February 1993 flood, is derived from estimated components of shortwave radiation, ground heat, and convection-condensation melting.

RESULTS

Surface runoff estimations using the HEC-HMS modeling system produced consistent results for all return period storms. Figures 5–10 show peak discharge hydrographs for 2, 5, 10, 25, 50, and 100 yr return period storm events under three AMCs and under current conditions, thinning treatment, and wildfire scenarios. The hydrographs usually reached their peak flow rates 10 to 20 hr after the onset of a storm event. Also, discharges continued for approximately 36 hr after the onset of the storm. It is important to note that for interpretation, AMC discharges in all hydrographs are the same as AMC II discharges unless the hydrograph shows otherwise.

Figure 5 shows that the peak discharges under AMC I and II for a 2 yr magnitude storm are the same, at less than 200 cfs. The 2 yr peak discharge is greatest at approximately 260 cfs in the wildfire scenario where the entire watershed is burned. Also, the discharge is greater among all wildfire scenarios under wet conditions for an extended period of time, compared with thinning and current condition scenarios. This extended discharge is a common trend shown by all hydrographs in every return period.

In Figure 6, a 5 yr precipitation storm over a watershed area completely burned by a wildfire produces peak discharges up to 1100 cfs in wet conditions. However, a 5 yr storm over the same wildfire burned area under average and dry conditions produces a discharge near 600 and 200 cfs respectively. Following a 5 yr storm, a wildfire that burns over one-quarter of the watershed produces slightly greater discharge than the thinning treatment.

In Figure 7, a 10 yr storm shows a difference in peak discharge among all scenarios and AMCs, with wildfire and wet conditions producing the higher discharge. A wildfire burn over the entire watershed and a wet AMC produce peak discharge of about 2500 cfs. The post-wildfire peak discharges would range between 400 and 1300 cfs if the AMC is average or dry. The peak discharges from intensely thinned areas range between 300 cfs under average or dry AMC and 900 cfs under the wet AMC.

In Figure 8, a 25 yr return period storm produces a peak discharge more than twice the historic peak discharge in soils of average AMC and almost four times greater in soils of wet AMC and after a wildfire that burned the entire watershed. Again, a thinning treatment would produce a peak discharge slightly higher than that under the current condition and slightly lower than wildfire that burned one-quarter of the watershed.

In Figure 9, a 50 yr storm produces peak discharges of great magnitude. The storm produces the highest peak discharges following all wildfire scenarios under all AMCs. The peak discharges produced under these conditions range from 700 to 6500 cfs. A 50 yr storm after intense thinning and under current condition would produce hydrographs that have maximum peak discharges of 3300 and 2800 cfs, respectively.

Figure 10 shows a 100 yr storm producing peak discharges from a watershed entirely burned by wildfire to be about 4.5 times greater than the historic discharge in the average AMC and 6.5 times greater in the wet AMC (Table 5). The peak discharges following wildfire burn range from 1000 to

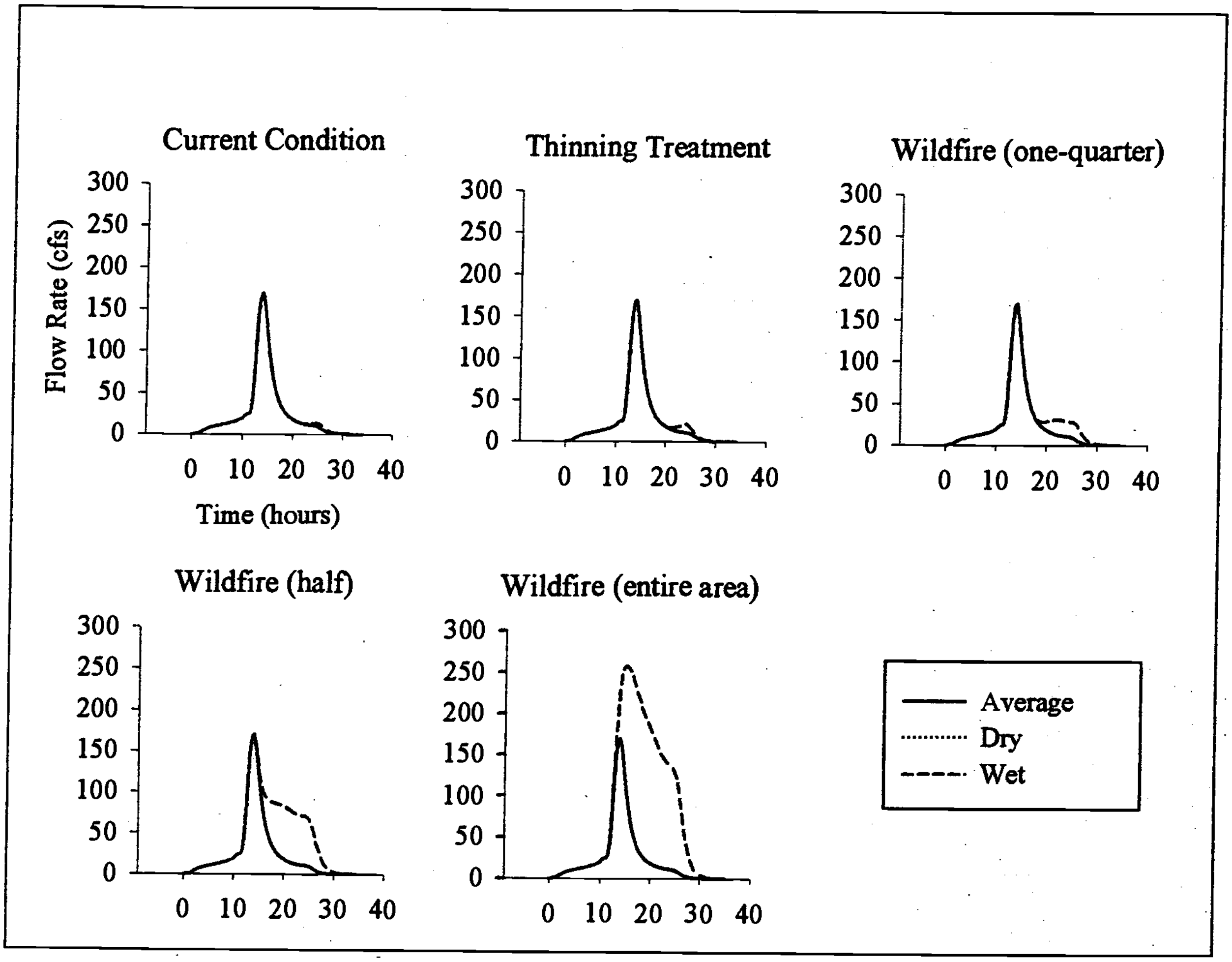

Figure 5. Hydrographs from a 2 yr storm showing peak discharge less than 260 cfs following the worst scenario of entire watershed burn.

8000 cfs under dry to wet AMC and small to large fire extent. The peak discharges produced under intense thinning and current condition and wet AMC are 1300 and 1100 cfs, respectively.

The reproduction of three historical floods produced mixed results. In Table 6, peak discharges from rainfall falling on top of melting snow and a tropical storm (Feb 1993 and Sep 1923 respectively) were significantly increased from their historical amount after wildfires. Following the 1923 event, there was no increase in peak discharge attributed to intense forest thinning. However peak discharges from the 1993 event were slightly higher after thinning the forest. Model results for the July 1980 flood were significantly less than the actual event, by more than 475 cfs, and did not change throughout all scenarios.

DISCUSSION

The results of hydrologic modeling for the Rio de Flag watershed may have some important implications for decision makers. These modeling results provide information on the amount of discharge coming from the watershed and entering the city of Flagstaff under existing conditions. Results also serve as the basis for watershed management decision making by pointing out the possible outcomes for various levels of area that the forest burns. This will help determine the location and level of treatment to conduct to prevent wildfires, and will provide needed information on the hydrologic effects of the treatments.

Increases in discharge following wildfire and thinning were similar to peak discharges reported by Robichaud et al. (2000), Baker (1984), and Gott-

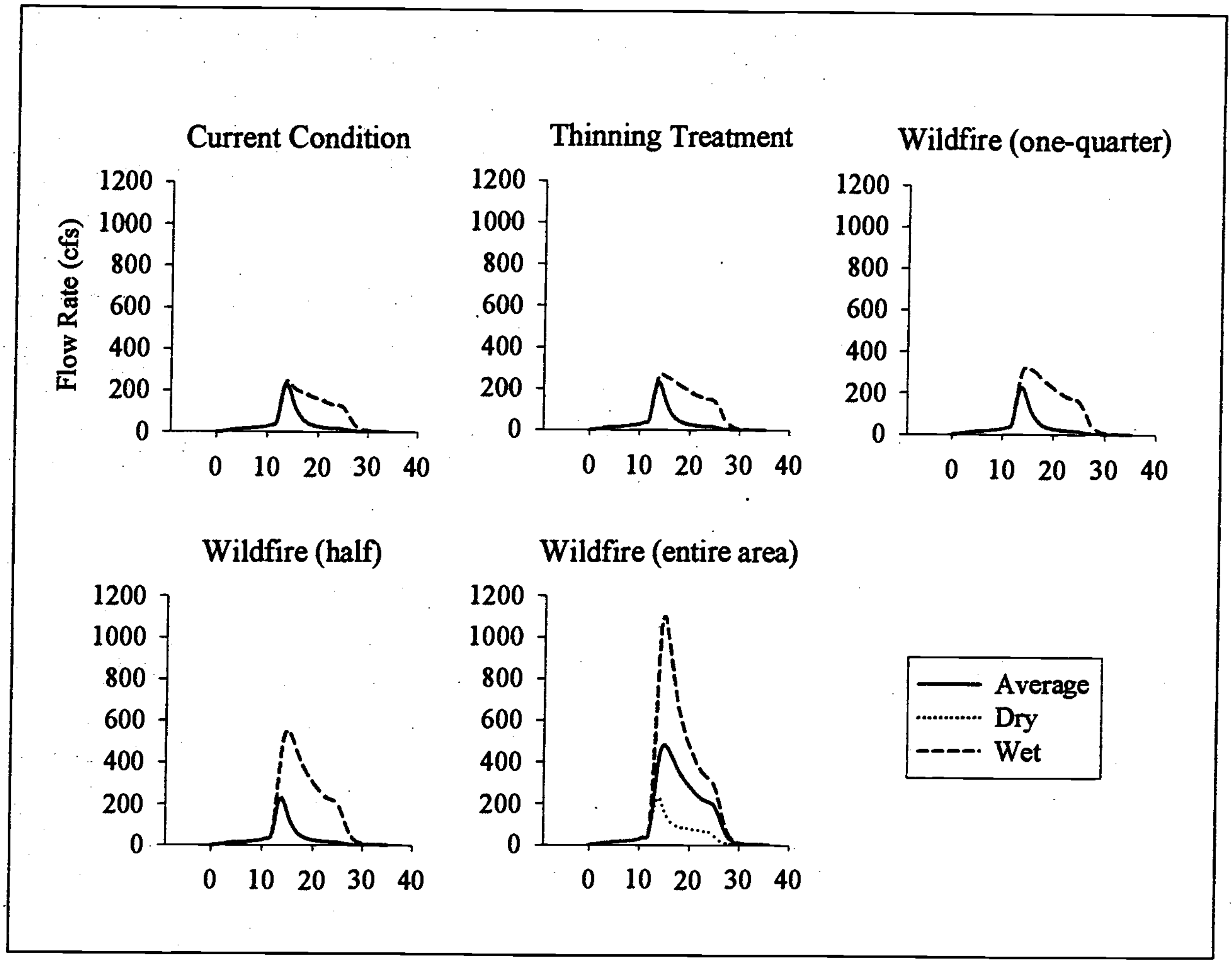

Figure 6. Hydrographs from a 5 yr storm following a wildfire that burned the entire watershed, producing significant flows of about 1100 cfs under wet antecedent soil moisture conditions (AMC) while storms after intensely thinned forest and following fires of lesser extent under all AMC types produce smaller peak discharges of less than 600 cfs.

Table 6. Estimated peak discharge using NRCS methods in HEC-HMS software for historical storm events under wildfire, thinning, and current condition scenarios.

Scenario	Reconstructed Storm Discharge (cfs)		
	Feb 93	Jul 80	Sep 23
Wildfire (entire area)	3143	119	3021
Wildfire (half)	1665	119	1815
Wildfire (quarter)	1280	119	1308
Thinning	1126	119	1175
Current condition	968	119	1010

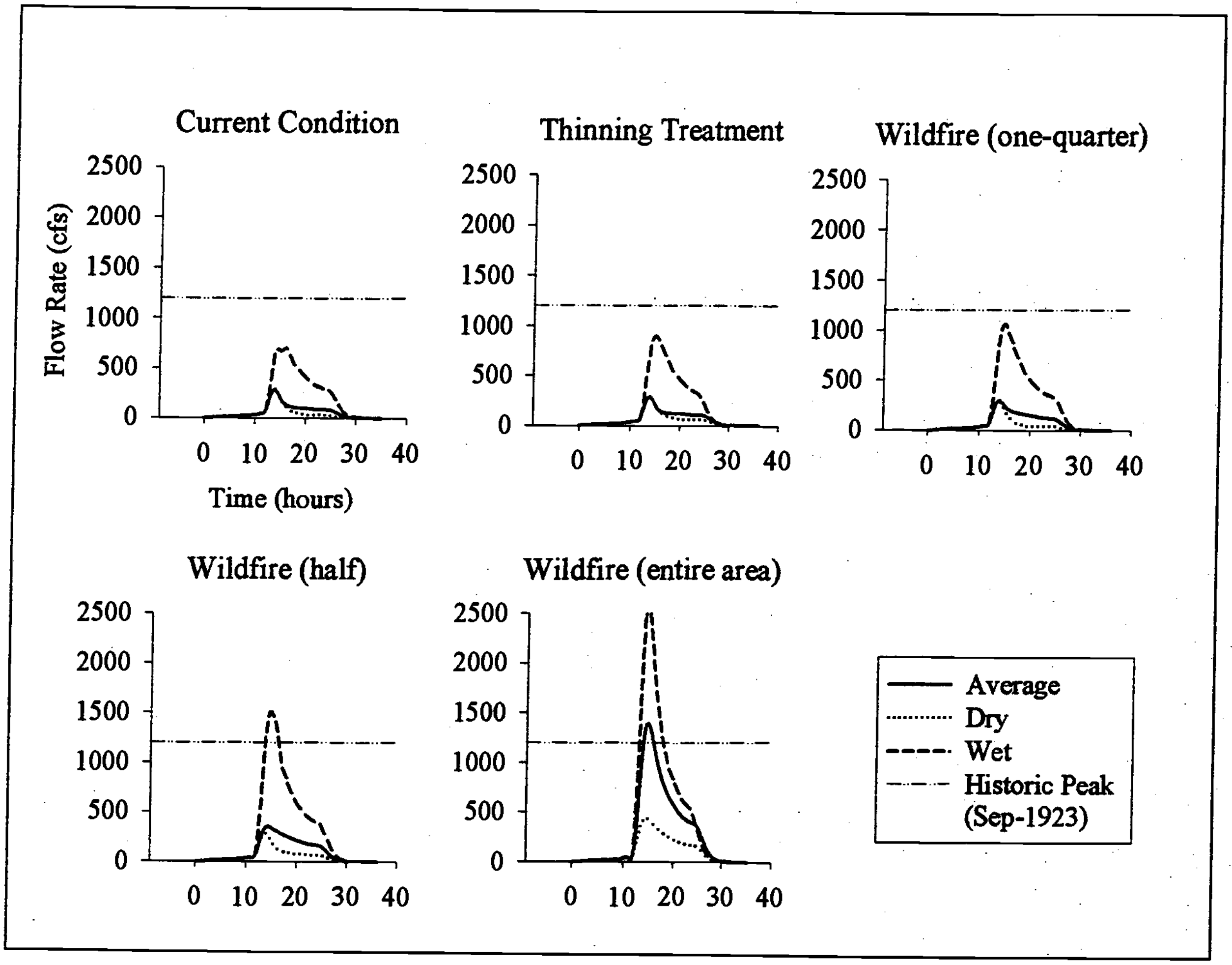

Figure 7. Hydrographs for a 10 yr storm show the peak discharges to be different under varying treatment scenarios and antecedent soil moisture conditions (AMC). The peak discharge following a wildfire that burned the entire watershed is approximately 2500 cfs. Other scenarios under average and dry AMC produce discharges between 300 and 1400 cfs after a 10 yr storm.

fried (1991). Precipitation from storms following wildfire and intensive forest thinning have the potential to yield peak discharges never recorded before. As the hydrographs show, peak discharges after wildfires are very high compared to those after treatments. Our analysis also shows that the impacts of intensive forest thinning on flooding are small compared to those of wildfire. As such, less intensive forest thinning distributed over 5 years or more should have less impact on flooding. The higher peak discharges after wildfire are due to the fire's impact on soils and vegetation. Water-repellent soils are common after severe wildfires, whereas forest thinning only increases soil bulk density. Furthermore, severe wildfires may kill all trees as well as the understory in the affected area, whereas forest thinning only removes trees designated for cutting and has less impact on the overstory and understory vegetation (Neary et al. 2003; DOE 2000).

Two factors that influence the values and interpretation of the modeling results are AMC and return period. Table 5 shows that the majority of flood events in the Rio de Flag occurred when the AMC was dry, and none of them were greater than a 25 yr storm depth. The less frequent and larger floods occurred over average and wet AMCs. Consequently, the larger floods have a higher likelihood of occurring during tropical storms or winter snow and snowmelt events, at less than or

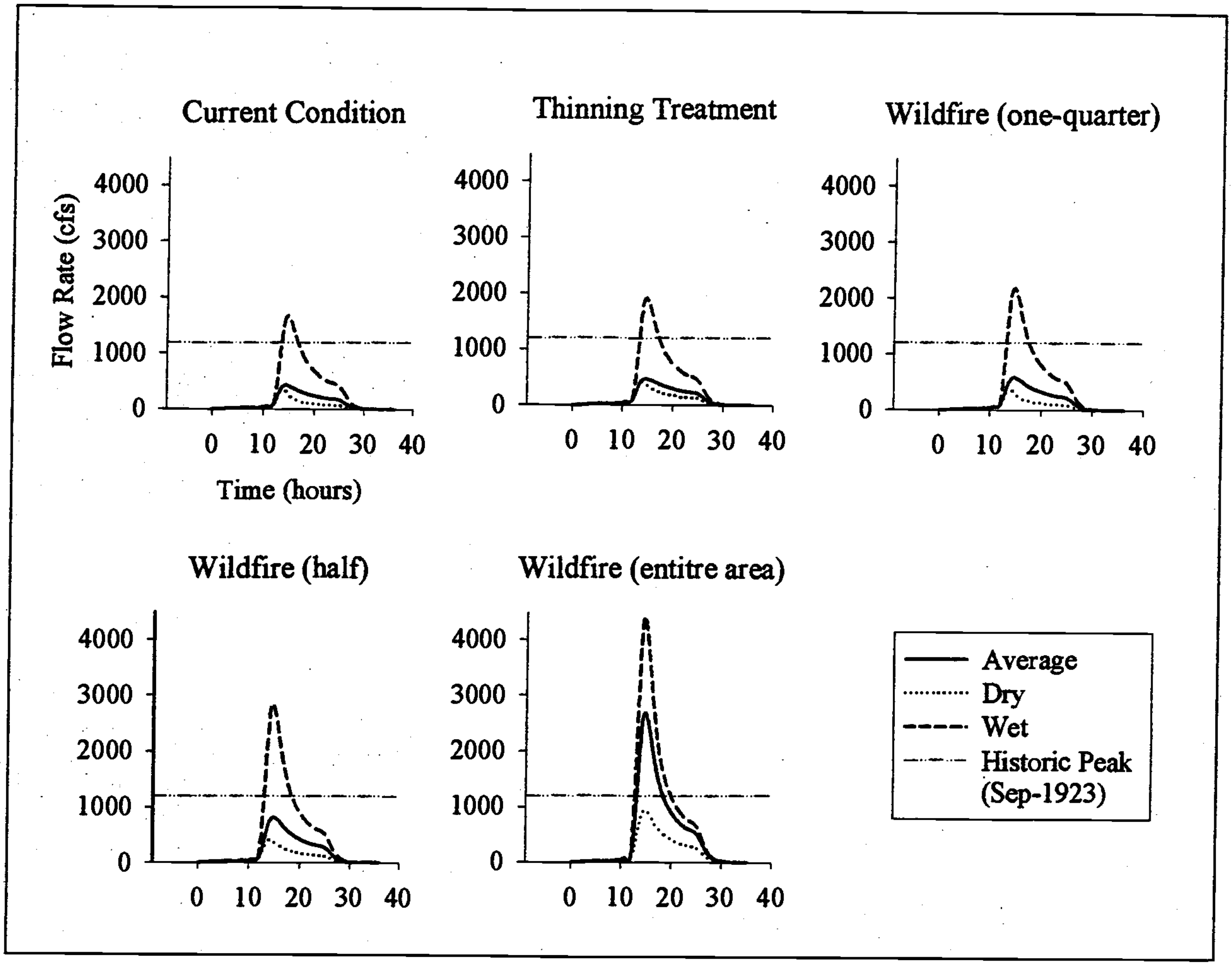

Figure 8. Hydrographs from a 25 yr storm over a wildfire that burned the entire watershed, producing discharge values greater than 2–4 times the historic peak discharge of 1200 cfs under average and wet antecedent soil moisture conditions (AMC). A similar storm over intensely thinned forest and any AMC type produces discharge at least 200 cfs below those over a wildfire that burned one-quarter of the watershed.

equal to 25 yr storm events. Storms over average and wet AMCs have resulted in some of the largest historical floods (see Table 5). However, most of the peak discharges during historical flood events in the period of data measurement occurred over dry AMCs. In the event that one of the six treatment scenarios occurs within the watershed, we recommend that scientists and decision makers interpret our modeling results as a range of possible discharge values over dry and wet AMCs.

For smaller and more frequent storm events such as 2 yr storms, peak discharges after wildfire and thinning do not seem to have great impact. According to the model, a wildfire will increase the amount of discharge by 60 cfs compared to the rest of the treatment scenarios. Storms over other scenarios would yield the same discharge regardless of the type of AMC. This is probably due to the high infiltration capacity of soils in the watershed. Also, forested watersheds reduce peak discharges for storms of low intensity and short duration, but cannot prevent the occurrence of floods from storms of higher intensity and long duration over a large area (Chang 2003). A 10 yr storm over a wildfire burned area can produce peak discharge greater than that of the 1923 peak discharge of about 1200 cfs. According to Gifford et al. (1967) the occurrence probability for a 10 year storm is during a period of one week in early August. All peak discharges from a 100 yr storm

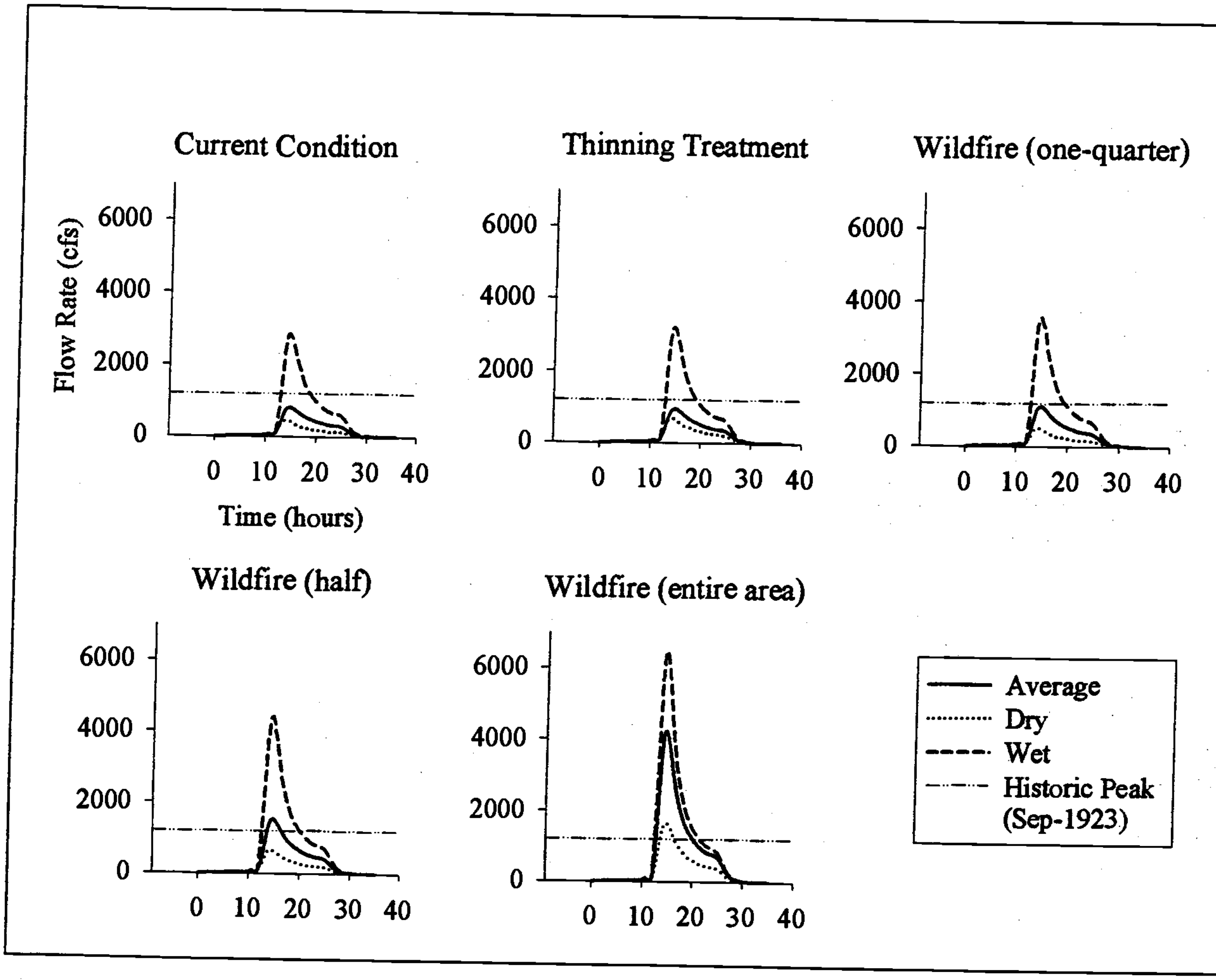

Figure 9. Hydrographs from a 50 yr storm showing a gradual increase with changes in treatment from current condition to wildfire over the entire watershed. Discharge after intense forest thinning is below the smallest wildfire scenario and above the current condition.

event exceed 1100 cfs. Moreover, the peak discharge following the worst-case scenario of wildfire over the entire watershed could be 2 to 6.5 times greater (depending on AMC) than the 1923 flood. Discharges in that range may cause extensive damage over parts of Flagstaff, especially if Flagstaff continues to encroach further into the floodplain. The most likely periods for the occurrence of a 100 yr storm event are during the months of July, August, December, January, and February (Gifford et al. 1967). Although the probability of a 100 yr event occurring is slight, it is essential to not underestimate unpredictable weather patterns due to future climate changes.

In previous flooding, large portions of Flagstaff have suffered damages and have been inundated with several feet of water. It is estimated that damages could total about $93 million if a 100 yr event, such as the September 1923 flood (Army Corp of Engineers 2000). Under the wildfire and thinning scenarios, Flagstaff could experience a flood of greater intensity and volume. According to the modeling results shown in Table 6, two possible historical events pose the greatest risk to Flagstaff if similar events occur in the future. These extreme events are rainfall on top of melting snow and a severe tropical storm. From the model, both events produced discharges between 1200 and 3100 cfs following wildfire. Storms over intensely thinned forest produced discharge less than 1200 cfs. Costs from a flood caused by an extreme storm event after a wildfire may significantly exceed $93

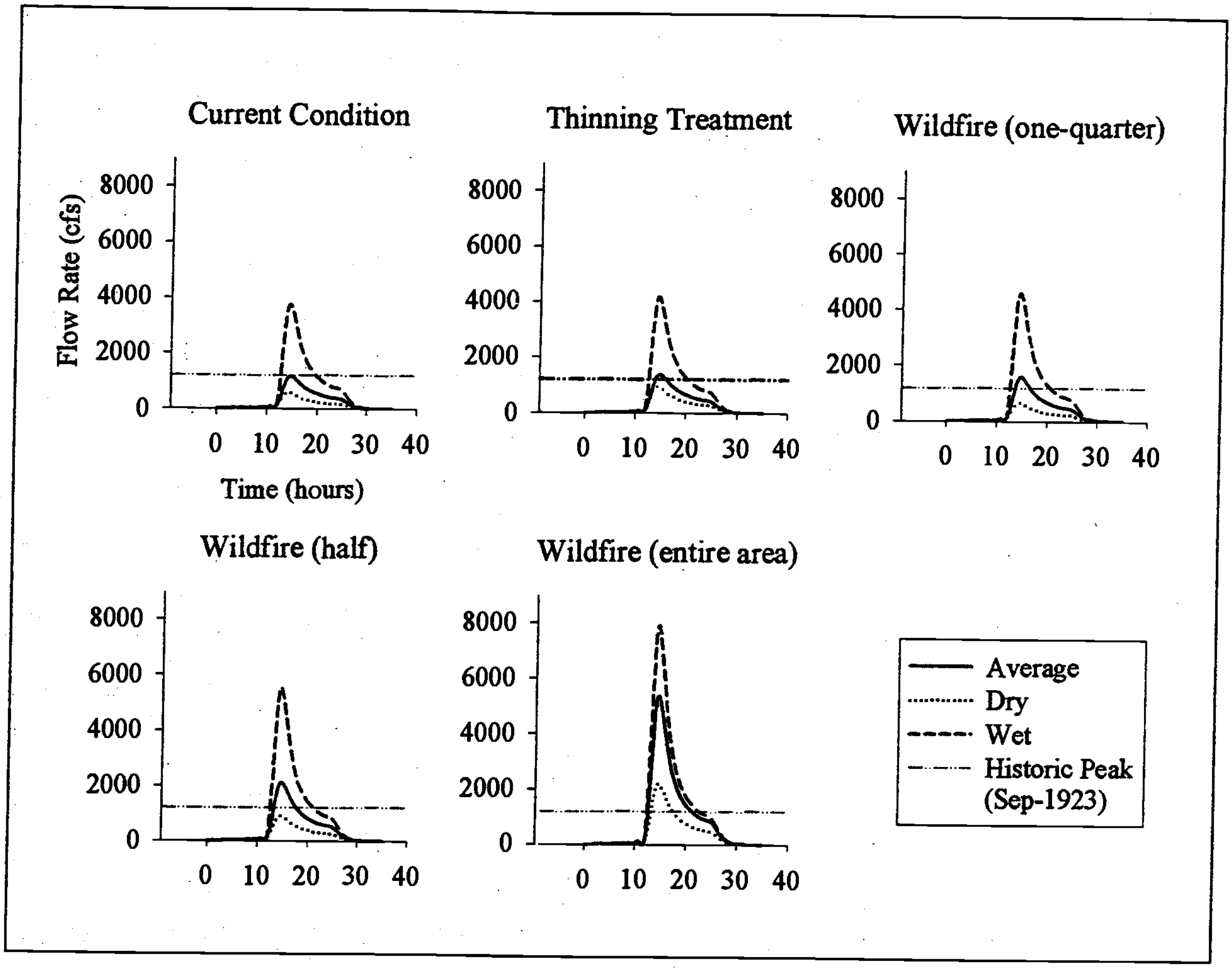

Figure 10. Hydrographs from a 100 yr storm showing peak discharges after a wildfire burned the entire watershed between 2 and 6.5 times greater than the historic peaks in all antecedent soil moisture conditions (AMC). Under average AMC the peak discharge from the current condition is equivalent to the historic mark of 1200 cfs and slightly higher at about 1500 cfs in the intensely thinned forest scenario.

million, and the costs of flooding from an extreme storm after forest thinning could possibly be less than $93 million.

The utility of the HEC-HMS model for predicting an event-based peak discharge in the upper Rio de Flag watershed may have a number of weaknesses that need proper consideration. Because the model is based on NRCS curve number methods it may not have an adequate mechanism to account for the high degree of ground water percolation in the area. The model indirectly attempts to account for the abundant faults and fissures within the watershed through some adjustment of the runoff curve number. However, the latter may not adequately explain the rapid infiltration rate in some areas of the watershed.

Another requirement of the model is the assumption of uniform precipitation distribution across the watershed. Precipitation does not fall uniformly over an area because elevation and local micro-site conditions play an important role on the distribution of precipitation. This is especially the case in Flagstaff because of the rugged topography along the slopes of the San Francisco Peaks and seasonal and local variation from frontal and convectional storm activity. However, tropical and winter storms typically cover large areas and are usually of long duration and lower intensity than summer storms (Beschta 1976). Consequently, this may explain why the model underestimated the reconstructed discharge of the July 1980 storm event.

Finally, SCS methods to predict runoff are a result of empirical data collected over much of the United States, and developed for small watersheds. As a result, local conditions for the study area may not be completely or accurately accounted for.

MANAGEMENT RECOMMENDATIONS

Several recommendations should be carried out to improve upon watershed modeling in the Rio de Flag. Other methods should be used to calibrate the current conditions of the watershed and then compare the precision of each method to real-time storm data. This will facilitate finding the best method for use in the HEC-HMS modeling software. Also, older gauging stations should be reinstated and new gauging stations should be installed in smaller watersheds using a paired-watershed approach (Viessman and Lewis 1996). The three watershed gauging stations (Hidden Hollow, Schultz Canyon, and Crescent Drive) should be reinstated because 11 years of gauging is not adequate to derive large flood events, and 11 years is a short period of record compared to the long-term meteorological data collected for Flagstaff. Paired watersheds will allow scientists to capture before and after effects from forest thinning or wildfires. Stream gauging stations should be installed in subwatersheds smaller than 100 acres and initially set aside from forest thinning. When paired watersheds are calibrated to one another (minimum 3 yr), thinning should be allowed in one of the subwatersheds while the other is a control. In addition, soil infiltration tests should be conducted in control, thinned, and wildfire affected areas to give scientists a better understanding of impacts to soil physical characteristics.

Forest thinning should continue throughout the urban interface and open forest in order to prevent wildfire. A few reasons to implement thinning as a preventative measure are that it (1) protects human life and property from fire, (2) improves forest health, (3) is less damaging to the ecosystem than a severe stand-replacing fire, and (4) allows managers to easily incorporate natural and prescribed fire into the ecosystem. After thinning is accomplished and ladder fuels and stand densities are reduced, prescribed fire should be implemented as a long-term management practice to achieve "complete" forest restoration (Covington et al. 1997). In the event of a wildfire, pinpointing the area affected and its characteristics may improve the precision of estimating peak discharges using HEC-HMS or other hydrologic models.

The Rio de Flag watershed is constantly changing its structure due to the dynamic environment around Flagstaff. We can expect variations in hydrologic phenomena over time, and continuous monitoring of management practices, land use, and the hydrology of the watershed are essential. In addition, small-scale collaborative projects to bring the community together should be implemented. These projects could include improving land management and development practices, planting riparian species, removing exotic species, and creating or enhancing greenbelts and wetlands along the stream channel (Riley 1998; Williams et al. 1997).

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